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Neodymium isotopes in peat reveal past local environmental disturbances

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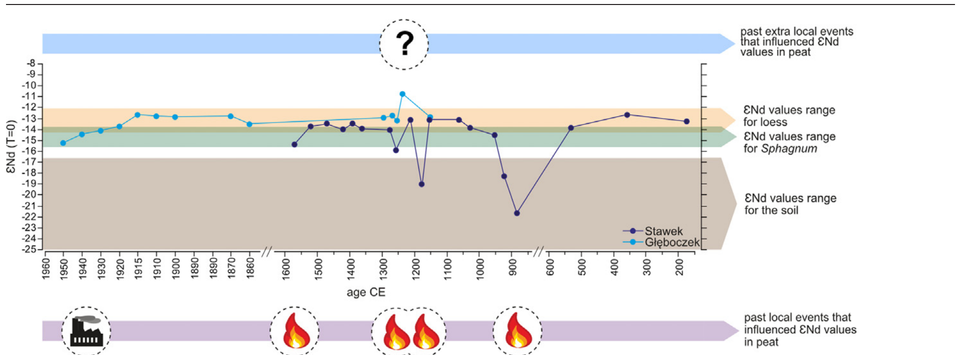
HIGHLIGHTS

- Environmental disturbances in peatlands are reconstructed with neodymium isotopes.
- Peat cores and moss surface samples are used to validate the method.
- Changes in neodymium isotope composition were related to fire activity and pollution.
- Recommendations for the use of neodymium isotopes in peat studies are provided.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the past decade, the neodymium (Nd) isotope composition of mineral matter from peat cores has seen increasingly common use as a tracer of dust influx associated with major changes in the Holocene atmospheric circulation. However, the incomplete understanding of the local controls on the sources of the sediment supplied to peatlands remains a key difficulty in the interpretation of the archived Nd isotope signals. Here, we used neodymium isotopes to reconstruct environmental disturbances in peatlands. We performed a multi-proxy study of two peatlands that experienced peatland burning and validated the recorded peat Nd signatures using reference surface sampling. Our data show a link between the Nd isotope signals and local environmental disturbances: peat burning, local fire activity and pollution fluxes. Our study illustrates the crucial role of identifying local events that influence the supply of mineral material to peatlands. Insufficient recognition of such local controls may either obscure the large-scale variations in the atmospheric circulation patterns, or introduce artefacts to the Holocene climate record. We also provide recommendations for the use of Nd isotopes in palaeoecological studies of peatlands.

1. Introduction

Ongoing global changes and anthropogenic pressure significantly influence ecosystems worldwide (IPCC, 2022). Peatland ecosystems comprise one of essential carbon stocks in the world and are necessary for climate change mitigation (IPCC, 2019; Parish et al., 2008). Peatlands are experiencing various forms of disturbances, which include drainage and substantial drying (Holden et al., 2006; Kettridge et al., 2015; Swindles et al., 2019), peat extraction (Bravo et al., 2020; Łuców et al., 2022), and fires (Guêné-Nanchen et al., 2022; Turetsky et al., 2015; Witze, 2020). All these disturbances damage peat carbon stocks, and significantly influence

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global carbon and methane emissions to the atmosphere (Gallego-Sala et al., 2018). To support ecosystem restoration and predict future trajectories of peatlands' development, it is crucial to recognize how disturbances impacted peatlands in the past (Karpińska-Kołaczek et al., 2022; Marcisz et al., 2022; Słowiński et al., 2019).

A number of proxies are commonly used in palaeoecological studies to reconstruct past disturbances. In both peat and lake sediments, charcoal is widely used as a proxy for past fire activity (Tinner and Hu, 2003; Whitlock and Larsen, 2001), whereas certain pollen types (such as *Secale cereale* or Cerealia) inform about human presence in the study area (Kołaczek et al., 2021; Poska et al., 2004; Schwörer et al., 2021). Plant macrofossils, such as brown mosses, *Sphagnum* mosses, or vascular plants, bring important information about past environmental conditions, peatland trophic status, and local vegetation changes (Birks, 2013; Mauquoy and van Geel, 2013). As the water table depth is an essential indicator of peatlands' stability and ecological status, past hydrological reconstructions based on testate amoeba communities are commonly used to support palaeoecological interpretations (Mitchell et al., 2008). Finally, X-ray fluorescence spectrometry can serve to assess element input from dust deposition or pollution associated with anthropogenic disturbances (Fiałkiewicz-Kozieł et al., 2018; Gałka et al., 2019; Turner et al., 2014).

Neodymium (Nd) isotope composition of mineral material is a technique commonly applied in a broad range of geological studies (e.g., Allegre et al., 1979; Belka et al., 2021; Jakubowicz et al., 2021; Pearce et al., 2013; van de Flierdt et al., 2016; White and Hofmann, 1982). In recent years, the Nd isotope composition of mineral material from peat has emerged as a new tool used in palaeoecological studies, most notably to reconstruct atmospheric dust fluxes. Owing to the distinct Nd isotope ratios of different types of crustal materials (Goldstein and Jacobsen, 1988; Shaw and Wasserburg, 1985), Nd isotopes are commonly used in geological studies to trace sediment provenance, including the transport of airborne particles (Goldstein et al., 1984; Grousset and Biscaye, 2005). In peat, Nd isotopes have served to identify atmospheric dust deposition, mainly from distant sources, such as volcanic dust or desert particles, over the Holocene period (Allan et al., 2013; Fagel et al., 2014; Le Roux et al., 2012; Pratte et al., 2017a; Pratte et al., 2017b; Vanneste et al., 2016; Vanneste et al., 2015). These studies focused on large-scale atmospheric circulation patterns, attributing the changes in Nd isotope signals to variations in the continent-wide transport of dust particles. Another set of studies applied Nd isotopes to detect traces of anthropogenic pollution in peatlands (Fiałkiewicz-Kozieł et al., 2022; Fiałkiewicz-Kozieł et al., 2016).

In this multi-proxy study, we provide high-resolution records of Nd isotope ratios ($^{143}Nd/^{144}Nd$) from two peat cores from Northern Poland to assess to what extent Nd isotopes can be used to identify local disturbance events in peatlands. Except for the peat, our Nd isotope analyses included samples of surface *Sphagnum* and local soil, enabling the identification of the local sources of material deposition in the peatland basin. We hypothesize that local environmental changes, such as fire or deforestation can lead to increased mineral and dust input into the peatland and thus affect its Nd isotope signatures. Our results provide important new constraints on the possible role of the local environmental changes in shaping the Nd isotope record archived in peat cores. On a more general scale, this study allows a better understanding of both the potential and limitations of the dust provenance studies based on the Nd isotope composition of peat cores.

2. Study sites and methods

2.1. Location of studied sites and fieldwork

We sampled two *Sphagnum*-dominated peatlands – Głęboczek and Stawek – located in Northern Poland in the Tuchola Pinewoods, a *Pinus sylvestris* monoculture forest (Fig. 1). Both sites are small kettle holes (< 1 ha) covered by birch and pine with numerous collapsed dead trees; their

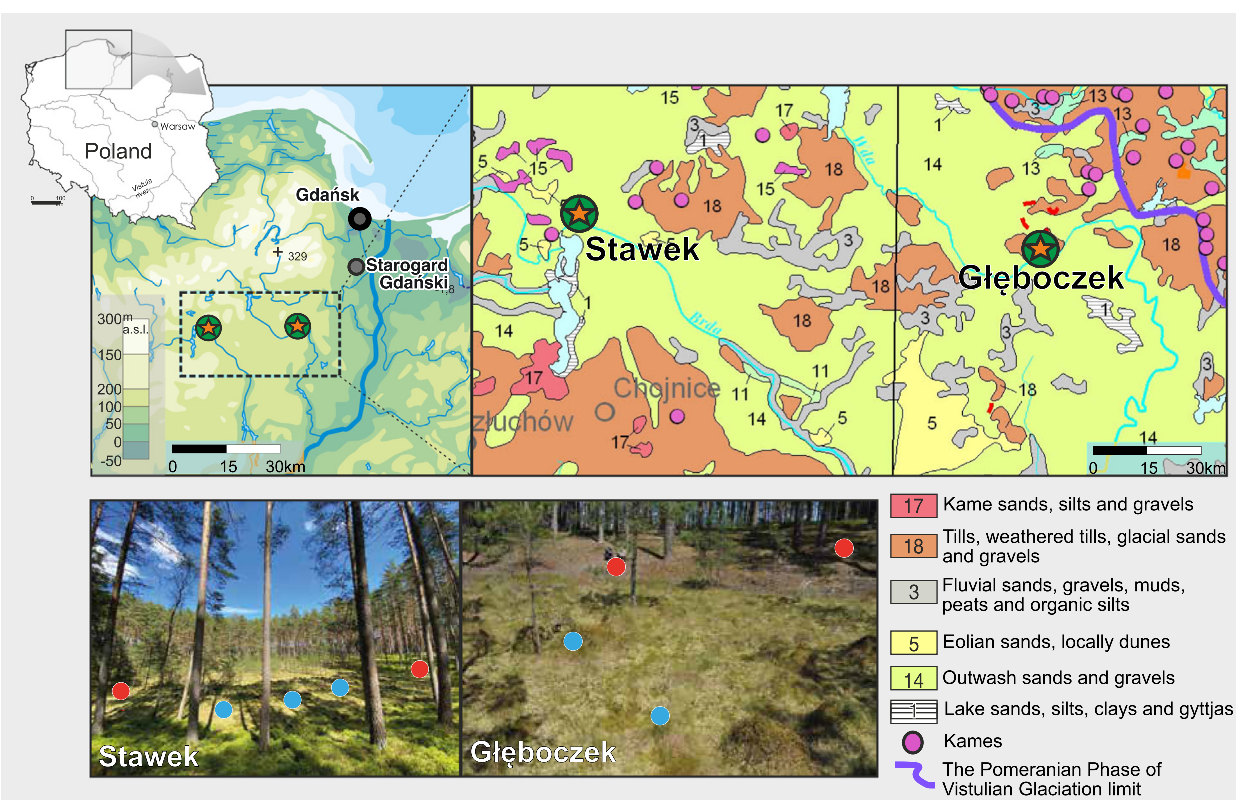

Fig. 1. Location, geological setting, and photographs of the studied peatlands. Photographs present the collection sites for surface samples included in the neodymium isotope analyses: red dots indicate the location of soil surface samples; blue dots indicate *Sphagnum* surface samples.

Table 1
Results of radiocarbon dating of charcoal sampled from peat from Stawek bog. The radiocarbon dates were calibrated using the IntCal20 calibration curve (Reimer et al., 2020).

Depth [cm]	Laboratory code	^{14}C date [yr. ^{14}C BP]	Calibrated age [yr. cal. CE] (95.4 % confidence interval)	Material dated
90–91	Poz-127,366	320 ± 30	1484–1644 (95.4 %)	Charcoal
95–96	Poz-127,367	565 ± 30	1308–1363 (53.7 %) 1386–1425 (41.8 %)	Charcoal
100–101	Poz-127,368	880 ± 30	1045–1085 (16.9 %) 1093–1105 (1.5 %) 1121–1228 (77 %)	Charcoal
105–106	Poz-127,572	1135 ± 30	774–787 (3.9 %) 830–855 (5.5 %) 873–993 (86.1 %)	Charcoal
109–110	Poz-127,369	1885 ± 30	78–101 (7.1 %) 107–234 (88.3 %)	Charcoal

vegetation is dominated by *Sphagnum* spp. The study area is close to the Pomeranian ice margin of the Vistulian Glaciation (ca. 17,000–16,000 cal. BP; Marks, 2012). The peatlands are located in a young glacial landscape dominated by glacial till, with common depressions and melting forms (Słowiński et al., 2015). The Głęboczek peatland basin is part of a larger lake and peatland cascade complex in the Czechowskie lake catchment (Lamentowicz et al., 2019; Ott et al., 2018), whereas the Stawek peatland is located in a depression formed by melting ice. The area of the Tuchola Pinewoods is characterized by a warm summer transitional climate, the coldest month being January (mean temperature for the period 1991–2021: −1.6 °C) and the warmest July (mean 1991–2021 temperature: 18.7 °C); the annual precipitation reaches 667 mm (Climate Data, 2022).

Peat coring in Głęboczek was done in March 2016, whereas coring in Stawek and surface sampling on both sites took place in May 2020. Both peat cores were retrieved using an Instorf corer – 1 m-long with 10 cm diameter in Głęboczek (Lamentowicz et al., 2019) and 50 cm-long with 5 cm diameter in Stawek. Peat cores were packed into plastic tubes and wrapped in plastic; *Sphagnum* from each peatlands' surface (picked by hand) and soil samples (sampled using a small shovel) were placed in string bags in the field and transported to the laboratory.

2.2. Laboratory work

From each peatland, a 20 cm-long peat sequence (Głęboczek bog: 16–36 cm; Stawek bog: 90–110 cm) has been analyzed contiguously every 1 cm. We performed the following analyses: peat properties, peat carbon accumulation rates, pollen, non-pollen palynomorphs, plant macrofossils, testate amoebae, and microscopic and macroscopic charcoal. Neodymium isotope ratios were measured from the peat core, from the same depths as the other proxies. Moreover, from each site, *Sphagnum* and nearby soil were sampled from the surface to obtain reference measurements for Nd isotope analyses (Fig. 1).

2.2.1. Radiocarbon dating and age-depth modelling

The absolute chronology of the cores is based upon Bayesian age-depth models. The sample selection for the ^{14}C AMS dates comprised plant macrofossils and macro-charcoal pieces. Moreover, in the case of the Głęboczek core, the topmost 28.5 cm were dated using the ^{210}Pb method. The age-depth model for the Głęboczek core is available in Lamentowicz et al. (2019). The age-depth model for the core from Stawek peatland is based on five ^{14}C AMS dates of charcoal pieces present in peat samples, resulting in five dates for a 20 cm-long profile (1 AMS date every 5 cm; Table 1, Fig. 2). This model was calculated in the OxCal software (*P_Sequence* function; Bronk, 1995; Bronk Ramsey and Lee, 2013), applying the IntCal20 radiocarbon age calibration curve (Reimer et al., 2020).

2.2.2. Peat properties and carbon accumulation rates

From the Głęboczek peatland, the material for bulk density, loss on ignition (LOI_{550}) and peat carbon accumulation rates (CAR) analyses was

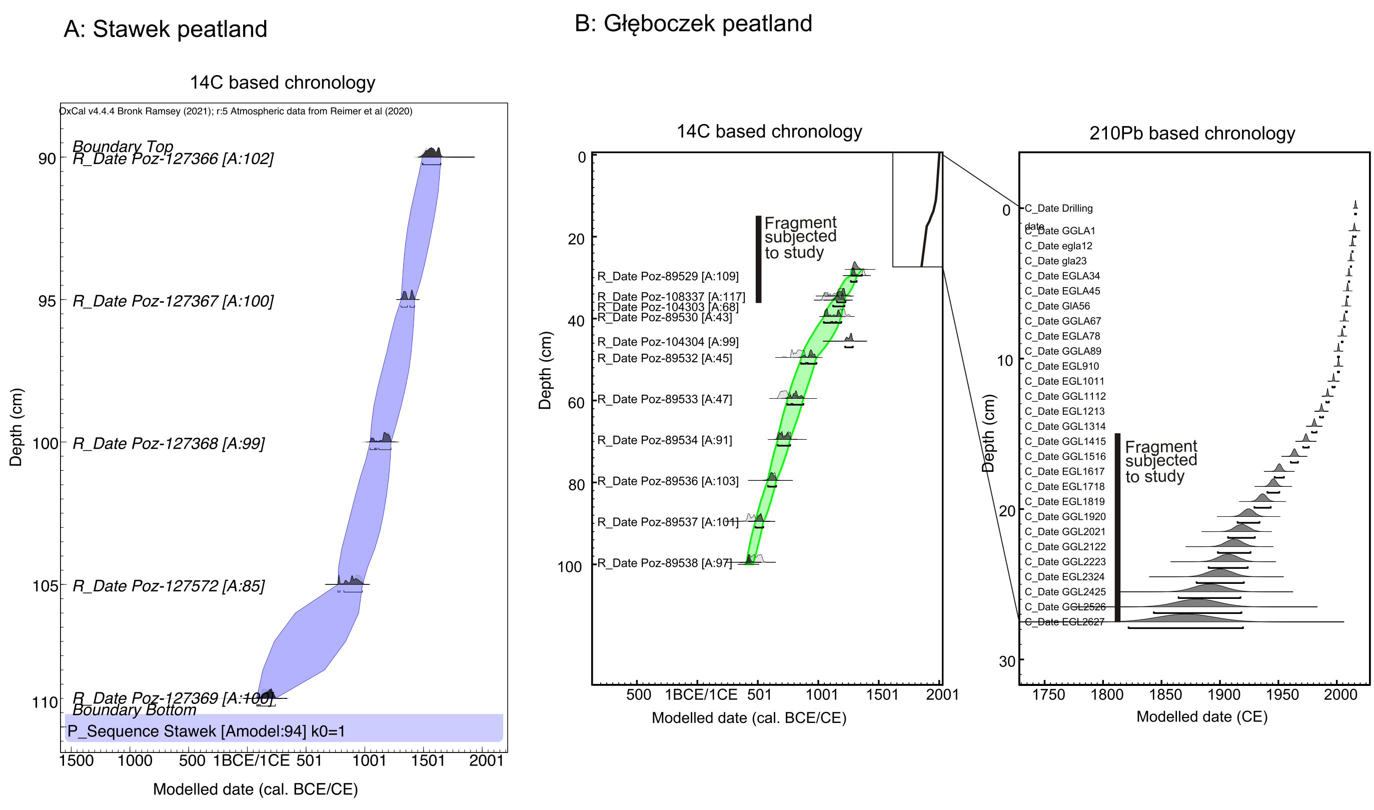

Fig. 2. Age-depth models for analyzed peat cores. A: The age-depth model for the Stawek peat sequence. The purple area outlines the 95.4 % confidence interval. B: The age-depth model for the Głęboczek peat sequence with highlighted segment investigated in this study. Details of the age-depth modelling are available in Lamentowicz et al. (2019).

recovered from the frozen peat core using an empty drill that produced a peat pellet of a known volume, which enabled a continuous 2-cm sampling resolution (see Lamentowicz et al. (2019) for details). From the Stawek peatland, the peat was carefully cut into slices (2 cm^3 in volume, uncompressed, continuously every 1 cm). Each peat sample was dried, weighed, burnt at 550 °C for 12 h, and weighed again, following the protocol by Heiri et al. (2001). The accumulation rates derived from the peat-core chronology were multiplied by the ash-free bulk density measurement and multiplied by 50 % to obtain CAR, following the protocol by Loisel et al. (2014).

2.2.3. Pollen and non-pollen palynomorphs

A total of 40 samples (2 cm^3 in volume) for palynological analysis were prepared using standard laboratory procedures (Berglund and Ralska-Jasiewiczowa, 1986). Four of twenty pollen samples from the Głęboczek core were described earlier in Lamentowicz et al. (2019). Samples were treated with 10 % HCl to dissolve carbonates and heated in 10 % KOH to remove humic compounds. Afterwards, acetolysis was applied for 2.5 min. Pollen and selected non-pollen palynomorphs (NPPs) were counted under a biological microscope until the total pollen sum (TPS) in each sample reached at least 500. Pollen grains and NPPs were identified with the help of identification keys (Beug, 2004; Moore et al., 1991) and online databases (Shumilovskikh et al., 2022). The results of the palynological analysis are expressed as percentages, based on calculations of the ratio of an individual taxon to the TPS, i.e., the sum of arboreal pollen (AP) and non-arboreal pollen (NAP) excluding aquatic and wetland plants but including Cyperaceae.

2.2.4. Plant macrofossils

The plant macrofossil composition of 40 peat samples (ca. 5 cm^3 in volume) was determined by wet sieving (mesh diameter: 125 μm). Plant macrofossils were analyzed using a binocular microscope and identified using a reference collection of type material (Mauquoy and van Geel, 2007; Tobolski, 2000). Volume percentages were estimated for all components, except seeds, roots, sand, cortex, wood and cones, counted and expressed as the number (n) present in each subsample. The plant macrofossil data from Głęboczek were published in Lamentowicz et al. (2019).

2.2.5. Testate amoebae and reconstructions of water table depth

The testate amoeba (TA) composition was determined from 40 peat samples (ca. 5 cm^3 in volume). Four of twenty TA samples from the Głęboczek core were presented earlier in Lamentowicz et al. (2019). Peat samples were washed under 300 μm sieves following the method described by Booth et al. (2010). Testate amoebae were analyzed under a light microscope with a minimum of 100 tests per sample whenever possible (Payne and Mitchell, 2009). Testate amoebae were identified with the help of taxonomic monographs (Clarke, 2003; Mazei and Tsyganov, 2006; Ogden and Hedley, 1980) and online resources (Siemensma, 2022). The results of the TA analysis were used for the quantitative water table depth reconstructions. Quantitative reconstructions of the TA-based depth to the water table (DWT) were performed in C2 software (Juggins, 2003), using training sets developed for northern Poland (Głęboczek; Lamentowicz and Mitchell, 2005, Lamentowicz et al., 2008), and a European transfer function model (Stawek; Amesbury et al., 2016).

2.2.6. Charcoal

Microscopic charcoal particles (>10 μm) were counted from pollen slides until the number of charcoal particles and *Lycopodium* spores, counted together, exceeded 200 (Finsinger and Tinner, 2005). Microscopic charcoal influx/accumulation rates (MIC; particles/cm^2/year) were calculated by multiplying charcoal concentrations (particles/cm^3) by peat accumulation rates (Davis and Deevey, 1964; Tinner and Hu, 2003).

For macroscopic charcoal analysis, peat samples (1 cm^3 in volume) were prepared following the method described by Whitlock and Larsen (2001). Charcoal particles (> 500 μm) were counted under a stereoscopic microscope. Macroscopic charcoal influx/accumulation rates (MAC, particles/cm^2/year, a proxy for local fires; Adolf et al., 2018; Conedera et al., 2009) were calculated using the charcoal concentrations and the peat accumulation rates. The charcoal data from Głęboczek were published in Lamentowicz et al. (2019).

2.2.7. Neodymium isotope measurements

All analytical procedures and isotopic measurements were carried out in the Isotope Laboratory of the Adam Mickiewicz University, Poznań, Poland. Peat samples, as well as surface *Sphagnum* and soil samples from both peatlands, were dried and burned at 550 °C overnight. Prior to preparation for isotopic measurements, the ash of peat and soil samples was dissolved on a hot plate (~100 °C for three days) in closed PFA vials using a mixture of concentrated hydrofluoric- and nitric acids (4:1). The ash of fresh plant material was digested in 16 N HNO_3. Miniaturized chromatographic techniques described by Pin et al. (1994) were utilized for the separation of Nd and Sr, with some modifications in column size and reagent concentrations according to Dopieralska (2003). The USGS reference material BHVO-2 was digested and analyzed during this study in order to monitor the analytical precision; it gave a value of 0.512986 ± 0.000006 (2σ; $n = 2$) for $^{143}Nd/^{144}Nd$. Neodymium (loaded as phosphate) was measured on rhenium (Re) in a double-filament configuration. Isotopic ratios were collected in dynamic mode on a Finnigan MAT 261 multi-collector thermal ionization mass spectrometer (TIMS). Total procedural blanks were <40 pg and were found to be negligible for the results. Nd isotope ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Repeated measurements of the AMES standard yielded $^{143}Nd/^{144}Nd = 0.512120 \pm 10$ (2σ, $n = 15$).

Nd isotope data are reported in the standard epsilon (ε) notation (DePaolo and Wasserburg, 1976), which is the deviation in parts per ten thousand from the chondritic uniform reservoir (CHUR):

$$\varepsilon_{Nd} = 10000 \times \left[{}^{143}Nd/{}^{144}Nd_{sample} - {}^{143}Nd/{}^{144}Nd_{CHUR}\right] / {}^{143}Nd/{}^{144}Nd_{CHUR}.$$

It has been calculated using $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$ for the present-day CHUR (Jacobsen and Wasserburg, 1980).

3. Results and interpretation

3.1. Absolute chronology

The analyzed segment of the Stawek peat core covers ca. 1400 years of peatland development (ca. 170–1570 CE; Table 1. Fig. 2). The age-depth model for this peat sequence has a high quality (very high agreement index = 94 %; cf. Bronk, 2008) and shows consistent peat growth (no outliers among the ^{14}C dates). However, regularly occurring charcoal horizons point to increased fire activity and a possibility of hiatuses in the peat.

The analyzed Głęboczek peat section covers ca. 800 years of peatland development (ca. 1150–1970 CE). The high-resolution model, based on ^{210}Pb and ^{14}C dates, enabled the identification of a ca. 500 year-long hiatus at a depth of 28 cm, which covers a period of ca. 1300–1850 CE (Lamentowicz et al., 2019).

3.2. Biotic proxies

Biotic proxy results from both peatlands show disturbances affecting their development and functioning. Both peatlands experienced local peat burning, and several charcoal layers are present in the peat.

In the Stawek peatland, the peat carbon accumulation rates were very low and the peat is highly decomposed, so most of the organic material could not be identified. The identified macrofossils enabled the classification of the sediment as herbaceous peat (Fig. 3, SFig. 4). The peatland was surrounded by forest composed mainly of *Pinus sylvestris*, with an admixture of *Betula, Alnus, Quercus* and *Carpinus betulus* (Fig. 3, SFig. 2). Some deforestation around the site was recorded in the layers between ca. 1260–1290 CE and ca. 1390–1570 CE. Three distinct charcoal layers that suggest increased local fire activity were identified at ca. 885 CE, 1185 CE and 1365 CE, i.e., before deforestation.

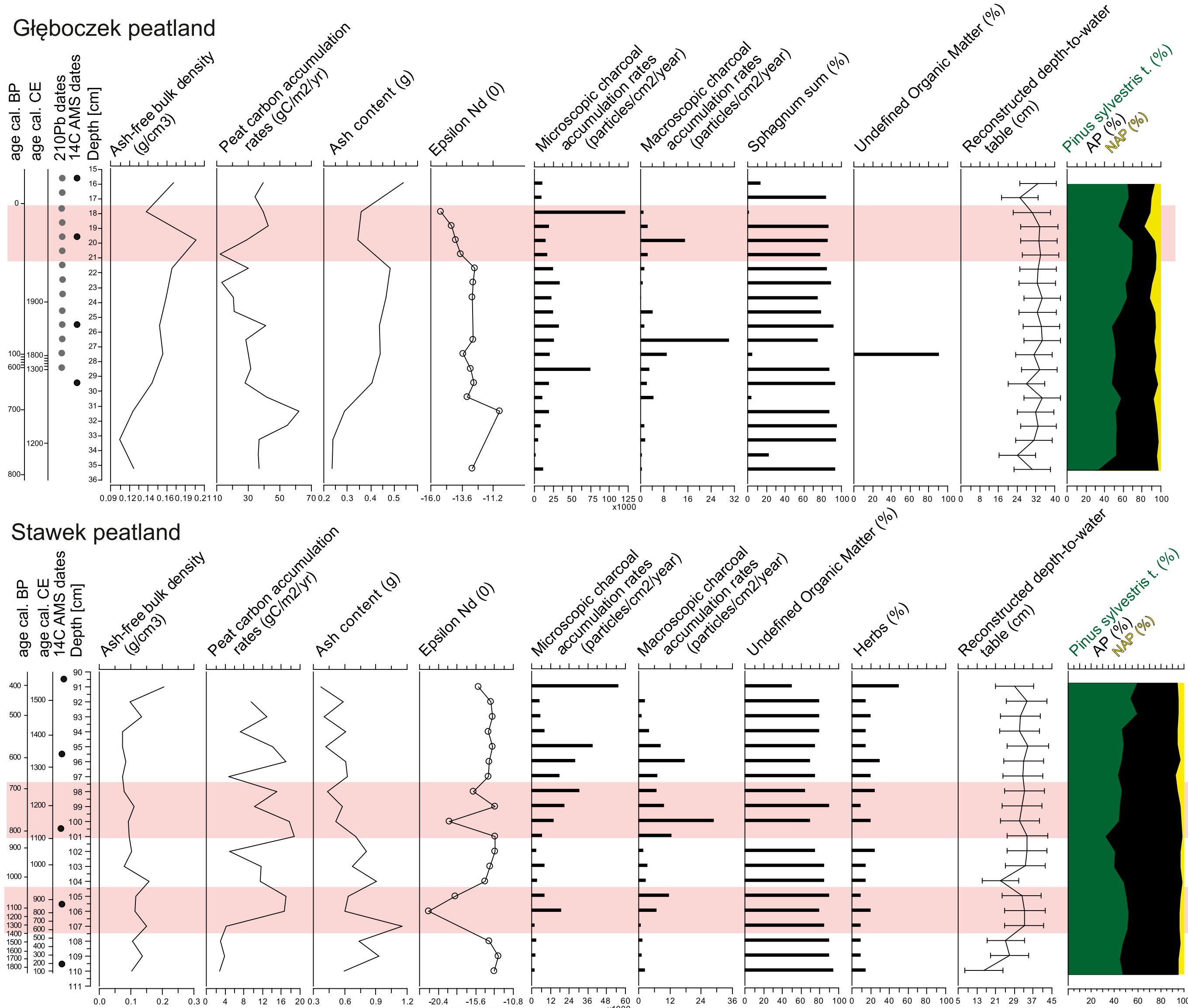

Fig. 3. ε_{Nd} and selected other proxy data for the Głęboczek and Stawek peatlands. Peat layers in which biotic proxy responses coincide with marked changes in the neodymium isotope signatures are highlighted in red.

The Głęboczek core is dominated by *Sphagnum* (mainly by *Sphagnum medium/divinum* and *Sphagnum cuspidatum*), with an exception at a depth of 28 cm, where, below the peak of microcharcoal, we recorded a hiatus marked by a high proportion of unidentified organic matter (Fig. 3, SFig. 4). Peat carbon accumulation rates decreased significantly in the sections above the recorded hiatus. Like in Stawek, Głęboczek bog was surrounded by a mixed forest dominated by *Pinus sylvestris*, with an admixture of *Betula, Alnus, Quercus*, and *Carpinus betulus* (Fig. 3, SFig. 2). The largest deforestation took place at ca. 1290 CE, 1900–1910 CE and 1940–1970 CE. Two layers with a substantial amount of macroscopic charcoal suggest two local fire episodes, in ca. 1875 CE and 1920 CE.

Both sites' hydrological conditions were very similar regarding the reconstructed water table depth and the testate amoeba community composition (Fig. 3, SFig. 3). At both sites, the reconstructed water tables were low (below 30 cm). Testate amoeba communities were dominated by the small agglutinated taxa *Cryptodifflugia oviformis* and *Schoenbornia humicola*, which are common in dry and disturbed habitats (Lamentowicz and Mitchell, 2005; Schönborn et al., 1987). Moreover, these species compose their shell from various sources, often agglutinating mineral material from the environment into their shells; their high abundance may indicate regular mineral deposition into the studied peatlands (Marcisz et al., 2021).

3.3. Neodymium isotopes

3.3.1. Reference surface samples

The Nd isotope measurements on reference surface samples from both sites document strongly unradiogenic ε_{Nd} signatures, higher in the mineral matter from *Sphagnum* samples (-13.8 and -15.5) than in the soil samples taken from nearby slopes (-16.6 and -26.5; Table 2). The study area is covered with young glacial material dominated by clay and sand originating from Scandinavia, which was transported and accumulated during the last glaciation (Marks, 2012). There have been no previous Nd isotope measurements of young glacial sediments from this area of Poland; however, the ε_{Nd} values from Scandinavian rocks (southern Sweden) are similar to those measured in our soil samples ($\varepsilon_{Nd} = -13.6$ to -26.1; (Johansson et al., 2006; Mansfeld et al., 2005)). The ε_{Nd} values observed in the local *Sphagnum* material overlap with those measured for Polish loess sediments (-12.2 to -14.1; M. Zieliński, unpublished data).

Table 2
Reference ε_{Nd} values measured in surface samples taken from the studied peatlands and their surrounding (Głęboczek – Gł; Stawek – pBS).

Sample code	Sampling spot, material	$^{143}Nd/^{144}Nd$ ($t = 0$)	ε_{Nd} ($t = 0$)
GŁ2	slope 1, soil	0.511787 ± 10	−16.6
GŁ3	slope 2, soil	0.511733 ± 10	−17.7
GŁ4	peatland, *Sphagnum*	0.511922 ± 11	−14.0
GŁ5	peatland, *Sphagnum*	0.511928 ± 10	−13.8
pBS1	peatland, *Sphagnum*	0.511867 ± 10	−15.0
pBS2	peatland, *Sphagnum*	0.511843 ± 13	−15.5
pBS3	peatland, *Sphagnum*	0.511899 ± 10	−14.4
pBS4	slope W, soil	0.511282 ± 10	−26.5
pBS5	slope E, soil	0.511776 ± 13	−16.8

3.3.2. Peat cores

Most of the analyzed peat samples show a moderate (~1–2.5 ε_{Nd} units) variability of ε_{Nd} values, ranging from −12.7 to −15.3 for the Stawek peatland, and from −12.6 to −13.7 for the Głęboczek peatland (Figs. 3 and 4). In several peat layers, the ε_{Nd} signatures are notably lower and similar to those measured from the soil samples (Table 2, Fig. 4). At Stawek, the lowest ε_{Nd} values were recorded at ca. 885–920 CE (−21.6 and − 18.3), ca. 1185 CE (−19.0), ca. 1265 (−15.9), and ca. 1570 CE (−15.3). In all these peat layers, an increase in the abundance of macroscopic charcoal is observed, and before the event at ca. 1185 CE, a drop in *Pinus sylvestris* pollen occurs (Fig. 3). This may indicate that the peat layers with lower ε_{Nd} signatures contain mineral material transported to the peatland from the nearby slopes by surface runoff and short-range aeolian deposition during disturbance events such as local fires or deforestation.

At Głęboczek, a trend toward lower ε_{Nd} values, down to −15.2, can be observed between ca. 1940 and 1960 CE. These low ε_{Nd} signatures coincide with a period of dynamic industrial and economic growth in the region, suggesting an anthropogenic source of the mineral material accumulated in the peatland basin.

We recorded only a single ε_{Nd} value (−10.7 at ca. 1245 CE at Głęboczek) higher than the signatures of the reference (surface) material. As this isotopic signal is not connected to changes in other proxies, it may reflect atmospheric dust deposition from extra-local sources.

4. Discussion

4.1. Connections between neodymium isotope signals and biotic proxy data

Local environmental disturbance can significantly impact the functioning of a peatland, mainly disrupting its carbon storage capacity and leading to carbon or methane emissions (Harris et al., 2022; Kettridge et al., 2015; Sothe et al., 2022). In terms of the vegetation, disturbances cause a change in local plant composition (Anggi et al., 2018), which is often observed as a shift between dominant moss communities (Gałka et al., 2019; Lamentowicz et al., 2020; Sim et al., 2019), or an expansion of vascular vegetation on the peatland surface (Buttler et al., 2015; Dieleman et al., 2015; Sillasoo et al., 2011), mainly when a drying trend is observed. The microbial food web is also significantly affected by disturbances, a pattern that has been observed in ecological (Jassey et al., 2013; Mitchell et al., 2003; Reczuga et al., 2018; Turner and Swindles, 2012) and palaeoecological studies (Lamentowicz et al., 2019; Marcisz et al., 2021; van Bellen et al., 2016; Zhang et al., 2020). Very often, the changes in local environmental components are an effect of significant disturbance – both natural and anthropogenic – and are seen in peat cores as shifts in dominant proxies present in peat layers (Dudová et al., 2012; Feurdean et al., 2017; Kołaczek et al., 2018; Sillasoo et al., 2011; Stivrins et al., 2014).

The recorded response of biological proxies and the Nd isotope measurements indicate that changes in ε_{Nd} values along the peat core were mainly related to local environmental changes and disturbances recorded at the investigated sites (Figs. 3 and 4). At Stawek, all of the peat samples with the lowest ε_{Nd} values show significant enrichment in charcoal. A high number of charcoal pieces indicates local fire activity that could have led to substantial changes in the peatland catchment. Fires could have resulted in forest removal, and thus an increased runoff into the peatland basin. The pollen record confirms deforestation for at least two charcoal layers dated to ca. 1185–1265 CE (Fig. 3). The Stawek peatland is a kettle hole mire surrounded by a ridge made of young glacial sediments, mainly moraine clay and sand (Fig. 1). After deforestations, the sedimentary material derived from the slopes, with its strongly unradiogenic Nd isotope composition, could have been washed or blown onto the peatland surface, leading to increased contribution of the local mineral matter to the observed ε_{Nd} values. Our macroscopic charcoal record from Stawek suggests that at least several local fire events in the past were sufficiently large to significantly impact the peatland basin and local vegetation.

In the most recent layers of the Głęboczek sequence, dated to ca. 1915–1950 CE, we recorded a consistent drop in ε_{Nd} signatures (from −12.6 to −15.2) in the time interval coinciding with a single local fire event that was followed by deforestation and an opening of the landscape (Fig. 3). The ε_{Nd} values drop slightly, but do not reach the values recorded in the Stawek profile. The change in ε_{Nd} signatures could be an effect of anthropogenic deforestation. Still, it could also be connected to dust deposition from industrial sources in the region, as Głęboczek is located close to a few cities (23 km from Starogard Gdański, 45 km from Tczew, and 60 km from Gdańsk) whose economies have grown in the 20th century. The main branches of local industries were related to shipbuilding and marine transportation. Industrial sources in Western and Central Europe have been shown to display variable ε_{Nd} signatures, from −9.7 to −17.5 (Lahd Geagea et al., 2008), with the lowest signals typical of heavy industry (e.g., steel plants). It is impossible to directly link the ε_{Nd} signatures from the considered peat layers to industrial dust fluxes from certain locations in this area, as no such Nd isotope data are available for this part of

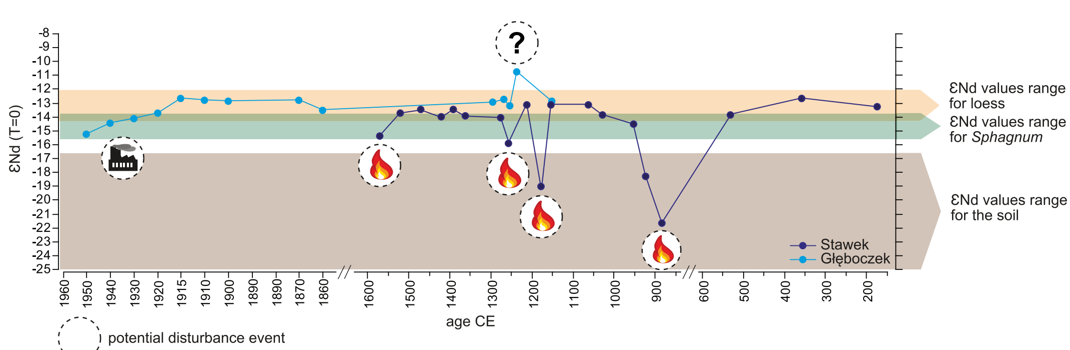

Fig. 4. Summary illustration of the neodymium isotope records (εNd values) from the Stawek and Głęboczek peatlands. The sections highlighted with colours show the ranges of εNd values for: Polish loess sediments (yellow; M. Zieliński, unpublished data), *Sphagnum* surface samples (green; this study), local soil (brown; this study) and past disturbance events (major fires and industrial activity) that potentially influenced the εNd values measured in peat.

Poland. However, this change in the Nd isotope composition could be an effect of both a local change in vegetation and fire activity, and an increasing industrial dust influx.

The only event that can be linked to atmospheric dust deposition mainly from distant sources was recorded in the Głęboczek peat dated to ca. 1245–1265 CE, in which we observed the highest ε_{Nd} value. This signature is higher than the range measured for Polish loess sediments and our reference surface samples (Fig. 4, Table 2). Unequivocal identification of the source of this ^{143}Nd-enriched material is difficult. One possible source of dust that could explain the Nd isotope composition of the concerned peat layer ($\varepsilon_{Nd} = -10.7$) is Saharan dust, in which ε_{Nd} values range from −10.0 to −15.0 (Abouchami et al., 1999; Grousset and Biscaye, 2005); a similar range of ε_{Nd} signatures, attributed to an influx of Saharan dust, have been observed in older peat from Europe (Le Roux et al., 2012). However, Clifford et al. (2019), who, based on the Colle Gnifetti ice core (Swiss-Italian Alps), reconstructed Saharan dust fluxes that reached Europe over the last 2000 years, recorded such an event at 1320–1370 CE – more than half a century later than the dust flux event observed in our peat record. Given the age difference between our record and Colle Gnifetti, as well as the wide range of the Saharan dust ε_{Nd} signatures, covering the entire set of our local signatures (Fig. 4), it is impossible to detect Saharan dust using Nd isotopes alone. Another possible source of dust in this layer could be a volcanic eruption recorded in the mid-13th century. Volcanic-derived materials typically show strongly radiogenic, positive ε_{Nd} values (e.g., Goldstein and Jacobsen, 1988; Shaw and Wasserburg, 1985). Icelandic volcanic ash ($\varepsilon_{Nd} = +5$ to $+10$; Cohen and O'Nions, 1982; Farmer et al., 2003; Grousset et al., 1993), which often reaches continental Europe, has been present in peat sediments throughout the Holocene in many European locations (Watson et al., 2016), including peatlands in northern Poland (Watson et al., 2017). Two mid-13th century eruptions of the Katla volcano, dated to 1245 CE and 1262 CE (Larsen, 2000), could have been a source of the ^{143}Nd-enriched material in this peat layer. A suitable candidate could also be a massive volcanic eruption dated to 1257 CE or 1258 CE (Emile-Geay et al., 2008; Oppenheimer, 2003), which happened in south-east Asia, possibly from the Samalas volcano located on Lombok Island in Indonesia (Lavigne et al., 2013). In the absence of additional evidence, such as the identification of volcanic tephra in the analyzed core, the exact origin of the atmospheric ash for the concerned interval cannot be identified with certainty; we can only imply an extra-local source of this dust influx.

4.2. Detection of local environmental disturbances and identification of local sediment sources using neodymium isotopes

Our study aimed to assess to what extent neodymium isotopes can archive local disturbance events. Therefore, it is essential to estimate the reference ε_{Nd} values of the dominant sources of mineral matter in the study area, based on which we can define the local and extra-local (regional to global) dust fluxes and their sources. Studies from Canadian peatlands showed that the most distinct changes in ε_{Nd} values are related to the type of peat investigated (Pratte et al., 2017a; Pratte et al., 2017b). In these studies, minerotrophic (fen) peat sequences yielded ε_{Nd} values between −29.0 and −36.0 (Pratte et al., 2017b) and between −17.0 and −21.0 (Pratte et al., 2017a). For ombrotrophic sections of the analyzed sequences, the ε_{Nd} signatures ranged from −12.0 to −20.0 (mean ≈ −13.0) in a peat bog in western Quebec (Pratte et al., 2017b), as well as from −11.8 to −13.1 and from −12.6 to −15.0 in peatlands in south-eastern Quebec (Pratte et al., 2017a). Studies from Belgium showed an even smaller variability of ε_{Nd} values, ranging from −10.0 to −13.0 (Fagel et al., 2014) and from −5.0 to −13.0 (Allan et al., 2013). The ombrotrophic sections gave ε_{Nd} values between −10.0 and − 13.0 (Fagel et al., 2014), whereas the minerotrophic sections: between −5.0 and −9.0 (Allan et al., 2013). A similar range of signatures in most of the peat samples (−7.5 to −12.5, with a single outlier having $\varepsilon_{Nd} = -1.0$) have been noted by Le Roux et al. (2012) from a Swiss peatland. The range of ε_{Nd} values of the mineral matter from our peat and surface *Sphagnum* samples (Table 2, Fig. 4) is similar to those from the ombrotrophic peat sections in Canada and Belgium. Both peat sections that we investigated represent ombrotrophic, *Sphagnum*-dominated peatlands, and thus show moderate variability in their Nd isotope signatures. Based on the comparison between previous research results and our reference measurements, the ε_{Nd} values of the dominant, background dust flux in Poland most likely ranges from −12.0 to −15.0, and are similar to other European locations and those in Canada. Therefore, any excursions in the ε_{Nd} record that are notably below or above this range likely reflect significant environmental changes in the peatland area. Moreover, due to the location of the studied peatlands in the young-glacial area, the sedimentary material on which the peatlands formed represents a mixture of various Scandinavian rocks (Marks et al., 2016), which possess a high variability of ε_{Nd} signatures – from −24.7 to +2.9 (Andersen et al., 2001; Andersson et al., 2007; Johansson et al., 2016; Kara et al., 2018; Mansfeld et al., 2005).

Interpretations regarding local dust or mineral sources in peat have been mentioned in some of the previously published Nd isotope studies. However, these studies did not include reference samples collected in close proximity to the peatlands, and they refer solely to ε_{Nd} data from the literature, measured at locations distant from the investigated sites (Allan et al., 2013; Fagel et al., 2014; Le Roux et al., 2012). Moreover, the authors did not define what they mean by a “local source”, and how far from the site this local source may be located. For example, Le Roux et al. (2012) attributed the observed variability in the ε_{Nd} values to shifts between a local source and Saharan dust, but, in the absence of additional data, provided no unequivocal evidence for the contribution of the latter. As illustrated by the present study, reference sampling from known sources of mineral material is vital to properly assess the range of the ε_{Nd} values available in the proximity of a study site, and thus to enable differentiation between the signals from local vs extra-local sediment sources. In Patagonia, for example, a wide set of local Nd isotope data (Gaiero et al., 2007) made it possible to define local sources of dust, such as morainic material or outwash deposits (Vanneste et al., 2016; Vanneste et al., 2015). Accordingly, a good knowledge of local geology, geomorphology and hydrology is necessary, to cover the highest possible range of input sources. This is especially important when no reference measurements are available from investigated areas – which is the case for many locations.

4.3. Detection of distant dust fluxes

The transport of dust particles is controlled by atmospheric conditions in a given area and dominant air masses that transport dust produced by different source regions or ecosystems. One of the main distant (extra-local) sources that can reach European peatlands is Saharan dust. It is most often observed in the Mediterranean region, but it has reached distant European locations (including UK or Scandinavia) many times in the past (Ansmann et al., 2003; Clifford et al., 2019; Varga, 2020). The transport of Saharan dust to Europe is associated with climate change resulting in the aridification of the Sahara and is connected with the cyclone activity inside and around the Sahara (Papayannis et al., 2008). Therefore, many palaeoecological studies in Europe directed toward the identification of potential drought periods linked some shifts in the ε_{Nd} values with Saharan dust influx (Allan et al., 2013; Fagel et al., 2014; Le Roux et al., 2012). Le Roux et al. (2012) interpreted the low ε_{Nd} values recorded in a Swiss peatland, falling between −12.5 and − 15.0, as a signal of Saharan dust; similarly, Allan et al. (2013) and Fagel et al. (2014) attributed the ε_{Nd} values of Belgian peatlands, ranging from −11.0 to −12.0 and from −12.5 to −13.5, respectively, to the influx of Saharan aerosols. The range of ε_{Nd} values measured for Saharan dust falls between −11.0 and −15.0 (Abouchami et al., 1999; Grousset and Biscaye, 2005). These signatures overlap with the range of ε_{Nd} values measured for the mineral matter from peat and surface *Sphagnum* samples in this study (−12.6 to −15.5) and peat from other European peatlands (−10.0 to −15.0; Allan et al., 2013; Fagel et al., 2014; Le Roux et al., 2012), and thus with the general (background) dust flux present in Europe (Lahd Geagea et al., 2008). A comparison of these records shows that it is practically impossible to identify Saharan dust supply to a peatland based only on Nd isotopes alone; other, supporting evidence is needed to unequivocally detect Saharan-derived materials. The apparent coincidence of a change in the ε_{Nd} values and a reconstructed age of a specific peat layer is not direct evidence, as age-depth models are often not precise enough to allow such direct comparisons (Trachsel and Telford, 2016).

Another common source of distant ash influx are volcanic eruptions, where ashes – under suitable conditions – can be transported to very distant locations, reaching other continents (Cashman and Rust, 2020; Stevenson et al., 2015). Volcanic layers have been identified using Nd isotopes in peatlands in Europe (Allan et al., 2013; Le Roux et al., 2012) and in Patagonia (Vanneste et al., 2016; Vanneste et al., 2015). Identification of the European volcanic influx may be difficult based on Nd isotope data alone, as there are no Nd isotope measurements available for European (Iceland, the Massif Central or Laacher See) volcanic tephras. Le Roux et al. (2012) attributed their Nd isotope record (ε_{Nd} values of −9.7 and −9.6) to a supply of the Icelandic Vedde Ash, but this interpretation was supported only by the age of the peat layer in which the change in the ε_{Nd} values occurred. Similarly, the highest measured ε_{Nd} value of −1.0 was assigned to two eruptions from the Massif Central, because of the similar age of this peat layer, rather than the similarity of the ε_{Nd} signatures (Le Roux et al., 2012). For a Belgian peatland, Allan et al. (2013) also linked the ε_{Nd} value of −5.5 to a volcanic ash influx from Iceland. However, there is no evidence for the specifically Icelandic origin of this ^{143}Nd-enriched material. In fact, in their interpretation, Allan et al. (2013) erroneously used the ε_{Nd} and La/Yb vs La/Sm signatures of subduction-related, island-arc volcanics (Handley et al., 2011), rather than that of, mid-ocean ridge-related, Iceland. Moreover, the amount of volcanic ash reaching Europe is relatively low and the volcanic signal may be too weak to dominate the local Nd signal. In contrast, studies from Patagonia, where tephra layers are often notable visually, were able to record tephra layers using the peat ε_{Nd} signals, because the Nd isotope data are available for many sources from the region, including Hudson volcano dust (ε_{Nd} = +2.8; Gaiero et al., 2007). Such layers have been recorded in two peatlands in Patagonia (Vanneste et al., 2016; Vanneste et al., 2015). The ε_{Nd} values observed in these peatlands, ranging from −1 to +2.8 (Vanneste et al., 2016) and from −3.9 to +2.6 (Vanneste et al., 2015), are different from the signatures observed in peatlands of the Northern Hemisphere.

The impact of anthropogenic activity on peatlands has constantly been rising over the last 200 years (Loisel et al., 2021; Swindles et al., 2019), and intensified in the 20th century (Tanneberger et al., 2021). As most of the anthropogenic dust from industrial sources in Europe shows ε_{Nd} values lower than −12.0, and even lower than −15.0 for heavy industry (Lahd Geagea et al., 2008), we interpret the decrease in the ε_{Nd} values observed in Głęboczek, in the first half of the 20th century, as an effect of increasing anthropogenic forcing. Publications focused on the anthropogenic impacts over the last centuries identified anthropogenic dust flux with ε_{Nd} values between −6.5 and −8.0 (Fiałkiewicz-Kozieł et al., 2022; Fiałkiewicz-Kozieł et al., 2016). However, these studies explored peatlands in Western Siberia (Fiałkiewicz-Kozieł et al., 2016) and North-Eastern China (Fiałkiewicz-Kozieł et al., 2022), which have different dust sources and thus possibly different ε_{Nd} values compared to European peatlands.

5. Conclusions and recommendations

We performed a multi-proxy palaeoecological study of two peat cores, combining biotic-proxy data with Nd isotopic analyses to reconstruct past disturbance events. Using reference sampling, we obtained detailed information about the Nd isotope composition of the local sources of mineral material available for both investigated sites. These data enabled the detection of changes in the sources of dust and mineral flux in both cores. Applying the constraints from the local ε_{Nd} values, we compared the biotic proxy and Nd isotope records, identifying mineral matter inputs associated with deforestation and fire, and distinguishing local, regional, and anthropogenic dust sources.

The relationship between the fire episodes and, to a lesser degree, human activity and pronounced shifts in the ε_{Nd} values documented in the studied peat cores illustrate the critical role of local controls in shaping the Nd isotope record archived in peatlands. Recognition of such a local influence, including identifying the ε_{Nd} signatures of local sediments and establishing possibly the most precise age constraints, is a prerequisite to addressing more advanced research questions, such as a possible contribution of dust influx from distant sources. As long as the background local Nd sources are not recognized, the implications of the Nd isotope data should be evaluated with caution, and cannot be used as standalone evidence for large-scale variations in atmospheric circulation patterns.

The most crucial issues regarding the use of Nd isotopes that we identified are:

1. *Commonly low sampling resolution of Nd isotope analyses*. In many cases in the past, the sampling resolution for Nd isotope analyses was lower than for other palaeoecological proxies. Therefore, the Nd isotope records possibly showed only a fraction of past environmental changes that could have been identified if high-resolution sampling was applied. Moreover, for relatively large samples, the Nd record will likely homogenize material accumulated during several deposition events. Hence, to assure better recognition of specific past events, we recommend higher sampling resolution for Nd isotope analyses.
2. *Interpretation of Nd isotope results by directly connecting the Nd record with low-resolution age-depth models to assess possible dust sources*. Direct comparison between the Nd record, biotic-proxy data and reconstructed age is difficult if peat dating is of low resolution and does not allow the identification of potential hiatuses, sediment mixing or recognition of different peat accumulation patterns. As shown by several studies, peatland age-depth modelling requires a dense set of radiocarbon and/or lead dates throughout the core (Fiałkiewicz-Kozieł et al., 2014; Kołaczek et al., 2019; Kołaczek et al., 2018). Hence, we recommend higher resolution dating of peat cores to assure the lack of hiatuses and better recognition of specific past events recorded with the associated Nd isotope record.
3. *Lack of reference sampling and assessment of local Nd pools and arbitrary selection of Nd reservoirs to compare with Nd isotope and proxy data*. Because the Nd isotope composition of local sediments has been established only for some regions and environmental settings, there are areas for which no such background ε_{Nd} data are available. Therefore, if no reference sampling from the investigated area is done, the Nd isotope records are compared with data from arbitrarily selected, commonly distant Nd reservoirs (e.g., Saharan or Mongolian dust for European records), whereas geographically closer sources are often omitted. As an effect, many suggested sources possess very broad – and largely overlapping – ranges of ε_{Nd} values that are difficult to interpret unambiguously.
4. *Interpretation of local vs regional inputs of Nd, as well as a direct comparison of ε_{Nd} signatures between the core and some potential sources while not accounting for mixing between several sources*. One limitation of most studies published to date is that they directly compare the ε_{Nd} values measured in peat to the ε_{Nd} signatures of potential sources (e.g., Saharan dust, distant volcanic eruptions). We recommend to primarily focus the interpretations of ε_{Nd} isotope records on major trends, rather than specific ε_{Nd} values. The ε_{Nd} values provide information about an increased contribution of a source that is ^{143}Nd-enriched or ^{143}Nd-depleted, but are often not conclusive about this source – as long as they do not fall outside the range of the background reference values. In the case of significant excursions, in turn, possible local controls should be established first, and only in the absence of 'local' explanations 'extra-local' sources can be considered.

CRediT authorship contribution statement

KM: funding acquisition, fieldwork, testate amoeba analysis, charcoal analysis, peat properties analysis, age-depth modelling, figures, writing (original draft); ZB: neodymium data interpretation, writing (review &

editing); JD: neodymium measurements, writing (review & editing); MJ: neodymium data interpretation, writing (review & editing); MK-K: testate amoeba analysis, writing (review & editing); PK: pollen analysis, age-depth modelling, figures, writing (review & editing); DM: plant macrofossil analysis, writing (review & editing); MS: fieldwork, figures, writing (review & editing); MZ: fieldwork, neodymium data interpretation, writing (review & editing); ML: fieldwork, plant macrofossil analysis, age-depth modelling, writing (review & editing).

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Data

All data associated with this article are openly available on Mendeley Data repository under the DOI: 10.17632/rv5h96zvpb.1.

Data availability

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161859.

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