Wetlands (2026) 46:22
https://doi.org/10.1007/s13157-026-02036-9

ORIGINAL RESEARCH ARTICLE

Nitrogen Storage Change and δ^{15}N Transitions of Peat Columns in Undrained and Forestry-drained Boreal Mires

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Received: 9 June 2025 / Accepted: 26 December 2025

Abstract

Peatland drying, driven by global warming and human impact alters nitrogen (N) cycling, potentially affecting gaseous and fluvial N fluxes, N stores in peat and in the underlying mineral subsoil, as well as the peat and subsoil N content and stable isotope ($^{15}N/^{14}N$) proportions (δ^{15}N). Complete peat columns may reveal effects of past climatic periods and drainage for forestry on N stratigraphy within the peat. We measured N concentrations and δ^{15}N values in peat and subsoil at undrained and drained peatlands in Finland. On three peatlands having paired natural and drained sites, we quantified changes in N, ^{15}N and ^{14}N storage, and calculated δ^{15}N values of the lost or gained N for bog having three synchronous layers on undrained and drained sites. There was preferential downward transfer of ^{15}N in the uppermost peat of drained bog. Also, the subsoil beneath the drained fen had increased δ^{15}N values compared to undrained site. δ^{15}N values were generally below zero, except in one bog and in the subsoil under a fen. In peat layers dating to the Mid-Holocene, high dry bulk density, C%, N%, and humification index, coupled with low C/N ratio, were connected to the highest δ^{15}N values in profile, similarly to those observed at the surface peat δ^{15}N maxima. Drainage decreased total N content and transferred N from upper peat layers to deeper strata. In opposite to expectations, on peatlands having parallel undrained and drained sites, δ^{15}N value increase or decrease was not connected clearly to decreased N mass.

Keywords Biogeochemistry · Peat · Fen · Bog · Nitrogen cycle · ^{15}N · Diagenesis · Drainage · Isotope ecology, paleoecology

Abstrakti (in Finnish)

Ilmaston lämpeneminen ja soiden ojitus muuttavat soiden typen (N) kiertoa. Kuivuminen ja lisääntynyt turpeen hajoaminen vaikuttavat kaasumaisen ja veteen liuenneen typen virtoihin, sekä turveprofiileihin varastoituneeseen ja turvekerrostumien alla olevan mineraalimaan typpeen. Kuivuminen voi vaikuttaa myös typen vakaiden isotooppien ($^{15}N/^{14}N$) suhteisiin (δ^{15}N). Kokonaisten turveprofiilien tutkiminen voi paljastaa menneiden ilmastokausien ja metsätalouteen liittyvän soiden kuivatuksen vaikutuksia turpeen typpikerrostuneisuuteen. Mittasimme typpipitoisuuksia (%) ja δ^{15}N-arvoja turveprofiileissa ja pohjamaassa ojittamattomilla ja ojitetuilla turvemailla seitsemältä kohteelta Suomessa. Kolmella turvemaalla, joissa oli vierekkäin ojittamattomia ja ojitettuja alueita, määritimme muutokset typpi-, ^{15}N- ja ^{14}N-varastoissa. Lisäksi laskimme kadonneen tai lisääntyneen typen δ^{15}N-arvot suolle, jossa oli kolme ojittamattomalla ja ojitetulla puolella erottuvaa synkronista (samoille historiallisille aikakausille ajoittuvaa) kerrosta. Raskaampi ^{15}N siirtyi ensisijaisesti nopeammin alaspäin kuivatetun suon ylimmissä turvekerroksissa kuin ^{14}N. Myös kuivatetun suon alla olevan pohjamaan δ^{15}N-arvot olivat korkeammat kuin ojittamattoman puolen pohjamaassa. δ^{15}N-arvot olivat yleensä kansainvälisenä standardina käytetyn ilmakehän typen arvoja pienempiä lukuun ottamatta yhtä karun suon turveprofiilia ja pohjamaan arvoja. Keskiholoseenilta peräisin olevissa turvekerroksissa korkea tilavuuspaino, C%, N% ja humifikaatioindeksi yhdistettynä alhaiseen C/N-suhteeseen liittyivät profiilin korkeimpiin δ^{15}N-arvoihin, samalla tavalla kuin pintaturpeen δ^{15}N-maksimissa. Ojitus vähensi kokonaistyppipitoisuutta ja mahdollisesti siirsi typpeä ylemmistä turvekerroksista syvempiin kerrostumiin. Vastoin odotuksia, suoalueilla, joilla rinnakkaisia ojittamattomia ja ojitettuja alueita voitiin verrata, δ^{15}N-arvon nousu tai lasku ei ollut selvästi yhteydessä ojituksen aiheuttamaan typen vähenemiseen.

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Published online: 19 February 2026

Introduction

Peatlands form an important storage of organic nitrogen. Despite covering only 3–4% of the global land area (Joosten and Clarke 2002; Yu 2011) peatlands contain 9.7 Gt of N, accounting for ~10% of the global terrestrial N pool (Loisel et al. 2014). The N storage in peat is linked to that of carbon (C) (Worrall et al. 2012), both of which can be influenced by changes in climate and human activities. As a result, peatlands could shift from being net sinks to net sources of N (Worrall et al. 2012).

Peatlands grow on plant remains. In vascular plants, assimilation of inorganic nitrogen prefers ^{14}N against the heavier isotope ^{15}N causing a relatively greater fraction of the ^{14}N to be incorporated into plant (Kalcsits et al. 2014), while bryophytes are lacking roots and thus have no fractionation in their nutrient uptake. Microbial mineralization of organic matter has enzymatic preference for the ^{14}N thus leading to ^{15}N depleted inorganic products and to ^{14}N depleted N remains to parent substrate. However, the $\delta^{15}N$ of a system not only reflects the $\delta^{15}N$ of the N source, but also N isotope fractionations, N gains and losses and N pool mixing are included in isotope systematics (Robinson 2001).

The $\delta^{15}N$ values of peat can reflect the conditions during N assimilation, relocation, and decomposition processes during peat formation (Biester et al. 2014; Larsson et al. 2017), however further alterations of the $\delta^{15}N$ values may occur during the subsequent phases of burial in the deeper peat strata (Drollinger et al. 2019, 2020).

Several studies have reported bulk $\delta^{15}N$ values of stratigraphic peat profiles in natural peatlands (Novák et al. 1999; Esmeijer-Liu et al. 2012) and in drained peatlands (Groß-Schmölders et al. 2020, 2022). However, studies of N storage changes in peat due to drainage remains limited (Choi et al. 2007; Drollinger et al. 2019, 2020) and studies linking $\delta^{15}N$ values with N storage dynamics are generally lacking. Furthermore, to our knowledge, no studies have examined $\delta^{15}N$ profiles in the mineral subsoils beneath peat. Thus, research on the potential impacts of anthropogenic and climatic change on N store and $\delta^{15}N$ isotopic values in peat profiles and subsoil is needed to predict the fate of peatland N in a changing environment.

Water sources and water table levels are key factors determining both the historical and current peatland types and vegetation patterns, as well as influencing the peat N content and $\delta^{15}N$ values. Inorganic N availability to vegetation originates from three main sources: biological N fixation (BNF), atmospheric deposition, and groundwater inputs. Minerotrophic fens receive N not only from atmospheric deposition but also from dissolved N transported from the surrounding catchment. In contrast, ombrotrophic bogs are hydrologically isolated from groundwater, relying solely on atmospheric deposition and BNF for their N supply (van Breemen 1995; Opelt et al. 2007). As a result, the minerotrophic fens generally have higher availability of N and other nutrients, higher water surplus, more diverse vegetation, and lower acidity than ombrotrophic bogs.

Peatland forestry requires permanent lowering of the water table by ditch-draining. Drainage exposes peat nutrient pools to tree roots, translocating mineralized N into their biomass and litter (Laiho and Laine 1994). On fens water table decrease is achieved by cutting waterways from mineral soil aided with ditches, while on bogs water table decrease is solely by ditches. On drained fens increase of available nutrients and drying leads to substantial change in vegetation and increase in tree growth. On drained bogs decrease in water table and increase in nutrient release are smaller, and thus not leading to profitable forestry as was the goal.

Besides original nitrogen sources, the $\delta^{15}N$ values in peat are related to oxidation gradients within the peat profile controlling the organic matter mineralization, and microbial community composition (Groß-Schmölders et al. 2020; Zhong et al. 2024). A lower water table and increased aeration promotes exposed organic matter mineralization and nitrification in the surface layers of fertile fens, while not in ombrotrophic bogs (Martikainen et al. 1993; Regina et al. 1996).

In this study, we analysed peat columns from 7 sites across three peatlands (Table 1) to assess N concentrations (%), N stores, and $\delta^{15}N$ profiles, and to evaluate the effects of drainage on these parameters. We compared profiles of paired natural and drained sites to examine drainage-induced changes in N store, $\delta^{15}N$ depth profiles, and the balance of ^{14}N and ^{15}N in bulk peat, employing similar methodology as in C balance (Pitkänen et al. 2013) and $^{12}C/^{13}C$ articles (Nykänen et al. 2020). A bog having three synchronous layers visible in peat profiles on undrained and drained sites along a border ditch offered us possibility to calculate nitrogen content and $\delta^{15}N$ value change between the drained and undrained peat sections. We utilized ^{14}C dating of close to surface peat and the basal peat to estimate recent and long term apparent N accumulation rates. We also studied the mineral subsoil under the peat with comparison between natural and drained parts of the peatland.

Drained peatlands have been used as model ecosystems considering potential drying of peatlands in response to climate change in the study of N_2O fluxes (Martikainen et al. 1993; Regina et al. 1996) and effects of water-level drawdown in northern peatlands to global climatic warming (Laine et al. 1996). In this study, we also compare historical warm and dry period signals in the peat columns, to support the implications from the current drainage effects on the peat profiles.

Table 1 General features of the study sites and site name abbreviations

Study site	Rahesuo and Ilajansuo			Lakkasuo			
Location, elevation AMSL	62°52' N 31°10' E, 162 m			61°47' N 24°18' E, 150 m			
Precipitation mm a^{-1}	681			709			
Mean temp. (°C)	2.2			3.5			
Peatland type	Bog			Fen		Bog	
Core basal age (cal. yr. BP)	10,200		1570 ± 35	3400		3000	
Site name	Rahesuo bog		Ilajansuo bog, hummock and lawn	Lakkasuo fen and mineral subsoils		Lakkasuo bog	
Status	Natural	Drained 1972	Natural	Natural	Drained 1961–1962	Natural	Drained 1961–1962
Abbreviation	RaBogUD	RaBogD	IlaBogUD-H/L	LaFenUD	LaFenD	LaBogUD	LaBogD
Stand volume (m^{-3} ha^{-1})	0	10	0	0	111	6	16
Water table (cm)	−2	−10	−8	−2	−36	−13	−26
Subsidence (cm)		−30			−23		
pH (surface)	4.2	4.1	4.0	5.6	4.5	3.8	3.8
N% (surface)	0.64	0.82	0.40/0.46	2.5	2.3	0.86	1.2
Peat column length (cm)	250	220	99	160	140	267	244

[1]Weather data averages (1980–2010) from [Pirinen et al. 2012], for Rahesuo data from Juuka (meteorological station), for Lakkasuo from Hyytiälä (meteorological station). Lakkasuo mire complex features are adopted and modified from Martikainen et al. 1993; Minkkinen et al. 1999; this study and Nykänen et al. 1998. Rahesuo features are adopted and modified from Pitkänen et al. (2013).

Materials and Methods

Study Sites

We studied mires at two geographical locations in the boreal coniferous forest area in Finland (Fig. 1; Table 1). Weather for the period 1981–2010 indicated mean annual temperature of 2.2 °C and precipitation 681 mm for Rahesuo and Ilajansuo, and 3.5 °C and 711 mm for Lakkasuo (Table 1). Snow cover is lasting from November to end of April, while the maximum snow depth (in March) is 43 cm at Lakkasuo area and 65 cm at Rahesuo and Ilajansuo (Pirinen et al. 2012). Precipitation during the snow free season is quite similar for both areas, 348 mm for Rahesuo and Ilajansuo, and 350 mm for Lakkasuo (Pirinen et al. 2012). Vegetation for the sites is described in Table 2. In southern Finland, where Lakkasuo is situated, the annual deposition of N (NO_3–N + NH_4–N) was about 0.2 g m^{-2} during 1950, increased towards 1990 to ~0.7 g m^{-2} and has decreased since to ~0.4 mg m^{-2} towards the end of 2020 (Smolander et al. 2023). At Rahesuo and Ilajansuo area N-deposition has similar pattern but is smaller.

The ombrotrophic Rahesuo peatland is a large, raised bog complex which was partially ditch-drained by 40 m ditch intervals during the winter 1971–1972, 37 years before the present sampling on June 26th, 2009. For more details of Rahesuo, see Pitkänen et al. (2013) and Nykänen et al. (2020). Drained Rahesuo bog shows a negligible increase in tree basal area (Table 1). We collected complete peat profiles from the mineral subsoil upwards and studied them on 10 cm vertical resolution. The undrained ombrotrophic site at Ilajansuo, is an aapa mire complex with wide minerotrophic central parts and progressive eccentric bog units on the marginal parts with a mean peat depth of 2.2 m. Iljansuo is located 6 km north of Rahesuo and is interconnected with Rahesuo. Cores from hummock (Z-62) and lawn (Z-100) are from an eccentric bog zone section (Z0 to Z120) of a previously investigated 360 m long transect (Tolonen 1967).

The Lakkasuo peatland complex comprises undrained and drained sites along a border ditch crossing the ombrotrophic and minerotrophic parts of the mire. Due to this partial drainage, Lakkasuo has been used in many previous studies as an example of drainage-induced changes on hydrology, vegetation pattern, nitrogen flows, C and N balances, $\delta^{13}C$ and $\delta^{15}N$ profiles and microbiology (Martikainen et al. 1993; Laiho and Laine 1994; Nykanen et al. 1998; Minkkinen et al. 1999; Krüger et al. 2016; Mpamah et al. 2017; Nykänen et al. 2018; Groß-Schmölders et al. 2020, 2022). Previous studies show that the drainage in 1961 has changed the ecosystem substantially (Table 1). According to the earlier studies, carbon store has decreased on drained Lakkasuo fen site, but possibly increased on the drained Lakkasuo bog compared to their undrained pairs (Minkkinen et al. 1999; Krüger et al. 2016). On drained Lakkasuo fen, afforestation was initiated by pine planting supported by fertilisation with N and K in 1966 and in 1984 (Martikainen et al. 1993). The ditching in Lakkasuo was conducted perpendicular to natural slope and water flow, thus partial drainage of Lakkasuo may have influenced also the undrained parts as a difference to Rahesuo drainage.

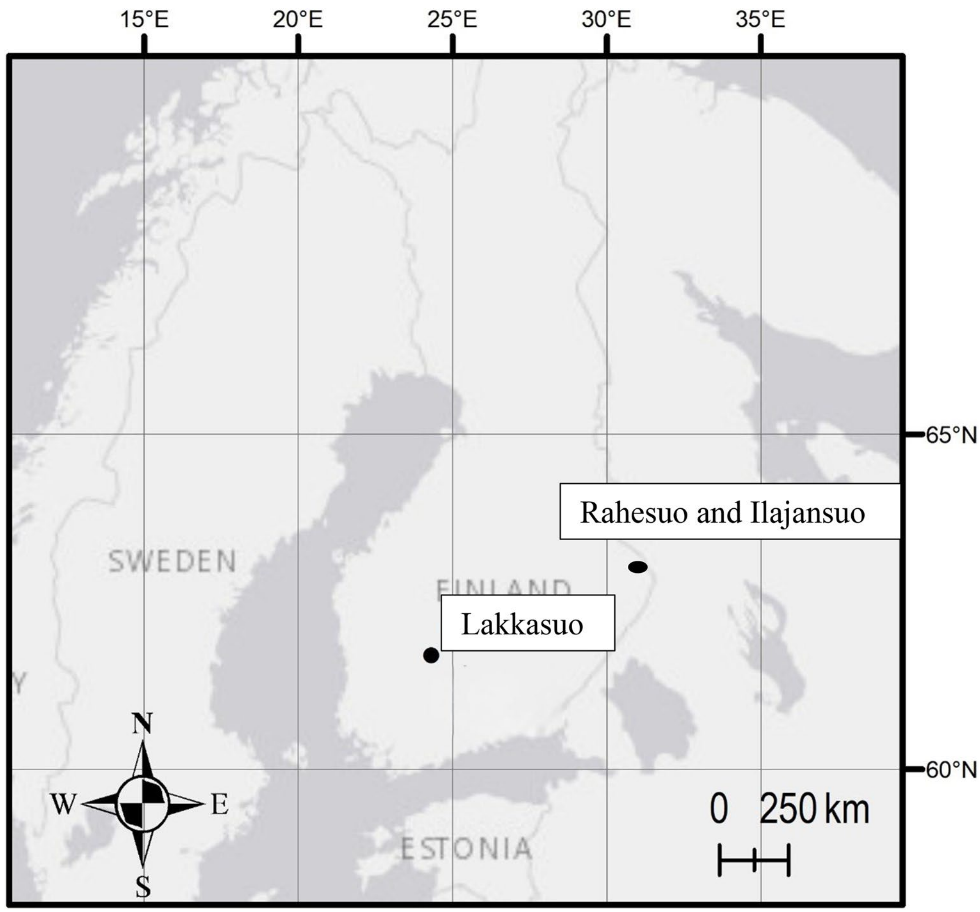

Fig. 1 Location of the studied peatlands Rahesuo, Ilajansuo and Lakkasuo

Subsoil, Peat and Vegetation Sampling

In the Lakkasuo natural fen basal peat and subsoil profiles (n=3) and those of the drained fen basal peat and subsoil (n=3), were sampled using a side-cutting Russian type peat corer (half cylinder diameter 54 mm, length 500 mm). Samples for analyses were divided on 5 cm depth resolution on site.

The samples collected from Rahesuo are the same as those investigated by Pitkänen et al. (2013) for peat C inventories and by Nykänen et al. (2020) for C store and bulk peat δ^{13}C transitions. The Rahesuo peat profiles were studied by 10 cm vertical resolution and matching of the profiles was confirmed by synchronous peat layers identified in the undrained and drained sites (Pitkänen et al. 2013), which were used in calculations of the N, ^{15}N and ^{14}N balances. Ilajansuo peat profile data of the hummock and lawn profiles has besides δ^{15}N, N% and C% data, also AMS-radiocarbon dating by the Poznań Radiocarbon Laboratory of *Sphagnum* stem fragment at 67 cm depth (45±30 cal. yr. BP, i.e., ca. 1905 CE; lab reference: Poz-131213) and of basal bulk peat at 99 cm depth (1570±35 cal. yr. BP, i.e. ca. 380 CE; lab reference Poz-131214).

The peat samples from the Lakkasuo were collected as described in (Mpamah et al. 2017; Nykänen et al. 2018). Randomly collected plants are from undrained and drained sites at Lakkasuo fen and bog. The sampling procedure, plants analyzed, methods and results for δ^{13}C and C for these analyses are available in Nykänen et al. (2018).

Analyses of δ^{15}N and N%

δ^{15}N data in this MS (except for Ilajansuo) was obtained from the same analyses as the results for δ^{13}C, C% and N% by Nykänen et al. (2018, 2020). The samples from Lakkasuo were analyzed with a Thermo Finnigan Advantage IRMS (Germany) coupled to an elementar analyzer Flash EA 1112 (Italy). The samples from Rahesuo were analyzed with an Elementar Cube (Elementar, Hanau, Germany) coupled to an Isoprime 100 (Isoprime Limited, Cheadle Hulme, UK) isotope ratio mass spectrometer (Nykänen et al. 2020). For C% and N% certified birch leaf standard (Elementar Microanalysis, UK) was used. This same standard was also used as internal laboratory standard for δ^{15}N values. This internal standard was run after each set of five samples for calibration. The Ilajansuo samples were analysed at the stable isotope facility of UC Davis (California, USA). These samples were analyzed for ^{15}N isotopes by using a PDZ Europa ANCA-GSL elemental analyzer interfaced to

Table 2 Vegetation of the studied sites

Site	Undrained	Drained
Rahesuo (Pitkänen et al. 2013)	**Hollow**: *Sphagnum balticum*, *Carex limosa*, *Scheuchzeria palustris* **Hummock**: *Vaccinium microcarpum*, *Sphagnum fuscum*, *Empetrum nigrum*, *Rubus chamaemorus*	**Hollow**: *Mylia anomala*, *Polytrichum strictum* **Hummock**: *Dicranum* spp., *Pleurozium schreberi*, *Betula nana*, *Vaccinium uliginosum*
Ilajansuo (this study)	**Lawn**: *Sphagnum balticum*, *Andromeda polifolia*, *Eriophorum vaginatum*, *Scheuchzeria palustris*, *Vaccinium oxycoccos***Hummock**: *Sphagnum fuscum*, *Empetrum nigrum*, *Andromeda polifolia*, *Chamaedaphne calyculata*, *Pinus sylvestris*	n.a.
Lakkasuo, Tall sedge fen, (Martikainen et al. 1993; Nykänen et al. 1998)	*Betula nana*, *Carex rostrata*, *Carex lasiocarpa*, *Andromeda polifolia*, *Eriophorum vaginatum*, *Polytrichum strictum*, *Sphagnum fallax*, *S. papillosum*, *S. angustifolium*	*Pinus sylvestris*, *Agrostis capillaris*, *Betula pubescens*, *Carex echinata*, *Dryopteris carthusiana*, *Polytrichum commune*, *P. strictum*, *Pleurozium schreberi*, *Dicranum* spp. *Sphagnum angustifolium*
Lakkasuo, Cottongrass pine bog (Martikainen et al. 1993; Nykänen et al. 1998)	*Pinus sylvestris*, *Eriophorum vaginatum*, *Polytrichum strictum*, *Empetrum nigrum*, *Sphagnum angustifolum*, *S. fuscum*, *S. russowii*	*Pinus sylvestris*, *Eriophorum vaginatum*, *Pleurozium schreberi*, *Cladonia* spp., *Dicranum polysetum*, *Empetrum nigrum*, *Sphagnum angustifolum*, *S. fuscum*

a PDZ Europa 20–20 IRMS (UK). The long-term standard deviation for the UC Davis stable isotope facility is 0.3‰ for ^{15}N (stableisotopefacility.ucdavis.edu).

The stable isotope compositions were expressed in the delta notation as a ‰ deviation of the heavy-to-light isotope abundance ratio in the sample from that of international standard for atmospheric N_2 having a set value of 0‰.

$$\delta^{15}N = \left(\frac{\left(\frac{^{15}N}{^{14}N}\right) sample}{\left(\frac{^{15}N}{^{14}N}\right) standard} - 1\right) * 1000 \tag{1}$$

Calculation of Bulk Inventory of N and the Quantities of ^{14}N and ^{15}N in Peat Profiles and δ^{15}N of Lost N in Rahesuo

In Rahesuo, where the matched profiles from drained and undrained sites were studied at 10 cm vertical resolution, it was possible to calculate the N inventory and ^{14}N and ^{15}N balance changes the same way as Nykänen et al. (2020) did for ^{12}C and ^{13}C for these same samples.

The drainage-related $\delta^{15}N$ values in Rahesuo was assessed from the differences in $\delta^{15}N$ values between corresponding original levels of the undrained and drained site profiles. The change of the isotope ratio was considered to reflect the drainage-related losses or gains of N from the profile by gaseous N fluxes, by plant assimilation and by seepage. The ^{14}N and ^{15}N amounts were back calculated to isotope values by using delta notation (Eq. 2).

$$at\% = \frac{100 * AR * \left(\frac{\delta^{15}N}{1000+1}\right)}{1 + AR * \left(\frac{\delta^{14}N}{1000+1}\right)} \tag{2}$$

Where at% is atomic percentage, AR = ratio of ^{15}N and ^{14}N isotopes of N of the reference material (air N_2).

Stratigraphy and Mass and ^{15}N/^{14}N Calculations

For each analysed site the total N inventory and the N mass weighted average of $\delta^{15}N$ was calculated for the entire peat profile, and separately for the uppermost 100 cm of each (except for 67 cm long Ilajansuo lawn core). The amounts of N were calculated from dry bulk density and N%. The mass weighted average of $\delta^{15}N$ value was calculated by multiplying the amount of N in each sample slice by its $\delta^{15}N$ value and by dividing the sum of these by the total mass of N in the analyzed profile.

The N mass and $\delta^{15}N$ value changes in the Rahesuo peat columns were determined based on three distinctive depth markers. The most surficial synchronous layer was the upper peat profile turning point determined as in (Alewell et al. 2011). At depth of 45 cm on the undrained site and at depth of 25 cm on the drained site. The upper synchronous layer in mass balance calculations was decreased 20 cm below the turning point ($STP_{UD65/D45}$) to avoid an error in N amounts and $^{15}N/^{14}N$ ratio estimates since exact location of synchronous layer top in the original 10 cm samples was not known. Thus, surface N amount and $^{15}N/^{14}N$ balances were calculated from 0 to 70 cm profile on undrained site and from corresponding 0–50 cm profile on drained site.

An ash layer from earlier forest fire was visible in peat column at undrained and drained site and was used as the middle synchronous layer. Ash layer was in undrained Rahesuo at depth of 165 cm and at drained site at depth of 135 cm (Pitkänen et al. 2013). This middle synchronous layer was elevated 10 cm to the next sample ($SCL_{UD155/D125}$) (above). Since the bottom of Rahesuo was sloping, full profile was deeper at the drained site. The basal level of profiles was based on the increase in ash content at 245 cm on undrained site and at 215 cm at drained site. Also, this bottom synchronous layer was elevated 10 cm and named $SAL_{UD235/D205}$.

For Rahesuo bog the Long-Term Average Rate of Nitrogen Accumulation (LORNA) was calculated by dividing the amount of N in the 250 cm long peat profile by its basal peat age (10220 years) (Mäkilä and Goslar 2008). For Lakkasuo fen, the amount of N in the 160 cm profile was divided by its basal age of 3400 cal. yr. BP (Minkkinen et al. 1999). For Ilajansuo hummock sampled on 2020, the age of 1640 years at the depth of 99 cm was used. Surficial dating of Ilajansuo hummock column at depth of 67 cm allowed also estimation of The Recent Rate of Nitrogen Accumulation (RERNA) during the last 115 years.

Statistical Analysis

Difference of δ^{15}N values and N% between drained and undrained Lakkasuo fen subsoils was tested by independent sample t-test. The assumptions of normality and homogeneity of variances were tested using Shapiro-Wilk and Levene's test, respectively. A linear model between δ^{15}N values and factors connected to decomposition proxies [C/N ratio and dry bulk density (BD)] for Rahesuo and Ilajansuo, based on Drollinger et al. (2020). Analyses were done with IBM SPSS Statistics version 25.

Results

Basal Peat and Mineral Subsoil δ^{15}N Stratigraphy at Lakkasuo Fen

The δ^{15}N values and N% differed significantly between the basal peat and the subsoil layers at both natural and drained Lakkasuo sites (t-test, $p<0.05$; Table 3). Average differences in the δ^{15}N and N% values between the basal peat layers of Lakkasuo fen natural and drained sites were not significant (Table 3), while drained site basal peat δ^{15}N values were statistically significantly higher 12.5 cm above the interface (Fig. 2AB). Both δ^{15}N and N% values were higher in the subsoil of the drained site, average differences were not statistically significant (Table 3), even there was statistically significant difference of δ^{15}N values at depths of 2.5, 17.5 and 22.5 cm in subsoil and in 22.5 cm depth below interface in N% (Fig. 2A) (t-test, $p<0.05$; df. =3). Moreover, δ^{15}N correlated with N% in the undrained and drained subsoils (Fig. 2C).

General Trends in the Peat Columns

The most negative δ^{15}N values, down to −6‰ were obtained for the undrained surface peats of Rahesuo and Ilajansuo (Figs. 3A and 4A, Sup. Figure S1) whereas the most positive values, ~ 2‰ were found in Lakkasuo bog, undrained and drained sites (Fig. 5E) and from Ilajansuo hummock basal peat (3.1‰) (Fig. 4A). Ilajansuo lawn had the largest change in δ^{15}N values downcore of the sites studied, 7.9‰. Clearest visual difference was between Lakkasuo fen undrained and drained pairs, there drained pair had more negative δ^{15}N values than undrained side in the whole peat column.

The upper 10 cm at Ilajansuo bog had low N content in both the lawn and hummock sites, 0.40 and 0.46%, respectively, while it increased over 2% in basal peat (Fig. 4B). Also, Rahesuo natural bog had low N content in the upper 10 cm (0.64 ± 0.04%) while N content increased on the drained Rahesuo bog to 0.72 ± 0.1% (Fig. 3B). In undrained Rahesuo, share of N was ~ 2% already at depth of 45 cm. In Lakkasuo bog, the N content in top was smaller in the undrained site (0.86 ± 0.1%) than in the drained one (1.2 ± 0.2%) (Fig. 5B). The treeless undrained Lakkasuo fen had a high N content (2.5 ± 0.3%), whereas it was slightly lower in the drained counterpart (2.3 ± 0.4%) (Fig. 5B).

The smallest inventory of N in the top 100 cm of peat column was found in drained Lakkasuo bog (385 g N m^{-2}); also, undrained Lakkasuo bog and Ilajansuo bog hummock contained low total N amounts. During drainage, the amount of N in the 100 cm of surface peat decreased 83.3 g m^{-2} in Lakkasuo bog and 15.6 g m^{-2} in Rahesuo bog (Table 4). In Lakkasuo fen, the N amount increased considerably (376.3 g m^{-2}) in upper 1 m due to peat subsidence and bulk density increase (Table 4). For the whole peat

Table 3 Comparisons of the δ^{15}N and N% values between the basal peat and the subsoil and between the undrained and drained sites of Lakkasuo Fen (average ± S.E.; $n=16$ for peat and $n=14$ for subsoil). The values represent the 0–30 cm peat layer above the interface between peat and the 0–25 cm subsoil below it. The results of t-tests between peat and subsoil are shown below, and between the undrained (LakFenUDbot) and drained sites (LakFenDbot) to the right of the tested averages. Significant differences obtained by independent sample *t*-test ($p<0.05$) are expressed with bold text

	LaFenUDbot	LaFenDbot	LaFenUDbot vs. LaFenDbot
$\delta^{15}N$ (‰) peat	−0.07 ± 0.1	0.04 ± 0.1	*t(29) = −0.87, p = 0.194*
δ^{15}N (‰) subsoil	1.91 ± 0.4	2.68 ± 0.7	*t(23.1) = −0.97, p = 0.171*
	t(14.4) = −4.58 *p* = 0.000	***t(12.3) = −4.49*** *p* = 0.001	
N% peat	2.1 ± 0.1	2.0 ± 0.1	*t(29) = 1.651, p = 0.055*
N% subsoil	0.88 ± 0.1	0.91 ± 0.2	*t(26.8) = − 0.135, p = 0.447*
	t(17.4) = 7.70 *p* = 0.000	***t(13.9) = 7.14*** *p* = 0.000	

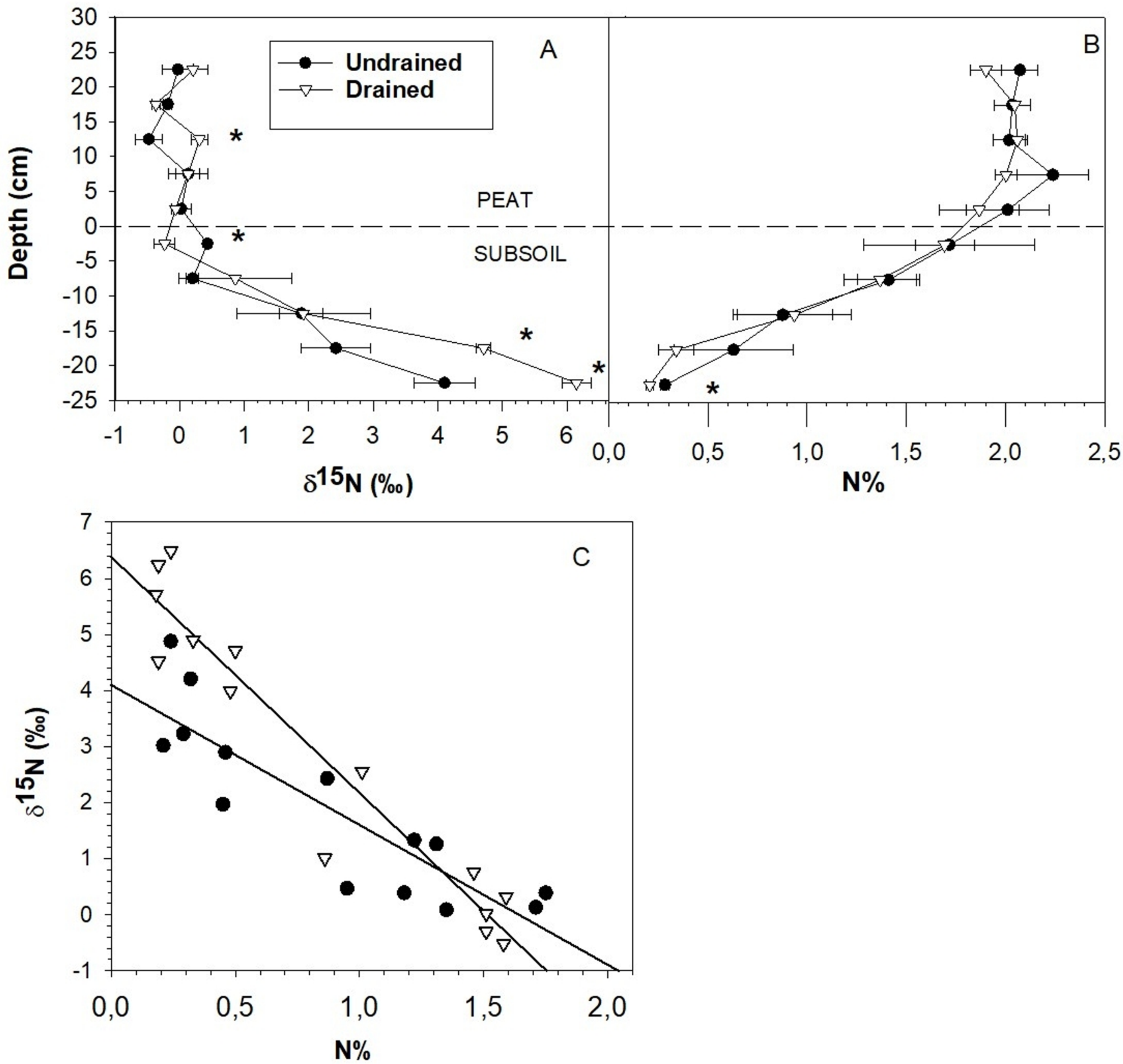

Fig. 2 Basal peat and subsoil profiles of $\delta^{15}N$ values (**A**) and N% (**B**) from the natural and drained Lakkasuo Fen, i.e. LaFenNbot and LaFenDbot. Zero level indicates the transition zone between peat and subsoil. Statistically significant differences are marked with asterix (T-test, $p<0$). Regression line between N% and $\delta^{15}N$ on undrained (black circle) and drained sites (open triangle down) subsoil variables (**C**). Linear regression for panel C: natural site subsoil: $\delta^{15}N = -2.50$ * (N%) – 4.10 ($r^2=0.76$, $p=0.000$, $n=12$) and drained site subsoil: $\delta^{15}N=-3.88$ * (N%) – 6.21 ($r^2=0.90$, $p=0.000$, $n=14$

profiles, also the lost peat N is included in calculation and balance between drained and undrained pairs results in N amount decreasing 155.7 g m^{-2} g N m^{-2} in Lakkasuo fen (Table 4) and 49.2±48 g m^{-2} (Average+S.E.) in Rahesuo bog (Table 5).

Ilajansuo hummock accumulated 172.2 g of N during the last 115 years to 67 cm peat layer thus RERNA was 1.50 g N m^{-2} yr^{-1}. At Ilajansuo hummock LORNA was 0.66 g N yr^{-1} for 99 cm profile in 1633 years, comparable to Lakkasuo natural fen (0.77 g N m^{-2} yr^{-1}). LORNA for the whole peat profile was 0.34 g N m^{-2} yr^{-1} in natural Rahesuo bog.

Vegetation N% and $\delta^{15}N$ at Lakkasuo

At Lakkasuo undrained fen, the $\delta^{15}N$ values of vegetation were −4.6±1.5‰, ($n=9$), and not statistically different from those at drained site (–2.9±0.8‰). At Lakkasuo bog there was no statistically significant difference between

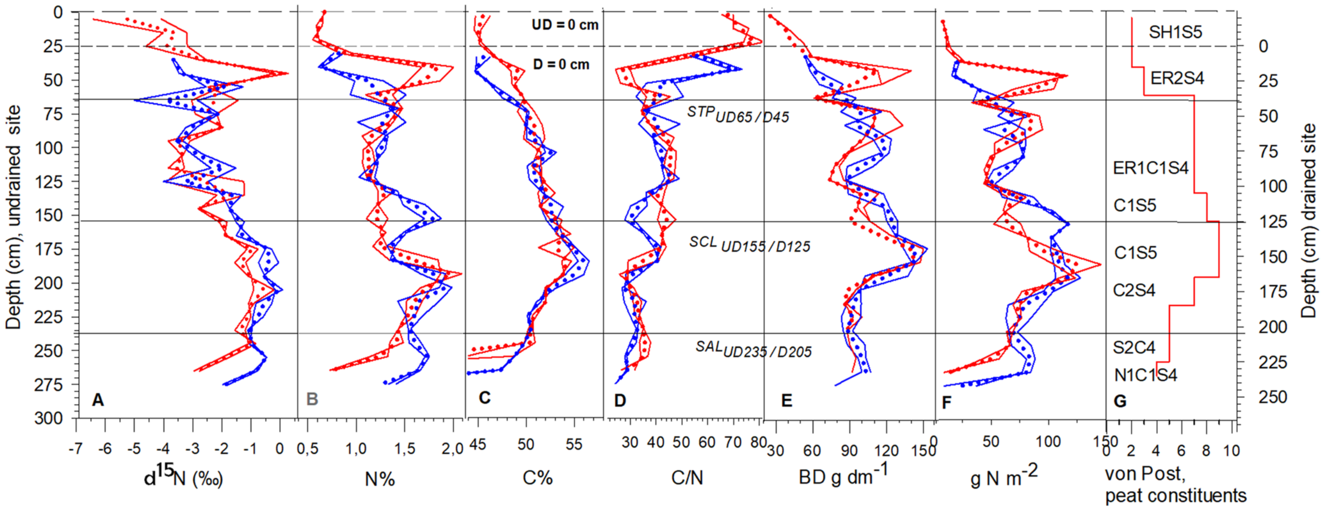

Fig. 3 Rahesuo stratigraphy of undrained (dotted red line is average, solid red lines show individual profiles) and drained site (dotted blue line is average, solid blue lines show individual profiles). Surface and synchronous levels are marked with vertical lines. $\delta^{15}N$ (‰) (**A**), N% (**B**), C% (**C**), C/N-ratio (**D**), BD (**E**), amount of N m^{-2} (**F**) and peat humification on von Post scale and peat constituents (**G**). Surface for undrained site (*N*=0 cm) and drained site (D=0 cm). Peat constituents on six grade scale: SH=*Scheuchzeria* (aquatic herbs), ER=*Eriophorum* (cotton grass), S=*Sphagnum* (moss), C=*Carex* (sedge), N=Nanolignidi (shrubs)

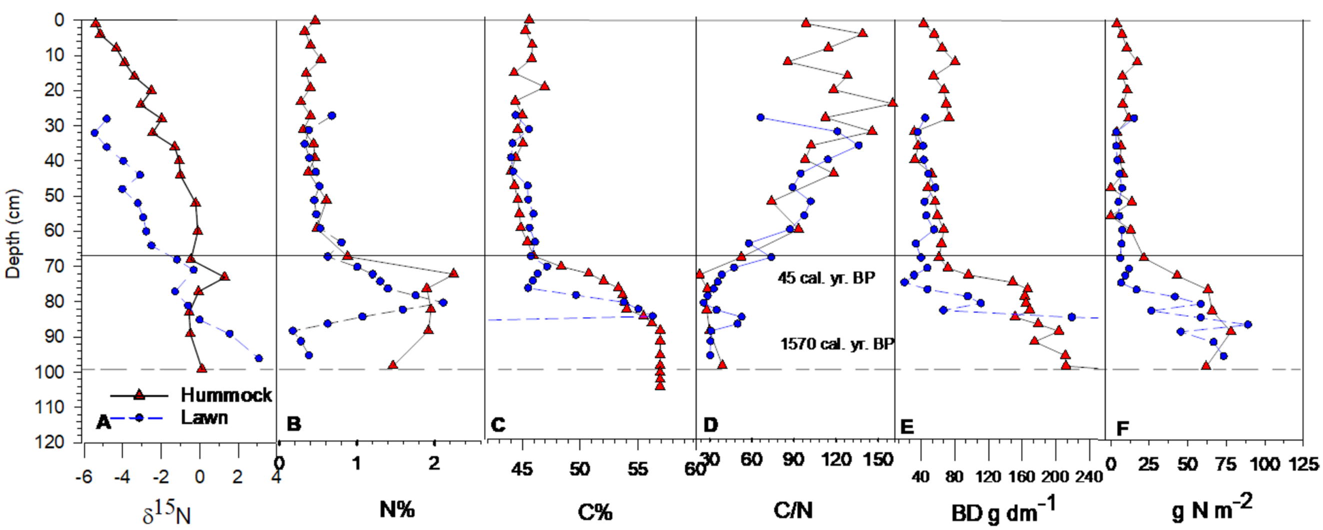

Fig. 4 Ilajansuo stratigraphy for profiles Z62 (hummock) and Z100 (lawn). Calibrated radiocarbon ages (before 1950) at depths 67 and 99 cm of the hummock core are marked with horizontal lines. $\delta^{15}N$ (‰) (**A**), N% (**B**), C% (**C**), C/N-ratio (**D**), BD (**E**) and g N m^{-2} (**F**). (In calendar years 45 cal. yr. BP=1905 CE, and 1570 cal. yr. BP=380 CE)

the vegetation $\delta^{15}N$ values of undrained (– 6.9±1.0‰) and drained sites (– 5.2 ± 0.7‰). The vegetation $\delta^{15}N$ values on drained Lakkasuo bog were statistically significantly more negative than on drained Lakkasuo fen. The nitrogen content of plants in undrained Lakkasuo fen was 0.82±0.15% (n=9), thus smaller than on the corresponding drained site (1.17±0.17%), but the difference was not statistically significant. The N contents of the plants at undrained and drained Lakkasuo bog were (0.88±0.14%) and (0.88±0.12%), respectively.

Rahesuo Bog Peat Constituents and $\delta^{15}N$, N% and C/N-ratio

The humification index (H_{1-10},) (von Post 1922) at the undrained site increased rapidly from H3 to H7 at a depth of 60 cm (Fig. 3G), coinciding with the depth where BD reached its maximum (Fig. 3E, G, Sup. Figure S1E). Deeper down in the profile, BD increased, and the most humified peat layer was associated with the highest N% and N content. In the lowermost part of the profile, below 200 cm, the

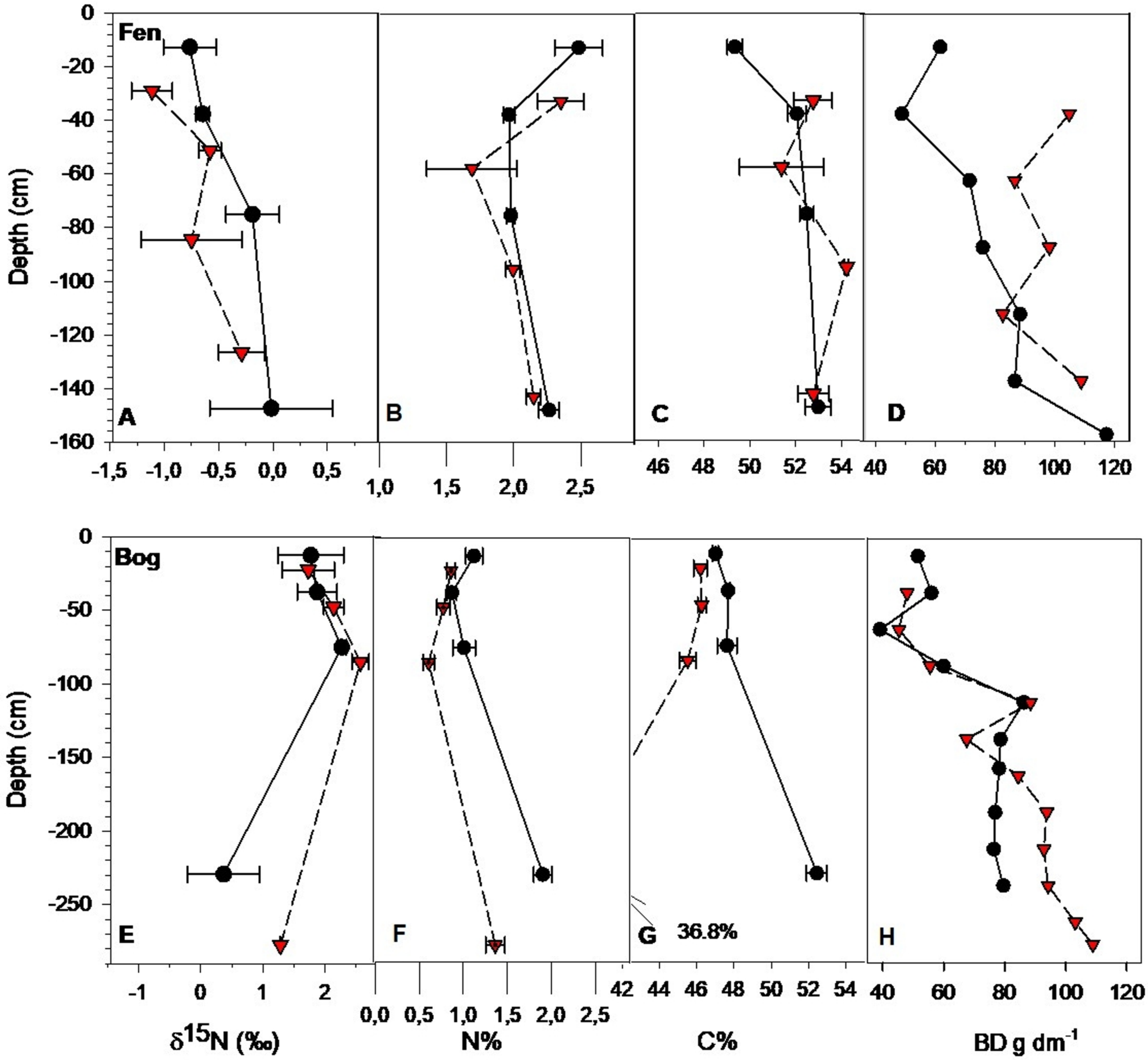

Fig. 5 Lakkasuo fen and bog depth profiles of $\delta^{15}N$ values (**A**,**E**), N% (**B**,**F**), C% (**C**,**G**), bulk density (BD) (**D**,**H**). Undrained sites = black circle, solid line. Drained sites = red triangle down, short dash line. (Average ± S.E., *n* = 3, except in BD, where *n* = 1)

humification index decreased from H9 to H4, mirroring the decrease of BD towards the basal peat layer.

The most negative $\delta^{15}N$ values in the Rahesuo peat columns were at the surface, where *Sphagnum* dominated with hygrophytic herbs. The $\delta^{15}N$ values were −5.25 ± 1.05‰ at natural site and −3.66 ± 0.05‰ at drained site (Fig. 3A, Sup. Figure S1 A). In the 0–100 cm peat strata more positive $\delta^{15}N$ values were found with maximum values of 0.03 ± 0.35‰ at the depth of 45 cm in natural site and −1.90 ± 0.05‰ at the depth of 25 cm in drained site (Fig. 3A, Sup. Figure S1 A). These $\delta^{15}N$ maximum value coincided with the maximum ash%, N%, BD, C and minimum C/N ratios in the upper peat strata (Sup. Figure S1 A-F); these rapid changes were clearer at the undrained site. Downwards below the $\delta^{15}N$ maxima, the $\delta^{15}N$ values steadily declined, reaching minimum at 115 cm (−3.57 ± 0.39‰) in the undrained site and at 95 cm (−3.24 ± 1.09‰) in the drained site (Fig. 3A). In undrained site, the $\delta^{15}N$ values increased to −0.56 ± 0.49‰ at 205 cm, and in drained site to −0.04 ± 0.16‰ at 175 cm. Below these levels, towards the basal peat-mineral subsoil boundary, the $\delta^{15}N$ values again began to decrease (Fig. 3A).

Table 4 The total N inventories for uppermost 1 m and whole profiles and mass weighted $\delta^{15}N$ averages ± S.E. Of the studied peat profiles (*n* = 3, except for Rahesuo bog *n* = 2 and for Ilajansuo bog lawn and hummock *n* = 1). Increase in drained pair N mass or $\delta^{15}N$ values is marked with arrow up (↑) and decrease in drained pair by arrow down (↓)

Site	Uppermost 0–100 cm		Whole profile		
	g *N* m^{-2}	$\delta^{15}N$ (‰)	Depth (cm)	g *N* m^{-2}	$\delta^{15}N$ (‰)
LakFenUD	1506.7 ± 22.3	−0.47 ± 0.14	160	2615.6 ± 48.56	−0.29 ± 0.10
LakFenD	1883.0 ± 48.5 ↑	−0.83 ± 0.19 ↓	130	2469.9 ± 51.20 ↓	−0.69 ± 0.19 ↓
LakBogUD	468.0 ± 43.5	2.08 ± 0.16	242	n.a	n.a
LakBogD	384.7 ± 25.3 ↓	2.20 ± 0.06 ↑	280	n.a	n.a
RahBogUD*	1066.4 ± 16.6	−2.02 ± 0.11	250*	3323.9 ± 69.19	−1.71 ± 0.07
RahBogD*	1050.8 ± 66.6 ↓	−2.86 ± 0.30 ↓	220*	3182.3 ± 57.65 ↓	−1.53 ± 0.01 ↑
IlaBogUD hummock	1080.1	−0.38	99	1080.1	−0.38
IlaBogUD lawn	n.a	n.a	67	502.0	−0.95

*Note: Nitrogen mass calculation similar as in carbon mass calculation in Pitkänen et al. (2013), thus depths are 10 cm deeper here than in Table 5 in N balance calculation between undrained and drained Rahesuo

Table 5 Rahesuo peat column mass weighted $\delta^{15}N$ values and mass weighted $\delta^{15}N$ values of nitrogen gained or lost. Nitrogen stores and their change due to drainage and annual change during 37 years of drainage (Average ± S.E., *n* = 2). In "Balance" column minimum and maximum $\delta^{15}N$ values of individual column pair comparisons in parentheses. Negative values in the masses indicate loss, while positive values indicate gain. Increase in drained pair N mass or $\delta^{15}N$ values is marked with arrow up (↑) and decrease in drained pair by arrow down (↓)

	Undrained	Drained	$\delta^{15}N$ of moved N^a Balance	Annual *N* balance during drainage
Above 70 cm N (*n* = 7) and 50 cm D (*n* = 5)				
$\delta^{15}N$ (‰)	−1.60 ± 0.01	−2.75 ± 0.3 ↓	0.89 (−0.26–2.19)	
g N m^{-2}	608.5 ± 29.3	412.0 ± 3.0 ↓	−196.5 ± 17.0	−5.31 ± 0.46
Between 70–160 cm N (*n* = 9) and 50–130 cm D (*n* = 8)				
$\delta^{15}N$ (‰)	−2.57 ± 0.22	−2.28 ± 0.06 ↑	0.59 (−2.9–4.4)	
g N m^{-2}	1116.1 ± 44.2	1193.9 ± 49.8 ↑	+77.8 ± 38.5	+2.10 ± 1.04
Between 160–240 cm N (*n* = 8) and 130–210 cm D (*n* = 8)				
$\delta^{15}N$ (‰)	−1.18 ± 0.07	−0.60 ± 0.05 ↑	−1.81 (−13.5–7.8)	
g N m^{-2}	1353.6 ± 57.7	1423.1 ± 93.2 ↑	69.5 ± 63.3	+1.9 ± 1.7
Above 240 cm N (*n* = 24) and 210 cm D (*n* = 21)				
$\delta^{15}N$ (‰)	−1.75 ± 0.06	−1.55 ± 0.01 ↑	−5.8 (−17.3–11.6)	
g N m^{-2}	3078.3 ± 42.8	3029.1 ± 40.3 ↓	−49.2 ± 34.0	−1.3 ± 0.91

[a]Added or lost nitrogen enrichment or depletion compared to original peat mass weighted $\delta^{15}N$ values. *Independent samples T-test t = 3.53, df. = 30, $p < 0.001$

The minimum N% was at the depth of 25 cm (0.58 ± 0.04%) in undrained Rahesuo bog and at 15 cm (0.63 ± 0.03%) in drained site (Fig. 3B, Sup. Figure S1B). N% increased rapidly downwards below these depths, from 0.89 ± 0.03% at 35 cm to 1.84 ± 0.28% at 45 cm in the undrained site. In the drained counterpart, no similar surface N% maximum was found. Instead, N% increased from 1.39% to peak at 125 cm (1.78%), while not on undrained site in the corresponding depth 155 cm (Fig. 3B). A second N% increase occurred at undrained Rahesuo around the depth of 185 cm, peaking at 195 cm (2.1%), below which N% again decreased (Fig. 3B). At drained Rahesuo, the corresponding peak in N% (2.0%) was 10 cm deeper. The C/N ratio increased in the top 25 cm in the undrained Rahesuo (from 67.7 to 77.9) and more sharply in the top 15 cm at drained Rahesuo (from 55.8 to 71.2). Below this peak at natural Rahesuo bog, the C/N ratio rapidly decreased toward $TP_{UD45/D25}$, reaching its minimum (27.0) at 45 cm. Below this depth, the C/N ratio increased again, peaking between 90 cm and 110 cm (average 45.3), before reaching a second minimum (27.3) at 195 cm. Below 195 cm, the C/N ratio remained relatively stable (average 32.7) down to the mineral soil. At drained Rahesuo site, the surface C/N minimum at 45 cm (36.2) was higher than that at natural site at Rahesuo. The maximum C/N ratio (46.1) occurred at 95 cm. Due to N% peak (above), the C/N ratio was low also at depth of 125 cm (31.2) at drained Rahesuo. The minimum (27.3) was at 175 cm. Below 175 cm, the average C/N ratio for the 180–230 cm profile was 31.0.

There was no correlation between the decomposition proxies (ash% and BD) in the drained Rahesuo peat profile. However, a regression equation could be constructed between C/N and $\delta^{15}N$ for the undrained Rahesuo and Ilajansuo lawn and hummock sites, as suggested by Drollinger et al. (2019). For Rahesuo, the Eq. (3) was:

$$\delta^{15}N = -0.1017 * C/N + 1.9787,\ r^2 = 0.48,\ p = 0.001 \quad (3)$$

and for Ilajansuo, (both lawn and hummock profiles combined), the Eq. (4) was:

$$\delta^{15}N = -0.0369 * C/N + 1.075,\ r^2 = 0.49,\ p = 0.001 \quad (4)$$

Drainage increased bulk density. In Rahesuo, the average BD for the whole profile was higher on the drained side (102.0 ± 22.3 g dm^{-3}) than on the undrained (93.4 ± 19.1 g dm^{-3}). Even with a 10 cm resolution, changes in layer synchrony due to subsidence could be estimated. The distance from the surface to $STPN_{UD65/D45}$ decreased 20 cm, and from $STPN_{UD65/D45}$ to $SCLN_{UD155/D125}$, distance decreased from 90 cm on the undrained site to 80 cm on the drained site. These decreases together account for the 30 cm subsidence due to drainage. In the deeper strata between $SCL_{UD155/D125}$ and $SAL_{UD235/D205}$, the distance remained constant at 80 cm. In contrast to the relatively stable BD values in the deeper peat layers, Rahesuo at natural condition exhibited a decrease in BD at 65 cm, coinciding with increases in the C/N ratio and water content (not shown) at this same depth (Fig. 3D).

Estimation of Lost or Gained N Amounts and their $\delta^{15}N$ at Rahesuo

In Rahesuo undrained site, the highest N contents within single 10-cm sections were recorded at depths of 45 cm (230.1 g N m^{-2}) and 185 cm (231.7 g N m^{-2}). In drained site, the N content increased downwards to the depth of 65 cm, below which depth it declined to a minimum of 96.6 g m^{-2} at 95 cm, followed by a rise to 222.5 g N m^{-2} at 125 cm. A secondary N inventory peak at drained site was found at 165 cm (212.6 g N m^{-2}), with a subsequent decline below that depth (Fig. 3 F).

By using three synchronous layers, the N content and $\delta^{15}N$ values between the drained and undrained profiles of the peat sections could be compared (Table 5). The original surface 70 cm had lost 196.5 ± 17.0 g N m^{-2}, and the mass weighted $\delta^{15}N$ value of the lost N was clearly more positive (0.89‰) compared to the original peat $\delta^{15}N$ value at the undrained site (−1.60‰). The annual N loss from this uppermost peat layer, during the drainage, was high, 5.31 ± 0.46 g m^{-2} yr^{-1} (Table 5). Big share of the lost N was found from deeper peat layers. There was a surplus of 78 g N m^{-2} captured to 50–130 cm layer of drained Rahesuo. The $\delta^{15}N$ value of the additional N was more positive than that of the original peat (0.6 vs. −2.6‰). The deeper 130–210 cm layer on drained site got 70 g N m^{-2} of ^{15}N depleted N (−1.8‰).

The total N content in the whole profile decreased from 3078.3 g N m^{-2} at undrained Rahesuo to 3029.1 g N m^{-2} at the drained site, resulting in a modest net N loss of 49.2 ± 34.0 g N m^{-2} (average ± SE) (Table 5). The mass-weighted $\delta^{15}N$ value for the entire profile was only 0.2‰ higher at the drained site (Table 5), thus also indicating that no major losses of $\delta^{15}N$ depleted N occurred.

Discussion

Mineral Subsoil N Processes

Our mineral subsoil sampling was done at Lakkasuo fen, which is formed by paludification on mineral soil. During paludification dry land is converted to mire through progressive waterlogging and peat formation. In our study, the downward transition from basal peat to deeper subsoil was marked by a downward decrease in N% and an increase in the $\delta^{15}N$ values. This is the opposite of $\delta^{15}N$ values in boreal forest mineral soils, which decrease with depth (Spohn and Stendahl 2023). Thus, current $\delta^{15}N$ profiles in the mineral sub soil profiles beneath peat are different to those in upland mineral forest soils, but still a possible starting point for Lakkasuo fen 3400 cal. yr. BP. The plausible explanation for this is that basal peat acts as a source for N to mineral subsoil. Turunen et al. (1999) showed that carbon density in mineral subsoil was 1.5-fold of that in the adjacent upland forest soil. Seepage of dissolved organic matter (DOM), as well as NO_3^- and in lesser extent NH_4^+, is possible even through whole peat columns, as studies have shown that water and dissolved organic carbon (DOC) can be transported from peatland surfaces to the basal peat (Charman et al. 1999). Pattern of preferential seepage of ^{15}N compounds is clearly visible in Lakkasuo undrained and drained profile $\delta^{15}N$ values. At the drained site, all profile values are lower; however, $\delta^{15}N$ values are only 0.4‰ lower than those at the undrained site. In DOM, organic N and C are coupled. The C stored in subsoils is linked to the adsorption of DOC onto minerals and its slow mineralization under anaerobic conditions (Turunen and Moore 2003). Furthermore, organic N compounds, due to their high charge density, preferentially adsorb to mineral surfaces (Spohn 2024).

Water seepage in the peat column has lasted as long as the peat layer had grown above the mineral subsoil. However, increasing difference between undrained and drained site $\delta^{15}N$ values deeper in the subsoil indicates that downward leaching of water may be responsible for this pattern, which appears more prominent in the drained site. On drained site, seepage of water through peat columns has probably increased and thus led also to increased flushing of DOM also from the basal peat to mineral soil. Besides preferential downward movement of isotopically heavier $^{15}N\text{-}NO_3$ (Bedard-Haughn et al. 2003), increases of $\delta^{15}N$ values deeper in the subsoil may also follow from change in microbial processes mineralizing DOM due to increased aeration in water of subsoil due to changed hydrology. Mpamah (2018) found that bacteria had outnumbered archae at Lakkasuo drained fen peat profile down to depth of 50 cm.

On average, there is 6.2 kg C m^{-2} in a 70 cm profile under mires (Turunen et al. 1999), and with a C/N ratio of ~35 in the subsoil (Nykänen et al. 2018), the amount of N stored in the subsoils could be as much as 170 g m^{-2}. In any case, N stores and N related processes in subsoils under peatlands need further studies since the area of subsoils corresponds to that of peatlands and fate of N in subsoils is probably influenced by hydrology changes on peatlands.

$\delta^{15}N$ Trends from Basal Peat to Peat Surface

In peatland development, vascular plants obtain nutrients from minerogenic water sources, N deposition, and nutrients released during the decomposition of organic matter (Vitt and Wieder 2006). At Lakkasuo mire, the basal peat column showed stable $\delta^{15}N$ values and N% throughout most of the 25 cm peat column, while drainage slightly decreased N%. At Rahesuo mire, the $\delta^{15}N$ values increased upwards through the basal peat column, but the drained site had higher $\delta^{15}N$ values and N% in the basal peat. Thus, drainage had no consistent effect on basal peat $\delta^{15}N$ values across sites.

The most positive $\delta^{15}N$ values in the peat column were observed at the depth of 170–220 cm in Rahesuo, where N%, BD, and the humification index (von Post) also increased, and the C/N ratio decreased. These depth layers correspond to minimum $\delta^{13}C$ values, marking the fertile fen era found at Rahesuo during the warm and moist Mid-Holocene probably 7950–6750 years cal. yr. BP (Nykänen et al. 2020). During this period, July temperatures were ~3 °C warmer, and precipitation was higher compared to present day conditions (Seppä and Birks 2001; Weckström et al. 2010). Particularly vascular fen vegetation benefit of warm and wet climate increasing organic matter decay and nutrient flow to peatlands. Vascular vegetation which decomposes faster than bryophytes, leading to higher C% and N%, and a lower C/N ratio, (Andersson et al. 2012), and also to higher $\delta^{15}N$ values in the remaining peat as shown in this study. Also, Hobbie et al. (2017) found isotopically heavier N in peat strata at time intervals characterized by a warmer climate.

Choi et al. (2007) made comparison between drained and undrained pairs from surface 30 cm of fertile partially drained fen in Alberta, Canada. In their study, $\delta^{15}N$ values of soil NH_4^+ and NO_3^- were depleted when compared to soluble organic N (SON) values (Choi et al. 2007). NH_4^+ and NO_3^- can be recycled into microbial biomass and vegetation, thereby not contributing to the $\delta^{15}N$ signature in the bulk peat. NH_4^+ can also be nitrified or denitrified producing ^{15}N-depleted gases (N_2, N_2O, NO_2, NO), which are lost to the atmosphere, while ^{15}N-enriched inorganic residuals remain (Deb et al. 2024) and can thus increase peat $\delta^{15}N$ values. On drained peatlands nitrification is increased in the surface peat and can lead to the leaching of NO_3^- down to the deeper, anaerobic peat and there increase denitrification and N_2O release (Regina et al. 1996). Vertical leaching preferentially exports heavier ^{15}N instead of ^{14}N compounds downward in the peat matrix, affecting the $\delta^{15}N$ pattern of the profile (Esmeijer-Liu et al. 2012; Novak et al. 2014). Furthermore, horizontal leaching aided by ditches is particularly important in drained peatlands, removing water and soluble nutrients from uppermost peat profiles (Nieminen et al. 2017).

In nutrient-poor bog peat, N is effectively mineralized and bound to microbial biomass (Damman 1988). Under limited N availability, all N is used, and denitrification is not preferring ^{14}N, thus suggesting that $\delta^{15}N$ value increase downcore is not caused by denitrification (Larsson et al. 2017). In any case, as microbial degradation progresses, $\delta^{15}N$ values increase downcore as seen in the peat $\delta^{15}N$ value increases at the upper peat strata at Rahesuo and Ilajansuo bogs.

N_2O emissions, indicative of organic matter mineralization, can reach up to 0.132 g N_2O-N m^{-2} yr^{-1} in fertile undrained fens (Ojanen et al. 2010; Minkkinen et al. 2020), and to emissions as high as 0.59 g N_2O-N m^{-2} yr^{-1} reported from drained fertile peatlands (Martikainen et al. 1993; Ojanen et al. 2010; Minkkinen et al. 2020). In this study, the live surface moss was depleted in ^{15}N relation to peat beneath it, thus indicating that ^{15}N depleted N was available to bryophytes. Other explanation – yet not ensured - could be downward leaching favoring ^{15}N-NO_3^- instead of lighter ^{14}N-NO_3^- molecules (Bedard-Haughn et al. 2003).

After the warm and moist period, the climate turned cooler and drier. Forests grew on peatlands during these dry climatic periods (Blytt 1876), indicating that water tables were low and nutrients available from decaying fertile peat. This drying may have caused further increases in nitrification, denitrification, and N_2O emissions, with an effect like recent drainage of fertile peatlands for forestry (e.g. Martikainen et al. 1993). Rahesuo in it fen phase, with low C/N ratio during the dry and cool period, may have experienced accelerated N cycling and gaseous N fluxes (Ernfors et al. 2011; Minkkinen et al. 2020), resulting in the preferential removal of ^{14}N and the formation of a $\delta^{15}N$ maximum in the remaining bulk peat.

Above the $\delta^{15}N$ Peak Zone

During the Late Holocene cool and moist climate conditions, commencing around 5700 cal. yr. BP, a decrease in N% and $\delta^{15}N$ values was found in the peat columns in Rahesuo. Furthermore, the main sources of N changed as the peat surface was elevated above the influence of mineral water from catchment area. This ombrotrophic period starting from the maximum $\delta^{15}N$ values showed rapid decrease of N% by 0.5% and N% remained low (1.1% – 1.4%) until a second maximum (1.84%) at the depth of 45 cm.

In bogs, additional N input mainly originates from biological nitrogen fixation (BNF), N capture by BNF can be ~200 mg N m^{-2} $year^{-1}$ to mire peat (Cleveland et al. 1999). The $\delta^{15}N$ value of biologically fixed N is approximately 0‰. Thus, in nutrient poor conditions, initial $\delta^{15}N$ values in surface peat should also be near 0‰. Despite the importance of BNF, $\delta^{15}N$ values throughout the whole peat columns were mainly negative in our study. Our results are in line with suggestion by Moore and Bubier (2020) that N in *Sphagnum* moss is primarily derived from decomposing peat rather than straight from BNF. Furthermore, ombrotrophic peatland surface vegetation faces significant variability in water table levels, temperatures, freezing and thawing and solar radiation annually, thus offering possibilities to decomposition and to N relocation in surficial peat layers.

$\delta^{15}N$ Values of Vegetation and Surface Peat

In peat soils, living vegetation N reflects the $\delta^{15}N$ values of inorganic N forms mineralized from peat N and are generally ^{15}N-depleted compared to the bulk soil (Amundson et al. 2003). Depletion of ^{15}N is even clearer when N comes through the degradation of organic matter by mycorrhizal fungi (Emmerton et al. 2001; Groß-Schmölders et al. 2020). In this study, the vegetation $\delta^{15}N$ values were ^{15}N-depleted compared to peat in Lakkasuo fen and even more on the bog. Drainage is supposed to increase the share of ^{15}N depleted N, when N is processed by mycorrhizal fungi. Despite this, vegetation $\delta^{15}N$ values were more positive on drained sites at Lakkasuo, thus increase in N availability did not lead to preferential use of ^{14}N. Drainage induced change in vegetation and decreased water table allowed roots to penetrate deeper in the peat. In general, deep-rooted plants are more enriched in ^{15}N than shallow-rooted plants (Moore and Bubier 2020). Furthermore, water table decrease, and subsidence may bring the layer with maximum N% and highest $\delta^{15}N$ values (turning point) to rooting zone of plants. Also, Choi et al. (2007) found, that drainage increased foliar $\delta^{15}N$ values of black spruce, tamarack and labrador tea.

Surface Peat $\delta^{15}N$ Value Maximum

A special feature in peat layers is the presence of turning point, a $\delta^{15}N$ value maximum or $\delta^{13}C$ minimum in the upper peat columns (Alewell et al. 2011). Previous studies have connected these turning points with changes in hydrology, such as frost uplift, drainage, or even rewetting of drained peatlands (Alewell et al. 2011; Krüger et al. 2017; Groß-Schmölders et al. 2020). Groß-Schmölders et al. (2020) found turning points from eight drained sites but not from undrained sites of nine drained and undrained peatland pairs. In the upper layer of undrained Rahesuo bog, both $\delta^{15}N$ values and N% increased like in Groß-Schmölders et al. (2020, 2022) downcore. Bulk density and ash content increase indicates active aerobic decomposition leading to peat mineralization and preferential ^{14}N loss. In the drained Rahesuo profile, a similar pattern was observed, but the $\delta^{15}N$ value maximum was closer to the current peat surface, and maxima was not so clearly different from above and below values. At Ilajansuo, the maximum was just below the 45 cal. yr. BP level. According to Groß-Schmölders et al. (2020, 2022), the $\delta^{15}N$ turning points marks the transition from fungal dominance in the aerobic peat layers to bacterial dominance in the deeper, partially oxygen-limited layers. The maximum $\delta^{15}N$ value closer to the current peat surface in the drained site of Rahesuo indicates that the $\delta^{15}N$ maximum was there already prior to drainage. The depth of the $\delta^{15}N$ maximum at Rahesuo fits to the average depth range (41 ± 23 cm) for raised bogs surface younger than 300 year in Finland (Mäkilä and Goslar 2008), similarly as the 45 ± 30 cal. yr. BP level in Ilajansuo.

According to this study and $\delta^{13}C$ profiles from the same site (Nykänen et al. 2020), turning point was not connected with the drainage implemented 37 years earlier and thus turning points do not serve as indicators of peatland degradation by human impact, contrary to the suggestion by Groß-Schmölders et al. (2020, 2022).

Diagenetic Processes Modifying $\delta^{15}N$ Values of Peat Columns

Viable microbes were present throughout the deep peat profiles studied (Putkinen et al. 2009; Mpamah et al. 2017; Mpamah 2018), thus allowing a slow decay by microbial metabolism in all peat layers. A relationship between $\delta^{15}N$ values and the C/N ratio (Larsson et al. 2017), as well as between $\delta^{15}N$, C/N ratios, and BD in peat columns (Drollinger et al. 2019), supports the assumption that current $\delta^{15}N$ signatures result from isotopic fractionation during peat decomposition, potentially obscuring the original $\delta^{15}N$ differences in the peat columns. However, some studies have reported no such correlation (Biester et al. 2014). In Rahesuo, the differences in $\delta^{15}N$ values within the peat column could be linked to historical climatic periods and transitions in mire types, like differences in the $\delta^{13}C$ values at the same site (Nykänen et al. 2020). In this study, the C/N ratio generally explained $\delta^{15}N$ values in the deeper peat profile of the undrained Ilajansuo and Rahesuo. This correlation was weaker at the drained site of Rahesuo, possibly due to structural changers in peat profile and N relocation within the peat profile there (below). Thus, in our studied sites, the $\delta^{15}N$ values have a clear imprint of the original peat formation and storage processes, even the original $\delta^{15}N$ values can be altered.

Lowered Water Table and $\delta^{15}N$ Values of Peat

We have assessed N changes in fens and bogs and compared adjacent undrained and drained sites flanking border ditches. In drained sites, the ditches withdraw water and increase aeration, which enhances internal nutrient release. In drained fens, the inflow of minerogenic water is halted as the border ditches sidetrack the water, while aeration enhances surface peat mineralisation, releasing nutrients for e.g. tree growth. Thus, it was expected that N% tends to be lower and $\delta^{15}N$ values higher on the surface layers of drained sites compared to their undrained counterparts. In Choi et al. (2007) study, drainage increased surface peat N%. In our study N% increased on bogs but decreased on fen. Also $\delta^{15}N$ pattern change was similarly not clearly connected to changes in N content in this study and in Choi et al. (2007). In their study $\delta^{15}N$ values of peat increased on drained site (range 1.3 to 2.3‰) but remained similar or decreased for SON (range 0.3 – −3.5‰) on surface 30 cm divided to 10 cm slices (Choi et al. 2007).

Trees on drained peatlands have clearly the biggest biomass increase and N store. Biomass of shrubs and other field layer species decreased from 350 to 190 g m^{-2} (d.w) (Laiho 1996) when tree stand biomass increased from 718 to 6338 g m^{-2} (d.w.) (Laiho and Laine 1997). Evapotranspiration increase, supported by drainage, keeps the water tables low, and trees capture nutrients from peat, returning some via litterfall (Laine and Vanha-Majamaa 1992). Litterfall on drained fen sites can range from 600 to 850 g m^{-2} yr^{-1} (d.w.) (Laiho and Laine 1994), and from litter released N is more depleted in ^{15}N than peat as our vegetation analyses show. Furthermore, at our studied sites, trees and to them captured nitrogen have not been removed from site. After drainage, gaseous N fluxes and N release to waterways increases. Average total N concentrations in the water from catchment with drained peatlands was 506 ± 232 µg l^{-1} (SD), thus larger than at undrained catchment area 394 (± 145) µg l^{-1} (Nieminen et al. 2021). In Finland, where more than half of the original peatland area is drained for forestry, drainage has increased N export to boreal surface waters (Finér et al. 2021).

In this study, N was lost from the drained fertile fen while in the nutrient poor bog N balance was not changed much. However, both the fen and bog exhibited only minor changes in average and mass weighted $\delta^{15}N$ values. Despite substantial N release as N_2O and uptake of N to tree stand and leaching to ditches at Lakkasuo drained fen, the drained site was ^{15}N-depleted in the whole peat column when compared to undrained site. The $\delta^{15}N$ values tend to increase during peat decomposition as processes like ammonification, nitrification, denitrification, enzymatic hydrolysis and mycorrhizal uptake preferentially remove ^{14}N, leaving ^{15}N-enriched products in peat (Wilson et al. 2016; Hobbie et al. 2017; Drollinger et al. 2019). Significant increase in $\delta^{15}N$ values of bulk peat require selective removal of ^{14}N instead of ^{15}N. Drainage accelerates N mineralisation; in a drained forested fen, 7.3 g N m^{-2} was mineralized in the uppermost 15 cm during the growing season (Regina et al. 1998). Of this mineralized N, 42% was lost as N_2O gas, 22% was leached as NO_3^- and 8% as NH_4^+. Large share of N_2O gas formation means that due to N isotope fractionation being 28–60‰ in nitrification or denitrification (Robinson 2001), produced NO_3 is enriched with ^{15}N and this can explain ^{15}N increase in plants. Unfortunately, we did not measure $\delta^{15}N$ values of trees having the biggest N store. Based on the data from Laiho and Laine (1994), forested peatlands drained 45–55 years earlier had stored 42 g N m^{-2} in trees on originally fertile drained peatlands (Laiho and Laine 1994). Yet, in fertile drained sites, this uptake and store represents only a small fraction of the total N in the 30 cm rooting zone (1815 g N m^{-2}) (Westman and Laiho 2003). Thus, N removal to trees would have a minimal impact on the $\delta^{15}N$ values of bulk peat.

Relocation of N in Peat Columns

Downward and lateral leaching can remove or redistribute N in peatlands (Novak et al. 2014). ^{14}C analyses show that DOC in the peat column can originate from newly formed surface peat (Tfaily et al. 2014; Wilson et al. 2016). This suggests that mineralized N or dissolved organic matter (DOM) from the whole peat column may also percolate through the peat columns. Since NO_3^- is highly soluble, it is susceptible to leaching, with $^{15}NO_3^-$ potentially being preferentially leached instead of $^{14}NO_3^-$ due to gravitation, although the impact on $\delta^{15}N$ values of this is unknown (Bedard-Haughn et al. 2003).

In the drained Rahesuo, increase in vegetation uptake of N was minimal due to the low increase in tree stand. Our N balance calculations and changes in the $\delta^{15}N$ values indicate that ^{15}N was lost more than ^{14}N from the upper peat layers, with ^{15}N-enriched N relocating to the deeper peat strata. Nitrogen accumulation at the deeper layers indicates that most of the N loss from the surface peat was recaptured deeper in the peat column. Furthermore, drained Rahesuo lost 6 kg m^{-2} carbon from the whole peat profile, while C amount increased 3 kg m^{-2} to the deepest layers during the drainage (Nykänen et al. 2020).

Even C%, $\delta^{13}C$ (Nykänen et al. 2020) and $\delta^{15}N$ pattern was quite similar on undrained and drained Rahesuo, it is also possible that the higher N content in the deeper peat stratum at drained Rahesuo reflects an original, albeit slight differences in peat original composition and thus N content between the sites. Pitkänen et al. (2013) suggested that surface peat cores provide more reliable C mass loss comparisons, since long cores may increase random effects on the results. This seems true for the N stores as well.

N balance, N Amounts and $^{15}N/^{14}N$

Long-term nitrogen accumulation rate for the whole Rahesuo peat column is comparable to estimates for Swedish oligotrophic fens and northern peatlands (Larsson et al. 2017; Loisel et al. 2014). In Ilajansuo, LORNA was within the range estimated for boreal bogs (Limpens et al. 2006), while at Lakkasuo fen LORNA was close to estimates for northern peatlands (Wang et al. 2014). Malmer and Holm (1984) report recent (50 years) N uptake rates (RERNA) of 1.4–3.2 g N m^{-2} yr^{-1} in bogs, depending on N deposition (Malmer and Holm 1984). At Ilajansuo hummock RERNA during the last 115 years was comparable, 1.50 g N m^{-2} yr^{-1}.

The N losses during the drainage period were smaller at Rahesuo (1.3 g N m^{-2} yr^{-1}) than at Lakkasuo (2.9 g N m^{-2} yr^{-1}). LORNA estimates were markedly lower for undrained Rahesuo bog: 0.33 ± 0.02 g N m^{-2} yr^{-1} compared to undrained Lakkasuo fen; 0.77 ± 0.01 g N m^{-2} yr^{-1}. This indicates that the peat N stores are diminishing at both peatlands.

Drained Peatlands as a Model Ecosystem for Climate Change Induced drying?

In contrast to forest drainage by ditches, climate change induced warming and water table decrease during summer retains N within the system and thus potentially increases gaseous N fluxes from peatlands. Moreover, artificial drainage for forestry is still a relatively short-term event compared to historical climatic periods, possibly explaining why the ^{15}N enrichment in peat columns seen during the Mid-Holocene dry period is not yet seen recurring in the recent drainage cases.

Conclusion

To our knowledge, no studies have examined the effects of peatland forestry drainage on the N balance or $\delta^{15}N$ values on entire peat profiles. In the present study, drainage had no clear effect on the average $\delta^{15}N$ values. Drainage induced loss of N was found in a forested fen, but not clearly in the bog with minimal tree growth. Analyzing $\delta^{15}N$ values alongside N flows throughout the peat profile provides an additional tool to explore potential mechanisms for the impact of water table lowering on N cycling in peatlands. However, changes in $\delta^{15}N$ values or turning points in $\delta^{15}N$ values are not to be used as direct indicators of peatland degradation.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13157-026-02036-9.

Acknowledgements This work was supported by Research Council of Finland grant 140964 for H.N., grant 346751 for A.J.R. and grant 311655 to T.T. During writing HN received financial support from the UEF Water research community, which is jointly funded by the Saastamoinen Foundation, the Wihuri Foundation, and the OLVI Foundation. Lukas Kohl and Carlos Palacin-Lizarbe are acknowledged for their valuable comments when preparing this MS.

Author Contributions Heikki Simola, Teemu Tahvanainen and Jukka Turunen contributed to the study conception, design and sampling at Rahesuo, while Teemu Tahvanainen was responsible for Ilajansuo site. Hannu Nykänen and Antti J. Rissanen contributed to the study conception, design and sampling at Lakkasuo sites. Material preparation, data collection and analysis were performed by Heikki Simola, Teemu Tahvanainen, Jukka Turunen, Hannu Nykänen and Antti J. Rissanen. All nitrogen stable isotope and N% analyses of Rahesuo and Lakkasuo samples were done by Hannu Nykänen and Antti J. Rissanen. The first draft of the manuscript was written by Hannu Nykänen and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by University of Eastern Finland (including Kuopio University Hospital).

Data Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest This work was supported by Research Council of Finland grant 140964 to Hannu Nykänen, grant 346751 to Antti J. Rissanen and grant 311655 to Teemu Tahvanainen. The authors have no relevant financial or non-financial interests to disclose.

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