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Snowmelt periods as hot moments for soil N dynamics: a case study in Maine, USA

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Abstract The vernal transition represents the seasonal transition to spring, occurring as temperatures rise at the end of winter. With rapid snowmelt, microbial community turnover, and accelerated nutrient cycling, this is a critical but relatively under-studied period of ecosystem function. We conducted a study over two consecutive winters (2015–2016) at the Bear Brook Watershed in Maine to examine how changing winter conditions (warming winters, reduced snow accumulation) altered soil nitrogen availability and stream N export during winter and the vernal transition, and how these patterns were influenced by ecosystem N status (N-enriched vs. N-limited). Of the two study years, 2016 had a warmer winter with substantially less snow accumulation and a discontinuous snowpack—and as a result, had a longer vernal transition and a snowpack that thawed before the vernal transition began. Across both years, snowmelt triggered a transition, signaled by increased ammonium concentrations in soil, decreased soil nitrate concentrations due to flushing by meltwater, and increased stream nitrate exports. Despite the contrasting winter conditions, both years showed similar patterns in N availability and export, differing only in the timing of these transitions. The vernal transition has conventionally been considered a critical period for biogeochemical cycling, because the associated snowmelt event triggers physicochemical and biochemical changes in soil systems. This was consistent with our results in 2015, but our data for 2016 show that this may not always hold true, and instead, that warmer, low-snow winters may demonstrate a temporal asynchrony between snowmelt and the vernal transition. We also show that ecosystem N status is a strong driver of the seasonal N pattern, and the interaction of N status and changing climate must be further investigated to understand ecosystem function under our current predicted trajectory of warming winters, declining snowfall, and winter thaw events.

Keywords Vernal transition · Forest soils · Nitrogen · N-enrichment · Snowmelt

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Introduction

Winters in the northeastern USA have been changing rapidly over the last few decades, with increases in air temperature (Wuebbles et al. 2017), declines in snowfall (Burakowski et al. 2008; Contosta et al. 2019), and shorter duration of winter (Burakowski et al. 2008; Contosta et al. 2020; Hamburg et al. 2013). Because snow provides thermal insulation for soils, changing winter conditions can alter subnivean (below-snow) temperature regimes and in turn, biogeochemical cycling (Tatariw et al. 2017; Sanders-DeMott et al. 2018, 2020). The vernal transition is the seasonal change from winter to spring, brought on by increasing air temperatures and rapid snowmelt at the end of winter. Soils under snowpack experience an abrupt transition to rapid warming upon the loss of snowpack that signals the start of a biogeochemical cascade as the ecosystem begins to "wake up" (Contosta et al. 2017). This transition period is characterized by increases in soil water availability (Harpold et al. 2015) as well as the mobilization and subsequent export of labile carbon (C) and N in soils and streams (Casson et al. 2014; Fuss et al. 2016). The soil microbial community undergoes turnover and succession due to rapidly increasing soil temperatures and changing nutrient availability, with microbial cell lysis releasing C and N in the soil (Schmidt and Lipson 2004; Sorensen et al. 2020). Microbial activity also increases with warming temperatures during the vernal transition, with greater rates of soil nutrient transformations such as C and N mineralization, nitrification, and denitrification (Morse et al. 2015b). The vernal transition is thus a critical period of temperate ecosystem function, but relatively under-studied because of the practical difficulties of sampling soils during winter and snowmelt. Recent work has reported earlier onset and increased duration of the vernal transition under warming winter conditions (Groffman et al. 2012; Musselman et al. 2017; Contosta et al. 2017), but the implications for these changes on N dynamics in forest soils during a critical ecosystem transition are not well understood.

In addition to warming winters, temperate forests have also experienced elevated atmospheric N deposition over the past century. N-enriched soils exhibit greater N mineralization and nitrification rates (Perakis and Sinkhorn 2011; Patel and Fernandez 2018) and increased N losses via leaching (Lovett and Goodale 2011; Templer et al. 2012b; Patel et al. 2019) and denitrification (Templer et al. 2012a; Morse et al. 2015a). Higher N deposition rates have also been found to decrease soil microbial biomass and alter microbial community structure (Carrara et al. 2018). Despite decades of research on N dynamics in forest ecosystems, relatively few studies have examined the effects of N-enrichment during the vernal transition (Buckeridge et al. 2010; Contosta et al. 2011; Freppaz et al. 2012). N deposition in the northeastern USA has declined over the last two decades, and current research is underway to investigate forest response to these declines.

Here, we report a case study examining the interactive effects of warming winters and experimental ecosystem N-enrichment on seasonal patterns of soil N dynamics. Specifically, we asked (a) if differences in the vernal transition period alter the timing and the magnitude of N availability and mineralization; and (b) are these differences more pronounced in N-enriched compared to N-limited systems? We sampled organic soils from the N-limited and experimentally N-enriched watersheds at the Bear Brook Watershed in Maine (BBWM) during 2015 and 2016, 2 years with strongly contrasting winter characteristics. We use physical environmental parameters to define the vernal transition and report on soil and stream N dynamics for the winter to growing season periods, including the vernal transition, as well as other transient thaw periods encompassed by the winter period.

Methods

Site description

The Bear Brook Watershed in Maine (BBWM, Fig. 1) is a long-term experimental watershed in eastern Maine, USA (44° 52' N, 68° 06' W), established to study the effects of elevated N and sulfur (S) deposition on ecosystem processes. BBWM is comprised of two paired watersheds, the reference East Bear Brook (EB, 11.0 ha) and the manipulated West Bear Brook (WB, 10.3 ha), treated with bimonthly aerial applications of ammonium sulfate at the rate of 25.2 kg N ha^{-1} $year^{-1}$. Vegetation is similar in both watersheds. This research was conducted at lower elevations at the site, dominated by deciduous species *Fagus grandifolia* (American beech), *Acer saccharum* (sugar maple), and *Acer rubrum* (red maple). Soils are coarse-loamy, mixed, frigid Typic Haplorthods (Norton et al. 1999b). Average annual air temperature (2005–2014) at the site was 5.6 °C (Patel et al. 2018a, b). Additional soil characteristics are included in Table 1.

Experimental design and sampling

The experimental design consisted of three transects in each watershed, arranged in a Y-pattern, with an angle of 120° between transects. The transects were 14 m long, with sampling locations at 1-m intervals along each transect. Soils were randomly collected, one sample from each transect ($n = 3$ per watershed per sampling day), on 13 sampling days from January 2015 to July 2016. This study focused on the surface organic soils (O horizon) sampled down to the mineral interface, 3–5 cm deep. Loose leaf litter was removed from the surface prior to sampling. Soil samples were stored overnight in the laboratory at 4 °C before processing.

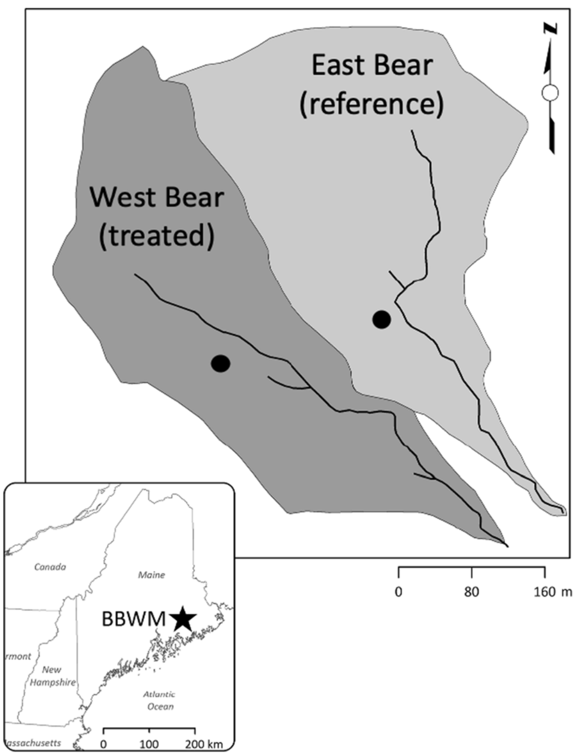

Fig. 1 Location and layout of the experimental site, Bear Brook Watershed in Maine (BBWM). The circles denote the sampling locations in the reference (East Bear, EB) and treated (West Bear, WB) watersheds. Map data sources not generated by BBWM team are as follows: US state outlines are from the National Atlas of the USA; Canadian map features are from the National Weather Service

Table 1 Summary of O horizon properties at BBWM

	East Bear (N-limited)	West Bear (N-enriched)
Organic matter % *w*/w	68	80
pH *	3.38	3.23
CEC_e $cmol_c\ kg^{-1}$ **	23	22
BS % ***	58	22
Total C %	44	41
Total N %	1.94	1.90
C/N	23	21

*pH measured using 0.01 M $CaCl_2$ 2:1 v/w

***CEC_e*, effective cation exchange capacity (Blume et al. 1990)

****BS*, base saturation (Blume et al. 1990)

Data taken from SanClements et al. (2010)

Laboratory processing and analysis

Field-moist soil samples were sieved through a 6-mm screen and homogenized before analysis. Soil available inorganic N (ammonium, NH_4^+-N and nitrate, NO_3^--N) was extracted using 2 M KCl (soil:extractant ratio 1:10), shaken for 30 min and filtered through Whatman® 42 filter paper. NH_4^+-N and NO_3^--N concentrations were determined colorimetrically (Keeney and Nelson 1982) on an Alpkem A/E ion analyzer (OI Analytics) at the Maine Agricultural and Forest Experiment Station (MAFES) Analytical Laboratory.

Stream discharge and chemistry

We examined stream discharge data for East Bear (USGS station 01022294, https://waterdata.usgs.gov/usa/nwis/uv?01022294). Stream discharge was monitored only for the EB stream, but the two streams have historically behaved in parallel, making additional WB monitoring redundant (Norton et al. 1999a). Stream samples were collected as grab samples and event samples (e.g., during snowmelt and rain events) using ISCO-automated samplers from both East Bear and West Bear streams to calculate dissolved inorganic N (DIN) exports. Stream samples were analyzed for NH_4^+ and NO_3^- using ion chromatography at the University of Maine Sawyer Environmental Research Center, and are reported here as NH_4^+-N and NO_3^--N for consistency with soil data.

Table 2 Air temperature thresholds and dates defining the seasons in this study

Season	Temperature thresholds	2015	2016
Winter (W)	< 0 °C	January 1 to April 12	December 31 (2015) to April 10
Vernal transition (VT)	0 to 10 °C	April 12 to May 4	April 10 to May 12
Growing season (GS)	> 10 °C	May 4 to October 6	May 12 onwards
Fall (F)	0 to 10 °C	October 6 to December 30	–

Temperature thresholds are for 7-day running average of air temperature. We do not include Fall 2016 because this experiment ended in September 2016

Temperature and snowpack measurements

Temperature and snowpack measurements were used to characterize the seasons across the two study years. Air and soil temperatures were recorded using Onset HOBO™ data loggers (Onset Computer Corporation, Bourne, MA, USA) (Patel et al. 2018a, b). Snowpack depth was measured on sampling dates using a meterstick. Additionally, weekly snow depth and snow water equivalent (SWE) records were obtained from the Maine Snow Survey for the site (Site ID 1117 Beddington: Maine River Flow Advisory Commission 2020).

Sampling dates were grouped into four seasonal categories—Winter, Vernal Transition, Growing Season, and Fall—defined using the 7-day moving average of daily air temperatures (Table 1). The vernal transition or "vernal window" has conventionally been defined in terms of snow-out and canopy-closure dates (Groffman et al. 2012; Contosta et al. 2017). However, snow-out date may not be an applicable metric during low-snow years (e.g., 2016; see Table 2), when the exposed soil is still frozen. Similarly, the canopy-closure metric is only applicable to hardwood forests, and therefore is not applicable universally. Therefore, for the purposes of this 2-year study, we used the available air temperature data to define the vernal transition. As defined here, the vernal transition began when the ambient conditions were permanently above freezing (i.e., 7-day moving average > 0 °C), and ended when the 7-day moving average permanently exceeded 10 °C, coincident with canopy closure in our hardwood stands (not documented here). By this definition, the vernal transition extended from April 12 to May 04 (23 days) in 2015, and from April 10 to May 12 (31 days) in 2016.

Statistical analysis

All data were log-transformed prior to statistical analysis to provide the best fit toward normal distribution with homoscedastic residuals. Student's *t* tests and one-way analysis of variance (ANOVA) were used to compare seasonal periods among soil types and years. Statistical significance was determined at $\alpha = 0.05$. All statistical analyses were conducted using R version 4.0.2 (2020-06-02). Data are archived at the Environmental Data Initiative (package ID edi.635.1, Patel et al. 2020).

Results

Meteorological parameters

The 2 years 2015 and 2016 had notably different winter conditions (Fig. 2, Table 3). The year 2016 has a warmer winter with less snow accumulation (represented as peak SWE). In 2015, snowpack persisted until mid-April. In 2016, the final snowmelt event occurred in late March, although there was a mid-winter thaw in February–March 2016 (Fig. 2).

Extractable inorganic N

When averaged across the winter to growing season period, EB soil NH_4^+-N concentrations in 2015 were twofold greater than in 2016 and WB NH_4^+-N concentrations were ~ 1.5-fold greater than in 2016 (Table 4). Overall, WB concentrations were approximately sevenfold greater than in EB. In EB soils, 2015 NH_4^+-N concentrations were highest in winter (32.8 mg kg^{-1}) and declined during snowmelt, with winter concentrations approximately threefold higher than the values reported during the vernal transition and growing season (Fig. 3a; Table 4). In EB soils in 2016, NH_4^+-N concentrations were ~ 5.0–11.0 mg kg^{-1} in winter and declined to 4.0 mg kg^{-1} during the vernal transition. In WB, NH_4^+-N concentrations in 2015 increased roughly twofold under the snowpack, peaking at ~ 140 mg kg^{-1} at the onset of the vernal transition in April, then declining

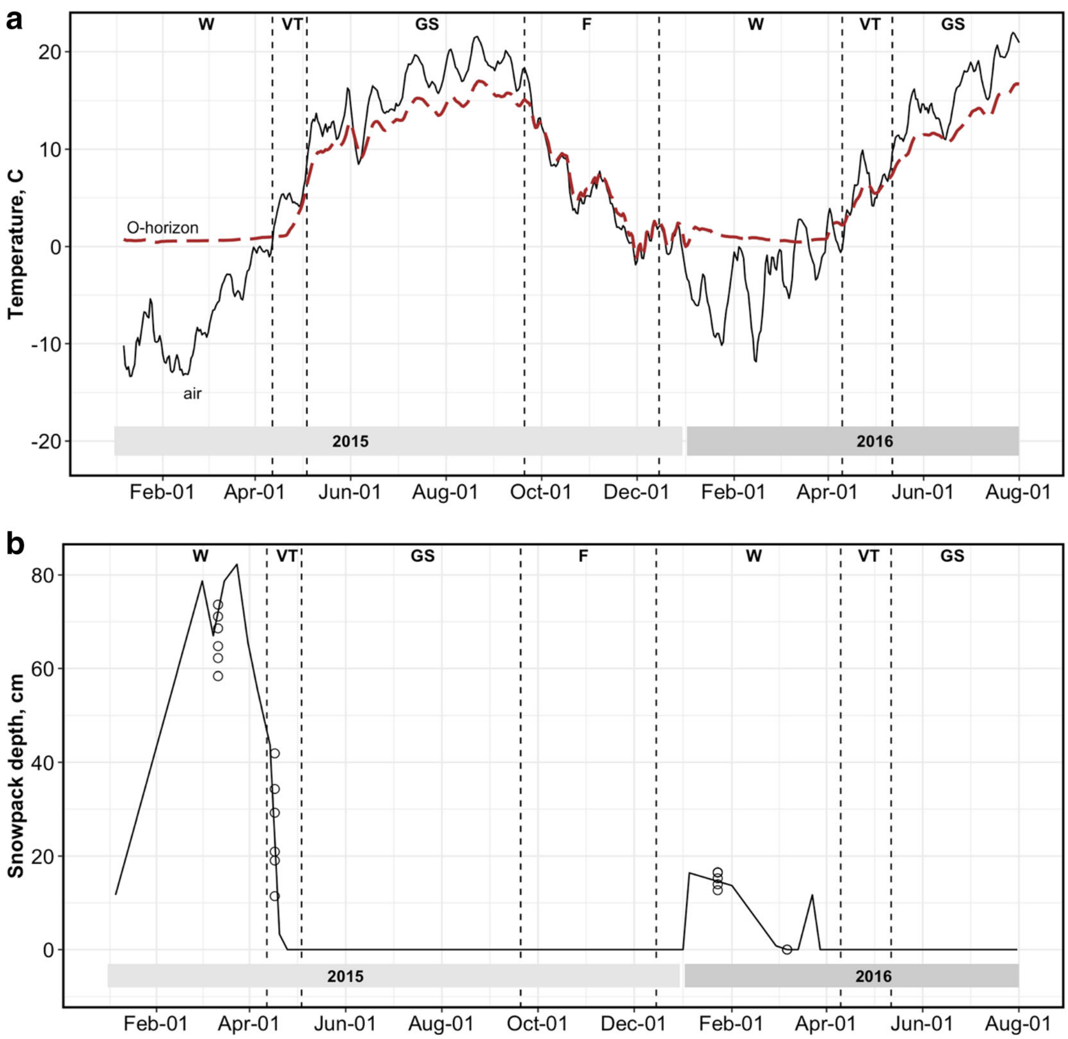

Fig. 2 **a** Air (solid line) and soil (dashed line) temperature at the Bear Brook Watershed in Maine (BBWM) during the study years 2015 and 2016. **b** Snowpack depth measured during this experiment (circles), and data obtained from the weekly Maine Cooperative Snow Survey (solid line). Dashed vertical lines mark the seasons as defined in Table 2. W, winter; VT, vernal transition; GS, growing season; F, fall

to ~ 80 mg kg^{-1} in the growing season (Fig. 3a). In 2016, NH_4^+-N concentrations were lowest (~ 11 mg kg^{-1}) under the snowpack and increased ~ 12-fold post-melt in March. Thereafter, NH_4^+-N concentrations generally declined over time, to ~ 29 mg kg^{-1} in July.

WB extractable NO_3^--N concentrations averaged 9.9 ± 1.8 mg kg^{-1} across the study period, whereas they were below 0.1 mg kg^{-1} for most of the EB soils (Table 4, Fig. 3b). In 2015, WB NO_3^--N concentrations were ~ 5 mg kg^{-1} under the snowpack, dropped to ~ 1 mg kg^{-1} during snowmelt, and thereafter increased to ~ 15 mg kg^{-1} during the growing season. In 2016, WB NO_3^--N concentrations were ~ 8 mg kg^{-1} under the snowpack and dropped to ~ 1 mg kg^{-1} during the mid-winter thaw. Post-melt, NO_3^--N concentrations increased to ~ 10 mg kg^{-1} in the growing season.

Stream flow and stream chemistry

Stream discharge also varied between the 2 years, in terms of total amount discharged, as well as temporal pattern. The total discharge for EB stream was 790.4 m^3 in 2015 and 641.5 m^3 in 2016, for the period from January 01 to July 31. The center of volume was April 20 in 2015 and April 07 in 2016, for the period from

Table 3 Temperature and snowpack metrics for the study period

	2015	2016
Average air temperature (°C)		
Winter	− 7.32 ± 0.44	− 2.68 ± 0.35*
Vernal transition	4.83 ± 0.29	6.19 ± 0.38*
Growing season	16.11 ± 0.27	-
Fall	5.73 ± 0.51	-
Average soil temperature (°C)		
Winter	0.67 ± 0.01	1.06 ± 0.06*
Vernal transition	2.42 ± 0.35	5.41 ± 0.24*
Growing season	13.32 ± 0.20	-
Fall	6.16 ± 0.46	-
Peak snow water equivalent (SWE)	21.4 cm	4.4 cm
Peak snow depth	82.3 cm	16.4 cm

Asterisks represent significant differences in temperature between years at $\alpha = 0.05$. We do not report seasonal means for growing season and fall of 2016 because temperature data collection ended in September 2016

January 01 to July 31. During 2015, highest streamflow (~ 165–170 cm gage height) coincided with snowmelt during the vernal transition, whereas in 2016, high-flow events were more frequent, and mostly occurred in the winter (Fig. 4).

Stream NO_3^--N concentrations for EB were below detection (0.0014 mg L^{-1}) for most of the year, and showed small increases (0.01–0.04 mg L^{-1}) during snowmelt. The WB stream had a base-flow NO_3^--N concentration of 0.05–0.12 mg L^{-1} during the growing season months, and peaked during snowmelt events, when concentrations were as high as 0.9 mg L^{-1}. These higher NO_3^--N concentrations were seen during the vernal transition of 2015, but during the winter thaws of 2016.

Discussion

Snow thaw as transition periods

Our results provide empirical evidence for the importance of the depth and duration of snowpack as critical drivers of soil N availability and transformation, and how the timing of snowmelt can influence temporal patterns of soil N dynamics. The thaw periods—spring snowmelt in 2015; mid-winter thaw and final snowmelt in 2016—triggered accelerated N dynamics, as reflected in soil and stream N concentrations. This research represents a case study of 2 years with dramatically different winters in terms of temperature and snowfall, yet certain patterns in soil N were common across both years:

(a) Exchangeable NH_4^+-N concentrations in WB soils increased during thaw periods, likely due to microbial inputs from the community turn-over that occurs with snowmelt (Schmidt and

Table 4 Seasonal means for extractable soil inorganic N species by year for EB (East Bear, N-limited) and WB (West Bear, N-enriched) organic soils

	EB		WB	
	2015	2016	2015	2016
Ammonium-N (mg kg^{-1})				
Winter	32.81 ± 3.07 a	8.73 ± 2.89 a**	67.26 ± 9.22 a	78.39 ± 24.58 a
Vernal transition	10.97 ± 2.41 b	5.00 ± 0.64 a*	118.28 ± 23.81 a	51.46 ± 19.05 a*
Growing season	11.11 ± 1.57 b	3.72 ± 0.79 a**	71.96 ± 15.80 a	28.87 ± 13.03 a
Average	14.68 ± 2.28	6.65 ± 1.51*	86.62 ± 12.07	61.16 ± 14.21*
Nitrate-N (mg kg^{-1})				
Winter	0.08 ± 0.00	0.10 ± 0.02	5.32 ± 3.62	4.98 ± 1.37
Vernal transition	0.11 ± 0.05	0.06 ± 0.00	12.11 ± 7.27	8.18 ± 2.29
Growing season	0.27 ± 0.15	0.06 ± 0.00	15.71 ± 5.15	10.38 ± 4.52
Average	0.18 ± 0.07	0.08 ± 0.01	12.78 ± 3.53	6.94 ± 1.27

Values reported as mean ± standard error. Different letters denote significant differences among seasons within a year at $\alpha = 0.05$. There were no differences among seasons for soil nitrate. Asterisks denote significant differences between years within a season for the watershed: $^{**}p < 0.05$; $^{*}0.05 \leq p < 0.1$

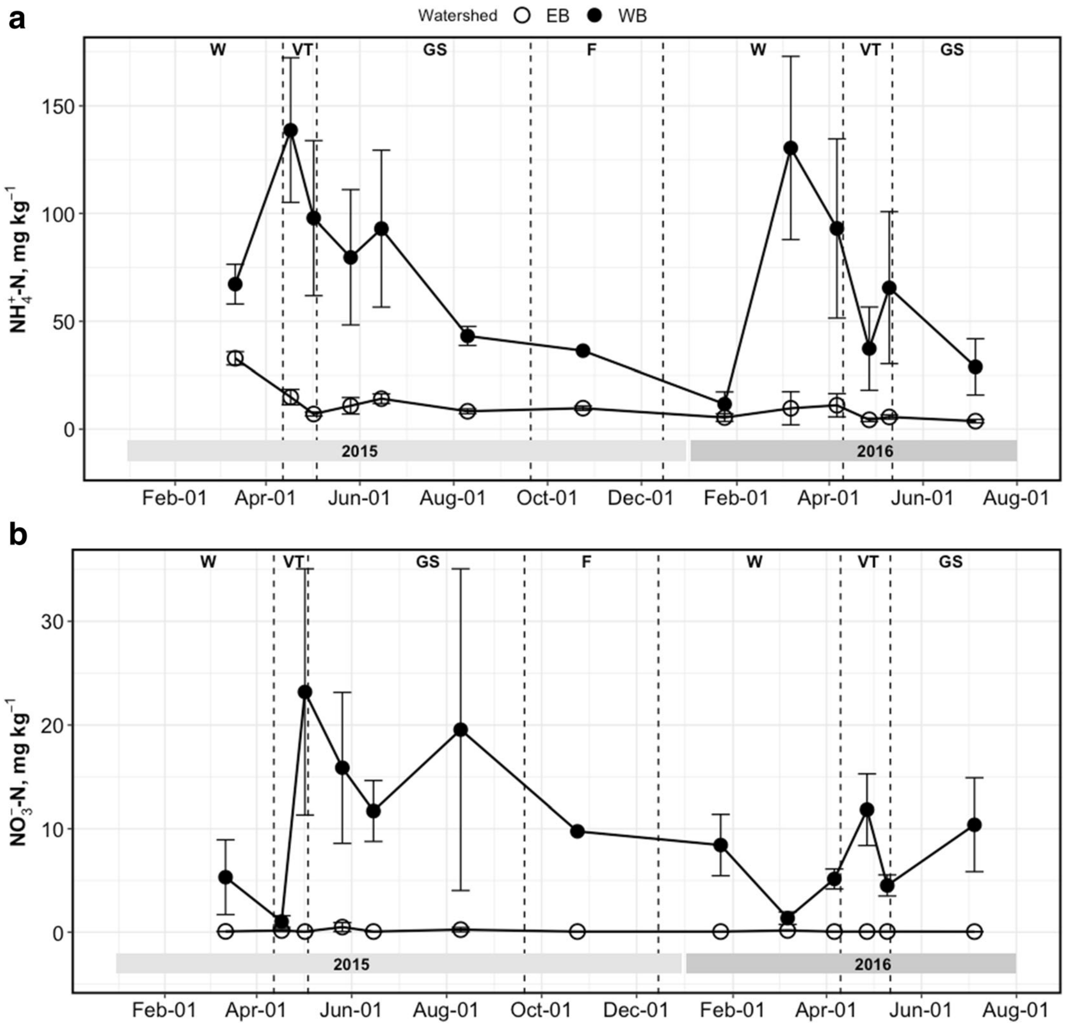

Fig. 3 (a) Extractable NH_4^+-N and (b) extractable NO_3^--N concentrations in organic soils of EB (East Bear, N-limited) and WB (West Bear, N-enriched). Dashed vertical lines mark the seasons as defined in Table 2. W, winter; VT, vernal transition; GS, growing season; F, fall

Lipson 2004; Sorensen et al. 2020). In a concurrent study in central Maine, we found that the increased NH_4^+-N concentrations during snowmelt were associated with an increase in labile organic C, suggesting inputs of microbial biomass C and N during snowmelt (Patel et al. 2018). While soil organic C characterization is beyond the scope of this study, it is likely that a similar phenomenon occurred in these soils as well. There were concurrent declines in microbial biomass during the 2015 snowmelt (26 μg/g soil in winter vs. 12 μg/g soil during snowmelt, data not presented), supporting our hypothesis of microbial cell lysis.

(b) Exchangeable NO_3^--N concentrations in WB soils declined during thaw periods, likely because NO_3^--N was flushed from the soils with meltwater, as has been described previously at BBWM and at other sites (Navrátil et al. 2010; Casson et al. 2014).

(c) Stream NO_3^--N concentrations peaked during thaw events, representing the highest values for the year. This was caused by soil NO_3^--N being flushed from the soils during thaw periods, and

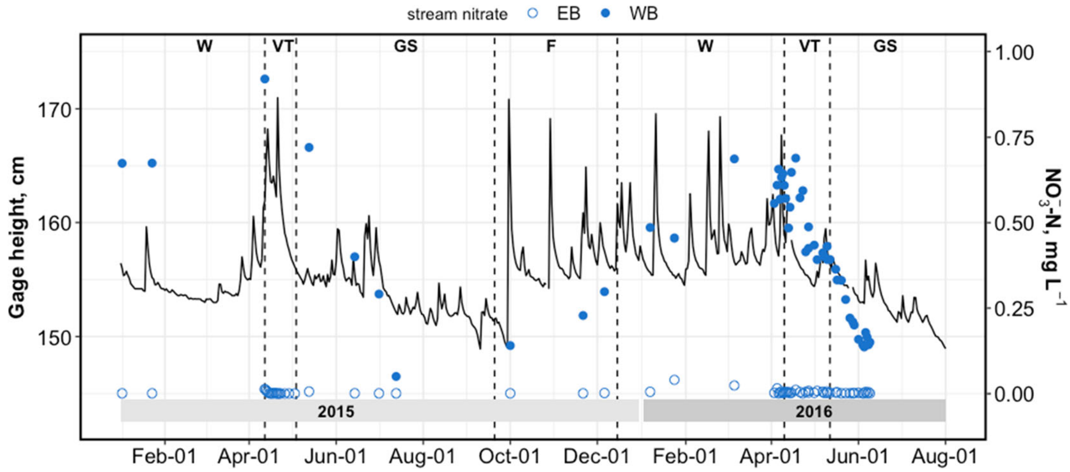

Fig. 4 Stream flow (line, primary y-axis) and stream NO_3^--N concentrations (points, secondary y-axis). Stream flow data are available only for EB stream, and stream NO_3^--N data are reported for East Bear (reference, open circles) and West Bear (treated, solid circles)

coincided with the low NO_3^--N concentrations seen in WB soils.

Despite inter-annual differences in winter soil NH_4^+-N concentrations, growing season concentrations did not differ between the 2 years (Table 3). This suggests a transient influence of winter-time disturbances like mid-winter thaws and reduced snow accumulation, although limited case study observations over 2 years should not be extrapolated to longer-term trends that may emerge with chronic changes to seasonality in these forests.

N-enrichment enhances seasonal N patterns

Multi-decadal experimental whole-ecosystem N enrichment in WB has altered soil N transformations (Patel and Fernandez 2018) and increased NH_4^+-N availability, which was especially evident during snowmelt. During snowmelt periods, NH_4^+-N concentrations in WB were 10–14-times the EB values, whereas during the growing season and fall, these differences were four- to fivefold. These seasonal differences can be attributed in part to the snow itself, as snow can be a source of N during melt periods (Bowman 1992). However, the N present in the snow was insufficient to cause the increases we observed in WB soils during snowmelt periods, as we report in Table 5. We hypothesize that the soil NH_4^+-N response between the adjacent reference and N-enriched sites during snowmelt reflects differences in microbial community composition. Fatty acid-based microbial community analysis showed that long-term N-enrichment at BBWM has decreased fungal biomass relative to bacterial biomass (Tatariw 2016), potentially resulting in a microbial community that is structurally less cold resistant (Pietikäinen et al. 2005). Thus, it is possible that soil microbial communities in WB are more sensitive to freezing, and therefore experience greater cell lysis during snowmelt compared to EB. While additional work is necessary to confirm this hypothesis, these findings suggest the possibility of this mechanism for increased labile inorganic soil N.

Implications of changing winters

The contrasting meteorological conditions between the 2 years of this study (Fig. 2; Table 3) exemplify the inter-annual variability that is becoming more frequent in our changing climate (Wuebbles et al. 2017). Despite the contrasting winter conditions, N patterns showed remarkable similarity between the 2 years, differing mainly in the timing of the NH_4^+-N and NO_3^--N "transitions" described previously (Figs. 2 and 3). While other environmental factors (e.g., soil frost, freeze-thaw cycles, and rain-on-snow events) could also influence winter/spring soil N dynamics, the interannual differences in temperature and snow accumulation (thickness and duration of snowpack) were substantial

Table 5 Ammonium (NH_4^+-N) content and changes over time in snowpack and soil in West Bear (WB) soils

Sampling date	Snow NH_4^+-N content kg ha^{-1}	Soil NH_4^+-N content kg ha^{-1}
12 March 2015	6.81	6.73
17 April 2015	2.76	13.87
	Δ = −4.05 kg ha^{-1}	Δ = +7.14 kg ha^{-1}
2 May 2015	0.00 (no snow)	9.79
	Δ = −2.76 kg ha^{-1}	Δ = −4.08 kg ha^{-1}
24 January 2016	0.01	1.17
7 March 2016	0.00 (no snow)	13.04
	Δ = −0.01 kg ha^{-1}	Δ = +11.87 kg ha^{-1}

We do not present data for East Bear (EB) soils, because those soils did not experience increases in soil NH_4^+-N concentrations during snowmelt. The Δ symbol refers to changes in snowpack NH_4^+-N content between sampling dates, with positive values indicating gain of N and negative values indicating loss of N

and likely were the driving influence on BBWM soils. There was no evidence of freeze-thaw cycles in our soils for the two winters (Fig. 2a), thus eliminating a potentially significant wintertime disturbance.

The vernal transition has conventionally been considered a critical period for biogeochemical cycling, because the associated snowmelt event triggers physicochemical and biochemical changes in soil systems. This was consistent with our results in 2015, but our data for 2016 show that this may not always hold true, and instead, that warmer, low-snow winters may demonstrate a temporal asynchrony between snowmelt and the vernal transition. Additionally, as soils in warmer and more variable winters may see more frequent freeze-thaw events ("winter weather whiplash"; see Casson et al. 2019), the N stored in the soils, which is normally leached in a single major event during the vernal transition, may be lost over a longer period during the winter, and may not be available for plant uptake in the spring. As northeastern forests are N-limited, any additional loss of N from the site can also have implications for productivity. During a period of accelerating climate change and declining N deposition, further losses of N could exacerbate stressors on forest ecosystem health (Groffman et al. 2018).

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