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Short Communication
Palsa Uplift Identified by Stable Isotope Depth Profiles and Relation of $\delta^{15}N$ to C/N Ratio

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ABSTRACT

Palsas develop as permafrost aggradation uplifts peat out of the zone influenced by groundwater. Here we relate $\delta^{15}N$ values to C/N ratios along depth profiles through palsas in two peatlands near Abisko, northern Sweden, to identify perturbation of the peat. The perturbation by uplift as well as the potential nutrient input from the adjacent hollows can be detected in soil $\delta^{15}N$ values when related to the C/N ratio at the same depth. Nine out of ten profiles show a perturbation at the depth where peat was uplifted by permafrost. Palsa uplift could be detected by the $\delta^{15}N$ depth pattern, with the highest $\delta^{15}N$ values at the so-called turning point. The $\delta^{15}N$ values increase above and decrease below the turning point, when permafrost initiated uplift. Onset of permafrost aggradation calculated from peat accumulation rates was between 80 and 545 years ago, with a mean of 242 (±66) years for Stordalen and 365 (±53) years for Storflaket peatland. The mean ages of permafrost aggradation are within the Little Ice Age. Depth profiles of $\delta^{15}N$, when related to C/N ratio, seem to be a suitable tool to detect perturbation and uplift of palsas. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: degradation; stable nitrogen isotopes; soil profiles; permafrost aggradation; Little Ice Age; perturbance

INTRODUCTION

The areal extent of palsa peatlands in discontinuous permafrost regions is projected to decrease dramatically due to the rapid warming in high northern latitudes (Fronzek *et al.,* 2006; de Jong *et al.,* 2010). Thawing of permafrost due to increasing temperatures could release carbon (C) from these peatlands (Dorrepaal *et al.,* 2009; Schuur *et al.,* 2009; Treat and Frolking, 2013). In addition, the perturbation of palsa peatlands in the Subarctic has ecological consequences for these unique peatland ecosystems (Luoto *et al.,* 2004).

Ratios in the natural abundance of stable isotopes (e.g. $\delta^{15}N$) reveal biogeochemical processes in oxic soils (Nadelhoffer *et al.,* 1996; Högberg, 1997; Robinson, 2001) and peatlands (Alewell *et al.,* 2011; Krüger *et al.,* 2014, 2015), and might also indicate perturbation of soils and ecosystems (Robinson, 2001; Conen *et al.,* 2013). Studies from northern Sweden have shown that $\delta^{15}N$ relates to nitrogen (N) loss from forest ecosystems (Högberg, 1990; Högberg and Johannisson, 1993). Boeckx *et al.* (2005) showed the relationship between $\delta^{15}N$ and total N indicates ecosystem resilience against disturbance.

The decomposition rate of soil organic matter accelerates under aerobic conditions, resulting in a greater loss of the lighter isotope (^{14}N) compared to the heavier isotope (^{15}N) (Nadelhoffer and Fry, 1988). Decomposers preferentially use the lighter ^{14}N, which leads to a relative enrichment of ^{15}N in the remaining soil organic matter (Högberg, 1997; Robinson, 2001). Another factor influencing soil $\delta^{15}N$ values can be mycorrhizal N transfer to plants, which enriches ^{15}N in fungi and the remaining organic material (Lindahl *et al.,* 2007; Hobbie and Hobbie, 2008). However, this enrichment does not account for all $\delta^{15}N$ changes; other soil processes, such as discrimination during decomposition, influence the $\delta^{15}N$ signal of a soil (Hobbie and Ouimette, 2009). Changes in N cycling can accelerate the loss of mobile forms of N, which are usually depleted in ^{15}N compared to bulk soil (e.g. NO_3^-, N_2, N_2O, NH_3^+), and enhance $\delta^{15}N$ values in the soil N pool they leave behind

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when they are lost via leaching or gaseous emission (Conen *et al.,* 2013). Simultaneously, C/N ratios decrease with progressing decomposition because of a relatively faster release of C over N during this process (Nadelhoffer and Fry, 1988).

Palsas are peaty permafrost mounds possessing a core of alternating layers of segregated ice and peat or mineral soil material (van Everdingen, 1998). Their uplifted nature leads to nutrient-poor and ombrotrophic conditions (Luoto *et al.,* 2004) because the mounds are outside the influence of groundwater. Several techniques can determine the time of palsa uplift, for example macrofossil analysis or pollen and peat stratigraphy, combined with radiocarbon dating (Seppälä, 2005). Stable carbon isotopes combined with peat accumulation rates have been used to determine the timing of uplift of palsas (Alewell *et al.,* 2011; Krüger *et al.,* 2014). A combination of macrofossil analysis and isotopic measurements has proven suitable for reconstructing the ecological conditions in a palsa peatland (Andersson *et al.,* 2012).

Recently, Conen *et al.* (2013) showed how the relation between δ^{15}N and C/N ratio can reveal *a priori* a perturbation in soil N cycling for different ecosystems in northern Eurasia. Soil δ^{15}N is within a relatively narrow range of values for any particular C/N ratio at unperturbed sites (Conen *et al.,* 2013). An accelerated metabolism of organic matter (e.g. mineralisation, nitrification, denitrification) increases or decreases δ^{15}N values beyond this narrow range, thereby indicating a recent or ongoing soil perturbation.

The aim of this study was to apply Conen *et al.*'s (2013) empirical model, which was developed for oxic mineral soils (including organic layers), to palsa peatlands in order to detect perturbation of these soils and to identify permafrost aggradation. We subscribe to the key implication of the model by Amundson *et al.* (2003), which is that bulk δ^{15}N of the soil N pool is determined only by the isotopic values of N inputs and losses. Furthermore, we assume that isotopic values of inputs and losses in palsa peatlands are determined by the same processes that have shaped the δ^{15}N values of soils on which our empirical model is based. Regarding absolute δ^{15}N values of inputs (N assimilation by nitrogenase, NO_3^- deposited with precipitation) we have good confidence in this assumption. Even larger differences in the relative contribution from either source would have little effect because δ^{15}N values of both sources are very similar (close to 0‰). Our confidence that N losses carry similar absolute δ^{15}N values in palsa peatlands and the empirical model is less strong because different pathways of N loss are associated with different δ^{15}N values (Robinson, 2001) and the relative importance of a pathway may differ between oxic and anoxic soils. In relative terms, we expect an increase of δ^{15}N values at the time (i.e. depth in the peat stratigraphy) when permafrost lifted the peat above the influence of groundwater, thereby: (i) accelerating mineralisation; and (ii) increasing N fixation by microorganisms under now aerobic conditions and ultimately N assimilation by plants due to higher growth rates (Figure 1). The C/N ratio of peat on the palsa can change by two factors. First, uplift by permafrost increases aeration, thereby accelerating mineralisation. This will decrease the C/N ratio, in addition to the expected increase in δ^{15}N. Second, ecological conditions before and after uplift will lead to vegetation changes and, possibly, related changes in the C/N ratio of input material (Figure 1). Since we do not have data on C/N ratios of plant material collected before and after palsa formation, we cannot account for this second factor, which may also have influenced C/N ratios.

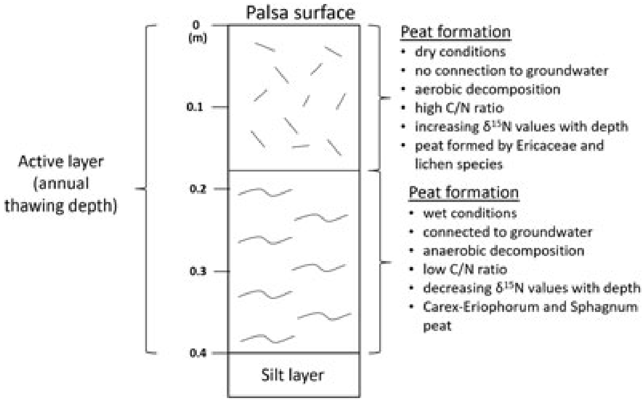

Figure 1 Schematic figure of a palsa profile. Peat formation occurred under dry and aerobic decomposition in the upper part of the profile (after uplift by permafrost) and under wet and anaerobic decomposition in the deeper part of the profile (before permafrost aggradation). All peat material was lifted up by permafrost out of the influence of groundwater.

We hypothesise that: (i) the empirical model by Conen *et al.* (2013) can locate in the profile the caused by palsa formation; and (ii) the time of permafrost-induced uplift can be identified by combining δ^{15}N depth profiles with peat accumulation rates.

MATERIALS AND METHODS

We took soil samples from two palsa peatlands, Stordalen and Storflaket, which are situated in the Torneträsk valley near Abisko (68°21′N, 18°49′E) in northern Sweden. The region is located in the discontinuous permafrost zone, 200 km north of the Arctic Circle. Onset of peatland formation has been dated at about 4700 and 6000 cal. years BP in the southern and northern part of the Stordalen peatland, respectively (Kokfelt *et al.,* 2010). All peatlands in this study have drier, elevated parts with underlying permafrost and adjacent, deeper and wetter parts (called hollows). The investigated palsas are physically separated from the groundwater due to permafrost aggradation. Permafrost onset was estimated to start at the peatlands in this region about 700–800 years ago (Malmer and Wallén, 1996; Kokfelt *et al.,* 2010). The active layer is about 0.5–0.6 m. In September and October 2012, peat cores were collected from palsas at the two peatlands, in three replicates per site (detailed site and sampling description in Krüger *et al.* (2014)). Samples described by Alewell *et al.* (2011) that were taken in June 2009 from the same two palsa peatlands were also used for this study. Samples of the entire layer that had thawed by that time were taken with a cylindrical soil auger (Giddings Machine Company, Windsor, CO, USA). Cores were cut into 20 mm sections in the laboratory and oven dried at 40 °C for 72 h. The uppermost bulk sample includes the living vegetation of the palsa peatland and represents the vegetation signal. All samples were ground and homogenised in a vibrating ball mill (MM 400, Retsch, Haan, Germany). Samples from 2012 were analysed for stable nitrogen isotopes, organic C and total N concentrations with a isotope ratio mass spectrometer (Thermo Finnigan, Delta plus XP coupled with a Flash EA 1112 Series elemental analyser; both instruments supplied by Thermo-Finnigan, Waltham, MA, USA) following standard processing techniques. Stable nitrogen isotope as well as C and N content analyses (samples from 2009) were accomplished using a continuous flow isotope ratio mass spectrometer (DELTA$^{\text{plus}}$XP, Thermo Finnigan, Bremen, Germany) coupled with a FLASH Elemental Analyzer 1112 (Thermo Finnigan, Milan, Italy) combined with a CONFLO III Interface (Thermo Finnigan, Bremen, Germany) following standard processing techniques. Stable nitrogen isotope ratios are reported as δ^{15}N (‰) relative to the atmospheric nitrogen standard with instrumental standard deviation of 0.15 per cent. The C/N ratio represents the atomic relationship between organic C and total N content of the peat material.

The turning point is defined as the highest δ^{15}N value in the depth profile with increasing values above and decreasing values below it. Regression analysis of δ^{15}N and depth was carried out with the software R2.15.1 (R Core Team, 2012). Ages of the turning points were determined based on peat accumulation rates for palsas reported in Alewell *et al.* (2011), with mean peat accumulation rates of 0.5 mm year^{-1} for palsas at Stordalen and 0.55 mm year^{-1} for palsas at Storflaket peatland. To test each sample for signs of perturbation, a δ^{15}N value for unperturbed soil was calculated from the measured C/N ratio based on the equation in Conen *et al.* (2013):

$$\delta^{15}\mathrm{N}[‰] = \frac{46.16}{\sqrt{\mathrm{C/N}}} - 8.76. \qquad (1)$$

Samples for which the measured δ^{15}N value deviates by more than 2.4 per mil (this encompasses 94% of the unperturbed samples in the study by Conen *et al.* (2013)) from the calculated, unperturbed value are defined as perturbed. Other samples are defined as unperturbed.

RESULTS AND DISCUSSION

Samples from the two palsa peatlands in northern Sweden have δ^{15}N values ranging from −5.2 to 5.7 per mil and C/N ratios from 14 to 160 (Figure 2). The δ^{15}N values are within the range of peatlands from the Subarctic/Arctic region (Jones *et al.,* 2010; Andersson *et al.,* 2012) and soils with tundra vegetation (Nadelhoffer *et al.,* 1996). Within this system many different fractionation effects, such as mycorrhizal N transfer, denitrification or gaseous losses, can influence the isotopic composition (Hobbie and Ouimette, 2009). Peat C/N ratios cover a wide range. Larger values are found in the upper part of the profiles and smaller values in deeper parts (Krüger *et al.,* 2014). Greater C/N ratios typify peatlands or peat sequences that accumulate during ombrotrophic conditions, whereas smaller C/N ratios are common for minerotrophic conditions (Andersson *et al.,* 2012). This is comparable to the species common on palsas (*Eriophorum vaginatum*) and bogs (*Sphagnum* spp.), which have mean (± SD) C/N values of 39 ± 24 and 46 ± 18, respectively, and species common in fens, such as *Eriophorum angustifolium* and *Carex* spp. with C/N values of about 19 ± 0.4 and 25 ± 3, respectively (Hodgkins *et al.,* 2014). Thus, a change in ecological conditions and hence vegetation can affect the C/N ratio of the remaining peat material.

The δ^{15}N values of most of our samples are within the uncertainty envelope of ±2.4 per mil of Eqn 1, whereas some are situated outside, indicating a perturbation (Figure 2). Samples above the uncertainty envelope indicate an accelerated N loss, whereas samples below indicate an accelerated N gain (Conen *et al.,* 2013). A rapid N loss is most probably due to the change in decomposition processes (anaerobic to aerobic conditions) as permafrost growth locally uplifts part of the peatland. Under anaerobic conditions there is little mineralisation, and hence little NH_4^+ is released and little N is lost in the form of (isotopically light) NO_3^-, N_2O or N_2. As a result, the δ^{15}N values of the soil are close to the δ^{15}N of the (isotopically light) input material (plants). As the material becomes oxic due to palsa formation, mineralisation accelerates, various forms of (isotopically light) N are lost (NH_4^+, NO_3^-, N_2O, N_2) and the remaining material becomes enriched in ^{15}N.

All depth profiles, except one, indicate a perturbation at the soil depth of the turning point (Figure 3). Samples directly above the turning points are also mostly classified as perturbed. They indicate a loss of ^{15}N-depleted forms, resulting in larger δ^{15}N values with decreasing C/N ratios and suggest continuing influences of change to the peat biogeochemistry due to uplift by permafrost. Most of the youngest samples, close to the profile surfaces, are classified as unperturbed, indicating that the ecosystem has adapted to the new conditions in the palsas. A rapid N gain, indicated by δ^{15}N values below the uncertainty envelope of Eqn 1, is mainly found in deeper samples and could be due to their proximity to the underlying silt layer and potential cryoturbation. The cryoturbation, a mixing of the peat and silt material, lowers C/N ratios, but probably maintains the δ^{15}N value. Furthermore, lateral flow of water from the surrounding minerotrophic hollows may enhance the N concentration in deeper parts of the palsa complex. The uplift changes the N source as the peat no longer receives nutrients from groundwater, but solely from the atmosphere. This could also influence the isotopic N signal of the peat. The relationship of δ^{15}N and C/N ratio in depth profiles

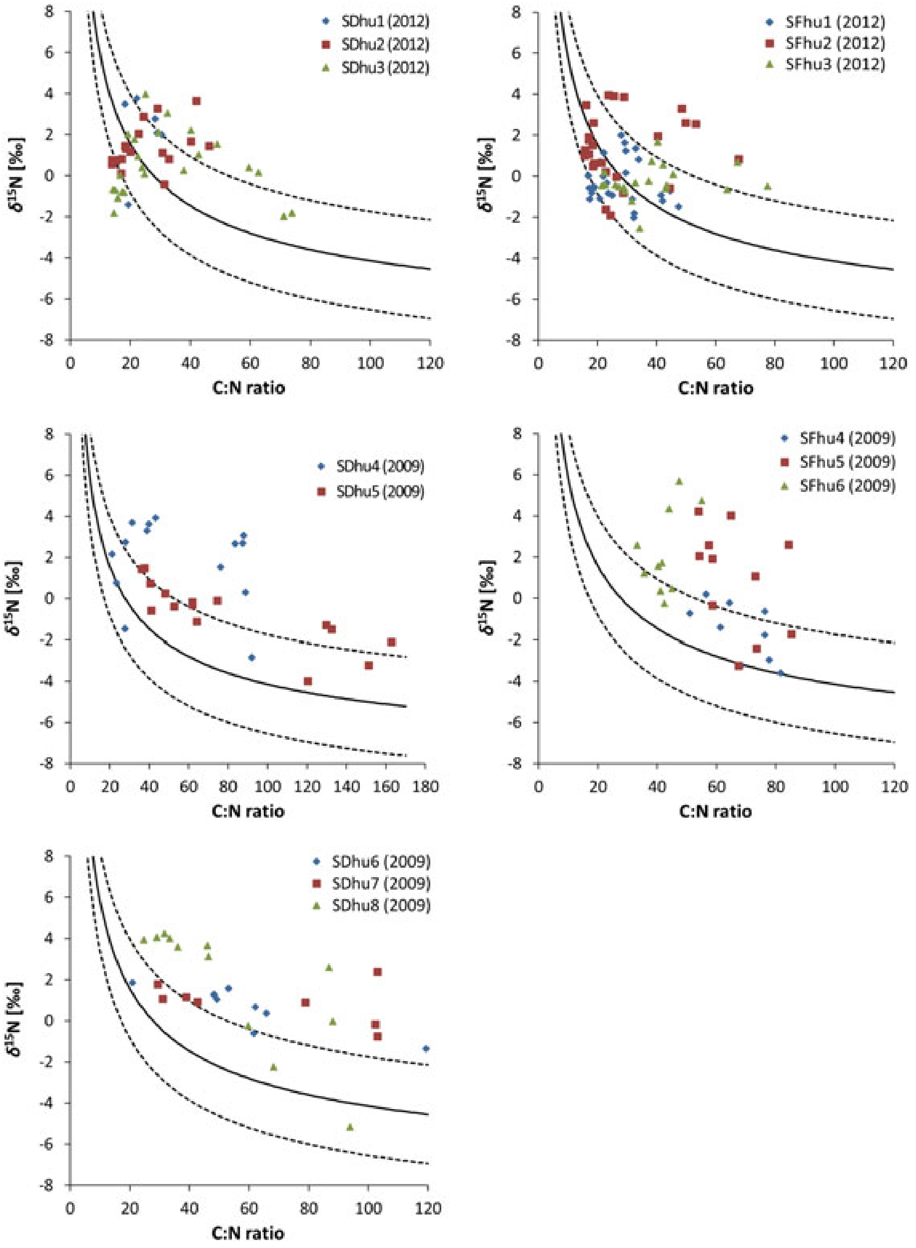

Figure 2 Relationship between δ^{15}N and C/N ratio at the palsas in the Stordalen (SD) and Storflaket (SF) peatland in northern Sweden. The relationship given by Conen *et al.* (2013) was used to classify unperturbed samples (located inside the uncertainty envelope) versus perturbed samples (located outside the uncertainty envelope). [Colour figure can be viewed at wileyonlinelibrary.com]

indicates a change in N cycling of these two peatlands during and after palsa formation.

Palsa uplift leads to a change in decomposition processes in the soil and is indicated by a turning point in the isotope profile (Figure 3). These soil depth patterns of δ^{15}N are also possible in ecosystems where N is not a limiting factor (Hobbie and Ouimette, 2009) but in peatlands N is usually a limiting nutrient. Six of eight at Stordalen, and five of six profiles at Storflaket, reveal a δ^{15}N depth pattern with a turning point (Figure 3). The change from increasing to decreasing δ^{15}N values with depth is supported by linear regression analyses in the upper and deeper part of the profiles (Table 1). All analyses of the upper part present a positive relationship between δ^{15}N and depth and all in the deeper part, except one, a negative relationship. The increase in δ^{15}N values by about 2–6 per mil from the upper part of the profile to the deeper-lying turning point corresponds to the increase in δ^{15}N values with depth in oxic tundra soils (Nadelhoffer *et al.,* 1996). Faster decomposition of soil organic matter results in N isotope fractionation with more

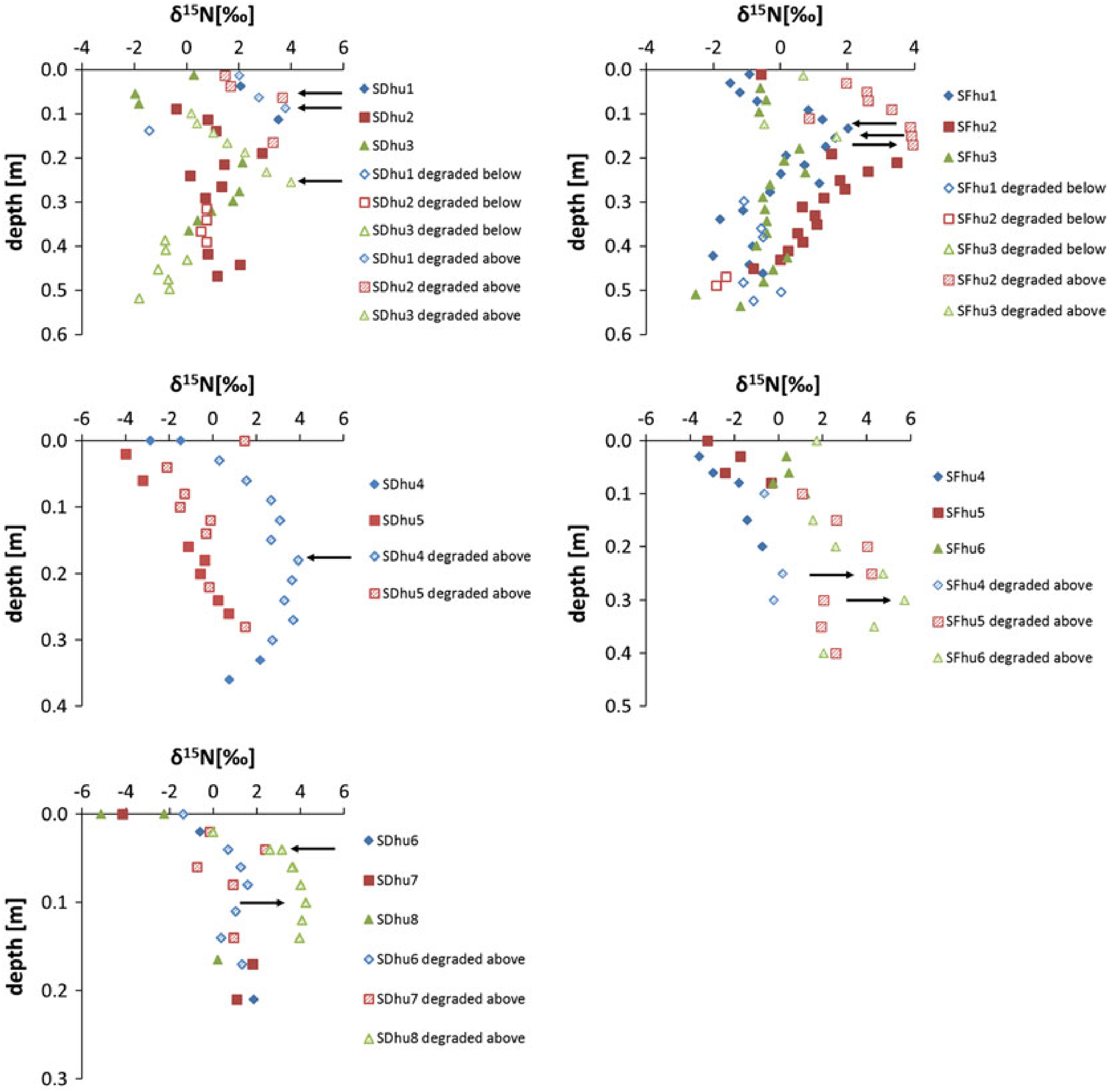

Figure 3 δ^{15}N depth profiles of palsas in the Stordalen and Storflaket peatland. Perturbation of the soil samples was tested by applying the equation given by Conen *et al.* (2013) with the relationship between δ^{15}N and C/N ratio (Figure 2). Unperturbed samples are located inside the uncertainty envelope and are displayed as filled symbols in the depth profiles. Samples that are below the uncertainty envelope are displayed as blank symbols and samples above the uncertainty envelope as striped symbols. Arrows indicate the turning point. [Colour figure can be viewed at wileyonlinelibrary.com]

positive δ^{15}N values in older soil organic matter and a decrease in the C/N ratio (Nadelhoffer and Fry, 1988). The highest δ^{15}N values at depth, where peat was uplifted by permafrost, could also be detected in a Russian peatland and is supported by the composition of the plant macrofossils and other geochemical measurements in the same peat profile (Andersson *et al.,* 2012). The change from fen to bog due to permafrost aggradation was evident in macrofossil and isotopic measurements (Andersson *et al.,* 2012). The uplift of peat and a corresponding change from minerotrophic to ombrotrophic conditions is supported by the large C/N ratios in the upper part and low C/N ratios

Table 1 Regression analyses of δ^{15}N (‰) and depth (mm) at palsas of the Stordalen and Storflaket peatlands with depth, δ^{15}N value and calculated peat age at turning points.

Site	Core (sampling year)	Turning point				Correlation coefficient			
		Depth (mm)	δ^{15}N (‰)	Age[a] (years)	Mean (± SE) age[a] (years)	Upper part		Deeper part	
Stordalen	SDhu1$_{(2012)}$	88	3.8	175	242 (±66)	$0.94^{\text{n.s.}}$	$n = 4$	$-0.89^{\text{n.s.}}$	$n = 3$
	SDhu2$_{(2012)}$	63	3.7	126		$0.91^{\text{n.s.}}$	$n = 3$	$-0.26^{\text{n.s.}}$	$n = 17$
	SDhu3$_{(2012)}$	254	4.0	508		0.87***	$n = 11$	−0.89***	$n = 13$
	SDhu4$_{(2009)}$	180	3.9	360		0.92**	$n = 8$	−0.89**	$n = 7$
	SDhu5$_{(2009)}$	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.
	SDhu6$_{(2009)}$	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.
	SDhu7$_{(2009)}$	40	2.4	80		$0.99^{\text{n.s.}}$	$n = 3$	$0.12^{\text{n.s.}}$	$n = 7$
	SDhu8$_{(2009)}$	100	4.2	200		0.88**	$n = 10$	$-0.84^{\text{n.s.}}$	$n = 4$
Storflaket	SFhu1$_{(2012)}$	134	2.0	243	365 (±53)	0.92**	$n = 7$	−0.71***	$n = 20$
	SFhu2$_{(2012)}$	170	4.0	309		0.73*	$n = 9$	−0.93***	$n = 17$
	SFhu3$_{(2012)}$	151	1.7	275		$0.29^{\text{n.s.}}$	$n = 6$	−0.76**	$n = 15$
	SFhu4$_{(2009)}$	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.
	SFhu5$_{(2009)}$	250	4.2	455		0.96***	$n = 8$	$-0.61^{\text{n.s.}}$	$n = 4$
	SFhu6$_{(2009)}$	300	5.7	545		0.87**	$n = 9$	$-0.99^{\text{n.s.}}$	$n = 3$

n.d. = not detected, n.s. = not significant,
*$p < 0.05$,
**$p < 0.01$,
***$p < 0.001$.
[a] Based on peat accumulation rates from Alewell *et al.* (2011) with mean peat accumulation rates of 0.5 mm year^{-1} for Stordalen and 0.55 mm year^{-1} for Storflaket peatland.

in deeper parts of the peat profiles (Krüger *et al.,* 2014). In some other peat cores from Stordalen the same C/N patterns were found, with a marked change in the C/N ratio from large to small values at a certain depth, and were interpreted as a change from minerotrophic to ombrotrophic conditions (Kokfelt *et al.,* 2010; Rydberg *et al.,* 2010). The large C/N ratios in the upper part of the profiles of our study are the result of low N concentrations of the soil, indicating ombrotrophic conditions, because these ecosystems receive N input only from atmospheric deposition (Jones *et al.,* 2010).

The δ^{15}N values at turning points varied from 2.4 to 4.2 per mil and from 1.7 to 5.7 per mil for Stordalen and Storflaket palsa peatland, respectively (Table 1). The δ^{15}N value in a peatland raised by permafrost in Russia was 5.5 per mil at the turning point (Andersson *et al.,* 2012), which is within in the range of values in our study. The age of turning points in the present study, based on peat accumulation rates determined by Alewell *et al.* (2011), is between 80 and 508 years at Stordalen (mean 242 years) and between 243 and 545 years at Storflaket (mean 365 years) (Table 1). The younger ages at Stordalen accord with the results in Alewell *et al.* (2011) and Krüger *et al.* (2014) based on stable carbon isotope depth profiles in combination with peat accumulation rates. At Stordalen, palsa initiation was dated to between 120 and 800 years before present (Malmer and Wallén, 1996; Kokfelt *et al.,* 2010; Rydberg *et al.,* 2010), which is within the range of our calculations for palsa uplift. This indicates that permafrost aggraded mainly during a prolonged cold period in the Little Ice Age (Bradley and Jonest, 1993) when most of the modern palsas formed (Zuidhoff and Kolstrup, 2000; Oksanen, 2005). Different turning point depths, or different times of permafrost uplift, could be due to small-scale differences in geomorphology and related exposure and climate conditions (precipitation, temperature, wind exposure). The missing turning points in some profiles from 2009 could be due to the early sampling in June, when the active layer had not yet fully thawed and resulted in a shallow sampling depth of only about 0.25 m.

CONCLUSIONS

The concept that soil perturbation is indicated by the relationship of δ^{15}N to C/N ratios was developed for oxic soils, but seems to apply also to Subarctic palsa peatlands. Permafrost onset in two peatlands could be detected by stable isotope depth profiles in combination with peat accumulation rates. The relationship between δ^{15}N and C/N ratio indicated a perturbance to the N-cycle of this ecosystem due to palsa uplift by permafrost. Furthermore, the data support our previous finding that palsas formed during the Little Ice Age. The relationship of C/N ratios to stable nitrogen isotope data in palsa peat not only indicates uplift by permafrost and a change from anaerobic to aerobic decomposition but also the perturbance introduced by these processes. The application of stable isotope depth profiles is straightforward and could be a suitable alternative to, or complement, pollen or macrofossil analyses.

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