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Black spruce boreal forest soil solution inorganic nitrogen is highly resilient to 20 years of elevated nitrogen deposition

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Abstract Soil solution is the liquid phase of soil containing nutrients that are essential for vegetation's health and growth. As such, soil solution chemistry is directly related to nutrient cycling and productivity in forest ecosystems. However, the long-term impacts of elevated N deposition on boreal forest soil solution composition remain uncertain. In this study, we investigate the effects of two decades of ammonium nitrate addition applied at rates of 3 (LN treatment) and 10 (HN treatment) times the ambient N deposition on soil solution collected weekly during the snow-free period at a black spruce boreal forest site located in eastern Canada. We show that N addition corresponding to 60 years (LN treatment) and 200 years (HN treatment) of accelerated ambient N deposition had nearly no important nor lasting impacts on soil solution NO_3^- and NH_4^+ concentrations. This reveals that N deposition will most likely not significantly impact Canadian boreal forests soil solution inorganic N concentration in the future. Based on these results and along with NOx emissions data measured globally in North America and on NO_3–N deposition recorded at our experimental forest site, it is also likely that N deposition never affected Canadian forests' soil chemistry in the past, even at the peak of N emission in North America in the 70 s. Our results indicate a surprisingly strong and widespread resilience of the eastern Canadian boreal forest soil solution chemistry and inorganic N content to long-term N deposition. This resilience can be partially explained by an important N-limitation in high-latitude forest ecosystems.

Keywords Boreal forest · Forest soil · Soil solution · Inorganic nitrogen · Nitrogen deposition

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Introduction

Boreal forests constitute a massive biome covering 17% of global terrestrial land (DeLuca and Boisvenue 2012). These ecosystems play crucial roles such as sheltering biodiversity and storing large amounts of carbon (C) (Pan et al. 2011). Boreal forests are often limited by nitrogen (N) because of unfavorable N mineralization conditions (i.e., low temperature,

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acidic soil) and because they receive very low atmospheric N deposition as they are usually relatively remote from major anthropogenic N sources (e.g., agriculture, transportation, industry).

Since the nineteenth century, anthropogenic N deposition considerably increased worldwide and caused global N cycle to double (Fowler et al. 2013). More recently, NO_3^- deposition globally decreased in North America due to emission regulation policies while NH_4^+ deposition increased with intensity varying among regions (Li et al. 2016; Ackerman et al. 2019). In eastern Canada, NO_3^- deposition also decreased since the 2000s, but NH_4^+ deposition did not significantly change (Houle et al. 2015). However, human activities such as logging or mining could tend to expand toward northern latitudes with climate change (Kirilenko and Sedjo 2007) and may increase the total N deposition received by boreal forests in the future.

Elevated N deposition can strongly impact forests productivity by modifying soil chemistry, soil microbiome composition and functions, and vegetation growth (Hasegawa et al. 2021; Renaudin et al. 2023; Tian et al. 2018; Yan et al. 2017). Therefore, it is crucial to estimate the impacts of potential higher N deposition on boreal forests to plan sustainable management and exploitation strategies and preserve the integrity of this important ecosystem. Despite not being often considered, soil solution can be a robust tool to study boreal forest response to N deposition, as higher elemental concentrations in soil solution below the rooting zone indicate increasing leaching and nutrient loss for the ecosystem. Previous studies performed in East Asia and North America successfully used soil solution as an indicator of the forest N status following N addition by monitoring NO_3^- and pH over 5–15 years (Geng et al. 2020; Magill et al. 2004; Pregitzer et al. 2004; Houle et al. 2024a). In the boreal forest, similar N addition experiments showed contrasted results. A 43-years study, where 40–80 kg N ha^{-1} yr^{-1} were applied via ammonium nitrate salt addition in the Swedish boreal forest, revealed increasing NO_3^- leaching and decreasing soil solution pH, indicating N saturation (Rappe-George et al. 2013). However, in the Canadian boreal forest, 4 years of ammonium nitrate addition at rate of 30 kg ha^{-1} yr^{-1} was reported to increase NO_3^- concentration in soil solution while not impacting NH_4^+ concentration (Jung and Chang 2012). Recently, a N fertilization study using the same experimental design as in our work (i.e., experimental unit size, duration and dose of treatments, fertilizer type and application method) on a sugar maple temperate forest and a balsam fir boreal forest in eastern Canada revealed that 18 years of N addition corresponding to 54–180 years of accelerated N deposition did not significantly modify soil solution chemistry NO_3^-, NH_4^+, Ca^{2+}, and pH (Houle et al. 2024a). This suggested that some eastern Canadian forest ecosystems had an important N retention capacity and that their soil solution chemistry were highly resilient to elevated N deposition, even after almost two decades.

Alike NO_3^-, some experiments performed in temperate and boreal forests demonstrated that 4–6 years of N addition led to higher Ca^{2+} concentrations in soil solution, revealing that elevated N deposition can cause higher Ca^{2+} leaching (Jung and Chang 2012; Geng et al. 2020). Soil Ca^{2+} is an important driver of boreal forest's vegetation composition and diversity (Närhi et al. 2011). Moreover, changes in Ca^{2+} soil concentration can modify soil Ca:Al and create Al toxicity for trees and plants (Tian and Niu 2015). Therefore, higher Ca leaching caused by elevated N deposition could have deleterious consequences on forest's vegetation growth and diversity.

As they remain limited, it is essential to gather more information on the long-term consequences of N addition on soil solution chemistry in boreal forest ecosystems to better predict the consequences of potentially rising anthropogenic N deposition on high-latitude forests health and productivity.

The objective of this study was to assess the long-term impacts of high N deposition on soil solution chemistry of a black spruce–moss forest, the largest bioclimatic zone of the boreal forest covering ~ 2 million km^2 in North America (Canada's National Forest Inventory 2022). For 20 years, N deposition was simulated by chronically adding ammonium nitrate at an experimental boreal forest site located in eastern Canada. Soil chemistry was investigated by measuring ion concentrations and pH in soil solution collected in lysimeters placed at 30 cm and 60 cm depths. Previous work performed on this experimental site revealed punctual increases in soil solution NO_3^- and NH_4^+ concentrations in units receiving N addition for 3–8 years, although no persistent concentration increase occurred (Houle and Moore 2008, 2019). Similarly, recent work on a sugar maple

temperate forest and a balsam fir boreal forest site, located 300–400 km south of the study site, showed that soil solution NO_3^-, NH_4^+, and Ca^{2+} concentrations did not significantly change following 18 years of N addition using the same experimental design as in this study (Houle et al. 2024a). Based on these previous results, we predicted that 20 years of chronic N addition would similarly lead to punctual soil solution cation concentrations increase and pH decrease but that these events would remain occasional and would not translate into significant and consistent changes in soil solution chemistry. This would suggest that soil solution chemistry would be resilient to N deposition in a black spruce boreal forest but would also show a generalized resilience pattern in high-latitude Canadian forests.

Material and methods

Study site description

The study site is located in the boreal forest of the province of Quebec, Canada, within the black spruce – moss bioclimatic zone (49°12′N 73°29′W). Black spruce (*Picea mariana* [Mill.] B.S.P) is the dominating tree species, with a basal area of ~ 28.5 $m^2.ha^{-1}$ (Houle et al. 2015), followed by jack pine (*Pinus banksiana* Lamb.). The understory vegetation mainly comprises feather mosses (e.g., *Pleurozium schreberi* [Willd. ex Brid.] Mitt., *Ptilium crista-castrensis* [Hedw.] De Not.) and ericaceous shrubs (e.g., *Rhododendron* groenlandicum [Oeder] Kron and Judd). Soil and humus are respectively classified as Orthic Humo-Ferric Podzol and Mor type (Soil Classification Working Group 1998) and organic F–H horizons pH is comprised between 2.8 and 3. Mean annual temperature is 0 °C whereas mean annual precipitation is 823 mm. Ambient N deposition is very low and is estimated to 3 $kg.ha^{-1}.yr^{-1}$ (Ste-Marie and Houle 2006).

Fertilization experimental design

The site used in this study is part of a N fertilization experimental network set up in 2000 and described in detail in Houle et al. (2024b). This study site consists of 9 experimental units measuring 10 × 10 m and receiving low N treatment (LN), high N treatment (HN), or no treatment (control, C). In 2000, each experimental unit comprised between 26 and 46 trees (between 20 and 30 black spruces and between 0 and 17 jack pines). LN and HN treatments respectively corresponded to a threefold and tenfold increase of ambient N deposition measured at the beginning of the experiment in 2000. LN and HN treatments corresponded to applications of 9 $kgN.ha^{-1}.yr^{-1}$ and 30 $kgN.ha^{-1}.yr^{-1}$ respectively, and consisted of applications of a NH_4NO_3 solution supplied as four passes using a backpack sprayer (Solo, Newport News, VA, USA). Treatment application started in June 2001 and was performed once a month during the snow-free period (i.e., from June to October) every year.

Sampling and chemical analyses

In October 2000, two tension lysimeters (Soil moisture Equipment Corp., Model 1911) per experimental unit were placed at 30 and 60 cm depths. Between 2002 and 2020, soil solution was collected from lysimeters weekly between May and November. In August 2012, strong winds created a total windfall on an HN treatment experimental unit. Therefore, all the observations from the two lysimeters placed on the disturbed HN unit were discarded to avoid any bias in the statistical analysis.

Precipitation was sampled weekly year-round from a bulk collector installed at a clearing near the forest study site from 1997 to 2020. All samples were stored at 4 °C until analysis shortly after collection.

Subsequently, soil solution and precipitation samples were filtered at 0.45 µm (Nucleopore) and their pH was measured with a probe. Soil solution NO_3^- and NH_4^+ concentrations were respectively measured by ion chromatography and colorimetry (Technicon AA2), while Ca^{2+} concentration was measured by plasma emission spectrometry. Limits of detection for NO_3^-, NH_4^+, and Ca^{2+} concentrations were respectively 0.02, 0.003, and 0.005 $mg.L^{-1}$. Observations falling under the detection limits were replaced by the detection limit value divided by two.

Statistical analyses

All statistical analyses were performed with R Studio v.4.3.1. (R Core Team 2023) and figures were built with *ggplot2* package (Wickham 2016).

Temporal evolution of NO_3–N, NH_4–N, and total inorganic N precipitation concentrations and atmospheric deposition measured between 1997 and 2020 were explored using Mann–Kendall tests. Differences on the 2002–2020 period in soil solution NO_3^- and NH_4^+ concentrations between lysimeter depths and N treatments were assessed with Kruskal–Wallis tests followed by post-hoc Dunn's tests (adjusted with the Benjamini–Hochberg method), as data was not normally distributed. Additionally, linear mixed-effects models were used to test the effects of N treatment, lysimeter depth and sampling year (i.e., fixed effects) on soil solution NO_3^- and NH_4^+ concentrations. For both models, lysimeter identity was set as random effect. Finally, Kendall's tau rank correlations between soil solution NO_3^- and Ca^{2+} concentrations and NO_3^- concentration and pH were performed to study the effects of N treatments on these relationships at 30 and 60 cm lysimeter depth.

Results

Temporal evolution of NO_3 and NH_4 concentrations and deposition in precipitation and control unit soil solution

Between 1997 and 2020, NO_3–N, NH_4–N, and total inorganic N precipitation concentrations and atmospheric depositions all significantly decreased (Fig. 1; Table S1). Mean annual concentration and deposition of NO_3–N decreased notably more drastically (tau = −0.231 for concentration and tau = −0.601 for deposition) than NH_4–N mean annual concentration and deposition (tau = −0.076 for concentration and tau = −0.362 for deposition). Mean annual concentration and mean annual deposition decreased from 0.28 to 0.11 mg.L^{-1} and from 1.64 to 0.83 kg.ha^{-1}.yr^{-1} respectively for NO_3–N and from 0.14 to 0.12 mg.L^{-1} and 1.07 to 1.04 kg.ha^{-1}.yr^{-1} respectively for NH_4–N. This significant decrease of NO_3–N and NH_4–N deposition at the study site follows the evolution of global Canadian and American NOx emissions which shifted from 24.4 to 8.1 million t on the same period (Fig. 2; CEDS, 2024).

Between 2002 and 2020, NO_3^- and NH_4^+ concentrations measured in soil solution at both 30 and 60 cm depths were very low in control units (80% of NO_3^- observations and 90% of NH_4^+ observations were below 0.020 mg.L^{-1}) and underwent almost no changes over time (Fig. 3).

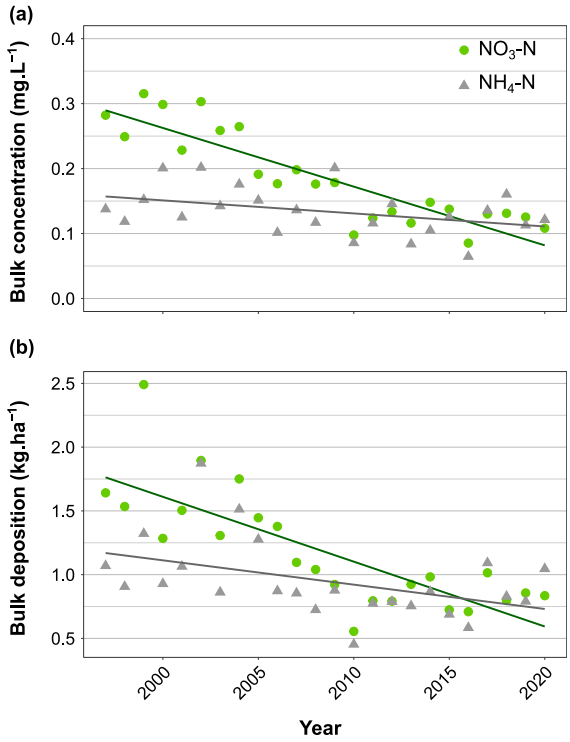

Fig. 1 Temporal variations (1997–2020) of annual NO_3–N (green dots) and NH_4–N (grey triangles) bulk precipitation concentrations (**a**) and atmospheric depositions (**b**) measured at an experimental boreal forest in Quebec, Canada. Green and grey straight lines represent linear regressions

Similarly, soil solution pH remained stable over the 20 years of the experiment but Ca^{2+} concentration slightly decreased (Fig. S1).

Effects of 20 years of N addition on soil solution chemistry

Linear mixed-effects models revealed that N treatment (F = 5.18; P = 0.02) and sampling year (F = 2.19; P = 0.002) had significant effects on NO_3^- concentrations while only lysimeter depth had a significant effect on NH_4^+ concentrations (F = 4.82; P = 0.04; Table 1), indicating that N addition had more pronounced impacts on soil solution NO_3^- than on NH_4^+ concentration.

In accordance with the models' results, soil solution NO_3^- concentration was significantly higher in HN treatment compared to LN and the control but

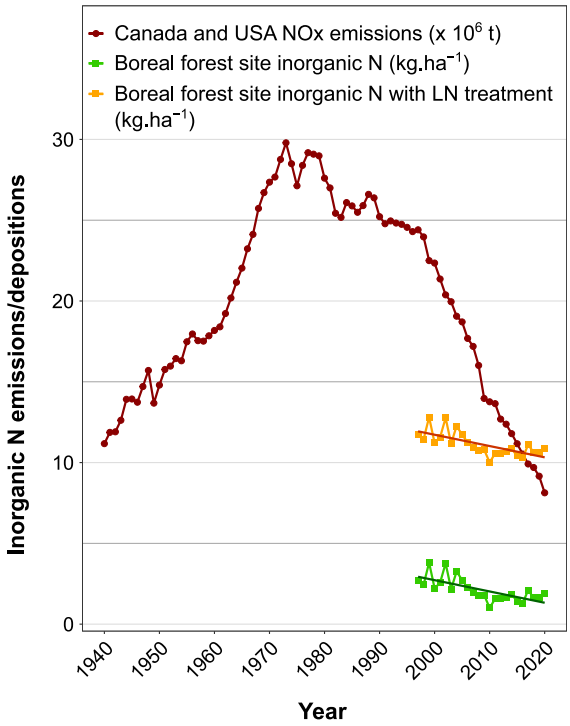

Fig. 2 Combined total NOx emissions from U.S.A and Canada measured between 1940 and 2020 (red), and inorganic N bulk deposition measured at the experimental boreal forest site used in this study between 1997 and 2020 with (orange) and without (green) N amount added via LN treatment. NOx emissions data were retrieved from Community Emissions Data System (2024). Orange and green straight lines represent linear regressions

the effects of N addition on NH_4^+ were less clear as concentrations were significantly higher in LN treatment compared to HN and the control (Fig. 4b, d; Table S2). However, differences between concentration means for each treatment were very small for both NO_3^- and NH_4^+ (Table S2), and statistically significant differences were mostly driven by occasional high concentration events, usually occurring a few days after the application of N treatments. Even under HN treatment, the vast majority of soil solution samples had very low NO_3^- and NH_4^+ concentrations, with 90% of observations being below 0.10 $mg.L^{-1}$ (Fig. 3b, d). Overall NO_3^- and NH_4^+ concentrations were also significantly lower at 60 cm than at 30 cm depth (Fig. 4a, c; Table S2).

While soil solution Ca^{2+} concentration and pH did not seem to be greatly impacted by N addition (Fig. S1), N treatments modified Ca^{2+} and pH relationships with NO_3^- (Table 2). At 60 cm depth, NO_3^- and Ca^{2+} concentrations were negatively correlated in control but positively correlated under HN treatment. At 30 cm, NO_3^- and Ca^{2+} concentrations were positively correlated for all treatments. NO_3^- and pH were also positively correlated in control and LN treatment at 30 and 60 cm depths but their correlation became negative under HN treatment at both lysimeter depths.

Discussion

Impacts of 20 years of N addition on soil solution chemistry

At the study site, overall NO_3^- and NH_4^+ soil solution concentrations were very low (Fig. 3), and a substantial number of concentration observations were below the detection limit, especially for NO_3^-. This can be explained by generally low inorganic N soil concentrations (Kranabetter et al. 2007) and low inorganic N leaching rates in boreal forest ecosystems (i.e., 0.01–0.3 $kg.ha^{-1}.yr^{-1}$; Sponseller et al. 2016). A study regrouping 33 sites located in the Swedish boreal forest similarly showed extremely low NO_3–N concentration in soil solution, averaging 0.008 $mg.L^{-1}$ at remote locations (Hellsten et al. 2015).

According to our hypothesis, 20 years of chronic N addition had weak impacts on forest soil solution chemistry. Treatment effects were only detected for NO_3^- concentrations and not for NH_4^+ (Table 1). Compared to NH_4^+, NO_3^- concentrations were respectively 2, 1.5, and 28 times higher in control, LN and HN treatment (Table S2), and seemed to fluctuate more over time (Table 1). This can be explained by the higher mobility of NO_3^- in soil, which is subsequently more prone to leaching via soil solution than NH_4^+ (Owen and Jones 2001). This is supported by the significant effect of lysimeter depth on soil solution NH_4^+ concentrations which were higher at 30 cm than at 60 cm, suggesting a greater retention of NH_4^+ at shallower soil depth (Table 1; Fig. 4a, c). However, soil solution NO_3^- and NH_4^+ responses to N addition manifested through punctual high concentration events rather than consistent concentration increases, as 80% of the concentration observations were below 0.020 $mg.L^{-1}$ (Fig. 3b, d). Considering the duration and application dose of the treatments, our results

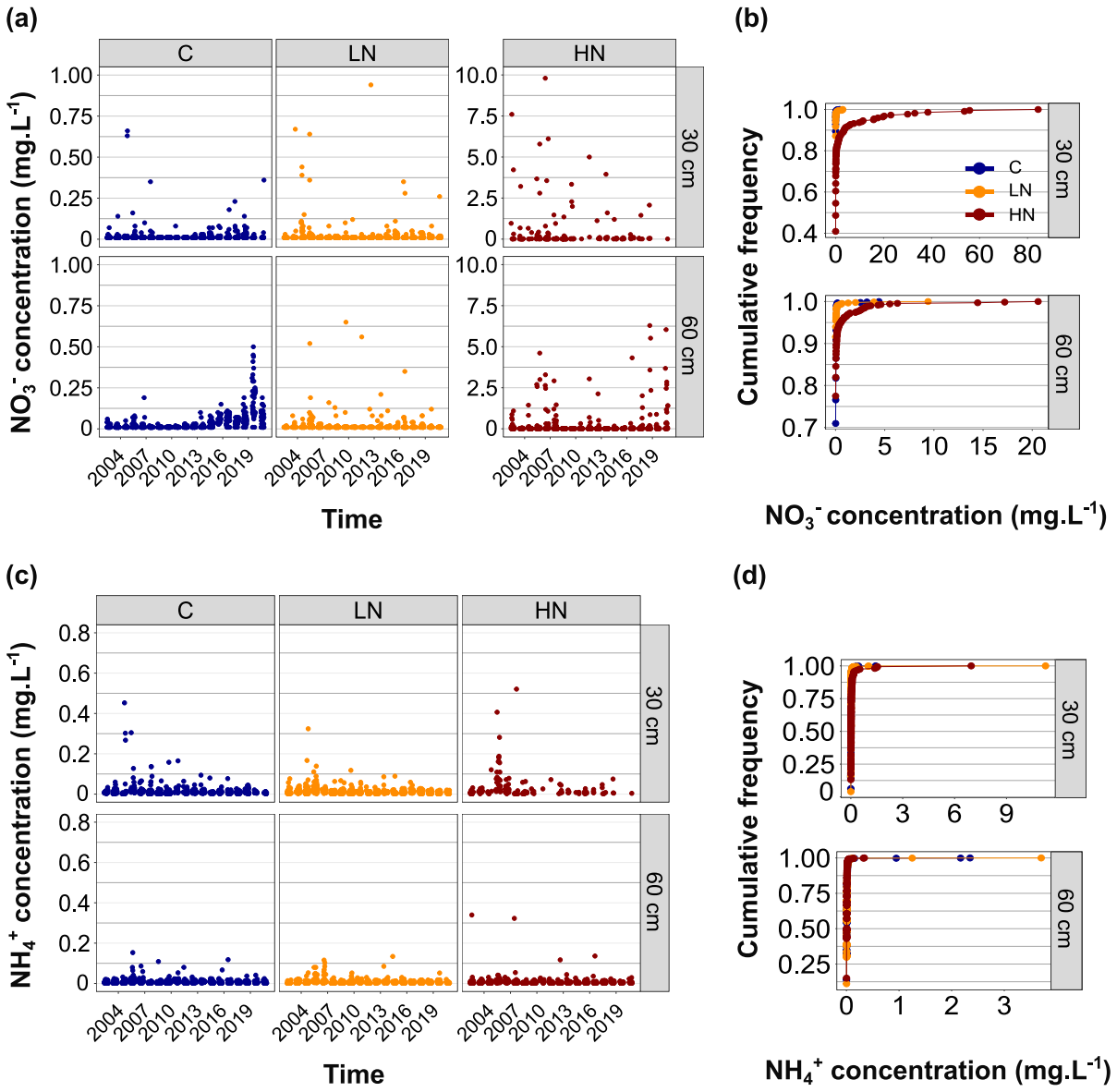

Fig. 3 Temporal variations (2002–2020) and cumulative frequencies of weekly measured soil solution NO_3^- (**a**, **b**) and NH_4^+ (**c**, **d**) concentrations at 30 and 60 cm depths at a Canadian experimental boreal forest submitted to three N treatments (control: C, low N addition: LN, and high N addition: HN). Point colors correspond to treatments. Observations from one of the HN treatment units were not included as a total windfall occurred in 2012 and greatly disturbed the unit's environment

indicate that two decades of N addition had globally very small effects on Canadian black spruce boreal forest soil solution inorganic N concentration.

Despite the low impact on NO_3^- concentration, N treatments influenced the relationships between NO_3^- and pH and NO_3^- and Ca^{2+}. Under HN treatment, soil solution NO_3^- was positively correlated with Ca^{2+} but negatively correlated with pH (Table 2). This reveals that high NO_3^- concentration caused punctual soil acidification and Ca^{2+} leaching. Soil acidification and base cations leaching following N addition are well-know phenomena that were also observed in many fertilization experiments in temperate and boreal forests (Högberg et al. 2006; Lucas et al. 2011; Tian and Niu 2015). Soil acidification can increase Ca^{2+} loss by leaching can ultimately

Table 1 Linear mixed-effects models testing the effects of N treatment, lysimeter depth and sampling year (i.e., fixed effects) on soil solution NO_3^- (a) and NH_4^+ (b) concentrations measured between 2002 and 2020 at an experimental boreal forest site. Lysimeter identity was set as random effect, and the models regroup 4477 observations for NO_3^- and 4108 observations for NH_4^+

	df	F	P^a
(a) NO_3^-			
Treatment	2	5.18	0.0239*
Depth	1	2.51	0.1392
Year	18	2.19	0.0026*
(b) NH_4^+			
Treatment	2	0.95	0.4129
Depth	1	4.82	0.0485*
Year	18	1.47	0.0903

[a] *, $P < 0.05$

impact tree nutrition and growth or modify boreal forests' vegetation composition and diversity (Närhi et al. 2011; Yadav et al. 2020). However, soil solution pH underwent small changes over time and, like NO_3^-, Ca^{2+} was driven by occasional high concentration events occurring shortly after N addition at the experimental site, and even showed a global decreasing evolution over 20 years in all experimental units (Fig. S1). Therefore, our results suggest that high N deposition would not cause durable and significant soil acidification and Ca^{2+} loss in the eastern Canadian boreal forest. This is supported by the absence of N treatment effects on soil pH and Ca^{2+} concentrations and stocks measured in organic and mineral horizons at the studied site (Houle et al. 2024b).

In our study, the annual N quantity added via LN treatment is most likely greater than the maximum ambient N deposition reached when N emissions where at their peak in the 70 s (Fig. 2; CEDS, 2024).

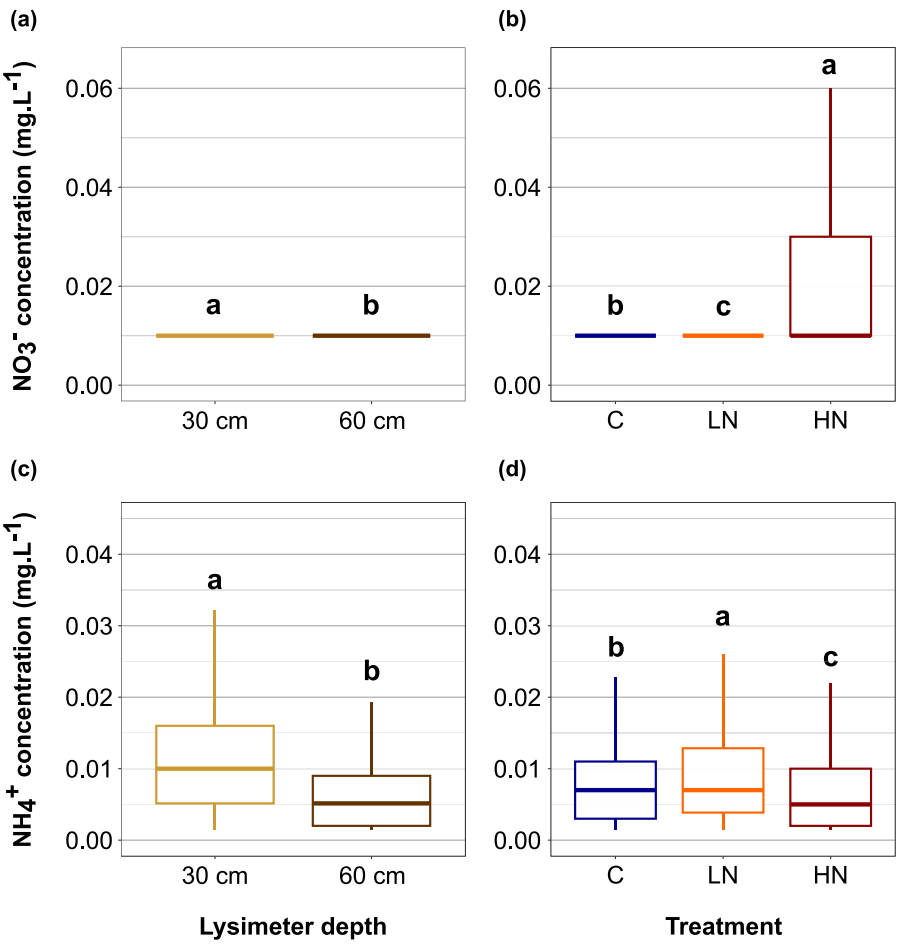

Fig. 4 NO_3^- (**a**, **b**) and NH_4^+ (**c**, **d**) concentrations in soil solution collected weekly between 2002 and 2020 at a Canadian experimental boreal forest site, at 30 and 60 cm depths, and submitted to three treatments (control: C, low N addition: LN, and high N addition: HN). Letters show significantly different concentrations between lysimeter depths and treatments. Note that only the median is visible for boxplots in panels **a** and **b** (C and LN treatments) because a substantial number of concentration observations is below the detection limit

Table 2 Kendall's tau rank correlations between NO_3^- and Ca^{2+} concentrations (a) and NO_3^- concentration and pH (b) measured in soil solution collected between 2002 and 2020 at an experimental boreal forest site submitted to three treatments (control: C, low N addition: LN, and high N addition: HN)

		Tau	Z	P^a
(a) NO_3^-–Ca^{2+}				
C	30 cm	0.087	2.83	4.71×10^{-3}*
	60 cm	−0.122	−5.12	2.97×10^{-7}*
LN	30 cm	0.101	3.47	5.16×10^{-4}*
	60 cm	0.058	2.23	2.54×10^{-2}*
HN	30 cm	0.202	3.84	1.22×10^{-4}*
	60 cm	0.125	4.41	1.04×10^{-5}*
(b) NO_3^-–pH				
C	30 cm	0.089	2.96	3.08×10^{-3}*
	60 cm	0.064	2.69	7.04×10^{-3}*
LN	30 cm	0.061	2.16	3.08×10^{-2}*
	60 cm	0.062	2.39	1.69×10^{-2}*
HN	30 cm	−0.106	−2.16	3.05×10^{-2}*
	60 cm	−0.135	4.75	2.03×10^{-6}*

[a] *, $P<0.05$

The sum of nitrogen oxide (NOx) emissions from the U.S.A (i.e., an important contributor to N deposition received at our study site) and Canada reached a maximum of 29.7 million t in 1973. In 2000 (i.e., beginning of the N addition experiment), the sum of NOx emissions from the U.S.A and Canada was estimated at 22.3 million t. As the ambient N deposition at our experimental site was measured as 3 $kgN.ha^{-1}.yr^{-1}$ in 2000, we estimated the maximum past N deposition received by our study site to be around 4 $kgN.ha^{-1}.yr^{-1}$. Therefore, the total N deposition at the study site most likely never reached LN treatment level (i.e., 9 $kgN.ha^{-1}.yr^{-1}$) and even less HN treatment level (i.e., 30 $kgN.ha^{-1}.yr^{-1}$).

Considering the near absence of LN treatment effects, we suggest that soil solution chemistry of the Canadian boreal forest was not or barely affected by past N deposition. Recently, similar resilience to 13–18 years of N addition was reported for organic and mineral soil chemistry at the same study site (Houle et al. 2024b). Moreover, 18 years of N addition also using this same experimental design on two more southerly sites located in a sugar maple temperate forest and a balsam fir boreal forest in eastern Canada similarly revealed a high resilience of soil solution chemistry to elevated N deposition (Houle et al. 2024a). This is also supported by a recent study revealing that N addition did not significantly modify soil bacterial and fungal communities' composition and diversity at the study site (Renaudin et al. 2023). These elements all point towards a strong and widespread resilience of high-latitude Canadian forests to high N deposition.

These findings greatly contrast with general observations from N fertilization experiments which often report important N accumulation in forest soils associated with soil acidification and base cations leaching (Chen et al. 2023; Tian and Niu 2015). However, elemental leaching rates greatly vary with geographic location and depend on the forest type and N status (Braakhekke et al. 2017). Boreal forests are often strongly limited by N, mainly because of their remoteness from anthropogenic sources and slow mineralization rates due to climatic and environmental conditions (Gundale et al. 2013; Du et al. 2020). In this study, extremely low NO_3^- concentrations in soil solution can suggest, in addition to a strong ecosystem's N retention capacity, low N inputs and a potential N limitation at the experimental site. In case of N limitation, extra N becoming available for the ecosystem is rapidly taken up and sequestered by vegetation and microbes (Högberg et al. 2017). Therefore, the observed resilience of the Canadian boreal forest to high N deposition could be due, at least partially, to its N limitation status causing high N retention at the ecosystem scale. This is supported by yearly analyses made between 2003 and 2014 on the study site showing that foliar N was higher in trees growing on HN treatment plots compared to LN treatment and control plots which indicated an enrichment of tree foliage under elevated N deposition (Houle et al. 2024b). This is also supported by the same study showing higher N concentration in the moss layer of our experimental site following 13 years of N addition compared to the control (Houle et al. 2024b). This result translates the high N retention capacity of boreal moss which ultimately reduces soil N availability for other organisms and lowers N leaching (Maaroufi et al. 2016; Koranda and Michelsen 2021).

Conclusion

In this work, we show that two decades of chronic N addition had weak impacts on soil solution NH_4^+

and NO_3^- concentrations in a Canadian black spruce boreal forest. The most noticeable effect of simulated N deposition was an increase of NO_3^- concentration under HN treatment. However, NH_4^+ and NO_3^- responses to elevated N were mainly driven by a greater frequency of high concentration events, as most of the observations remained low (<0.10 mg. L^{-1}). This indicates that the Canadian black spruce boreal forest soil solution chemistry can be highly resilient to high N deposition, possibly because of the strong N limitation widespread in boreal forests and inducing rapid extra N uptake by vegetation and microbes. This finding echoes similar conclusions made on a sugar maple temperate forest and a balsam fir boreal forest in eastern Canada, suggesting a generalized resilience pattern of Canadian high-latitude forest ecosystems to elevated N deposition. This also suggests that the Canadian boreal forest won't be significantly affected by potential future high N deposition, especially given the current global decrease of NO_3^- deposition in eastern North America (Gilliam et al. 2019). However, more work is needed to evaluate the impacts of other anthropogenic contaminants such as organic and metal pollutant on boreal forest ecosystems, especially with human activities developing progressively further in northern regions.

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Author contributions Marie Renaudin: Data curation; formal analysis; methodology; software; validation; visualization; writing – original draft preparation; writing – review and editing. Daniel Houle: Conceptualization; data curation; funding acquisition; investigation; methodology; resources; writing – review and editing. Jean-David Moore: Conceptualization; methodology; resources; writing – review and editing. Louis Duchesne: Data curation; investigation; resources; writing – review and editing.

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Data availability Data supporting the findings of this study is available upon request.

Declarations

Conflict of interest The authors declare they have no conflicts of interest.

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Canada's National Forest Inventory (2022) Table 14.2. Area (1000 ha) of forest land by species group, age class and boreal zone in Canada. Combined remeasured (2007–2017) and projected (2006–2017 with NFI projection system) data (Version 2, November 2022) https://nfi.nfis.org/resources/general/summaries/t1/en/BORE/pdf/bore_t14_lsage20_area_en.pdf

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