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Rozwój i funkcjonowanie torfowisk mszarnych na terenach plantacji sosny zwyczajnej w Europie Środkowej

Development and functioning of Sphagnum*-dominated peatlands in the Scots pine plantations in Central Europe*

Rozprawa doktorska napisana pod kierunkiem
prof. dr hab. Katarzyny Marcisz

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Rozprawa składa się z trzech artykułów naukowych. W dwóch z nich (artykuły nr 1 i 2) doktorant jest pierwszym i korespondencyjnym autorem, natomiast w trzecim artykule (nr 3) figuruje jako drugi współautor. Wszystkie artykuły zostały opublikowane w międzynarodowych czasopismach posiadających współczynnik Impact Factor (IF). W niniejszym rozdziale, jak i w dalszej części rozprawy, stosowana jest numeracja przypisana poszczególnym artykułom. Łączny IF artykułów wynosi **11,6**. Liczba punktów zgodnie z listą Ministerstwa Nauki i Szkolnictwa Wyższego (MNiSW) wynosi **420**.

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   https://doi.org/10.5194/bg-21-5143-2024
   Q1 (Web of Science), IF_{2024}=3,9, 140 punktów według listy MNiSW, cytowania wg Scopus: 3

2. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Jakubowicz, M., Andrews, L., and Marcisz, K.: Twentieth-century ecological disasters in central European monoculture pine plantations led to critical transitions in peatlands, Biogeosciences, 22, 3843-3866, 2025, *opublikowany*
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   Q1 (Web of Science), IF_{2023}=3,8, 140 punktów według listy MNiSW

STRESZCZENIE W JĘZYKU POLSKIM

Plantacje monokulturowe, w tym plantacje sosnowe, cechują się szczególną podatnością na różnego rodzaju zaburzenia i zjawiska ekstremalne, takie jak susze, pożary, silny wiatr, epidemie insektów. Wynika to z uproszczonej struktury ekosystemu, tj. ograniczonych powiązań w sieci troficznej, i trwałych zmian siedliskowych takich jak zubożenie i zakwaszenie gleby oraz obniżenie poziomu wód gruntowych. Zjawiska te stanowią zagrożenie nie tylko dla tych plantacji, lecz również są niebezpieczne dla sąsiadujących z nimi ekosystemów, w tym dla torfowisk. Relacja pomiędzy torfowiskami a plantacjami sosnowymi w Polsce przez długi czas pozostawała słabo rozpoznana. Jeszcze do niedawna niewiele było danych na temat wpływu wprowadzenia planowej gospodarki leśnej w północnej i zachodniej Polsce pod koniec XVIII wieku na stan torfowisk oraz konsekwencji zaburzeń i zjawisk ekstremalnych (które występują w obrębie tych monokultur) dla funkcjonowania torfowisk.

Niniejsze opracowanie wypełnia istniejącą lukę w wiedzy na temat relacji pomiędzy plantacjami sosny zwyczajnej a funkcjonowaniem torfowisk. W badaniach wykorzystano wysokorozdzielcze datowanie radiowęglowe, wielowskaźnikową analizę paleoekologiczną, obejmującą badania szczątków makroskopowych roślin, ameb skorupkowych, ziaren pyłku roślin, palinomorf niepyłkowych i węgielków. Dane te zostały wsparte analizami geochemicznymi (izotopy neodymu), geofizycznymi (spektroskopia Ramana), danymi dendrochronologicznymi i dendroklimatycznymi, technikami teledetekcyjnymi oraz analizą materiałów historycznych i archiwalnych opracowań kartograficznych. Badania przeprowadzono na trzech torfowiskach zlokalizowanych w obrębie jednych z największych w Polsce kompleksów plantacji sosnowych: w Borach Tucholskich (stanowiska Jezierzba oraz Stawek) oraz w Puszczy Noteckiej (stanowisko Miały).

Uzyskane wyniki jednoznacznie wskazują na zmianę warunków hydrologicznych i troficznych na torfowiskach, będącą konsekwencją wprowadzenia planowej gospodarki leśnej oraz towarzyszących jej działań i zjawisk. Planowe zarządzanie lasami, w tym monogatunkowe nasadzenia sosnowe, melioracje, a także zjawiska ekstremalne, takie jak pożary i gradacje szkodników, doprowadziły do zakwaszenia torfowisk, co potwierdza stwierdzone obniżenie wartości pH. W efekcie doszło do rozwoju torfowców, które wyparły mchy brunatne oraz rośliny z rodziny ciborowatych. Ponadto torfowce, przyrastając, odcinały torfowiska od dostaw wód gruntowych. Wyniki te są istotne dla gospodarki leśnej oraz zarządzania torfowiskami, ich ochrony i restytucji.

Słowa kluczowe: paleoekologia, torfowiska, gospodarka leśna, szczątki makroskopowe roślin

STRESZCZENIE W JĘZYKU ANGIELSKIM

Monoculture plantations, including Scots pine plantations, are particularly susceptible to various types of disturbances and extreme events such as droughts, fires, strong winds, and insect outbreaks. This results from the simplified structure of the ecosystem, i.e., limited connections within the food web and lasting habitat changes such as soil impoverishment and acidification, as well as a lowering of the groundwater level. These phenomena pose a threat not only to the plantations themselves but also dangerous for the neighbouring ecosystems, including peatlands. The relationship between peatlands and Scots pine plantations in Poland has long remained poorly understood. Until recently, there has been little data on the impact of introducing planned forest management in northern and western Poland at the end of the 18th century on the condition of peatlands, as well as the consequences of disturbances and extreme events occurring within these monocultures for the functioning of peatlands.

This study fills the existing knowledge gap regarding the relationship between Scots pine plantations and the functioning of peatlands. The research involved high-resolution radiocarbon dating and multi-proxy palaeoecological analysis, including studies of plant macrofossils, testate amoebae, pollen, non-pollen palynomorphs, and charcoal. These data were supported by geochemical analyses (neodymium isotopes), geophysical analyses (Raman spectroscopy), dendrochronological and dendroclimatic data, remote sensing techniques, and the analysis of historical materials and archival cartographic studies. The research was carried out on three peatlands located within some of the largest pine plantation complexes in Poland — the Tuchola Forest (sites Jezierzba and Stawek) and the Noteć Forest (site Miały).

The obtained results indicate changes in the hydrological and trophic conditions of the peatlands as a consequence of introducing planned forest management and accompanying activities and phenomena. Planned forest management, including monoculture pine planting, drainage works, as well as extreme events such as fires and insect outbreaks, has led to the acidification of peatlands, as confirmed by the recorded decrease in pH values. As a result, *Sphagnum* mosses have developed, replacing brown mosses and plants from the Cyperaceae family. Additionally, the growing *Sphagnum* mosses gradually cut the peatlands off from their groundwater supply. These results are significant for forestry management, peatland management and their protection and restitution.

Key words: palaeoecology, peatlands, forest management, plant macrofossils

WPROWADZENIE

Zmiany klimatu objawiające się coraz wyższymi średnimi temperaturami powietrza oraz zmianami częstotliwości i sezonowości opadów wpływają na ekosystemy na całym świecie. Wnioski płynące z modeli klimatycznych są ostrzeżeniem przed coraz częstszym i gwałtowniejszym występowaniem zdarzeń ekstremalnych – długotrwałych susz, pożarów, huraganów czy epidemii (gradacji) owadów (EEA Report, 2012; Seneviratne et al., 2012). Szczególnie podatne na tego rodzaju zaburzenia są ekosystemy homogeniczne w swej strukturze, tj. plantacje leśne (Booth, 2013; Guariguata et al., 2008; McNulty et al., 2013), w tym monokultury sosnowe (Łuców et al., 2021; Schüle et al., 2023).

Zastępowanie lasów mieszanych w wielu regionach świata monogatunkowymi drzewostanami, choć ułatwia zarządzanie nimi i zwiększa produkcję drewna (Liu et al., 2018), prowadzi jednocześnie do istotnego uproszczenia sieci troficznych – zmienna biotyczna – oraz trwałej zmiany zajmowanych przez nie siedlisk – zmienna abiotyczna (Chapin et al., 2012). W konsekwencji plantacje leśne stają się bardziej podatne i mniej odporne na działanie czynników ekstremalnych. Spośród zagrożeń związanych ze zmianami klimatu szczególnie niepokojące są pożary lasów. Prognozy przewidują, że będą one występować coraz częściej, obejmując obszary, które dotychczas nie były narażone na tego typu klęski, takie jak Alaska, Grenlandia czy północna Skandynawia (Evangeliou et al., 2019; Hayasaka, 2021). W lasach monokulturowych, z uwagi na ich jednorodną kompozycję, pożar rozprzestrzenia się szybciej i łatwiej niż w lasach mieszanych. Zjawisko to stanowi poważne zagrożenie dla ludzi, infrastruktury, różnorodności gatunkowej i zasobów naturalnych. W Polsce szczególnie tragiczne były wydarzenia z sierpnia 1992 roku, kiedy to najpierw w Puszczy Noteckiej pożar strawił ponad 5000 ha plantacji sosnowej (Fabijański, 1996a, b), a następnie – w okolicach Kuźni Raciborskiej w województwie śląskim – spłonęło ponad 9000 ha monokultury sosnowej (Szczygieł, 2012).

Monokulturowe plantacje drzew iglastych, oprócz wcześniej wspomnianych cech plantacji leśnych w ogóle, wykazują również niższą zdolność do akumulacji dwutlenku węgla wychwytywanego z atmosfery w porównaniu z lasami liściastymi lub mieszanymi. W związku z tym ich rola w procesie łagodzenia skutków wzrostu globalnej temperatury pozostaje kwestią dyskusyjną (Naudts et al., 2016). Niezależnie jednak od składu gatunkowego lasu, pożary stanowią istotne zagrożenie z perspektywy emisji dwutlenku węgla do atmosfery. Węgiel zmagazynowany w biomasie drzew zostaje podczas pożaru gwałtownie uwolniony, przyczyniając się do wzrostu stężenia tego gazu cieplarnianego w atmosferze.

Kolejnym istotnym problemem stają się zjawiska silnego wiatru, w tym huragany i trąby powietrzne (Grondin et al., 2014). W ostatnich kilkunastu latach spowodowały one olbrzymie szkody i zniszczenia tysięcy hektarów lasów również w Polsce. Skalę degradacji spowodowaną tymi zjawiskami dobrze ilustrują przypadki z Borów Tucholskich: tornado z lipca 2012 roku, które zniszczyło ponad 500 ha lasu (Łuców et al., 2021) oraz huragan z sierpnia 2017 roku w okolicach Rytla, który w ciągu zaledwie 15 minut uszkodził prawie 120 000 ha lasu, z czego ponad 39 000 ha wymagało całkowitego odnowienia (Trębski, 2017). W lipcu 2017 roku gwałtowny front atmosferyczny, któremu towarzyszyła trąba powietrzna, zniszczył 1500 ha lasu w okolicy Kuźni Raciborskiej (Biernat, 2025).

Dotkliwe w skutkach stają się także epidemie insektów, które atakują osłabione lasy. Największe kompleksy plantacji sosnowych w Polsce wielokrotnie, w ciągu ostatnich ponad stu lat, były poważnie atakowane przez szkodniki. Największa gradacja wystąpiła w latach 1922-1924 i zniszczyła ponad 220 tysięcy hektarów lasu w ówczesnych granicach Rzeczpospolitej (Broda, 2003). Spowodowana była przez szkodnika pierwotnego sosny zwyczajnej, strzygonię choinówkę (*Panolis flammea*), motyla z rodziny sówkowatych (Szmidt, 1993). Wydarzenie to dotknęło zarówno Puszczę Notecką, jak i Bory Tucholskie, których drzewostany zostały zniszczone w ponad 90%. Podobnie poważne zagrożenie dla plantacji sosnowych stanowi brudnica mniszka (*Lymantria monacha*), gatunek motyla z rodziny mrocznicowatych. W latach 1978-1986 jej pojaw objął ponad 7,3 mln hektarów lasów w Polsce, z czego 6,3 mln poddano zabiegom chemicznym (Broda, 2000; Śliwa, 1989). Warto zaznaczyć, że skutki gradacji owadów nie ograniczają się jedynie do zniszczenia drzewostanów. Obejmują one również szereg naturalnych procesów geofizycznych będących konsekwencją utraty drzew: ograniczoną retencję wody, zmniejszone zacienienie, zmianę mikroklimatu oraz mniejszą ewapotranspirację. Dodatkowo, po takim zdarzeniu, stosowane są zabiegi gospodarcze związane z odlesieniem i przygotowaniem gruntu pod nowe nasadzenia, takie jak: oranie, bronowanie i rylowanie. Techniki te zwiększają spływ powierzchniowy z lasów do naturalnych zagłębień terenu (w tym torfowisk) oraz dostarczają do nich materiał mineralny. Bliźniaczo sytuacja ma się w przypadku niszczycielskich tornad i trąb powietrznych – konsekwencje tych zjawisk również niosą za sobą deforestację (usunięcie uszkodzonych drzewostanów) i silnie ingerującą w podłoże gospodarkę przygotowawczą pod odnowienia, najczęściej sztuczne.

Skutki pożarów, huraganów i gradacji szkodników – prowadzące do odlesień, zmian w składzie gatunkowym czy przekształceń w sposobie gospodarowania – stanowią poważne zagrożenie nie tylko dla samych lasów, ale i dla ekosystemów sąsiadujących z nimi, w tym dla torfowisk. Pożary torfowisk powinny dodatkowo zwracać szczególną uwagę, ponieważ to ekosystemy, które aktywnie akumulują węgiel. Torfowiska, a w szczególności te zdominowane przez mchy torfowce (*Sphagnum*), są wydajnym pochłaniaczem węgla z atmosfery. Szacuje się, że choć torfowiska zajmują jedynie około 3% powierzchni lądów, to magazynują około 30% węgla organicznego zawartego w glebie (Rydin and Jeglum, 2013). Torfowiska wycofują ogromne ilości węgla z tzw. szybkiego cyklu węglowego, czyli odbywającego się w krótkim czasie procesu wymiany węgla między atmosferą, litosferą (i zawartą niej pedosferą) oraz hydrosferą (Limpens et al., 2008). Bardzo trudno jest precyzyjnie określić ilość zgromadzonego w torfowiskach węgla, ponieważ problematyczną kwestią jest dokładne zmierzenie powierzchni torfowisk i miąższości zawartego w nich torfu. Szacuje się jednak, że na półkuli północnej torfowiska przechowują ponad 1000 Gt węgla (Amesbury et al., 2019), choć najczęściej przyjmuje się wartość 600 Gt (Yu et al., 2010). Podkreślenia wymaga fakt, że torfowiska gromadzą dwukrotnie więcej węgla niż cała biomasa lasów świata (Beaulne et al., 2021), a pod względem zawartości węgla ekosystemy te ustępują jedynie oceanom (Rydin and Jeglum, 2013). Przewaga torfowisk nad lasami wynika nie tylko z większych zdolności pochłaniania węgla, ale także z faktu, że wykluczają go z obiegu na wiele tysięcy lat (Blodau, 2002; Gorham, 1991).

Zjawiska ekstremalne, występujące w monokulturach sosnowych zaburzają również warunki hydrologiczne i troficzne torfowisk położonych w ich obszarze. Prowadzą do modyfikacji reżimu zasilania torfowisk w wodę i przekształcenia ich roślinności. Często takie zmiany doprowadzają torfowiska do osiągnięcia punktów krytycznych, czyli takiej zmiany warunków hydrologicznych i troficznych, po których powrót do stanu sprzed zaburzenia staje się niemożliwy. Z tego względu, a także z uwagi na wspomniane wcześniej wyjątkowe właściwości torfowisk – zdolność do retencji wody oraz akumulacji węgla, czyli cechy kluczowe w kontekście zmian klimatycznych – ekosystemy te podlegają lub powinny podlegać szczególnej ochronie. W Unii Europejskiej część torfowisk, jako unikalny rodzaj siedliska przyrodniczego, podlega ochronie na mocy tzw. dyrektywy siedliskowej, która wraz z tzw. dyrektywą ptasią stanowią podstawę systemu ochrony przyrody Natura 2000. Wśród typów siedlisk przyrodniczych wyróżniono między innymi żywe torfowiska wysokie z roślinnością torfotwórczą, torfowiska wysokie zdegradowane, lecz zdolne do naturalnej i stymulowanej regeneracji, torfowiska przejściowe i trzęsawiska (przeważnie z roślinnością z *Scheuchzerio-Caricetea nigrae*, tj. niskoturzycowymi, bogatymi w mszaki zbiorowiskami łąk bagiennych). W Polsce część torfowisk objęta jest także torfowiskowymi rezerwatami przyrody, w których przedmiotem ochrony są zbiorowiska i gatunki torfowisk niskich, przejściowych i wysokich. Według stanu na 20 lipca 2025 roku na terenie Polski istniało 208 rezerwatów torfowiskowych o łącznej powierzchni ponad 19 tysięcy hektarów. Pod względem liczby ustępowały miejsca tylko rezerwatom leśnym (728), przy łącznej liczbie wszystkich rezerwatów przyrody wynoszącej 1636 (dane własne na podstawie: Centralny Rejestr Form Ochrony Przyrody (CRFOP), https://crfop.gdos.gov.pl/CRFOP/search.jsf, dostęp: 20.07.2025).

Wraz z globalnym wzrostem temperatury w obszarze niektórych torfowisk doszło do całkowitego zaprzestania akumulacji torfu. Tworzy się on bowiem w specyficznych warunkach hydrologicznych, tj. przy odpowiednio wysokim poziomie wody ograniczającym dostęp tlenu atmosferycznego i blokującym rozwój mikroorganizmów aerobowych (tlenowych) rozkładających materię organiczną (Tobolski, 2000). Osuszone torfowiska część środowiska naukowego zajmującego się zmianami klimatu zaczęła nazywać „tykającymi bombami węglowymi" (ang. *ticking carbon bomb*), ponieważ uwalniają one do atmosfery olbrzymie ilości dwutlenku węgla, zgromadzonego w nich przez setki, a nawet tysiące lat (Carrington, 2025). Zniszczone i osuszone torfowisko jest tym bardziej niebezpieczne, kiedy zwierciadło wód gruntowych spada do poziomu krytycznego grożącego pożarem. Wyniki badań wskazują, że kiedy poziom wód gruntowych spada do około 11,7 cm w stosunku do powierzchni terenu dochodzi do zmiany gatunkowej roślinności (Lamentowicz et al., 2019). Przy spadku do poziomu 20-25 cm całkowicie zanikają mchy torfowce (Jassey et al., 2018), główny komponent torfu na torfowiskach mszarnych (wysokich i przejściowych). Przy poziomie wód gruntowych na rzędnej 40 cm pod powierzchnią terenu gwałtownie rośnie ryzyko wystąpienia pożaru (Wösten et al., 2006). Szczególnie niebezpieczne jest zjawisko tlenia się torfu (ang. *smouldering*). Na większych głębokościach może ono trwać latami i obejmować duże obszary, a także pozostawać aktywnym w okresie zimowym w formie tzw. „pożarów zombie" (ang. *zombie fires*) (Witze, 2020).

Duże kompleksy leśne, w obszarze których występują torfowiska z przewagą torfowców, są zatem szczególnie ważne dla globalnego obiegu węgla ze względu na bardzo duże właściwości akumulacyjne torfu i węgla. Ponadto, wilgotne torfowiska utrzymują wysoki poziom wód gruntowych na przyległych terenach, wspierając inne ekosystemy, m.in. lasy. Rozpoznanie reżimów pożarowych tych obszarów jest kluczowe przy wyborze strategii gospodarowania nimi i ich ochrony. Informacje o przeszłej aktywności pożarowej są niestety rzadko wykorzystywane jako pomoc przy zrozumieniu zjawiska występowania pożarów, ich częstotliwości i nasileń. Z takiej wiedzy powinni korzystać zwłaszcza zarządcy lasów i uwzględniać ją w planach zarządzania. Niewiele jest informacji o historycznych pożarach monokultur sosnowych na obszarze północnej i zachodniej Polski (Gałka et al., 2013; Lamentowicz et al., 2019; Marcisz et al., 2015, 2016, 2017, 2019, 2023, 2025). Z tego powodu wciąż aktualne pozostaje określenie reżimu pożarowego przed i po zmianie sposobu gospodarowania lasami pod koniec XVIII wieku, tj. po przejściu z lasów mieszanych do monokultur sosnowych.

Informacje dotyczące wpływu wielkopowierzchniowych gradacji owadów oraz ich konsekwencji w lasach sąsiadujących z torfowiskami były dotychczas jedynie szczątkowe lub niekompletne. W Borach Tucholskich problematykę tę podjęli między innymi Łuców et al. (2021) i Słowiński et al. (2019); w Puszczy Noteckiej zaś – w szerszym zakresie niż w Borach Tucholskich – Barabach (2014), Lamentowicz et al. (2015) i Milecka et al. (2017). Podkreślić jednak należy, że analizy przeprowadzone w powyższych badaniach opierały się na rdzeniach, pokrywających stosunkowo wąski przedział czasowy (przeważnie nie obejmując okresu przed wprowadzeniem monokultury), co nie pozwoliło na pełne odtworzenie historii środowiskowej badanych obiektów, a tym samym ograniczało możliwości odniesienia wyników do warunków referencyjnych.

Wysokorozdzielcze analizy paleoekologiczne mogą dostarczyć istotnych informacji niezbędnych do prognozowania rozwoju torfowisk w warunkach zmian klimatycznych i antropopresji, ich reakcji na różnego rodzaju zaburzenia i zjawiska ekstremalne. Ponadto mogą wesprzeć ich monitoring i ochronę. Badania rdzeni torfowych, nazywanych także „archiwami paleoekologicznymi", pozwalają na odtworzenie historii środowiska sięgającej setek bądź tysięcy lat wstecz. Umożliwiają śledzenie zarówno naturalnych procesów zachodzących w przyrodzie, jak również uchwycenie zmian spowodowanych działalnością człowieka. Rejestrują zmiany zachodzące w roślinności (analiza palinologiczna, analiza szczątków makroskopowych roślin), hydrologii (analiza ameb skorupkowych) i umożliwiają prześledzenie aktywności pożarowej (analiza fragmentów węgielków). Jednoczesne zastosowanie szeregu metod paleoekologicznych w ramach jednego badania, tzw. wielowskaźnikowa analiza paleoekologiczna (ang. *multi-proxy palaeoecological analyses*), pozwala na uzyskanie bardziej szczegółowych danych, zawężenie interpretacji i uzyskanie pełniejszego obrazu zmian zachodzących w środowisku, zarówno w skali lokalnej, jak i regionalnej. Dodatkowo, zastosowanie podejścia wysokorozdzielczego, w którym poszczególne próbki dotyczą wąskiej warstwy osadu i tym samym krótkiego przedziału czasu, zwiększa wiarygodność chronologii rekonstruowanych procesów oraz umożliwia dokładniejsze powiązanie wyników badań ze stanem wiedzy archeologicznej i historycznej. W celu zbudowania utylitarnej chronologii najlepiej zastosować próbkowanie o rozdzielczości jednego centymetra dla wszystkich wskaźników paleoekologicznych (ang. *proxy*).

Podkreślone powyżej znaczenie interdyscyplinarności rekonstrukcji paleoekologicznych, wykorzystywanych nie tylko w naukach o Ziemi, lecz także w archeologii i historii, pozwala na połączenie wiedzy eksperckiej z różnych dziedzin oraz stworzenie kompleksowego obrazu zmian zachodzących w środowisku — ich przyczyn i skutków, a także na właściwe rozpoznanie i rozróżnienie czynników antropogenicznych od naturalnych. W niniejszej rozprawie dane paleoekologiczne zestawiono z wynikami nowoczesnych nauk, metod i technik, takich jak dendrochronologia, dendroklimatologia, teledetekcja, geochemia (analiza nieradiogenicznych izotopów neodymu) oraz spektroskopia Ramana, aby uzyskać pełniejszy obraz zmian środowiskowych. Ponadto, wykorzystano potencjał archiwalnych map, innych materiałów kartograficznych (m.in. zobrazowań lotniczych) oraz źródeł historycznych. Porównanie danych paleoekologicznych z tak szerokim zestawem dodatkowych pomiarów i obserwacji jest nowe i unikalne dla badań nad paleoekologią torfowisk.

Niniejsza dysertacja koncentruje się na znalezieniu odpowiedzi na pytanie, w jaki sposób gwałtowne wprowadzenie monokultury sosny zwyczajnej (*Pinus sylvestris*) w północnej i zachodniej Polsce pod koniec XVIII wieku wpłynęło na funkcjonowanie torfowisk zlokalizowanych na tych obszarach (cel nr 1), a także jak ekosystemy te reagowały na zaburzenia i zjawiska ekstremalne typowe dla monokultur (cel nr 2). W tym celu przeanalizowano trzy stanowiska badawcze usytuowane w dwóch rozległych monokulturowych kompleksach leśnych – Borach Tucholskich oraz Puszczy Noteckiej. Bory Tucholskie, obejmujące około 3000 km^2, oraz Puszcza Notecka, rozciągająca się na powierzchni blisko 1400 km^2, należą do największych zwartych obszarów leśnych w Polsce. Oba te kompleksy, co jest kluczowe dla realizacji celu nr 1, zostały w znacznym stopniu przekształcone w jednorodne plantacje sosnowe, tak że obecnie sosna zwyczajna pokrywa ponad 90% ich powierzchni. W kontekście realizacji celu nr 2 o wyborze obszarów badawczych zdecydowały udokumentowane w ciągu ostatnich 200 lat, dotykające je bezpośrednio zjawiska ekstremalne, w tym między innymi gradacja strzygonii choinówki w latach 1922-1924 (Puszcza Notecka, Bory Tucholskie), susze i spowodowane nią pożary w latach 50. XX wieku (Bory Tucholskie), gradacja brudnicy mniszki w latach 1978-1986 (Bory Tucholskie), oraz pożar z 1992 roku (Puszcza Notecka). Badania przeprowadzono na torfowiskach mszarnych reprezentowanych przez trzy stanowiska: Jezierzba[1] i Stawek w Borach Tucholskich oraz Miały

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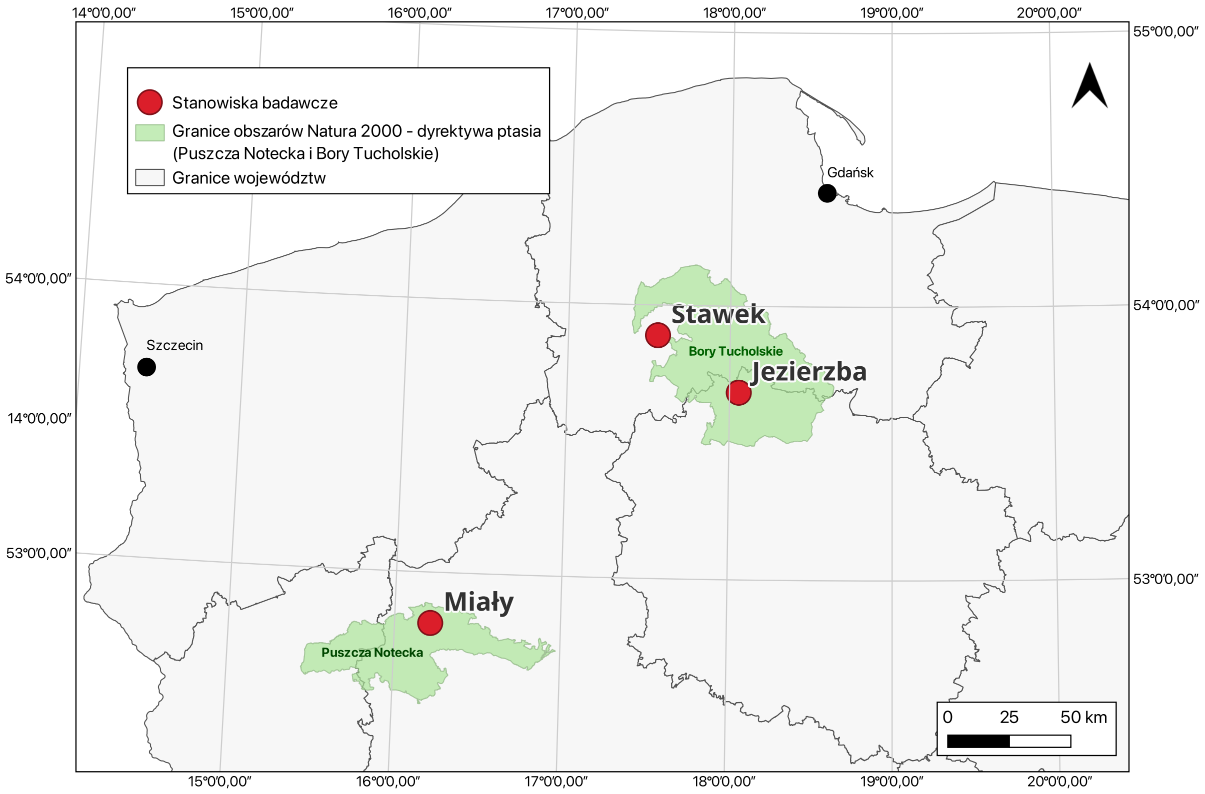
[1] W artykule Bąk et al. (2024) zastosowano zapis torfowisko Okoniny (Jezierzba), ponieważ w tamtym czasie do określenia tego stanowiska stosowane były równolegle obie nazwy. W grudniu 2024 roku obiekt ten znalazł się w granicach nowo powstałego rezerwatu przyrody „Torfowisko Jezierzba”, stąd też w niniejszym autoreferacie stosowana już będzie wyłącznie nazwa wynikająca z aktów prawa – Jezierzba.

w Puszczy Noteckiej (Ryc. 1). Dodatkowo, wszystkie trzy stanowiska charakteryzują się niezaburzoną chronologią osadów, co jest kluczowe dla właściwej interpretacji danych.

Wybór stanowisk badawczych w dwóch różnych kompleksach plantacji sosnowych był motywowany również poszukiwaniem odpowiedzi, czy procesy i zaburzenia zachodzące na terenie monokultur sosnowych w Polsce i ich wpływ na położone w ich obszarze torfowiska mają charakter lokalny, czy są charakterystyczne dla tego rodzaju ekosystemu (cel nr 3).



Ryc. 1. Lokalizacja stanowisk badawczych na mapie północno-zachodniej Polski. *Opracowanie własne.*

Wnioski z rozprawy są ważne dla ekologii lasów monokulturowych w regionach o klimacie umiarkowanym, w kontekście postępujących zmian klimatu i antropopresji. Ponadto, stanowią cenne uzupełnienie wiedzy na temat gospodarki leśnej i konsekwencji wyboru planowego podejścia do zarządzania lasem. Są również wsparciem badań nad ekologią torfowisk, dostarczając informacji o ich reakcji na zmianę otoczenia, tj. przejście z lasów mieszanych do plantacji jednogatunkowych, oraz na zaburzenia i zjawiska ekstremalne. Wreszcie, podkreślają znaczenie badań interdyscyplinarnych, łączących różne dziedziny nauki, różne metody i techniki badawcze.

CEL BADAŃ

Wyróżniono **trzy główne cele badawcze** rozprawy doktorskiej:

1. ocena wpływu wprowadzenia planowego zarządzania lasem pod koniec XVIII wieku na obszarze dzisiejszej północno-zachodniej Polski oraz towarzyszących jej działań na funkcjonowanie torfowisk, ze szczególnym uwzględnieniem zmian w ich hydrologii i składzie roślinności;

2. identyfikacja konsekwencji zdarzeń katastrofalnych oraz innych zaburzeń zachodzących w plantacjach sosnowych dla ekosystemów torfowiskowych;

3. ustalenie, czy planowa gospodarka leśna oraz związane z nią zaburzenia i zjawiska ekstremalne wywołały porównywalne reakcje środowiskowe torfowisk zlokalizowanych w dwóch różnych kompleksach leśnych.

W odniesieniu do **artykułu nr 1** głównym celem była ocena wpływu gospodarki leśnej – przede wszystkim wprowadzenia monokultur sosnowych – oraz zmian klimatycznych na roślinność, a także warunki hydrologiczne i troficzne torfowiska Jezierzba (Bory Tucholskie) poprzez połączenie różnych źródeł danych – paleoekologii, dendrochronologii, dendroklimatologii, teledetekcji i materiałów historycznych. Ponadto podjęto próbę weryfikacji, czy torfowiska rejestrują i reagują na zjawiska ekstremalne zachodzące zarówno *in situ*, jak i w otoczeniu torfowiska. Założono także, że zaburzenia występujące w plantacjach monokulturowych zostaną wykazane w analizie przyrostów rocznych sosny zwyczajnej i tym samym potwierdzą oraz uzupełnią paleoekologiczną rekonstrukcję torfowiska. W związku z tym, wykorzystując opartą na datowaniu radiowęglowym ^{14}C wysokorozdzielczą chronologię osadów, wyodrębniono warstwy torfu odpowiadające okresom zjawisk ekstremalnych udokumentowanych w źródłach historycznych i zestawiono je z danymi dendrochronologicznymi i dendroklimatycznymi.

W odniesieniu do **artykułu nr 2** podstawowym celem była rekonstrukcja około dwutysiącletniej historii środowiskowej torfowiska Miały (Puszcza Notecka) z wykorzystaniem wielowskaźnikowej analizy paleoekologicznej, obejmującej analizy: palinologiczną (pyłkową i palinomorf niepyłkowych), ameb skorupkowych, szczątków makroskopowych roślin oraz fragmentów węgielków, a także analizy geochemicznej opartej o sygnatury nieradiogenicznych izotopów neodymu. Dodatkowo zidentyfikowano warstwy torfu odpowiadające poważnym w skutkach zdarzeniom katastrofalnym – gradacji strzygoni choinówki z lat 1922-1924 i pożarowi z 1992 roku – w celu oceny ich wpływu na ekosystem torfowiskowy i zrozumienia zależności między zakłóceniami zachodzącymi w otaczającym lesie a reakcją torfowiska. Sygnatury nieradiogenicznych izotopów neodymu posłużyły do wykrycia lokalnych zakłóceń w osadach torfowych, takich jak pożary i wylesienia. Zastosowanie takiego podejścia jest rzadko spotykane w literaturze, ponieważ metoda ta wykorzystywana jest najczęściej do identyfikacji odległych źródeł pyłu atmosferycznego. Uchwycenie dwóch tysięcy lat historii torfowiska Miały umożliwiło również ustalenie warunków referencyjnych dla samego torfowiska, jak i otaczającego go lasu, tj. stanu w okresie poprzedzającym rozpoczęcie planowej gospodarki leśnej.

W odniesieniu do **artykułu nr 3** głównym celem była rekonstrukcja zmian w funkcjonowaniu ekosystemu torfowiska Stawek (Bory Tucholskie) na przestrzeni ostatnich około 700 lat, wynikających z ujednolicenia struktury gatunkowej i wiekowej drzewostanów leśnych, a w szczególności wpływu gospodarki leśnej na roślinność torfowiskową, warunki hydrologiczne oraz aktywność pożarową. Rdzeń z torfowiska Stawek różnił się od innych tym, że był jedynym, który zawierał wyraźnie widoczną warstwę żarową. Zastosowano wielowskaźnikową rekonstrukcję paleoekologiczną opartą na analizach pyłku i palinomorf niepyłkowych, szczątków makroskopowych roślin, ameb skorupkowych oraz – co szczególnie warte podkreślenia – szerokim zakresie analiz węgielków, tj. obejmujących nie tylko analizy sumy cząstek i typów morfologicznych, ale także nowatorską metodę spektroskopii Ramana dostarczającą informacji o intensywności pożarów.

MATERIAŁY I METODY BADAŃ

Niniejszy rozdział w sposób zwięzły opisuje stanowiska badawcze, pobrany materiał, wykorzystane dane i zasoby oraz zastosowane metody badawcze w podziale na poszczególne artykuły. Zdecydowano się na syntetyczny przegląd powyższych zagadnień z uwagi na to, że ich pełne opisy znajdują się w artykułach składających się na dysertację. Ponadto na końcu każdego z trzech opisów wyszczególniono wkład doktoranta w powstawanie artykułu.

Artykuł nr 1

Artykuł nr 1 skupia się na rekonstrukcji około 280-letniej historii środowiskowej torfowiska Jezierzba (53°40′52″–53°41′21″ N; 18°03′09″–18°03′40″ E), o powierzchni około 27 ha, położonego w południowo-zachodniej części Borów Tucholskich (od 2024 roku torfowisko jest objęte ochroną w ramach rezerwatu przyrody „Torfowisko Jezierzba”), na zachód od zabudowań wsi Okoniny, 20 km na północny wschód od miasta Tuchola. W lutym 2022 roku przy użyciu próbnika Wardenaar pobrano tam rdzeń o wymiarach 96 cm × 10 cm × 10 cm, który następnie opróbowano w sposób ciągły, co jeden centymetr, z wyjątkiem górnej, dziesięciocentymetrowej warstwy (pierwsza próba odpowiadała warstwie 0–4 cm, następne trzy – warstwom 4–6, 6–8 i 8–10 cm). W rezultacie otrzymano 90 próbek, które następnie podzielono na konkretne analizy paleoekologiczne w zależności od objętości potrzebnego materiału zgodnie ze standardowymi protokołami tychże analiz.

Do zbudowania chronologii osadów wykorzystano szczątki makroskopowe roślin z dziesięciu próbek i poddano je datowaniu radiowęglowemu ^{14}C w Poznańskim Laboratorium Radiowęglowym. Przeprowadzono analizę gęstości objętościowej torfu (ang. *bulk density*), tempa akumulacji torfu (ang. *peat accumulation rate*) oraz tempa akumulacji węgla w torfie (ang. *peat carbon accumulation rate*). Wykonano analizy makroszczątków roślinnych, ameb skorupkowych, pyłku, palinomorf niepyłkowych oraz fragmentów makroskopijnych i mikroskopijnych węgielków. Zastosowane metody posłużyły do rekonstrukcji odpowiednio: lokalnej szaty roślinnej, warunków hydrologicznych i troficznych, szaty roślinnej otoczenia oraz aktywności pożarowej.

Powyższe dane paleoekologiczne zestawiono z chronologią przyrostu słojów dwudziestu trzech sosen zwyczajnych z Borów Tucholskich (z których pozyskano pięćdziesiąt rdzeni) z wykorzystaniem dopasowania krzyżowego (ang. *cross-dating*). Wyznaczono zależności klimat-przyrost (temperatura-przyrost oraz opady-przyrost) w oparciu o miesięczne średnie temperatury powietrza oraz miesięczne sumy opadów dla okresu 1920-2022. Zidentyfikowano pozytywne oraz negatywne lata wskaźnikowe dla sosny zwyczajnej w Borach Tucholskich (ang. *pointer years*), tj. wystąpienie jednokierunkowych zmian (spadku lub wzrostu liczby słojów rocznych) w co najmniej 85% analizowanych sekwencji przyrostowych obserwowanych w badanej grupie drzew.

Dane teledetekcyjne zostały zebrane w nalocie (lotniczym teledetekcyjnym systemie obserwacji) przeprowadzonym w lipcu 2022 roku z wykorzystaniem wielosensorowej platformy powietrznej. Uzyskano zdjęcia multispektralne (zarejestrowane kamerą IXM-100), hiperspektralne (zarejestrowane za pomocą skanera HySpex VS-725) oraz dane z lotniczego skanowania laserowego (pozyskane za pomocą skanera Riegl VQ780-II). Na podstawie tego zestawu danych obliczono wskaźniki NDVI (ang. *Normalized Difference Vegetation Index*; znormalizowany różnicowy wskaźnik wegetacji), MSI (ang. *Moisture Stress Index*; wskaźnik stresu wodnego) oraz LST (ang. *Land Surface Temperature*; wskaźnik temperatury gruntu).

Przeanalizowano również materiały kartograficzne, w tym mapę Schröttera–Engelhardta z 1803 roku w skali 1:150000, mapę topograficzną Messtischblatt (arkusz nr 982) z 1874 w skali 1:25000, mapę geologiczną i rolniczą (arkusz 2374) z 1905 roku w skali 1:25000, szczegółową mapę Polski z 1933 roku w skali 1:25000, oraz zobrazowania lotnicze z lat 1964, 1984 oraz 1997.

Wkład doktoranta: Doktorant uczestniczył w pracach terenowych związanych z pozyskaniem rdzenia do analiz. Brał udział w laboratoryjnej obróbce rdzenia. Przeprowadził analizy gęstości objętościowej, tempa akumulacji torfu oraz tempa akumulacji węgla w torfie. Wybrał szczątki makroskopowe roślin do datowania radiowęglowego ^{14}C (10 próbek). Współtworzył model wiek-głębokość. Wykonał analizę szczątków makroskopowych roślin dla wszystkich 90 próbek. Przeprowadził analizę źródeł archiwalnych, map i zobrazowań lotniczych. Dokonał interpretacji i syntezy danych. Stworzył samodzielnie ryciny nr 1, 3, 10 oraz współtworzył ryciny nr 2, 4, 5, 6. Napisał pierwszą wersję manuskryptu, którą jako autor korespondencyjny opracowywał w kolejnych edycjach manuskryptów, odpowiadając na komentarze i uwagi recenzentów.

Artykuł nr 2

Artykuł nr 2 koncentruje się na odtworzeniu około 2000-letniej historii środowiskowej torfowiska Miały (53°48′52″–52°48′48″ N; 16°12′47″–16°13′00″ E), zajmującego powierzchnię około 1,6 ha, położonego w północno-środkowej części Puszczy Noteckiej, na zachód od zabudowań wsi Miały, 16 km na południowy wschód od miasta Krzyż Wielkopolski. W październiku 2021 roku przy użyciu próbnika Wardenaar pobrano tam rdzeń o wymiarach 97 cm × 10 cm × 10 cm, który następnie opróbowano w sposób ciągły, co jeden centymetr, z wyjątkiem pierwszej, górnej warstwy (0–2 cm). W rezultacie otrzymano 96 próbek, które następnie podzielono na konkretne analizy paleoekologiczne w zależności od objętości potrzebnego materiału zgodnie ze standardowymi protokołami tychże analiz.

Do zbudowania chronologii osadów wykorzystano makroszczątki roślinne z dwunastu próbek i poddano je datowaniu radiowęglowemu ^{14}C w Poznańskim Laboratorium Radiowęglowym (dwie z nich uznano za wartości odstające i wyłączono poza główną trajektorię modelu). Przeprowadzono – podobnie jak w artykule nr 1 – analizę gęstości objętościowej torfu, tempa akumulacji torfu oraz tempa akumulacji węgla w torfie. Wykonano analizy szczątków makroskopowych roślin, ameb skorupkowych, pyłku, palinomorf niepyłkowych oraz fragmentów makroskopijnych i mikroskopijnych węgielków. Zastosowane metody posłużyły do rekonstrukcji odpowiednio: lokalnej szaty roślinnej, warunków hydrologicznych i troficznych, szaty roślinnej otoczenia oraz aktywności pożarowej.

Powyższe dane paleoekologiczne zestawiono z analizą geochemiczną – sygnatur nieradiogenicznych izotopów neodymu – przeprowadzoną w Poznańskim Laboratorium Izotopowym przy Fundacji Uniwersytetu im. Adama Mickiewicza w Poznaniu z wykorzystaniem wielodetektorowego spektrometru masowego z jonizacją termiczną Finnigan MAT 261.

Wyniki uzyskane z analizy paleoekologicznej oraz analizy sygnatur nieradiogenicznych izotopów neodymu potwierdzono podejściem statystycznym z zastosowaniem analizy odpowiedzi głównych krzywych (ang. *principal response curves*; PrCs), do której następnie dopasowano mieszane uogólnione modele addytywne (ang. *Generalized Additive Mixed Models;* GAMMs).

Wkład doktoranta: Doktorant uczestniczył w pracach terenowych związanych z pozyskaniem rdzenia torfowego do analiz paleoekologicznych oraz prób powierzchniowych do analiz izotopwych. Brał udział w laboratoryjnej obróbce rdzenia. Przeprowadził analizy gęstości objętościowej, tempa akumulacji torfu oraz tempa akumulacji węgla w torfie. Wybrał szczątki makroskopowe roślin do datowania radiowęglowego ^{14}C (12 próbek). Współtworzył model wiek-głębokość. Wykonał analizę szczątków makroskopowych roślin dla wszystkich 96 próbek. Dokonał interpretacji i syntezy danych. Stworzył samodzielnie ryciny nr 1, 3, 6, 7 oraz współtworzył ryciny nr 2 i 4. Napisał pierwszą wersję manuskryptu, którą jako autor korespondencyjny opracowywał w kolejnych edycjach manuskryptów, odpowiadając na komentarze i uwagi recenzentów.

Artykuł nr 3

Artykuł nr 3 prezentuje około 700-letnią historię środowiskową małego torfowiska kotłowego Stawek (53°53′21″–53°53′23″ N; 17°33′05″–17°33′08″ E), o powierzchni około 0,2 ha, położonego w północno-zachodniej części Borów Tucholskich, na zachód od zabudowań wsi Asmus, 21 km na północ od miasta Chojnice. W kwietniu 2022 roku przy użyciu próbnika Wardenaar pobrano tam rdzeń o wymiarach 95 cm × 10 cm × 10 cm, który następnie opróbowano w sposób ciągły, co jeden centymetr, z wyjątkiem górnej, ośmiocentymetrowej warstwy, którą opróbowano co 2 cm (0–2, 2–4, 4–6, 6–8 cm). W rezultacie otrzymano 91 próbek, które następnie podzielono na konkretne analizy paleoekologiczne w zależności od objętości potrzebnego materiału zgodnie ze standardowymi protokołami tychże analiz.

Do zbudowania chronologii osadów wykorzystano szczątki makroskopowe roślin z dziesięciu próbek i poddano je datowaniu radiowęglowemu ^{14}C w Poznańskim Laboratorium Radiowęglowym. Przeprowadzono analizę gęstości objętościowej torfu, tempa akumulacji torfu oraz tempa akumulacji węgla w torfie. Wykonano analizy szczątków makroskopowych roślin, ameb skorupkowych, pyłku, palinomorf niepyłkowych oraz fragmentów makroskopijnych i mikroskopijnych węgielków. Zastosowane metody posłużyły do rekonstrukcji odpowiednio: lokalnej szaty roślinnej, warunków hydrologicznych i troficznych, szaty roślinnej otoczenia oraz aktywności pożarowej.

Ze względu na obecność w torfie warstw żarowych zdecydowano się na rozszerzenie analizy fragmentów węgielków. Z warstw odpowiadających największej koncentracji węgielków (81-95 cm) wyizolowano fragmenty tychże, które następnie poddano spektroskopii Ramana w celu określenie wartości separacji pasm Ramana, z których wyprowadza się miarę intensywności pożarów.

Wkład doktoranta: Doktorant uczestniczył w laboratoryjnej obróbce rdzenia. Przeprowadził analizy gęstości objętościowej, tempa akumulacji torfu oraz tempa akumulacji węgla w torfie. Wybrał makroszczątki roślinne do datowania radiowęglowego ^{14}C (10 próbek). Współtworzył model wiek-głębokość. Wykonał analizę szczątków makroskopowych roślin dla wszystkich 91 próbek. Brał udział w interpretacji i syntezie danych, szczególnie wynikającej z analizy makroszczątków roślinnych. Stworzył samodzielnie rycinę nr 1 oraz współtworzył ryciny nr 2 i 3. Uczestniczył w edycji i komentowaniu kolejnych wersji manuskryptu.

WYNIKI BADAŃ

Artykuł 1

W publikacji Bąk et al. (2024) przedstawiono ostatnie 280 lat lokalnej historii rozwoju i funkcjonowania torfowiska Jezierzba. Skupiono się na reakcji torfowiska na zmianę sposobu zarządzania otaczającego je lasu pod koniec XVIII wieku, tj. wprowadzenie plantacji sosnowych i przejście z lasów o charakterze mieszanym do monokultur (Bory Tucholskie). Zbadano także odpowiedź ekosystemu torfowiskowego na zaburzenia i zjawiska ekstremalne występujące w obszarze Borów Tucholskich na przestrzeni ostatnich dwustu lat, w tym susze, gradacje owadów i pożary. W artykule, jak już zostało wspomniane, połączono wyniki analiz paleoekologicznych z wynikami badań dendrochronologicznych, dendroklimatycznych, teledetekcyjnych oraz z informacjami odczytanymi z archiwalnych opracowań kartograficznych i zobrazowań lotniczych.

Badania wykazały, że po zmianie sposobu prowadzenia gospodarki leśnej doszło do zmiany warunków hydrologicznych i troficznych analizowanego stanowiska. Obiekt o charakterze płytkiego jeziora gwałtownie przekształcił się w torfowisko. Nastąpiła szybka ekspansja mchów torfowców, które wyparły rośliny jednoliścienne, głównie z rodzin ciborowatych i wiechlinowatych. Doszło do całkowitego zaniku cyjanobakterii i słodkowodnych glonów. W diagramie palinologicznym zanikły hydrofity, takie jak: pływacz (*Utricularia* spp.), rdestnica (*Potamogeton* spp.), grzybienie (*Nymphaea* spp.). Przemianę ekosystemu z wodnego w lądowy udokumentowały również archiwalne mapy i zobrazowania lotnicze.

W otoczeniu torfowiska doszło do zmiany składu gatunkowego lasu. W diagramie palinologicznym uwydatnił się wśród pyłku drzew spadek udziału pyłku drzew liściastych – dębu (*Quercus* spp.), buka zwyczajnego (*Fagus sylvatica*), graba pospolitego (*Carpinus betulus*) oraz leszczyny pospolitej (*Corylus avellana*) – na korzyść udziału pyłku sosny zwyczajnej (*Pinus sylvestris*).

Celem artykułu była również ocena wpływu zmian klimatu na aktualną kondycję sosny w Borach Tucholskich. Pobrano 50 rdzeni z 23 sosen pospolitych, rosnących 9,5 km na zachód od stanowiska Jezierzba, w okolicy osady Woziwoda. Najstarsze z drzew liczyły 222 lata. Wyniki badań dendrochronologicznych i dendroklimatycznych potwierdziły, że sosna zwyczajna w Borach Tucholskich znajduje się pod silną presją klimatyczną i reaguje negatywnie na ocieplenie klimatu oraz zmieniający się reżim opadów. Chociaż sosny z Woziwody wykazywały podobną reakcję wzrostową na klimat jak inne sosny z północnej Polski, ich wrażliwość klimatyczna była większa.

Najsilniejszą ujemną korelację dla rocznego przyrostu radialnego sosny zwyczajnej z Woziwody stwierdzono w odniesieniu do średniej temperatury powietrza w lipcu. Ponadto wykazano silniejszą zależność przyrostu radialnego sosny zwyczajnej od opadów w czerwcu. Miesiące te – czerwiec i lipiec – odpowiadają za najintensywniejszą fazę wzrostu drzew, co wiąże się ze zwiększonym zapotrzebowaniem na wodę. Jednocześnie to właśnie w tym okresie, w ostatnich latach, coraz częściej występują epizody suszy. Sosny zwyczajne w Borach Tucholskich są zatem szczególnie wrażliwe na deficyty wodne w sezonie letnim. Wyniki potwierdzają, że w warunkach klimatycznych typowych dla Europy Środkowej to dostępność wody będzie kluczowym czynnikiem środowiskowym wpływającym na dynamikę wzrostu drzew w najbliższej przyszłości. Większą wrażliwość klimatyczną sosen na stanowisku Woziwoda potwierdza również liczba negatywnych lat wskaźnikowych – odnotowano ich łącznie 14 w okresie 1814–2022. Dwa ostatnie przypadły na lata 2015 i 2018, natomiast ostatni rok wskaźnikowo pozytywny wystąpił w 1983 roku.

Zbadano także aktualny stan torfowiska, wykorzystując dane teledetekcyjne. Pomiary wskaźnika LST (ang. *Land Surface Temperature*; wskaźnik temperatury gruntu) uwidoczniły wysoką temperaturę powierzchni torfowiska latem, osiągającą miejscami nawet 46 °C (wschodnia część torfowiska). Wskazuje to na silne odwodnienie w tym fragmencie torfowiska. Obszar ten charakteryzował się także stosunkowo niskim wskaźnikiem NDVI (ang. *Normalized Difference Vegetation Index*; znormalizowany różnicowy wskaźnik wegetacji) oraz wyższym wskaźnikiem MSI (ang. *Moisture Stress Index*; wskaźnik stresu wodnego), co oznacza niską ilość biomasy oraz słabą kondycję roślin.

Torfowisko Jezierzba zarejestrowało także anomalie i zjawiska ekstremalne, które bezpośrednio je dotykały lub występowały w jego otoczeniu. Koncentracje węgielków potwierdziły między innymi znane ze źródeł historycznych pożary w Borach Tucholskich we wczesnych dekadach XIX wieku oraz susze i pożary końca lat 40. i 50. XX wieku. Susze lat 50. XX wieku znalazły odbicie także w zbiorowiskach ameb skorupkowych. W tym czasie nastąpił gwałtowny wzrost udziału gatunku *Phryganella acropodia*, który jest wskaźnikiem suchych warunków. Gradacje owadów z lat 1866-1868 i 1922-1924 odznaczyły się spadkiem udziału pyłku sosny zwyczajnej w danych palinologicznych. Gradacja z lat 1866-1868 zamanifestowała się także obecnością aparatów szparkowych sosny. Może to mieć związek z masowym opadem igieł sosnowych na powierzchnię torfowiska. Lata pogradacyjne – 1869 i 1925 – zaznaczyły się także jako negatywne lata wskaźnikowe w danych dendrochronologicznych.

Nowatorskość badań polegała nie tyle na coraz bardziej powszechnym w paleoekologii podejściu wielowskaźnikowym, co na ujęciu interdyscyplinarnym, integrującym wiele różnorodnych zbiorów danych. Warto tutaj także zaznaczyć, że preprint artykułu (Bąk et al., 2024) został dołączony do dokumentacji wniosku o stworzenie rezerwatu przyrody „Torfowisko Jezierzba”, czyniąc go jednym z niewielu obiektów posiadających dokumentację paleoekologiczną.

Artykuł 2

W publikacji Bąk et al. (2025) przedstawiono ostatnie około 2000 lat lokalnej historii rozwoju i funkcjonowania torfowiska Miały (Puszcza Notecka). Skoncentrowano się na reakcji torfowiska na zjawiska ekstremalne, których doświadczyła Puszcza Notecka w XX wieku – gradacji strzygoni choinówki w latach 1922-1924 oraz pożaru w 1992 roku. Analizowano, czy wydarzenia te mogły prowadzić do tzw. krytycznych przejść (ang. *critical transitions*) na torfowisku. Zarysowano również kontekst historyczny omawianych wydarzeń, zwracając uwagę na wprowadzenie plantacji sosnowych, tj. przejście od lasów o charakterze mieszanym do monokultur w Puszczy Noteckiej pod koniec XVIII wieku. Podkreślono znaczenie długookresowego tła środowiskowego sprzed wprowadzenia planowej gospodarki leśnej jako istotnego punktu odniesienia. Było to pierwsze badanie wielowskaźnikowe z tego obszaru, obejmujące tak rozległy przedział czasowy. Dzięki temu można wesprzeć negację powszechnego przekonania, że na sandrowych piaskach Puszczy Noteckiej tylko sosna była zdolna do wzrostu. Dane palinologiczne wskazują na duży udział dębu, graba pospolitego i buka zwyczajnego w kompozycji otaczającego lasu przed momentem wprowadzenia monokultury.

Gradacja strzygoni choinówki w latach 1922-1924 została dobrze zarejestrowana w torfie. W warstwie odpowiadającej temu wydarzeniu nastąpił spadek udziału pyłku drzew na korzyść pyłku taksonów terenów otwartych i ruderalnych. Podniósł się poziom wody, co może wskazywać na zalanie torfowiska wodą ze zwiększonego spływu powierzchniowego. Ogołocone z igieł i liści drzewa straciły zdolność do retencji wody, jak również ograniczona została ewapotranspiracja. Dodatkowo po usunięciu zniszczonych drzewostanów woda mogła swobodnie spływać do naturalnych zagłębień terenu. Pojawiły się zarodniki grzyba *Sphaerodes retispora* (jedyne wystąpienie w diagramie palinologicznym), który rozwija się na martwym i rozkładającym się drewnie, a także zarodniki grzybów koprofilnych typu *Sordaria*, które mogą być wskaźnikiem terenów otwartych i obecności zwierząt hodowlanych.

Po niszczycielskiej gradacji nie wykorzystano szansy na przebudowę monogatunkowego drzewostanu i ponownie zdecydowano o masowym sadzeniu sosny. Pyłek sosny tuż przed gradacją stanowił około 72% pyłku drzew, 40 lat po gradacji – już ponad 81%. Nastąpiła gwałtowna ekspansja torfowców, które wyparły mchy brunatne oraz rośliny jednoliścienne, w tym w szczególności turzyce. Udział szczątków mchów torfowców w analizie makroskopowej roślin przekroczył 80%. Zniknęły cyjanobakterie i słodkowodne glony, co, w połączeniu z rozprzestrzenieniem się torfowców i wzrostem kwasowości, może wskazywać na odcięcie torfowiska od dostawy wód gruntowych. Zmieniły się także sygnatury izotopów neodymu, co potwierdza znaczne zmniejszenie dostawy materii mineralnej do torfowiska. Wśród ameb skorupkowych dominowała *Galeripora discoides*, która toleruje niestabilne sezonowo warunki hydrologiczne.

Pożar z 1992 roku nie zapisał się w torfie tak dobrze, jak oczekiwano. Choć istnieje szereg wskaźników paleoekologicznych, które potwierdzają jego wystąpienie, nie odnotowano znaczącego wzrostu koncentracji i akumulacji węgielków, zarówno makroskopijnych, jak i mikroskopijnych. Z danych otrzymanych od Lasów Państwowych wiadomo, że pożar objął torfowisko, a do dzisiaj można znaleźć na nim spalone fragmenty drzew. Na brak zapisu pożaru z danych pochodzących z analizy węgielków mogło wpłynąć kilka czynników. Po pierwsze wysoka intensywność pożaru – im pożar intensywniejszy, tym mniejsze cząsteczki węgli produkuje, a przez to mogą być one dalej przenoszone. Po drugie, intensywny deszcz tuż po dotarciu pożaru do torfowiska, który mógł dokonać dyspersji fragmentów węgielków do stref krawędziowych torfowiska (rdzeń pobierany był z środka torfowiska). Podkreślić zatem należy, że nie każdy pożar zapisuje się w torfie w postaci obecności węgielków.

O pożarze świadczy jednak fakt, że podniósł się poziom wody na torfowisku, co może wskazywać – podobnie jak w przypadku gradacji z lat 1922-1924 – na swobodny spływ powierzchniowy do zagłębienia po zniszczeniu drzew, a następnie ich usunięciu. Zaznaczył się także znaczący spadek udziału pyłku drzew, przy jednoczesnym wzroście udziału pyłku taksonów terenów otwartych i ruderalnych. W warstwie odpowiadającej pożarowi zaobserwowano także większy niż w pozostałych warstwach rdzenia udział aparatów szparkowych sosny zwyczajnej, co może wskazywać na gwałtowny opad igieł na powierzchnię torfowiska.

Pionierski aspekt badań: po raz pierwszy w wielowskaźnikowych badaniach paleoekologicznych torfowisk Puszczy Noteckiej uchwycono historię obiektu sięgającą dalej niż okres funkcjonowania lasu monokulturowego. Ponadto w badaniu wykorzystano izotopy neodymu jako dodatkowy wskaźnik lokalnych zaburzeń; wskaźnik ten jest wykorzystywany w paleoekologii torfowisk dopiero od kilku lat.

Artykuł 3

W publikacji Marcisz et al. (2025) przedstawiono ostatnie 700 lat lokalnej historii rozwoju i funkcjonowania torfowiska Stawek (Bory Tucholskie). Skoncentrowano się na reakcji torfowiska na wprowadzenie plantacji sosnowych, tj. przejście od lasów o charakterze mieszanym do monokultur w Borach Tucholskich pod koniec XVIII wieku. Podobnie jak we wcześniejszych artykułach potwierdzono, że wprowadzenie nowych metod gospodarowania lasem miało wpływ na funkcjonowanie torfowiska, prowadząc do krytycznych zmian w składzie roślinności i warunkach hydrologicznych. Skupiono się jednak na zmianie reżimu pożarowego przed i po wprowadzeniu planowego zarządzania lasem, wykorzystując analizę liczby cząstek węgielków, ich typów morfologicznych oraz nowoczesne technologie laserowe w postaci spektroskopii Ramana do rekonstrukcji intensywności dawnych pożarów.

W torfowisku Stawek zidentyfikowano dwa krytyczne przejścia. Pierwsze miało miejsce na początku XVII wieku i zaznaczyło się nagłą zmianą typu osadu – z silnie rozłożonego torfu bogatego w węgielki do warstw zawierających torfowce i charakteryzujących się zwiększonym tempem akumulacji torfu. W okresie od XIV do XVII wieku torfowisko w skutek przesuszenia narażone było na powierzchniowe pożary – potwierdzone obecnością cząstek węgielków i strzępków grzybni w komórkach zwęglonego drewna. Gwałtowny spadek aktywności pożarowej mógł być związany z działalnością rolniczą okolicznych społeczności, co zamanifestowało się wzrostem udziału pyłku zbóż (zwłaszcza żyta) i otwarciem się drzewostanu.

Drugie przejście krytyczne wiąże się z ponownym zagęszczeniem lasu i wprowadzeniem monokultury sosnowej pod koniec XVIII wieku. Zmniejszył się udział drzew liściastych, a dominację uzyskała sosna zwyczajna. Wraz z nowym zarządzaniem wprowadzono także melioracje i odwadnianie terenów podmokłych, co prowadziło do wzrostu zakwaszenia i torfienia siedlisk. Warto także ponownie zaznaczyć, że również sama sosna ma zdolność do zakwaszenia gleby. W przeciwieństwie do stanowiska Jezierzba zaburzenia, takie jak: susze, pożary i gradacje szkodników, nie pozostawiły wyraźnych śladów w zapisie paleoekologicznym i nie wpłynęły na torfowisko.

Warstwy torfu odpowiadające okresowi od XIV do XVI wieku zdecydowano się poddać szczegółowej interpretacji. Wysoką aktywność pożarową uzasadniały zrekonstruowane poziomy wód gruntowych, które oscylowały wokół wartości poniżej 20 cm. Nie występowały gatunki ameb miksotroficznych, co sugeruje, że torfowisko nie było wówczas silnie zakwaszone. Jak zostało wcześniej wspomniane, wysokiej koncentracji węgielków towarzyszyły spadek udziału drzew liściastych i wzrost udziału taksonów terenów otwartych, co może wskazywać, że gatunki były celowo pozyskiwane przez ludność jako drewno budowlane i opałowe. Strzępki grzybni znalezione w ścianach komórek zwęglonego drewna świadczą o tym, że kolonizowały one martwe i ulegające rozkładowi drewno, co z kolei wskazuje na to, że sosny spaliły się *in situ*. Spalenie biomasy nasyconej wodą w dobrych warunkach hydrologicznych byłoby niemożliwe.

Szczegółowe analizy wyraźnej i niezwykle miąższej warstwy żarowej w torfie pokazują, że zwiększona aktywność pożarowa, zarejestrowana na podstawie nagromadzenia węgielków, nie świadczy jednoznacznie o intensywności spalania. Próbki ze zrekonstruowaną największą intensywnością pożarów rzadko pokrywały się z tymi, w których występowały najwyższe sumy węgielków. Niska suma węgielków przy jednocześnie wysokiej rekonstruowanej intensywności może wskazywać na intensywne lokalne pożary, które spaliły większość dostępnego paliwa. Z kolei rekonstruowane intensywne pożary współwystępujące z wysokimi sumami węgielków mogą sugerować krótkotrwałe epizody ognia. W związku z tym, aby uzyskać jak najdokładniejszy obraz przeszłych reżimów pożarowych w artykule postuluje się o równoczesne stosowanie rekonstrukcji intensywności pożarów z wykorzystaniem spektroskopii Ramana w połączeniu z analizą ilościową węgielków.

Innowacyjny charakter badań: rdzeń z torfowiska Stawek był pierwszym pobranym z torfowiska kotłowego, gdzie zaaplikowano spektroskopię Ramana w celu rekonstrukcji intensywności pożarów. Ponadto w badaniu jasno wykazano, że ilość węgielków w torfie nie jest wskaźnikiem intensywności pożarów.

PODSUMOWANIE

Rekonstrukcje paleośrodowiskowe zaprezentowane w niniejszej rozprawie doktorskiej, opracowane w wysokiej rozdzielczości, pozwoliły na sformułowanie szeregu unikalnych wniosków dotyczących reakcji torfowisk na wprowadzenie monokultur sosnowych w ich sąsiedztwie oraz na anomalie i zjawiska ekstremalne występujące w tychże monokulturach.

Wszystkie trzy stanowiska – Jezierzba, Miały oraz Stawek – wykazały reakcję na zmiany w sposobie zarządzania otaczających je lasów (cel główny nr 1). Wprowadzenie monokultur sosnowych pod koniec XVIII wieku doprowadziło do zmiany warunków hydrologicznych i troficznych torfowisk, co w konsekwencji wpłynęło na zmianę składu roślinności je porastającej. Zmiany te mogły mieć charakter stopniowy – jak w przypadku stanowiska Stawek, gdzie sosna, dzięki swojej naturalnej zdolności do zakwaszania siedlisk, wpływała na środowisko powoli – lub gwałtowny, jak w przypadku stanowiska Jezierzba, gdzie istotną rolę odegrały dodatkowe działania związane z gospodarką leśną, w tym kopanie rowów melioracyjnych. Zmiana leśnego otoczenia okazała się dla torfowisk krytyczna – doprowadziła do tzw. krytycznych przejść, czyli trwałych przekształceń, po których torfowiska nie były już w stanie powrócić do wcześniejszego stanu funkcjonowania.

Do krytycznych zmian na torfowisku mogą prowadzić również skutki zjawisk ekstremalnych, co dobrze ilustruje przykład torfowiska Miały. Niszczycielska gradacja strzygoni choinówki w latach 1922-1924 doprowadziła do odlesienia, zwiększonego spływu powierzchniowego oraz zmiany w dostawie materii mineralnej do torfowiska. Następnie obszar został ponownie zalesiony niemal wyłącznie sosną zwyczajną, bez większych prób wzbogacenia drzewostanu o gatunki liściaste. Wszystkie te konsekwencje przyczyniły się do gwałtownego, krytycznego przejścia w funkcjonowaniu torfowiska Miały.

Potwierdzono, że torfowiska stanowią archiwa przeszłych zaburzeń i zjawisk ekstremalnych, zachodzących zarówno *in situ*, jak i w ich otoczeniu (cel główny nr 2). Rejestrują one m.in. susze, pożary oraz gradacje owadów. Choć nie zawsze możliwe jest jednoznaczne zidentyfikowanie takich anomalii na podstawie pojedynczych śladów, takich jak obecność węgielków czy szczątków owadów, to – jak wykazano w niniejszej rozprawie – duży potencjał diagnostyczny posiada zintegrowana analiza wielu wskaźników paleoekologicznych, takich jak pyłek roślin, aparaty szparkowe, zarodniki grzybów mikroskopijnych, szczątki makroskopowe roślin oraz ameby skorupkowe.

Zarówno zmiana w sposobie gospodarowania lasem, jak i konsekwencje susz, pożarów oraz gradacji insektów wywołały porównywalne reakcje środowiskowe torfowisk zlokalizowanych w dwóch monokulturowych kompleksach leśnych – Puszczy Noteckiej i w Borach Tucholskich (cel główny nr 3). Wnioski płynące z rozprawy dają zatem solidne fundamenty pod badania paleoekologiczne w innych lasach monokulturowych.

Wyniki badań są ważne dla gospodarki leśnej, ekologii lasów i ekologii mokradeł. Przyczyniają się do wzrostu wiedzy na temat funkcjonowania torfowisk w warunkach presji antropogenicznej i klimatycznej, tym samym dają podstawy do lepszego prognozowania reakcji torfowisk na rosnącą działalność człowieka oraz ocieplenie klimatu. Wyniki otrzymane w trakcie powstania niniejszej rozprawy doktorskiej wsparły realizację projektu „Ochrona cennych ekosystemów Borów Tucholskich" realizowanego przez Nadleśnictwa Woziwoda i Tuchola, dofinansowanego ze środków Mechanizmu Finansowego Europejskiego Obszaru Gospodarczego 2014-2021 i Budżetu Państwa. Efektem współpracy administracji leśnej z autorem rozprawy doktorskiej oraz z większością współautorów artykułów składających się na tę rozprawę jest między innymi publikacja „Jak chronić torfowiska w lasach?" pod redakcją Mariusza Lamentowicz i Stefana Konczala, wydana w 2024 roku (Lamentowicz and Konczal, 2024).

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ZAŁĄCZNIKI

KOPIE ARTYKUŁÓW WCHODZĄCYCH W SKŁAD ROZPRAWY DOKTORSKIEJ

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Assessing the impact of forest management and climate on a peatland under Scots pine monoculture using a multidisciplinary approach

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Abstract. Assessing the scale, rate and consequences of climate change, manifested primarily by rising average air temperatures and altered precipitation regimes, is a critical challenge in contemporary scientific research. These changes are accompanied by various anomalies and extreme events that negatively impact ecosystems worldwide. Monoculture forests, including Scots pine (*Pinus sylvestris* L.) monocultures, are particularly vulnerable to these changes due to their homogeneous structure and simplified ecosystem linkages compared to mixed forests, making them more sensitive to extreme events such as insect outbreaks, droughts, fires and strong winds. In the context of global warming, forest fires are becoming extremely dangerous, and the risk of their occurrence increases as average temperatures rise. The situation becomes even more dramatic when fire enters areas of peatlands, as these ecosystems effectively withdraw carbon from the rapid carbon cycle and store it for up to thousands of years. Consequently, peatlands become emitters of carbon dioxide into the atmosphere.

In this study, we aim to trace the last 300 years of historical development of a peatland situated in a Scots pine monoculture. Our focus is on the Okoniny (Jezierzba) peatland located within Tuchola Forest in northern Poland, one of the country's largest forest complexes. We delved into the phase when the peatland's surroundings transitioned from a mixed forest to a pine monoculture and investigated the impact of changes in forest management on the peatland vegetation and hydrology. Our reconstructions are based on a multi-proxy approach using pollen, plant macrofossils, micro- and macro-charcoal, and testate amoebae. We combine the peatland palaeoecological record with the dendrochronology of *Pinus sylvestris* to compare the response of these two archives. Our results show that a change in forest management and progressive climate warming affected the development of the peatland. We note an increase in acidity over the analysed period and a decrease in the water table over the last few decades that led to the lake–peatland transition. These changes progressed along with the strongest agricultural activity in the area in the 19th century. However, the 20th century was a period of continuous decline in agriculture and an increase in the dominance of Scots pine in the landscape as the result of afforestation. Dendroclimatic data indicate a negative effect of temperature on Scots pine and pressure from summer rainfall deficiency. Additional remote sensing analysis, using hyperspectral, lidar and thermal airborne data, provided information about the current condition of the peatland vegetation. With the application of spectral indices and the analysis of land surface temperature, spatial variations in peatland drying have been identified. Considering the context of forest management and the protection of valuable ecosystems in monocultural forests, the conclusions are relevant for peatland and forest ecology, palaeoecology, and forestry.

1 Introduction

Peatlands, which play an important role in the global carbon cycle and whose destabilization can create positive feedback for climate warming, are vulnerable to various types of change (Gallego-Sala et al., 2018; Wilson et al., 2016). Peatlands, although they only cover about 3 % of the Earth's total land area (Parish et al., 2008; Rydin and Jeglum, 2013), store more than 30 % of the organic carbon (C) (Freeman et al., 2004; Gorham, 1991; Harenda et al., 2018), which is far more carbon than the entire biomass of the world's forests (Beaulne et al., 2021b). Their advantage over forests is due to not only their ability to accumulate C but also the fact that they do not emit decomposed carbon from the so-called rapid carbon cycle for up to thousands of years (Blodau, 2002; Gorham, 1991). Estimation of the C content accumulated in peatlands is challenging (Sanderson et al., 2023), although some studies indicate ca. 600 Gt C in the Northern Hemisphere alone (Yu et al., 2010). It has recently been shown that even the smallest kettle-hole peatlands effectively accumulate C and serve as important C hot spots (Karpińska-Kołaczek et al., 2024).

Insufficient awareness of the ecological importance of peatlands has led to them being treated as wastelands and drained for hundreds of years, to obtain land for agriculture and forestry or to exploit commercially as an energy resource (Joosten et al., 2012; Łuców et al., 2022; Paavilainen and Päivänen, 1995). Many of these areas have also had to adapt to a changing environment resulting from the use of various forest management techniques, e.g. the replacement of mixed forests with more easily managed monoculture forests (plantations; Lee et al., 2023; Łuców et al., 2021; Słowiński et al., 2019). Mixed forests, through greater biodiversity, are more resilient and better able to adapt to environmental change (Bauhus et al., 2017; Messier et al., 2022), providing a more comprehensive range of ecosystem services (Felton et al., 2016; Huuskonen et al., 2021).

Despite being more straightforward to manage, forest monocultures are characterized by simplified ecosystem linkages (Chapin et al., 2012). As a result, they are more susceptible to various extreme events and disturbances both natural and anthropogenic, including droughts, fires, strong winds and pest infestations (Grondin et al., 2014). This is particularly important as disturbances of these types of forests are becoming more common (Seidl et al., 2014; Westerling, 2016). Natural disturbance regimes in forests are mainly a response to climate change (Hanson and Weltzin, 2000; Pureswaran et al., 2015; Seidl et al., 2017; Trumbore et al., 2015); therefore, they are expected to increase in frequency and severity in the coming years (Gregow et al., 2017; Moritz et al., 2012; Wotton et al., 2010). Moreover, the problem applies to all kinds of monoculture forests regardless of the dominant species and climate zones (Booth, 2013; Guariguata et al., 2008; McNulty et al., 2013; Spiecker, 2000), including pine plantations in the temperate climate zone of Central and Eastern Europe (Łuców et al., 2021; Schüle et al., 2023). Thus, peatlands located in areas of forest monocultures are crucial in terms of their impact on global climate change and are even more vulnerable to extreme phenomena and disturbance, despite the already high climatic and anthropogenic pressure.

The history of peatlands' development can be traced using palaeoecological analyses, which allow numerous reconstructions of past environmental conditions including climate change (Lamentowicz et al., 2015a; Mauquoy and Yeloff, 2008). These include reconstructions of vegetation changes in the peatland and its surroundings, changes in the water table, and reconstructions of past fire activity (Gałka et al., 2022; Kołaczek et al., 2018; Marcisz et al., 2017, 2020b; Mroczkowska et al., 2021). Peat archive records contain a wide range of preserved micro- and macrofossils, for example, pollen, spores, microbial remains and charcoal are deposited in situ and brought in by wind or water (Godwin, 1981). While palaeoenvironmental reconstructions based on peat records have become common, few studies integrate palaeoecological data with other methods. For example, studies that combine palaeoecological and dendrochronological records, including dendroclimatic reconstructions based on analysis of the annual growth of tree rings, are still relatively rare (Ballesteros-Cánovas et al., 2022; Beaulne et al., 2021a; Dinella et al., 2021; Edvardsson et al., 2016, 2019, 2022; González de Andrés et al., 2022; Kuosmanen et al., 2020; Lamentowicz et al., 2009b). Yet combining peat records with dendrochronological data can benefit interpretations of trees, forest resilience and resistance to disturbances compared to local environmental changes recorded in peat. Such a view of past environmental changes through several proxies and other archive types is fundamental and will be helpful for forest management and nature conservation in the future. To assess the current state of the peatland, we also included remote sensing data in the analysis. Remote sensing methods have been applied to study wetland conditions for over 50 years and are currently regarded as some of the most useful methods in this research area (FAO, 2020; Guo et al., 2017). Remote sensing technologies enable the remote and non-invasive acquisition of information about the research object using specialized sensors, typically mounted aboard satellites or aircraft. In this study, data obtained from a multisensor aerial platform were used to assess the extent of peatland, to identify drainage ditches and to monitor the condition of the current vegetation.

Our study aims to assess the impact of forest management (the introduction of pine monoculture) and changing climate on the vegetation as well as on the hydrological and trophic conditions of a peatland in Central and Eastern Europe by integrating various data sources – palaeoecology, dendrochronology, remote sensing and historical information. We assumed that the introduction of pine monoculture led to changes in the species composition of peatlands in favour of *Sphagnum* mosses, as well as to the stabilization of the water table. We also undertook to confirm whether peatlands register and respond to extreme events, both in situ and in the immediate environment. We assumed that the disturbances that occurred in the monoculture forest would be recorded in the tree-ring (annual growth) record of Scots pine (*Pinus sylvestris* L.) and would confirm and complement the palaeoecological reconstruction of the peatland. Thus, we have identified peat layers corresponding to the occurrence of extremes gathered from historical sources and compared dendrochronological (dendroclimatic) data to them.

2 Materials and methods

2.1 Study site

The Okoniny (Jezierzba) peatland (53°40′52″–53°41′21″ N 18°03′09″–18°03′40″ E according to the WGS 84) is located in northern Poland, about 60 km north of Bydgoszcz and about 20 km northeast of Tuchola (Fig. 1). The study area is located within the Tuchola Forest mesoregion (Kondracki, 2001), close to the Pomeranian ice margin of the Vistulian glaciation dated to ca. 17 000–16 000 cal BP (Marks, 2012). The entire area of Tuchola Forest is a young glacial landscape covered by glacial till, sand, and numerous depressions and other forms originating from melting dead ice (Błaszkiewicz et al., 2015). Based on the analysis of remote sensing data, it was determined that the surface area of the peatland is 27.08 ha, with approximately 7.00 ha designated as non-forested area. The direct catchment area of the peatland covers a surface of 33.23 ha. The current elevation of the peatland is around 119 m a.s.l., with the highest-elevated area within the direct catchment reaching around 128 m a.s.l. It is part of a protected area (regulation no. 64/97, 1997) included within the boundaries of Tuchola Landscape Park (created in 1985). Moreover, since 2008 the entire complex of Tuchola Forest has been included on the Natura 2000 list as a special protection area. Since 2010, it has been listed as a UNESCO biosphere reserve.

The Okoniny (Jezierzba) peatland is located in a temperate latitude zone, with a transitional climate influenced by continental air masses from eastern Europe and oceanic air masses from the Atlantic Ocean (Beck et al., 2018). According to climate data obtained from the Institute of Meteorology and Water Management from the meteorological station in Chojnice (35 km west of the study area) for the period between 1991 and 2020, the coldest month is January, with an average temperature of −1.5 °C, and the warmest month is July, with an average temperature of 18.0 °C. Between 1961 and 1990, both January and July were cooler by 1.6 °C compared to 1991–2020. The average annual temperature increased from 6.9 °C in 1951–1990 to 8.1 °C in 1991–2020. In terms of precipitation, February has the least amount, with an average of 31.1 mm for the period of 1991–2020, and July has the most, with an average of 80.7 mm for the period of 1991–2020. Compared to 1951–1990, the average precipitation for February increased by 7.7 mm, and for July it decreased by 4.1 mm. Mean annual rainfall increased from 558.1 mm for 1951–1990 to 612.4 mm for 1991–2020.

Samples for dendroclimatic analysis were taken from forest division no. 91 in Woziwoda Forest, Woziwoda forest district, about 9.5 km west of the study site (Fig. 1). The oldest pine trees in the forest district were selected for the study according to the indications of the forest survey and taxonomic descriptions.

2.2 Peat and tree core sampling

A peat core was taken from the northwestern part of the peatland in February 2022 using a Wardenaar corer (chamber dimension: 10 cm × 10 cm × 100 cm; Wardenaar, 1987). The entire length of the sampled peat core – 96 cm long monolith – was analysed. The core was sampled continuously every 1 cm, except for the top 10 cm, which contained a living *Sphagnum* layer. The first sample covered 4 cm of the surface layer (0–4 cm), and the following three samples were taken every 2 cm (4–6, 6–8, and 8–10 cm). We obtained 90 samples and analysed them for bulk density, ash content, peat and carbon accumulation rates, plant macrofossils, testate amoebae, macroscopic and microscopic charcoal, and pollen.

The research tree stem material was taken in April 2023 from 23 living and healthy trees at the Woziwoda site, ca. 9.5 km west of the Okoniny (Jezierzba) peatland. From each tree, a minimum of two cores was taken (from the eastern and western sides) at chest height (1.3 m) using a Pressler increment corer. In total, 50 cores were acquired from the Scots pine tree stems.

2.3 Radiocarbon dating and chronology

We used 10 samples containing *Sphagnum* stems and leaves for accelerator mass spectroscopy (AMS) ^{14}C dating of the entire length of the profile. The survey was conducted at the Poznan Radiocarbon Laboratory in Poland (laboratory code marked Poz; Table 1). The IntCal20 (Reimer et al., 2020) and Bomb21NH1 (Hua et al., 2021) atmospheric curves were used to calibrate the dates.

The absolute chronology of the entire core was based on a Bayesian age–depth model using OxCal v4.4.4 (OxCal v4.4.4, 2023). The `P_Sequence` command with a parameter k of 0.1 cm^{-1} was used to calculate the model, assuming $\log_{10}(k/k_0) = 2$ and an interpolation of 1 cm. The most pronounced change in peat composition, as manifested

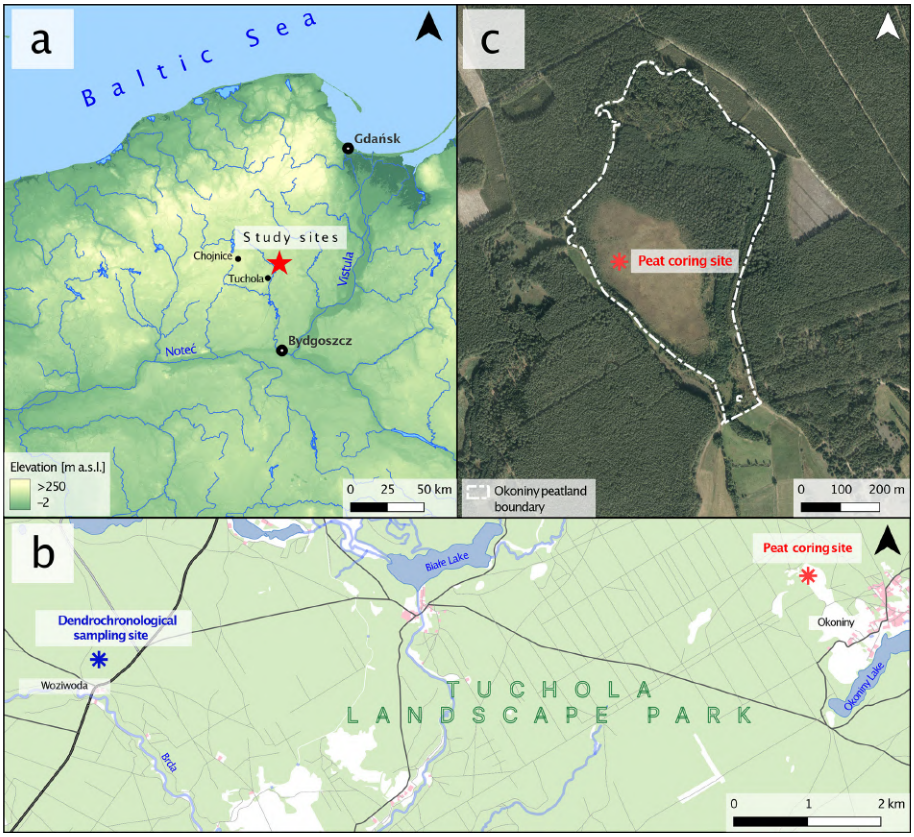

Figure 1. Location of the study area. **(a)** Location on a map of northwestern Poland. **(b)** Location of the two study sites – dendrochronological sampling site and peat coring site. **(c)** Okoniny (Jezierzba) peatland sampling site with current peatland boundaries.

by changes in pollen concentration, testate amoeba species composition and species composition of plant macrofossils (which may signal changes in peat accumulation rates), was input using the `Boundary` command at a depth of 66 cm. For better readability of the age–depth model, mean values (μ) were introduced and used to illustrate the modelled age.

2.4 Peat properties and carbon accumulation rate

Analyses of bulk density (BD), loss on ignition and peat carbon accumulation rate (PCAR) were carried out for each of the 90 samples. Each sample's volume [cm^3] was carefully measured beforehand using calipers to avoid compressing the material. Each sample was then placed in a separate crucible and dried to determine the percentage of water content. The weighed and dried samples were incinerated at 550 °C for 12 h and reweighed according to the protocol of Heiri et al. (2001) to determine the ash mass [g]. Bulk density [g cm^{-3}] was obtained by dividing the dry sample mass by the volume of the fresh sample according to Chambers et al. (2010). Loss on ignition [g] was obtained by subtracting the ash mass from the dry sample mass. Accumulation rates obtained from the peat core chronologies were multiplied by the bulk density without ash and by 50 % to obtain the PCAR, following the protocol of Loisel et al. (2014). The top 11 cm of the core (0–11 cm) was discarded for PCAR assessment due to the unrepresentative nature of the results obtained, as increased values of carbon accumulation in near-surface peat cannot be used for inference (Young et al., 2019).

2.5 Plant macrofossil analysis

The analysis of plant macrofossils was carried out using the modified protocol of Mauquoy et al. (2010). Each sample of approximately 5 cm^3 was wet sieved (mesh diameter: 200 µm). The generalized content of the sample was estimated in percentage using a binocular microscope. Fruits, seeds, caryopses, achenes, perigynia, bud scales, catkin scales, whole preserved leaves, whole preserved needles, cones, anthers, sporangia, opercula, fungi sclerotia and wood pieces were counted as total numbers in each sample. The tissues of monocotyledon species and moss leaves (brown and *Sphagnum* mosses) were identified on slides using magnifications of ×200 and ×400. The material was compared with the guides (Anderberg, 1994; Berggren, 1969; Bojňanský and Fargašová, 2007; Mauquoy and van Geel, 2007). The diagram for the analysed proxy was plotted using the riojaPlot package for R (Rioja, 2023).

Table 1. The list of radiocarbon dates with calibration from Okoniny (Jezierzba) peatland in the OxCal v4.4.4 software using the IntCal20 calibration curve for the atmospheric data and Bomb21NH1 curve for bomb series.

No.	Laboratory code – sample number	Depth (cm)	^{14}C date (^{14}C BP)	Calibrated dates (cal CE; 2σ – 95.4 %)	Material dated
1	Poz-150386	10.5	100.86 ± 0.33 pMC	1952–1958 (33.9 %) 2013–2022 (61.5 %)	*Sphagnum* stems
2	Poz-150387	20.5	107.92 ± 0.34 pMC	1952–1958 (11.1 %) 1996–2009 (84.4 %)	*Sphagnum* stems
3	Poz-150388	30.5	132.8 ± 0.36 pMC	1958–1962 (20.8 %) 1972–1984 (74.6 %)	*Sphagnum* stems
4	Poz-150445	40.5	165 ± 30	1661–1706 (17.2 %) 1720–1818 (44.0 %) 1832–1892 (14.9 %) 1906–2022 (19.5 %)	*Sphagnum* stems
5	Poz-150446	50.5	85 ± 30	1688–1730 (26.1 %) 1806–1924 (69.3 %)	*Sphagnum* stems
6	Poz-150447	60.5	105 ± 30	1682–1736 (25.9 %) 1802–1936 (69.5 %)	*Sphagnum* stems
7	Poz-150449	70.5	135 ± 30	1674–1766 (32.8 %) 1774–1776 (0.6 %) 1798–1942 (62.0 %)	*Sphagnum* stems
8	Poz-150450	80.5	165 ± 30	1661–1706 (17.2 %) 1720–1818 (44.0 %) 1832–1892 (14.9 %) 1906–2022 (19.5 %)	*Sphagnum* stems
9	Poz-150631	90.5	280 ± 30	1505–1596 (55.0 %) 1616–1665 (37.8 %) 1784–1794 (2.6 %)	*Sphagnum* stems
10	Poz-150633	95.5	100 ± 30	1683–1735 (26.1 %) 1802–1930 (69.3 %)	*Sphagnum* stems

2.6 Testate amoebae analysis

Samples for testate amoeba analysis (volume of ca. 5 cm^3) were washed under 300 µm sieves following the method described by Booth et al. (2010). Testate amoebae were analysed under a light microscope with ×200 and ×400 magnifications until the sum of 100 tests per sample was reached (Payne and Mitchell, 2009). Several keys and taxonomic monographs (Clarke, 2003; Mazei and Tsyganov, 2006; Meisterfeld, 2001; Ogden and Hedley, 1980) as well as online resources (Microworld, world of amoeboid organisms, 2023, last access: 26 April 2024) were used to achieve the highest-possible taxonomic resolution. The results of the testate amoebae analysis were used for the quantitative depth-to-water table (DWT) and pH reconstructions. Both the full diagram and the reconstructions were performed in the C2 software (Juggins, 2007) using the European training set (Amesbury et al., 2016).

2.7 Pollen and non-pollen palynomorphs

Samples for palynological analysis (volume of 2 cm^3) were prepared using standard laboratory procedures (Berglund and Ralska-Jasiewiczowa, 1986). To remove the carbonates, samples were treated with 10 % hydrochloric acid. This step was followed by digestion in hot 10 % potassium hydroxide (to remove humic compounds) and soaking in 40 % hydrofluoric acid for 24 h (to remove the mineral fraction). Next, acetolysis was carried out. Three *Lycopodium* tablets (batch 280521291, containing 18 407 spores per tablet, produced by Lund University) were added to each sample during the laboratory procedures for the calculation of microfossil concentration (Stockmarr, 1971). Pollen, spores and selected non-pollen palynomorphs (NPPs) were counted under an upright microscope (Zeiss Axio SCOPE A1) until the number of total pollen sum (TPS) grains in each sample reached at least 500, apart from 23 samples in which pollen concentrations were very low. Sporomorphs were identified with the assistance of atlases, keys (Beug, 2004; Moore et al., 1991), various publications and the image database in the case of NPPs, for which there are no atlases (Miola, 2012; Shumilovskikh et al., 2022; Shumilovskikh and van Geel, 2020). The results of the palynological analysis were expressed as percentages; calculations are based on the ratio of an individual taxon to the TPS, i.e. the sum of AP (arboreal pollen) and NAP (non-arboreal pollen) excluding aquatic and wetland plants (together with Cyperaceae and Ericaceae), cryptogams, and fungi. The pollen diagram for the analysed proxy was plotted using Tilia graphing software (Grimm, 1991, 1992).

2.8 Macro- and micro-charcoal analysis

Microscopic charcoal particles (size of $> 10\,\mu m$) were counted from the same slides as pollen until the number of charcoal particles and *Lycopodium* spores, counted together, exceeded 200 (Finsinger and Tinner, 2005; Tinner and Hu, 2003). Microscopic charcoal influx or accumulation rates (MIC) were calculated by multiplying charcoal concentrations by peat accumulation rates (PAR; Davis and Deevey, 1964; Tinner and Hu, 2003).

For macroscopic charcoal analysis, samples (volume of $2\,cm^3$) were prepared by bleaching to create a more visible contrast between the charcoal and the remaining organic matter following the method described by Whitlock and Larsen (2001). Samples were sieved through a $500\,\mu m$ mesh and only large charcoal fragments $> 600\,\mu m$ were analysed to obtain a local fire signal (Adolf et al., 2018). Samples were analysed with a binocular microscope using 60× magnification. Macroscopic charcoal influx or accumulation rates (MAC; particles $cm^{-2}\,yr^{-1}$) were calculated using the charcoal concentrations and PAR.

2.9 Tree core chronology construction

Tree cores underwent a standardized dendrochronological procedure (Zielski and Krąpiec, 2004). Polished cores were scanned between 1200 and 2400 DPI using an Epson Perfection V700 photo scanner. Annual growth rings were measured from digital images with an accuracy of 0.01 mm using CooRecorder. This facilitated the selection of individual growth sequences, which were utilized to form a chronology for each plot. Visual comparisons were made between individual sequences, and the significance of correlations was assessed using Student's *t* test (Baillie and Pilcher, 1973). Subsequently, cross-dating was conducted using the COFECHA software (Grissino-Mayer, 2001), which evaluates each data series according to the reference chronology created and compares the correlation coefficients obtained. Raw chronologies were derived by employing an arithmetic mean. For climate–growth analysis, standardized chronologies were used, obtained by fitting a spline function (i.e. the n-year spline was set to $2/3$ of the wavelength of n years of single growth series) using the `dplR` package (Bunn, 2008), package version 1.7.6 (2023), in the software R, version 4.3.0 (R, 2023). Using this standardization method, random variation in the radial growth was removed (Cook et al., 1990). For the chronologies obtained, i.e. raw (TRW) and standardized (RWI), values for the following descriptive statistics were computed: the mean correlation between series (inter-series correlation or Rbar), the GLK index (*Gleichläufigkeit*; Eckstein and Bauch, 1969) and EPS (express population signal; McCarroll and Loader, 2004).

2.10 Dendroclimatological and pointer year analysis

The `chron` function from the `dplR` package allowed for the making of a residual chronology, which was used for climate–growth analysis. The `dcc` function and its moving response (25-year window) function method were used to determine the effects of climate conditions on the growth of Scots pine using the `treeclim` package (Zang and Biondi, 2015) version 2.0.6.0 in R (R, 2023). This package allows the use of the bootstrap procedure to test the significance and stability of the coefficients of determination (r2) over a set period (Guiot, 1991). Monthly mean air temperature (Temp) and total monthly precipitation (Prec) were used to analyse climate–growth for the period of 1920–2022 (Klein Tank et al., 2002). Climate data were acquired via Climate Explorer (Trouet and van Oldenborgh, 2013) and calculated from the monthly gridded observational dataset E OBS v. 25.0e (Haylock et al., 2008) obtained for the 53.50–53.75° N, 17.75–18.00° E grid.

The Becker algorithm (Becker et al., 1994) was used to determine the pointer years in the Woziwoda chronology. Calculations were made using the "dplR" package in R and the "pointer" function (Bunn, 2008). Pointer years were calculated using adjustable thresholds of relative variation in radial growth set to a 10-year time window and the number of series exhibiting a similar incremental growth pattern. The main criterion for determining pointer years was the occurrence of unidirectional changes (i.e. a decrease or increase in the number of annual rings) in a minimum of 85 % of the tested sequences of annual increments observed in a group of trees at the Woziwoda site.

2.11 Acquisition and post-processing of remote sensing data

The analysis of the current state of Okoniny (Jezierzba) peatland was conducted using airborne remote sensing data. The data were acquired from a multi-sensor aerial platform by the MGGP Aero company on 25 March 2022 (leaf-off collection) and 20 July 2022, one of the warmest days of the year, which was particularly important for acquiring thermal data (leaf-on collection). Multispectral images (acquired with the IXM-100 camera) and airborne laser scanning data (ALS; acquired with the Riegl VQ780-II scanner) were obtained in the leaf-off season. Subsequently, during the vegetation season, the dataset was enhanced by acquiring hyperspectral data (collected using the HySpex VS-725 scanner) and thermal data (obtained with the InfraTEC 9400 camera). Based on the multispectral images, an orthophotomap was generated with a ground sampling distance (GSD) of 10 cm. Hyperspectral data were used to create a mosaic consisting of 430 bands (in the range from 400 to 2500 nm), ALS data were applied for the development of a digital terrain model (DTM) and thermal data were used to produce a land surface temperature (LST) mosaic. Thermal and hyperspectral mosaics and DTM were prepared with GSD = 1 m.

Photo interpretation was carried out to assess the extent of peatlands and the course of drainage ditches using orthophotos and the DTM as a base map. The DTM was also used to delineate the catchment area of the peatland. Hydrological modelling methods based on watershed analyses were employed for this purpose. A hyperspectral mosaic was used to calculate spectral indices such as the Normalized Difference Vegetation Index (NDVI; Rouse et al., 1974) and Moisture Stress Index (MSI; Hunt and Rock, 1989). Spectral indices are mathematical formulae that enable the simultaneous analysis of reflectance across multiple spectral ranges. The NDVI is a measure of healthy, green vegetation ranging from -1 to 1. Vegetation values typically range from 0.2 to 0.8, with higher values indicating healthier and denser vegetation. The MSI is sensitive to increasing leaf water content. Its values range from 0 to more than 3, but the common values for vegetation are from 0.4 to 2. Higher values indicate greater water stress and less water content in this case. Thermal data were used to calculate land surface temperature (LST), measured in °C.

2.12 Historical and cartographic information

Several historical cartographic studies were used to assess changes to the peatland and its surroundings. The oldest of the materials used is the Schrötter–Engelhardt map of 1803. Work on creating the map began in 1796 under the leadership of the Prussian government minister Friedrich Leopold von Schrötter (1743–1815) and topographer Friedrich Bernhard Engelhardt (1768–1854). The first version was produced at a scale of 1 : 50 000. Still, due to the concerns of the Prussian army command about the map being too detailed and capable of being used by enemy armies, a generalized version was eventually published at a scale of 1 : 150 000. A larger-scale version of the map was not available until the 1920s (Jäger, 1981, 1982). In this article, the generalized version of the map is used.

The Prussian topographic map *Messtischblatt* of 1874 (on a scale of 1 : 25 000, sheet no. 982, Zalesie section) was also analysed, along a detailed map of Poland issued by the Military Geographical Institute in 1933 at a scale of 1 : 25 000 (PAN map sheet 34 – SLUP 26 – B (Linsk)). In addition, a geological–agricultural map compiled between 1899 and 1900 using the topographic *Messtischblatt* of 1874 was considered. The Prussian Geological Survey produced the map (*Königlich-Preußische Geologische Landesanstalt*), which provides information on alluvial and diluvial deposits covering the area under study. The maps show the changes in the peatland and its surroundings from the early 19th century to the 1930s. Aerial images from 1964, 1984 and 1997 obtained from the Head Office of Geodesy and Cartography were also used for the same purpose (license no. DIO.7211.457.2023_PL_N).

Insect outbreak data are based on the literature (Orłowicz, 1924; Schütte, 1893; Wilson, 2012).

3 Results and interpretation

3.1 Age–depth model and peat accumulation rate

The age–depth model showed an agreement index (A_{model}) of 60 % (Fig. 2), precisely at the limit of the recommended minimum for its reliability (60 % according to Bronk Ramsey, 2008). The model spanned a period of ca. 282 years, with a maximum uncertainty of ca. 30 years (mostly in the time period of ca. 1883–1783 cal CE). Most of the core consisted of well-preserved *Sphagnum* peat, while the lower part consisted of sedge peat. The peat accumulation rate averaged 3.6 mm yr^{-1}, with the highest values associated with the un-decomposed acrotelm zone. The upper layers located between 0 and 11 cm were excluded from the analysis of peat accumulation rates. The fastest rate was 0.71 cm yr^{-1} (at 11.5 cm), and the slowest was 0.1 cm yr^{-1} (at 91.5 cm). The mean BD value across the core was 0.07 g cm^{-3}. It was highest in the lower part of the core, with 0.10 g cm^{-3} between 96 and 70 cm, and lowest in the middle part – 0.05 g cm^{-3} between 69 and 30 cm. In the upper part between 29 and 0 cm, it was 0.06 g cm^{-3}. Similarly, this upper, un-decomposed layer was excluded from the peat carbon accumulation rate (PCAR) analysis. For the rest of the core (11–96 cm), PCAR averaged 112 g C m^{-2} yr^{-1}. The mean water content of the wet sample was 93.8 %, and the mean organic matter content of the dry sample was 95.5 %.

3.2 Palaeoecological analyses

3.2.1 Phase 1 (~ 1726–1838, 96–74 cm): wet conditions and low human impact

The plant macrofossil and pollen analyses point to the presence of a shallow water body during this time interval. Plant macrofossil analysis (Fig. 3) showed that the peatland vegetation in this phase was strongly dominated by vascular vegetation, mainly *Carex* spp. monocotyledons. Shallow water and edges of the water body were overgrown by sedge communities (Cyperaceae pollen, 2.8 %–14.5 %; Fig. 5). Additionally, this was indicated by the presence of macrophytes represented by pollen of *Potamogeton* subgen. *Eupotamogeton* (0 %–0.9 %), *Nymphaea* (0 %–0.4 %) and *Utricularia* (0 %–0.3 %) (Fig. 5). The high percentage of aquatic non-pollen palynomorphs (NPPs) such as cyanobacteria and the algae *Tetraëdron minimum*, *Scenedesmus*, *Botryoccocus* and *Pediastrum* (Fig. 5) confirms the results of plant macrofossil and pollen analyses.

This phase was also characterized by the presence of the brown moss *Straminergon stramineum* (max 9 % of the subsample content; Fig. 3). This species occurs in a wide range of habitats (Hedenäs, 1993) but is most common in wet,

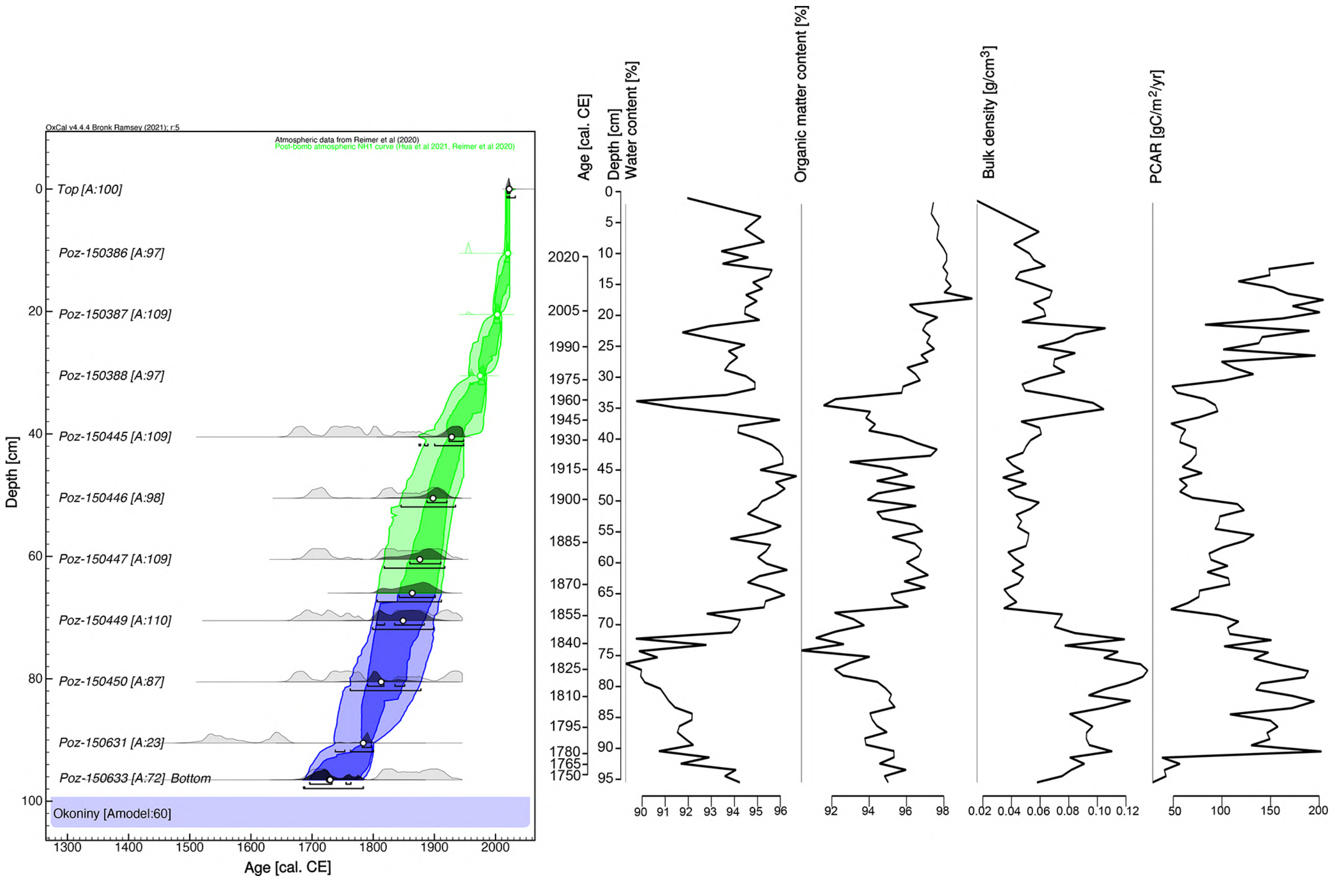

Figure 2. ^{14}C age–depth model of the Okoniny (Jezierzba) peat profile. Water content, organic matter content, bulk density and PCAR are also marked.

moderately acidic habitats (Blockeel, 2010). *Straminergon stramineum* is usually found as scattered stems or small patches among other mosses but occasionally forms scattered mats – sometimes partially submerged in water, next to lakes, on the edges of peatland or in lakeside marshes (Hill and Blockeel, 2014).

This phase of peatland development was characterized by a very low concentration of testate amoebae in the samples. *Centropyxis aculeata* was the most abundant species (Fig. 4). The dominance of plagiostomic species from the genus *Centropyxis* may point to the presence of mineral input into the peatland (Lamentowicz et al., 2009a; Marcisz et al., 2020a). The water level in the peatland was quite unstable and fluctuated between 4.3 and 16.5 cm below the ground; and the pH value ranged between 4.5 and 5.2, but due to the low number of identified tests, these reconstructions should be viewed with caution (Fig. 4).

The surrounding vegetation was characterized by the dominance of forests, as evidenced by the high proportion of arboreal pollen (AP; 83.6 %–91.1 %) in the total pollen (TP) content (Fig. 5). The main species recorded were *Pinus sylvestris* (62.6 %–81.3 % AP) and *Betula* (6.8 %–16.0 % AP), with admixtures of *Alnus* (2.5 %–7.7 % AP), *Quercus* (1.8 %–8.1 % AP), *Corylus avellana* (0.6 %–3.8 % AP), *Carpinus betulus* (0 %–3.4 % AP) and *Fagus sylvatica* (0.4 %–3.3 % AP). Cerealia pollen (0 %–7.8 % TP) along with *Centaurea cyanus*, a crop weed, indicated a stable presence of cultivated fields.

This phase also had the highest influx of macroscopic charcoal (MAC) of all three of the phases distinguished (Fig. 3). Towards the end of the phase at depths of 79.5 and 78.5 cm (first half of the 1820s according to the calibrated dates), the influx reached the highest values throughout the core and equaled 24.5 and 11.5 particles $\mathrm{cm^{-2}\,yr^{-1}}$, respectively. The highest influx of MAC in both subsamples corresponded with the influx of microscopic charcoal (MIC), reaching over 53 200 particles $\mathrm{cm^{-2}\,yr^{-1}}$ for the 79.5 cm subsample and over 125 000 particles $\mathrm{cm^{-2}\,yr^{-1}}$ for the 78.5 cm subsample (Fig. 5). This distinct fire event was followed by a slight decrease in pH, an appearance of wet-indicator mixotrophic testate amoeba species (*Amphitrema wrightianum, Archerella flavum, Hyalosphenia papilio*), and the disappearance of cyanobacteria and algae (Fig. 4).

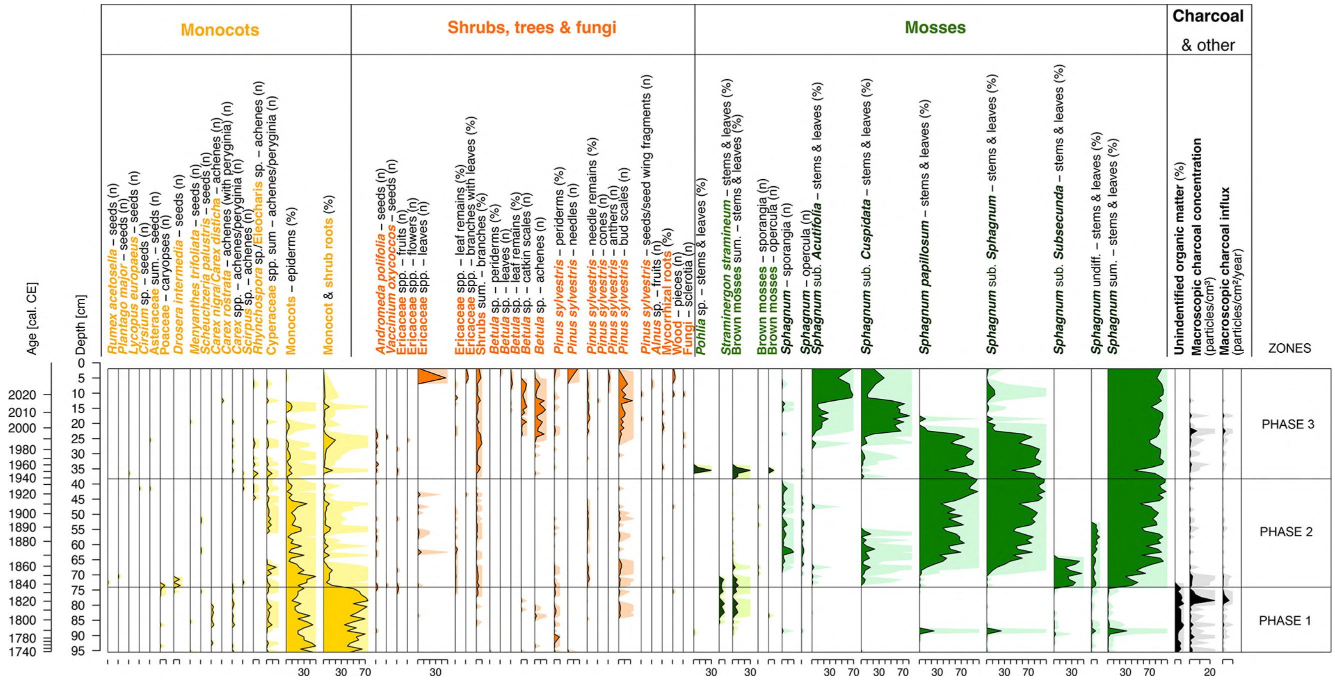

Figure 3. Diagram showing macrofossil percentages, macroscopic charcoal concentrations and influx as a local fire proxy. An exaggeration of 10 times is marked using lighter-coloured shading behind the main curves in the lower part of the figure.

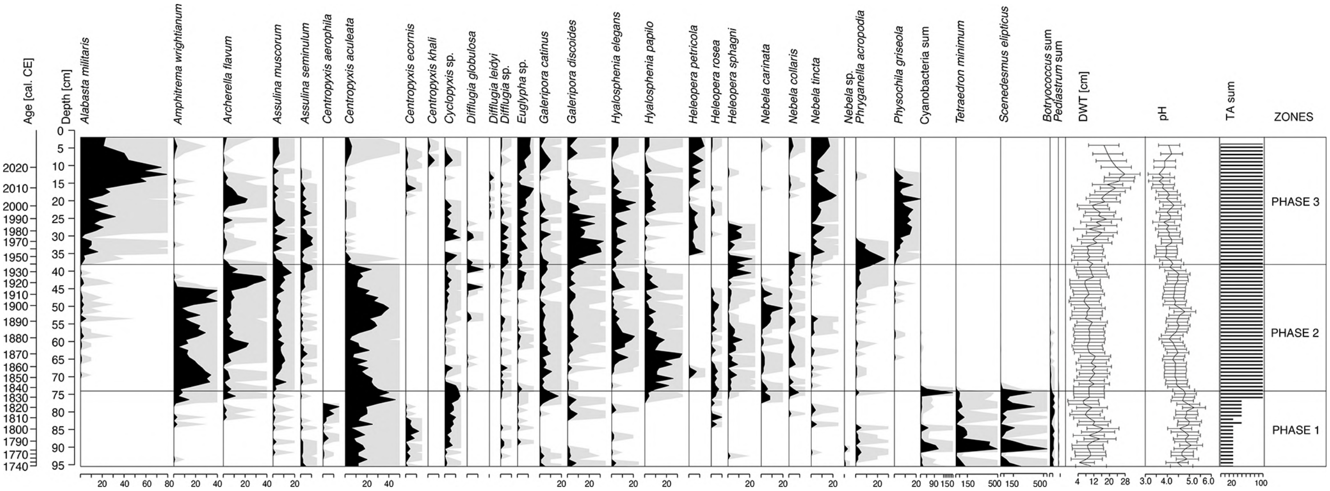

Figure 4. Testate amoebae and selected aquatic non-pollen palynomorphs (Cyanobacteria, *Tetraedron minimum*, *Scenedesmus*, *Botryococcus* and *Pediastrum*). Percentages are shown in black, and the 10 times exaggeration is marked using light-grey shading behind the main curves. The testate amoeba-based depth-to-water table (DWT) and pH reconstructions as well as the sum of testate amoeba shells counted in each sample (TA sum) are presented.

3.2.2 Phase 2 (∼ 1838–1945, 74–37 cm): stabilization of the water table and increase in acidity, a transition from mixed forest to pine monoculture and agricultural development

The local vegetation (Fig. 3) in this phase was dominated by *Sphagnum*, first by the subgenus *Subsecunda*, then for most of this period by *Sphagnum papillosum*. *S. papillosum* occupies the more oligotrophic lawns with a preference for open spaces (Clymo and Hayward, 1982; Laine et al., 2018). Along with the appearance of *Sphagnum* from the subgenus *Subsecunda*, *Drosera intermedia* was also recorded. Currently, in Poland, it is a very rare species, found in dispersed peatlands (Mirek et al., 2006). Individuals often stand in the water throughout the season. *Andromeda polifolia* also appeared in this phase. Initially, the presence of *Sphagnum* was

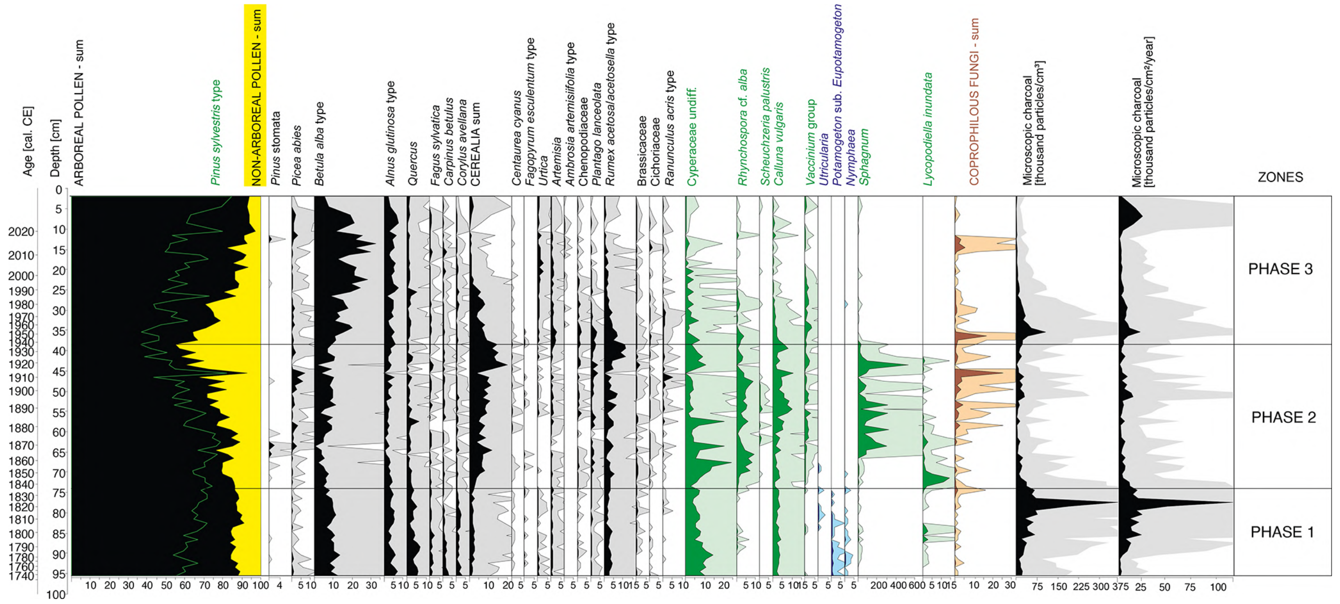

Figure 5. Pollen diagram with selected taxa presented (list of taxa presented in the associated open dataset). Pollen percentages are shown in black, and the 10 times exaggeration is marked using lighter-coloured shading behind the main curves in the lower part of the figure. Microscopic charcoal concentrations and influx as a proxy for non-local fires are also presented.

accompanied by *Straminergon stramineum* (max 10 %), but later it disappeared completely. By the beginning of the 20th century, a relatively high proportion of monocotyledonous plants was also observed, represented in the samples by their epidermis, averaging about 20 % in a sample, with a much higher proportion in the early stages. All these taxa indicate an intermediate environment between a shallow lake and a moss peatland.

After an initial decline (from 9.2 cm at 73.5 cm, 1838 cal CE, to 13.0 cm at 66.5 cm, 1862 cal CE), the water table level increased and stabilized at a high level, reaching a maximum of 6.8 cm at 47.5 cm, 1907 cal CE (Fig. 4). The abundance of individual testate amoeba species also increased. Initially, *C. aculeata* dominated, but later *Amphitrema wrightianum* and *Hyalosphenia papilio*, mixotrophic taxa that contain endosymbiotic photosynthetic algae, begin to prevail (Lamentowicz and Mitchell, 2005a; Marcisz et al., 2020a; Fig. 4). Subsequently, the proportion of *A. wrightianum* and *H. papilio* begun to decline in favour of *Archerella flavum* and *Hyalosphenia elegans* (Fig. 4). All four species are associated with the presence of *Sphagnum*, with *A. flavum* and *A. wrightianum* tolerating very wet or even submerged *Sphagnum* habitats, which correspond to a stably high water table. Then, from the mid-1880s for another ca. 20 years, *C. aculeata* again became dominant. After this period, species associated with *Sphagnum* – *A. wrightianum*, *A. flavum* and *Heleopera sphagni* – began to dominate again. During this phase, further acidification of the site was noted through a drop in the pH value from the initial 4.8 to 4.1 (Fig. 4).

The forests surrounding the peatland (55.1 %–92.7 % TP) were still dominated by pine (64.5 %–92.8 % AP), although the percentage has decreased in comparison to phase 1, especially during the 1920s and 1930s (Fig. 5). Deciduous taxa such as *Quercus*, *Corylus avellana*, *Carpinus betulus* and *Fagus sylvatica* retreated. The percentage of Cerealia in the TP increased significantly, from 0 %–7.8 % TP in the first phase to 2.8 %–19.8 % in the second phase, with a peak in the late 1910s and early 1920s, indicating the development of agriculture in the vicinity of the peatland (Fig. 5). Around the same time, the proportion of *Rumex* also increased significantly (0 %–11.5 %). The low values of MAC (Fig. 3) and MIC (Fig. 5) indicated low fire activity in the area studied.

3.2.3 Phase 3 (∼ 1945–present, 37–0 cm): lowering of the groundwater table, further afforestation with *Pinus sylvestris*, a succession of *Betula*

The local vegetation (Fig. 3) underwent several changes during this phase. Although *Sphagnum* dominated for the entire time, the subgenus *Sphagnum* receded in favour of first the subgenus *Cuspidata* and then the subgenus *Acutifolia*. The beginning of the phase was marked by *Pohlia nutans*, which can win the competition in unstable habitat conditions such as during the dry season (Boulc'h et al., 2020). Its occurrence correlated with the presence of *Phryganella acropodia* among testate amoebae (Fig. 4), which is an indicator of low water levels in *Sphagnum* peatland (Diaconu et al., 2017; Lamentowicz and Mitchell, 2005b).

This was followed by *Alabasta militaris* (average of 25.5 %), *Galeripora discoides* (average of 10.5 %) and

Nebela tincta (average of 8.2 %) beginning to dominate (Fig. 4). *G. discoides* is typically present in acidic sites with unstable hydrological conditions (Lamentowicz and Mitchell, 2005b; Sullivan and Booth, 2011). *N. tincta* tolerates dry, highly acidic conditions with a mineral matter supply (Booth, 2002; Koenig et al., 2018; Lamentowicz et al., 2011). *A. militaris*, dominant in recent years, is indicative of dry and markedly acidic conditions (Amesbury et al., 2016; Booth, 2002; Lamentowicz et al., 2011; Marcisz et al., 2020a; Sullivan and Booth, 2011). Based on testate amoebae, this phase was distinguished by a significant drop in the groundwater table, from an average level of 9.6 cm below the ground surface in the second phase to 15.7 cm. In the last decade, the most significant decline was observed, with an average level of 21.9 cm and with a maximum of 27.5 cm, 1983 cal CE. The pH continued to decrease, from 4.4 to 4.0 (Fig. 4).

On a regional scale, there is an increase in the relative abundance of *Pinus* pollen in the TP, from about 46 % at the beginning of the phase to about 85 % today, as an effect of afforestation (Fig. 5). The *Betula* pollen percentage has an apparent increase, from 0.7 %–11.3 % in the second phase to 5.6 %–32.5 %. The increased percentage of *Betula* pollen, combined with macroscopic remains in the form of achenes and catkin scales, indicates the intensive succession of this species on the peatland surface. The ruderal species *Urtica* and *Artemisia* were also more strongly present. The average proportion of *Urtica* pollen in the TPS increased distinctly (from 0 %–0.7 % to 0 %–2.9 %). The percentage of Cerealia in TP has decreased significantly, from nearly 20 % in the early 1920s to just over 1 % today.

Local (Fig. 3) and regional (Fig. 5) fire activity continued to be low, although two slightly more intensive periods of regional fires were marked – ca. 1945–1963 and in the early 2020s.

3.3 Dendrochronological and pointer year analysis

A total of 50 tree-ring series of 23 *Pinus sylvestris* L. trees from the Woziwoda site were successfully cross-dated. Based on the TRW (Fig. 6) and RWI, a well-synchronized tree-ring series spanning 222 years (1801–2022) was developed. The statistical characteristics of the ring-width series and the statistical parameters indicating the signal strength of the regional RWI chronology are shown in Table 2. The mean EPS was 0.93, which is well above the threshold value (EPS = 0.85) required to produce a statistically robust RWI chronology. Mean series inter-correlation, MS, SNR and other statistical parameters indicating the strength of chronology signals were also high, indicating the suitability of chronology for climate–growth analysis.

Across the study period (1920–2022) a significant positive relationship between growth and February mean temperature was identified (Fig. 7). The moving correlation analysis showed an increasing trend in the sensitivity of tree growth to climatic factors (Fig. 8). The positive response of tree growth to February mean temperature remained constant throughout the study period (1920–2022; Fig. 8). However, the sensitivity of tree growth to summer temperature increased. The relationship between annual growth and summer temperature was not stable during the period of 1920–2022. Nevertheless, in the last 30 years, a significant negative relationship between annual growth and June mean temperature was observed.

Table 2. Descriptive statistics of standardized *Pinus sylvestris* L. (RWI) chronology for the Woziwoda site.

Chronology length	1801–2022
Mean tree age [years]	197
Number of trees / number of cores	23 / 50
Mean ring width (mm) ± SD	1.256 ± 0.702
Series inter-correlation	0.623
Average mean sensitivity	0.265
Expressed population signal (EPS)	0.93
Signal-to-noise ratio (SNR)	12.97
Rbar.eff (effective chronology signal)	0.361

Climate–growth analysis for monthly data did not show a statistically significant relationship between growth and precipitation (Fig. 7). However, the moving response analysis revealed significant short-term relationships between tree growth and precipitation. Furthermore, we demonstrated that the influence of precipitation in the months of the current year on tree growth, calculated for the years 1960–2022, was more significant than the relationships calculated for the years 1921–1959. In recent years, a particularly positive relationship between tree growth and early-year (February–April) precipitation, as well as June precipitation, has become apparent.

For the Woziwoda site, 8 positive and 13 negative pointer years were identified for the period of 1814–2022 (with a minimum sample depth of 10 trees; Fig. 6). The most-pronounced positive pointer years with more than 90 % tree response were as follows: 1847, 1863, 1912, 1941, 1945, 1957 and 1983. The most-pronounced negative pointer years were 1839, 1868, 1869, 1911, 1925, 1940 and 1950. Figure 6 provides indicators of pointer years together with meteorological and ecological characteristics.

3.4 The current state of the peatland based on remote sensing data analysis

Presently, the non-forested part of the peatland is drained by two parallel ditches. One is located in the northern area, and the other is in the southern, non-forested part of the peatland. The analysis of thermal data obtained on a midsummer day indicates that the average LST for the non-forested part of the peatland is approximately 34.29 °C, with a temperature range extending from 19.22 to 46.37 °C. There is a distinct inter-

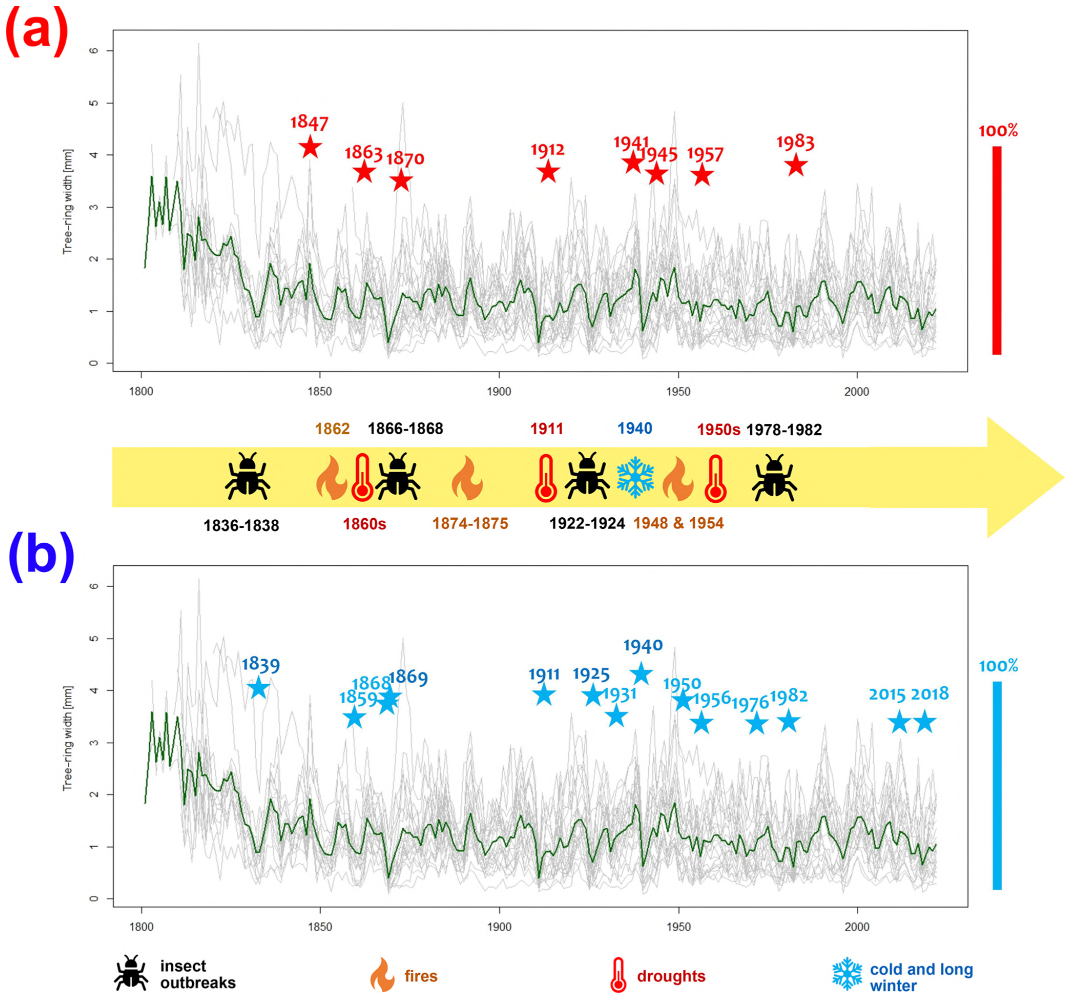

Figure 6. The grey lines depict the individual tree-ring series of each tree, while the green line represents the average raw chronology of *Pinus sylvestris* L. at the Woziwoda site. Identified within the Scots pine chronology from Woziwoda are pointer years, categorized as negative (NEG) **(a)** and positive (POS) **(b)**. These pointer years are highlighted with coloured asterisks: red for positive pointer years and blue for negative pointer years. The position of the asterisks refers to a scale of 0 %–100 %. Information on extreme phenomena is based on Orłowicz (1924), Schütte (1893), Broda (2000) and Wilson (2012).

nal variability in LST values within the studied area. Higher values, indicative of more significant dehydration, were identified in the eastern part of the peatland, while lower values were observed in the western part. A repeating spatial pattern of values was observed in the analysis of vegetation indices (NDVI and MSI). High NDVI values and low MSI values, indicative of good vegetation condition and low water stress, were observed in the western and southwestern parts of the peatland (Fig. 9). The average NDVI value in these areas is 0.71, and MSI is 0.6. Conversely, low NDVI values and high MSI values, indicative of significant dehydration of the peatland and low vegetation vigour, were observed in the eastern part of the area (Fig. 9), where NDVI averages 0.63, and MSI is around 0.69. The overall average NDVI for the area was 0.65, and for MSI, it was 0.68.

3.5 Historical maps and airborne images as confirmation of changes shown in palaeoecological data

Analysis of historical materials (Fig. 10), including maps and airborne images, confirms the results of the palaeoecological analysis. Both the Schrötter–Engelhardt map of 1802 and the *Messtischblatt* of 1874 indicate the existence of a small lake in the coring area. Again, however, it should be noted that the Schrötter–Engelhardt map is a highly generalized study and does not give much information about the surroundings of today's peatland, other than that we are dealing with an area with the character of a dense forest complex with wetlands in isolated places. The *Messtischblatt* allows us to better interpret the surroundings of the modern peatland at the time in which the map was prepared. A small lake named

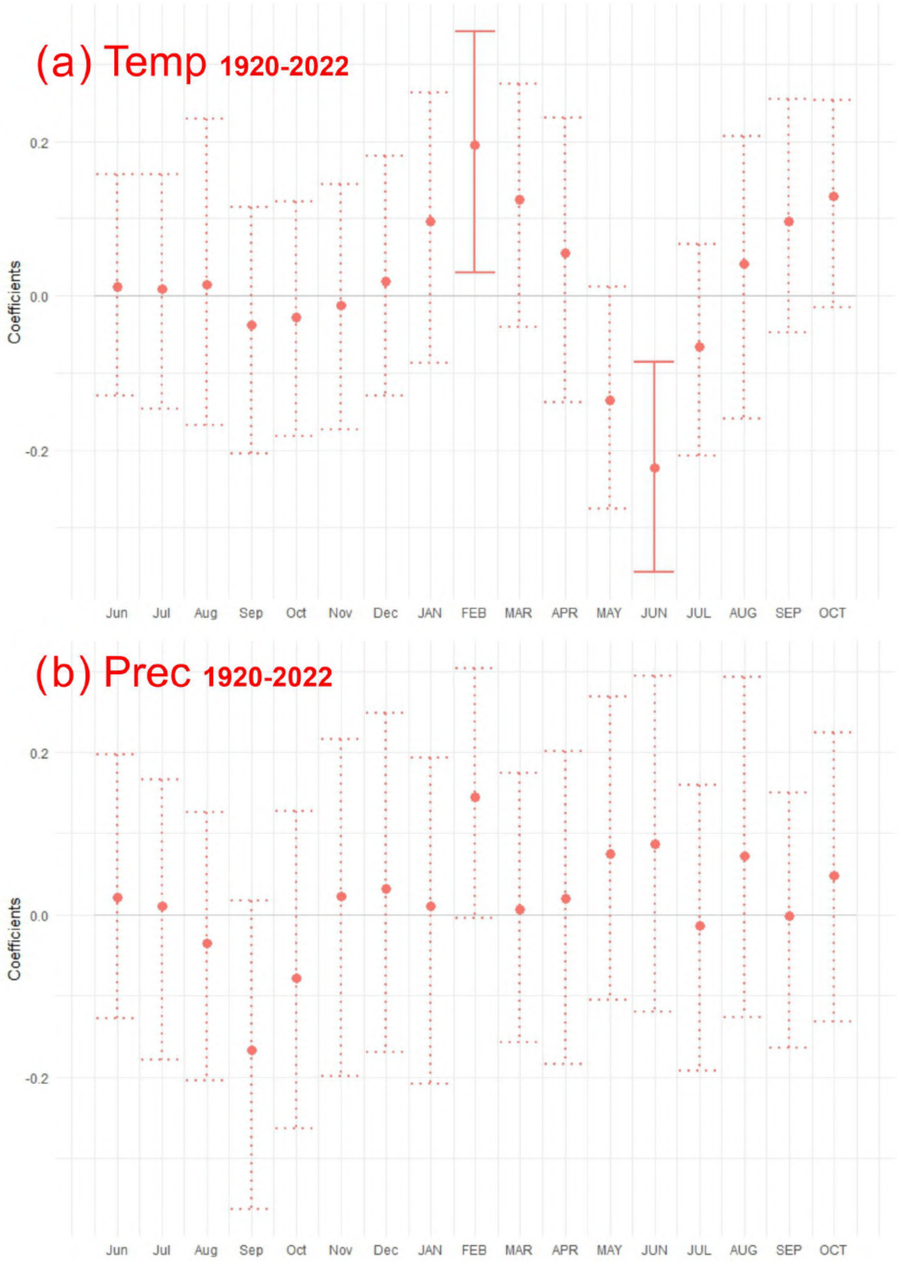

Figure 7. Response function coefficients between residual *Pinus sylvestris* L. chronology and climate variables: **(a)** mean air temperature (Temp) and **(b)** precipitation (Prec) for the period of 1920–2022. Months in upper case are the current year, whereas the standard abbreviations indicate months from the previous year. Solid lines represent significant coefficients at $p < 0.05$.

Kolze See is observed in an advanced stage of development, i.e. progressive overgrowth. This lake is surrounded by wetlands (*Bruch* in German), somewhat distant heathland (*Heide* in German) and wasteland (*Ödland* in German) (the original nomenclature of the map legend was adopted). This lake and two other lakes close by are enclosed within a single catchment area. To the south, the area of the current peatland was adjacent to an open, extensive meadow.

Even more information is provided by a 1905 geological–agricultural map prepared on the topographic base of the *Messtischblatt* map of 1874. In addition to land use, it shows the type and thickness of alluvial and diluvial deposits. According to this map, the area around the lake was covered by alluvial sediments – humus with peat subsoil and shallow groundwater (German original – *Humus (Peat) mit Torf-Untergrund und nahem Grundwasser*). The thickness of the peat was marked at 2 m. However, it should be noted that

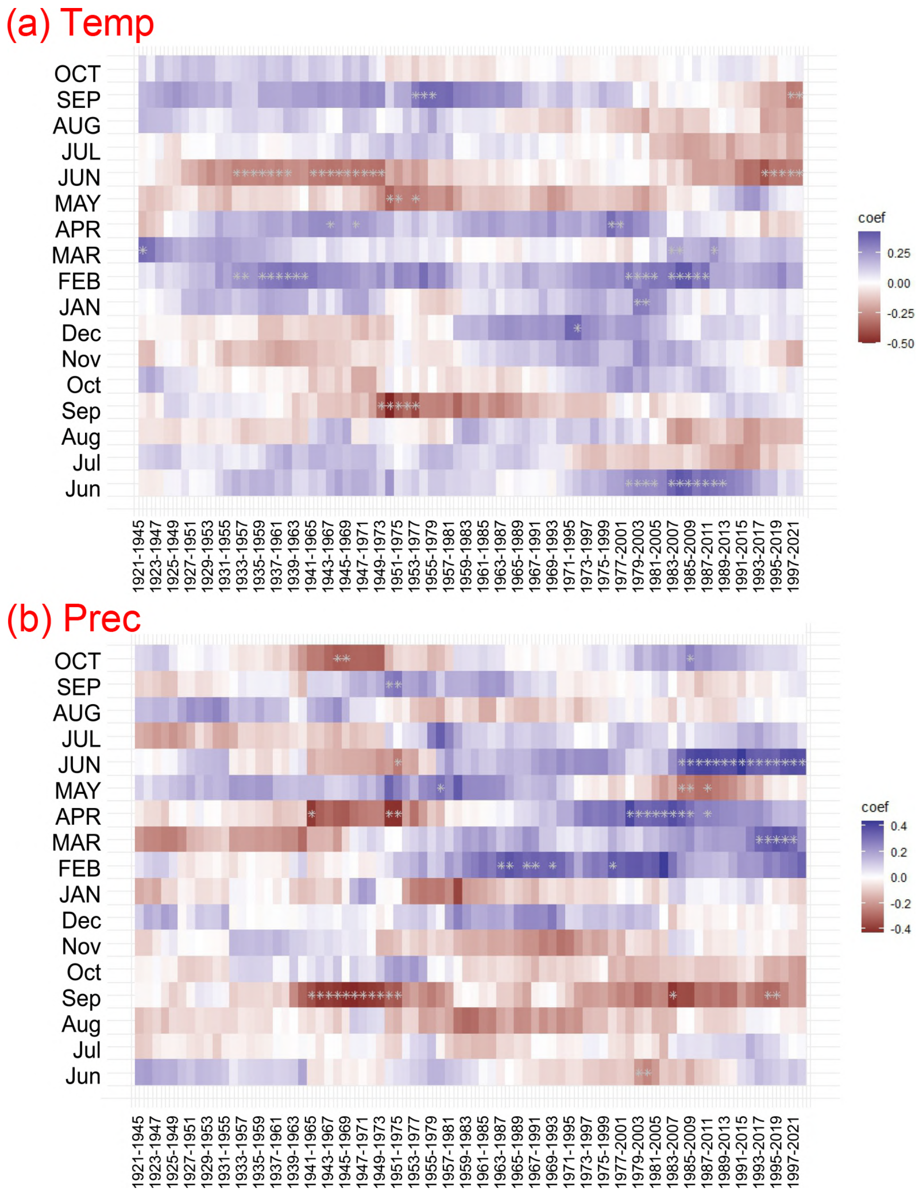

Figure 8. Moving response correlations (25-year window) between residual *Pinus sylvestris* L. chronology and climate variables: **(a)** mean air temperature (Temp) and **(b)** precipitation (Prec) for the period of 1920–2022. The colour code represents the response function coefficients. Significant correlations are indicated by white asterisks.

drilling surveys at that time only covered a maximum depth of 2 m, so the maps do not provide information on the total thickness of the sediments (Jasnowski, 1962). Places that were used as heathland and wasteland on the topographic map are covered by sandy humus on a sandy substrate with shallow groundwater (German original – *sandiger Humus mit Sand-Untergrund und nahem Grundwasser*) and by humic sands on a substrate of permeable sands with shallow groundwater (German original – *humoser Sand mit durchlässigen Sand-Untergrund und nahem Grundwasser*).

A detailed map of Poland from 1933 documents the change in the ecosystem from lake to land. The area, which on Prussian topographic maps was a lake with a surrounding bog, is described as a meadow on this map. Moreover, the adjacent meadows to the south were marked with drainage ditches, which were not marked on the Prussian maps. The area's surroundings, as before, were dominated by coniferous forests.

Aerial photos document subsequent changes in the ecosystem. The 1964 photo shows the northern part of the peatland's agricultural use today (regular surface layout). Lake Kały, located nearby, became completely overgrown, and its area was later drained by several ditches brought to the peatland. The surrounding area of the peatland is dominated

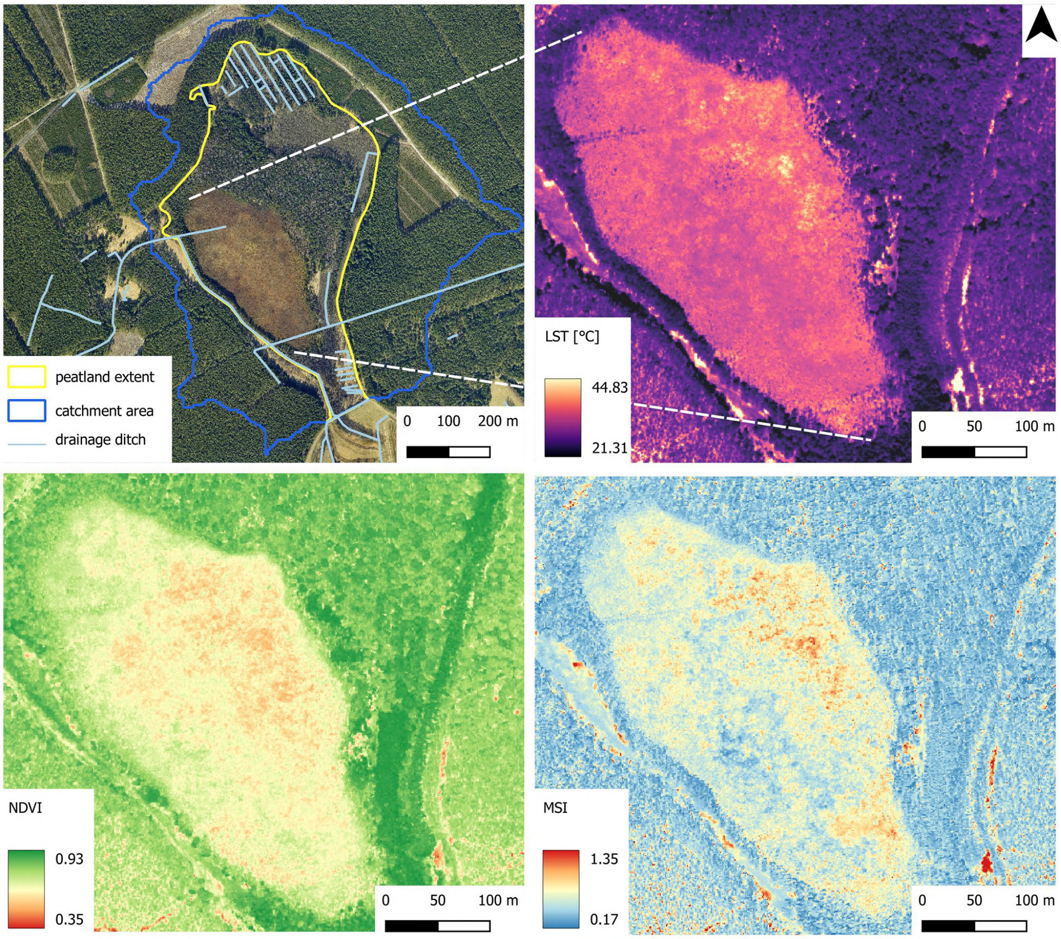

Figure 9. Remote sensing characteristics of Okoniny (Jezierzba) peatland based on multi-sensor airborne data acquired in 2022.

by dense forest with occasional open clear-cutting areas. A photo from 1984 documents the succession of trees in the north–central part of the peatland. In the surrounding area, open forest areas have entirely disappeared. A photo from 1997 clearly shows the development of trees on the peatland, which have formed a dense block in its north–central part. A distinct area of *Sphagnum*-dominated peatland with a well-marked edge has also emerged. Currently, the northernmost part of the peatland is overgrown by pine; it is almost impossible to identify the maximum extent of the peatland surface in the field (Fig. 1).

4 Discussion

4.1 Exceptionally high peat accumulation rate

In the Okoniny (Jezierzba) peatland, a rapid rate of peat accumulation is observed, averaging 3.56 $\mathrm{mm\,yr^{-1}}$, with a maximum value of 7.1 $\mathrm{mm\,yr^{-1}}$ at a depth between 11 and 12 cm. This accumulation rate is not commonly observed. There are only a few peatlands in Poland for which higher accumulation rates were reported. In Tuchola Forest, these were Dury – 10 $\mathrm{mm\,yr^{-1}}$ (Pawlyta and Lamentowicz, 2010); Mukrza – 4.6 $\mathrm{mm\,yr^{-1}}$ (Lamentowicz and Obremska, 2010); Jelenia Wyspa mire, where the accumulation rates reached 0.4 $\mathrm{mm\,yr^{-1}}$ for the first 3000 years but accelerated to 3 $\mathrm{mm\,yr^{-1}}$ in the last 150 years (Lamentowicz et al., 2007); and the Tuchola kettle-hole bog – 1.2 $\mathrm{mm\,yr^{-1}}$, and after ca. 1320 cal BP the accumulation rate dropped to 0.4 $\mathrm{mm\,yr^{-1}}$ (Lamentowicz et al., 2008a). In other pine monocultures, such as Noteć Forest, the Rzecin peatland stands out for its high accumulation rate – an average of 6.8 $\mathrm{mm\,yr^{-1}}$ in one profile and 7.5 $\mathrm{mm\,yr^{-1}}$ in the other one (Milecka et al., 2017). Peatlands in Tuchola Forest, including Okoniny (Jezierzba) peatland, generally have a faster accumulation rate than peatlands located in other parts of Pomerania, especially small kettle-hole peatlands that accumulate carbon the fastest of all peatland types (Karpińska-Kołaczek et al., 2024). In Pomeranian peatlands, the highest accumulation rates were reported for the period between ca. 150 and 1230 cal. CE and reached 2.2 $\mathrm{mm\,yr^{-1}}$ in Stążki (Lamentowicz et al., 2008b) and 1.38 mm between 1830 and

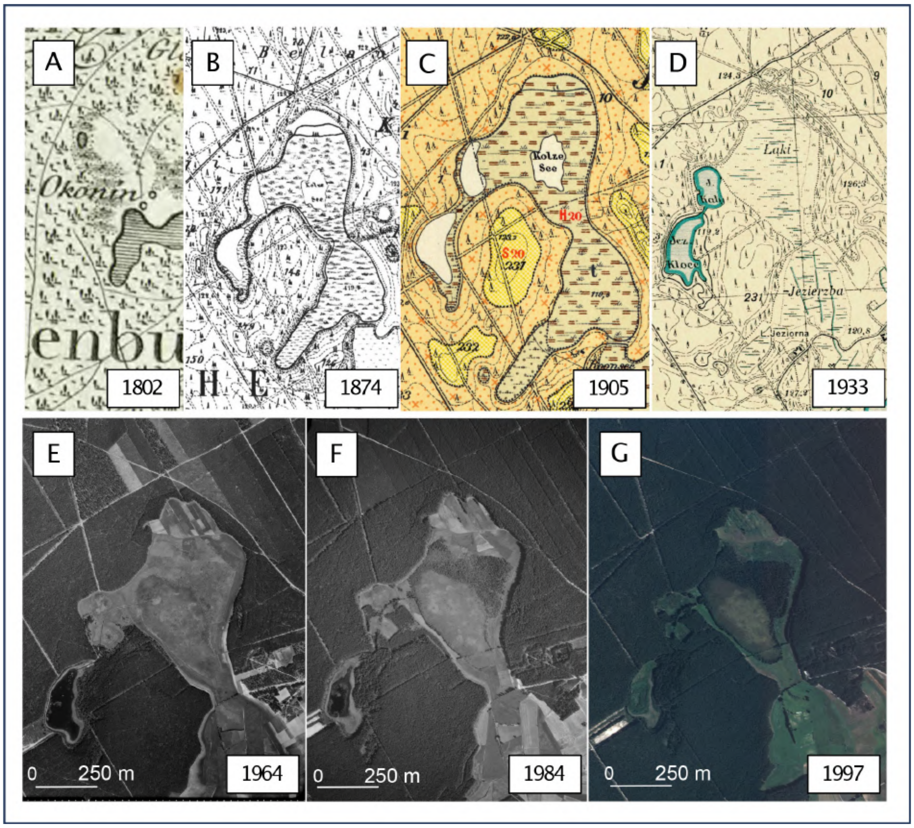

Figure 10. Changes in the peatland and its surroundings since the beginning of the 19th century based on historical maps and aerial images. **(a)** Schrötter–Engelhardt map, 1 : 150 000 (1802); **(b)** *Messtischblatt* map no. 982, 1 : 25 000 (1874); **(c)** Prussian geological and agricultural map no. 2374, 1 : 25 000 (1905); **(d)** detailed map of Poland, 1 : 25 000 (1933); **(e)** aerial photograph from 1964; **(f)** aerial photograph from 1984; and **(g)** aerial photograph from 1997. The maps in **(a)**, **(b)**, **(c)** and **(d)** are in the public domain. Aerial photographs are © Head Office of Geodesy and Cartography in Poland, license no. DIO.7211.457.2023_PL_N.

2006, although the highest accumulation rate was 5 $\mathrm{mm\,yr^{-1}}$ (during 840–860 cal. CE) in the Słowińskie Błota raised bog (Lamentowicz et al., 2009b). At the Gołębiewo sites, the maximum accumulation rates were 1.85 and 0.36 $\mathrm{mm\,yr^{-1}}$ (Pędziszewska and Latałowa, 2016). For many *Sphagnum*-dominated peatlands in other parts of Poland, the average PAR varied between 1.4 and 2.5 $\mathrm{mm\,yr^{-1}}$ (Gałka et al., 2015; Lamentowicz et al., 2015a, 2020; Marcisz et al., 2020b). Such high accumulation rate values are also rare in other parts of the temperate climate zone of Europe. Teiči bog (Latvia) showed similar accumulation rates – 3.5 $\mathrm{mm\,yr^{-1}}$ – from 1835 to 1965 cal. CE and 10 $\mathrm{mm\,yr^{-1}}$ after 2000 (Stivrins et al., 2018). Okoniny (Jezierzba) peatland after 2000 (between 21.5 and 11.5 cm) recorded an accumulation of 5.7 $\mathrm{mm\,yr^{-1}}$. Saxnäs Mosse in Sweden showed an almost linear peat accumulation rate of 2–2.5 $\mathrm{mm\,yr^{-1}}$ (van der Linden et al., 2014). The maximum accumulation was recorded at around 2310–2250 cal BP in the Estonian Hara bog (31–15 cm), reaching 2.4 $\mathrm{mm\,yr^{-1}}$ (Łuców et al., 2022). A comparison with other regions of Poland and Europe shows that the exceptionally high accumulation rates at the analysed site are worth highlighting.

4.2 Relationships between forest management and pollen analysis

4.2.1 The complex history of Tuchola Forest and its influence on the forest

The results of the pollen analysis of the collected cores enabled us to illustrate how the forest was managed over the past 300 years. Due to political changes and several administrative decisions, the management strategies of Tuchola Forest underwent vital changes. The consequences of the implementation of forest management techniques were visible in the palaeoecological record.

With the first partition of Poland by Prussia in 1772, regulations for planned forest management began to be introduced. The main planting species was Scots pine, which over time began to dominate the forest, replacing deciduous admixture species (Broda, 1993). The region's forest cover and forest composition were also affected by later political and administrative developments. For more information on the history of forest management in the late 18th and early 19th centuries; see File 1 in the Supplement.

Our data confirm an increase in the proportion of pine pollen in the forest composition and a decrease in the proportion of pollen of other species. From the 1730s to the mid-1860s, the share of pine pollen in the pollen of all trees increased from about 60 % to about 90 %. Our pollen diagram shows the rapid increase in the *Pinus sylvestris* pollen percentage after 1850. It can, therefore, be assumed that this resulted from the *Pinus sylvestris* introduced by mass monoculture plantings in the early 1830s reaching reproductive capacity. Pine usually reaches sexual maturity between 10 and 15 years of age (Sullivan, 1993), although the threshold age has been set at 25 years (Matthias and Giesecke, 2014). The decline in the share of deciduous species and the increase in the share of Scots pine in the landscape began in Poland with the formation of the state. However, at that time, it was associated with the expansion of agriculture and the harvesting of preferred species such as *Carpinus betulus* (Czerwiński et al., 2021). Nevertheless, in the Prussian partition, planned forest management permanently changed the composition of Poland's largest forest complexes, which were dominated by easy-to-grow pine (Broda, 1993; see File 1 in the Supplement). A dynamic increase in the share of pine pollen until the 1860s in Tuchola Forest was also recorded at Czechowskie Lake (Słowiński et al., 2019). An increase in pine pollen percentage since the 19th century was also shown in pollen diagrams from other sites in Pomerania – Stążki (Lamentowicz et al., 2008b) and Słowińskie Błota (Lamentowicz et al., 2009b) – and in other monoculture plantation complexes from the Prussian partitioning area – i.e. the Rzecin peatland in Noteć Forest (Milecka et al., 2017).

Although attempts were undertaken to correct earlier mistakes, this did not stop the massive deforestation (among other consequences of war events and administrative regulations for settlement, more in File 1 in the Supplement). Until the 1870s, the feudal system was still mixed with capitalist components, but from the 1870s onward, under monopoly capitalism, timber trade and processing began to reach a significant level (Broda, 2000). However, it has been noted that forests regulate air temperature, store water in the soil more efficiently and reduce wind speed, preventing soil erosion, which can help local agriculture facing difficult environmental conditions (Wilson, 2012). For this reason, as early as the 1870s, the state administration encouraged landowners to protect forest stands on their lands and establish forestry cooperatives. The government also guaranteed funds for the reforestation of private and municipal lands. In the mid-1870s, the *Landtag* set aside a budget for the purchase and reforestation of wasteland by the state. However, these funds were only used to a small extent, although this somewhat reduced the share of forested private property (Broda, 2000; Wilson, 2012). In 1886, the Royal Settlement Commission (German original – *Königliche Ansiedlungskommission*) was established to buy up the estates of impoverished Polish nobility to acquire agricultural land for German settlers (Wilson, 2012).

At the end of the 19th century, Tuchola Forest became the largest timber production hub in the Prussian partition. The Bydgoszcz timber industry region also played a major role in wood processing. The first steam sawmill in the Bydgoszcz region was built in 1873, and by 1913, there were 20 of them, processing some 500 000 m^3 of wood and employing more than 1600 people (Broda, 2000). All this resulted in a significant decline in the share of tree pollen in the total pollen share in our diagram, to less than 60 % by the late 1920s and early 1930s. At the same time, we have seen intensive agricultural development. At Okoniny (Jezierzba), the proportion of Cerealia pollen doubled between ca. 1900 and 1920. This trend is also confirmed by pollen data from the site in Okoniny Nadjeziorne on the other side of Okonińskie Lake (Tipton, 2023), as well as from Czechowskie Lake, about 25 km northeast of our site (Słowiński et al., 2019). Despite intensive deforestation in general, further afforestation with pine was also progressing. In 1893, pine forests accounted for 99 % of all forests in Tuchola county (Szwankowski, 2005). Intense changes in forest management (pine dominance) and agricultural development (high percentage of Cerealia pollen) in the 19th century are also evident in records of profiles outside large, dense forest complexes – i.e. Kusowskie Bagno (Gałka et al., 2014) and Linje mire (Marcisz et al., 2015).

4.2.2 Impact of forest management on peatland vegetation

As a result of changes related to forest management, the lake-to-peatland transition occurred rapidly. We assume that this was primarily the result of drainage, which was undertaken in the area at the end of the 19th century (see drainage ditches on the southern side and a dike in the middle part of the site on maps in Fig. 6), and secondly, to a lesser extent, the result of the transition from mixed forests to pine monoculture. These activities contributed to an increase in the acidity of the peatland. Forest drainage is often associated with the acidification of surface waters (Miller et al., 1990). The introduction of forest drainage in or near peatlands to improve tree growth has become quite common in northern and northeastern Europe (Westman and Laiho, 2003). The oxidation of organic sediments and the detachment of H^+ ions increase acidity (Ulrich, 1980). In addition, the supply of alkaline cations to the peat is impeded by drainage ditches (Minkkinen et al., 2008). However, the long-term consequences of drainage are devastating to peatlands, as they initiate vegetation succession, in which species typical of peatlands are replaced by forest vegetation (Laine et al., 1995). In the example of our palaeoecological data, the dynamic succession of pine and birch in the Okoniny (Jezierzba) peatland is evident, which is also supported by aerial imaging. As already mentioned, the successive decline in pH is also the result of the impact of pine plantations growing in catchments. A drop in pH in Okoniny (Jezierzba) has likely enabled the rapid growth and expansion of *Sphagnum* and the peatland initiation. The crowns of forests, especially the needles, can increase the uptake of atmospheric pollutants such as sulfur and nitrogen components, contributing to the acidification of surface waters (Nisbet, 2001; Reynolds et al., 1994). Conifers also can capture ions of marine origin – Na and Mg cations. These in turn, displace hydrogen and aluminium cations from the soil, leading to acid runoff from the forests along with surface runoff, which is known as the sea-salt effect (Drinan et al., 2013; Harriman et al., 2003; Reynolds et al., 1994). We observed the presence of *Pinus* needles at the beginning of phase 2 (from 1838 cal CE), at the transition from pond to peatland ecosystem. Moreover, *Pinus* stomata were also present in palynological samples at that time, pointing to more frequent needle falls. The presence of *Pinus* stomata has been suggested as a possibly important proxy for insect outbreaks in palaeoecological records in previously published studies from another pine monoculture forest in Poland, Noteć Forest (Barabach, 2015), where this phenomenon has been observed (Słowiński et al., 2019). More pine trees in Tuchola Forest resulted in much higher quantities of needles and other pine fragments accumulating on the forest floor, leading to soil acidification. This, together with drier conditions, could quickly lead to acidification around the pond, forming perfect conditions for *Sphagnum* to encroach – as a floating mat that successively grows over the pond. We sampled the peat core close to the edge of the peatland, in the place where moss encroachment on the open water body began; therefore, we were able to track this succession in our record. This succession and the disappearance of Lake Kolze are also clearly visible on historical maps (Fig. 10). Other examples of quick encroachment of floating mats on the surface of the lake have been observed and mapped in other open water bodies in Tuchola Forest (Kowalewski, 2003; Kowalewski and Milecka, 2003) and in other regions (Warner, 1993).

4.3 Anomalies and extreme events

4.3.1 The impact of droughts and fires on the forest and peatland

Historical sources indicate that in the 18th and 19th centuries, Tuchola Forest was relatively often affected by droughts resulting in fires (Wilson, 2012). In 1781, there was a fire in Tuchola (ca. 16 km to the southwest), during which a large part of the city including the church and town hall burned down, and in 1792, Starogard Gdański (ca. 42 km to the northeast) burned almost to the ground (Orłowicz, 1924). Major fires also occurred in 1794 and 1807, when more than 34 000 ha of forest burned (Orłowicz, 1924; Schütte, 1893). Fires in 1809, 1810, 1812, 1813 and 1828 in the Świt forest district about 15 km from the study site were also recorded (Cyzman, 2008). Palaeoecological data, especially MIC, confirm high fire activity in the first decades of the 19th century (a rapid increase). Słowiński et al. (2019) emphasized that data on fires before the 1830s, especially regarding their area, should be treated with caution due to the lack of accurate measurement techniques. In the Woziwoda forest district, within which the Okoniny (Jezierzba) peatland is located, the forests of the Biała and Barłogi forest districts also burned in 1842 (Cyzman, 2008). Intense fires also appeared in Tuchola Forest between 1846 and 1848 (Orłowicz, 1924; Schütte, 1893).

Later, numerous fires were also reported in the Woziwoda forest district. Between 1860 and 1889, 310 fires were observed, destroying 4206 ha of the forest (Orłowicz, 1924; Schütte, 1893). The highest number of fires in this period was registered in 1862–1864 and 1874–1875 when 3565 ha of forest burned; altogether, nearly 85 % of the area burned in 1860–1889 (Schütte, 1893). The largest area burned in 1863 equaled 2333 ha, including more than 1250 ha in the Woziwoda forest district; altogether, 25 % of the whole forest burned during 1860–1889 (Orłowicz, 1924; Schütte, 1893). Meteorological data confirm dry years in the period from 1862 to 1865. In 1862 and 1863, the annual precipitation in Bydgoszcz was only a little over 450 mm (Kirschenstein, 2005), and it was then that the largest number of hectares of forest in the known history of Tuchola Forest burned (Dietze et al., 2019).

The number of fires can also be linked to political events (Orłowicz, 1924; Schütte, 1893; Wilson, 2012). In 1901, in the nearby Trzebciny and Gołąbek forest districts, a fire consumed 663 ha of forest (there was a parallel children's strike in Września province; Orłowicz, 1924; Wilson, 2012). Fires could also be caused by agricultural activities and land preparation for crops (Poraj-Górska et al., 2017). By the 1830s, charcoal production was widespread (McGrath et al., 2015), and forest burning was used to create heathlands for beekeeping (Bienias, 2009).

Fires in the 1860s provide a regional signal at another site in Tuchola Forest – Czechowskie Lake (Dietze et al., 2019). Increased fire activity in the mid-19th century was also observed at the Lake Jaczno site (Poraj-Górska et al., 2017). At the Okoniny (Jezierzba) peatland, MIC and MAC values decreased after 1850, but at the same time, the water level stabilized and remained high. Fire activity remained low in areas where wet conditions prevailed, such as southern Finland (Väliranta et al., 2007) and eastern Estonia (Sillasoo et al., 2011).

In 1948, about 450 ha of forest burned near Osieczna, and in 1954, 80 ha burned near Ocypel (Cherek, 2007). Palaeoecological data record an increased MIC supply during this period. The first of these fires was also recorded in the sediments of Czechowskie Lake (Słowiński et al., 2019). The summer drought of 1921 occurred over a larger area of Europe, from Poland and Czechia to the UK (van der Schrier et al., 2021). Summer droughts also affected Tuchola Forest in

1951 and 1959. In 1959, Bydgoszcz received only 37 mm of precipitation from August to October (Mitosek, 1960), and from 1950 to 1958 Bydgoszcz received less than 500 mm of rain per year (Kirschenstein, 2005). Our palaeoecological data confirm droughts in the 1950s. There is a sharp increase in the proportion of *Phryganella acropodia* among the testate amoebae, an indicator of dry conditions (Diaconu et al., 2017), and an expansion of brown mosses in the form of *Pohlia nutans* (up to 30 % of the peat sample composition) is also marked. Dendroclimatic data recorded the negative impact of climatic conditions on pine, especially strong in 1950 and 1956.

Studies show that particle size illustrates the distance of the fire from the site: the heavier the particles, the shorter distances they travel (Clark, 1988; Peters and Higuera, 2007). However, many factors determine the particles' transport – the intensity of the fire, the burning areas and the wind direction. Adolf et al. (2018) point out that the charcoal source area of both MIC and MAC can reach a radius of 40 km. However, it is often assumed that MAC indicates fires that occurred up to 1–3 km away (Clark, 1990; Higuera et al., 2007; Oris et al., 2014). The distances which particles move are also determined by terrain and vegetation. They move longer distances over flat terrain covered with grasses (Woodward and Haines, 2020), while they move shorter distances in dense forests (Kelly et al., 2013; Oris et al., 2014). In this context, we must conclude that the local fire activity in the peatland was low, with an average of 0.36 particles $\mathrm{cm}^{-3}\,\mathrm{yr}^{-1}$, although fires are known to have occurred nearby, according to historical sources.

4.3.2 Insect outbreaks and their impact on pine monoculture

Palaeoecological studies based on the presence of insect head capsules and/or faeces, as well as other insect remains, could be helpful, but these methods are rarely used (Bhiry and Filion, 1996; Lavoie et al., 2009; Simard et al., 2006; Waller, 2013). Often the main obstacle to performing this method is bad preservation of insect remains in peat. In the Okoniny (Jezierzba) peatland, we found no insect remains, even though quite a large sample volume was analysed for the plant macrofossil analysis. Therefore, we can interpret the effect of insect outbreaks using other sources of evidence.

The earliest information on insect outbreaks from the region of Tuchola Forest under planned forest management dates back to 1836–1838. An infestation of *Panolis flammea* occurred at that time (Schütte, 1893). The insects also attacked between 1866 and 1868. As a result of this infestation, 1380 ha of forest were destroyed in the Woziwoda forest district alone (Schütte, 1893). The pollen diagram from the Okoniny (Jezierzba) peatland documents the phenomenon in the 1860s, with a decrease in *Pinus sylvestris* pollen and an increased presence of *Pinus* stomata that may be indicators of the insect outbreak (Barabach, 2015). The needles that fell were partially decomposed and carried downwind to the peatland, where they were preserved (Słowiński et al., 2019). The same effect was noted in another nearby peatland in Okoniny Nadjeziorne, where the 1866–1868 infestation also corresponds with increased numbers of *Pinus* stomata (Tipton, 2023). In 1855, *Lymantria monacha* appeared in large numbers but damaged only some of the younger stands (Schütte, 1893).

A serious incidence of *Panolis flammea* infestation also occurred in 1922–1924 (Kiełczewski, 1947; Mokrzecki, 1928). Between 1978 and 1985, with a peak in 1982, the forests in the northern part of the country were overrun by *Lymantria monacha*, and this was the largest infestation since the establishment of the national forests in 1924, with salvage treatments covering more than 6.3×10^6 ha of forest over 7 years (Broda, 2000; Jabłoński, 2015; Śliwa, 1987, 1989). Both major infestations are reflected in palynological data, manifested by declines in the pollen percentage from trees, primarily *Pinus* and *Picea*. A decrease in conifer pollen during the infestation period has also been shown by studies of other sites in Tuchola Forest (Łuców et al., 2021; Tipton, 2023). Another pine monoculture area in Poland, Noteć Forest, was also affected by infestation in 1922–1924, and this event manifested itself in palaeoecological data (Barabach, 2015; Lamentowicz et al., 2015b; Milecka et al., 2017). Among other things, Barabach (2015) noted an increase in *Glomeromycota* fungal spores, which according to this author may indicate intense soil erosion caused by the felling of dead trees and a marked increase in *Calluna* and Poaceae, indicating an increase in the openness of the landscape. Lamentowicz et al. (2015b) noted an increase in mineral content in the sediment as indicated by *Centropyxis platystoma*, which was confirmed by X-ray microcomputed tomography (XMT) analysis of the peat. Milecka et al. (2017) described higher ash and charcoal content in the sediments. Although Tuchola Forest and Noteć Forest are in the region with the highest risk of outbreaks, other areas in Poland were also affected, such as the Kampinos Forest in 1972 (Śliwa, 1974) or over the last decade, the Białowieża primeval forest (Grodzki, 2016; Kamińska et al., 2021).

It is difficult to assess unequivocally whether the infestations affected the immediate vicinity of the peatland or whether this is a regional signal. Historic maps could be helpful, but these usually do not show the difference between old and new plantings (Barabach, 2012). However, dendrochronological data obtained from pine trees could help to reconstruct the extent of the outbreak. The main problem in monoculture forests, however, is that the forest is successively cut and new trees are planted regularly. However, for our dendrochronological record, we were able to obtain samples from the oldest pine trees in the area. The oldest trees in the region analysed in this study were planted over 200 years ago in the close vicinity of the Woziwoda forest district after the introduction of the Prussian forest management strategies and have been kept there by foresters to obtain tree saplings and for monitoring. The influence of insect outbreaks has been recorded in these pine trees, and we were able to track all the outbreak events in the wood. The first years after the infestations – 1839, 1869, 1925 and 1982 – manifested very strongly in the dendrochronological data as negative indicator years.

4.4 The current condition of the peatland vs. remote sensing and dendroclimatic data

The assessed growth reactions of pine trees to climate factors at the Woziwoda site may be considered typical. The effect of February air temperatures on Scots pine growth in northern Poland was previously noted (Cedro, 2001; Cedro and Lamentowicz, 2011; Feliksik and Wilczyński, 2009; Koprowski et al., 2011, 2012; Matulewski et al., 2019; Zielski, 1996; Zielski et al., 2010; Zielski and Sygit, 1998). Although the pines from Woziwoda showed a similar growth response to climate as other pines from northern Poland, their climate sensitivity was greater. The highest negative correlation for pine radial growth from the Woziwoda site was found with July's mean air temperature.

Another factor commonly affecting the radial growth of Scots pine according to the literature is pluvial conditions in February. This linkage was identified by Cedro (2001), Feliksik and Wilczyński (2009), and Koprowski et al. (2011) in the Pomeranian region (northern Poland). The present study confirmed a short-term relationship between pine radial growth and precipitation totals in February (Fig. 7). Late February and early March are when additional water is required due to the initiation of biochemical processes in trees (Przybylski, 1993). Additionally, in our study, a stronger dependence of pine radial growth on precipitation was demonstrated in June. A similar result for pine from northern Poland was obtained by Matulewski et al. (2019) and Zielski and Barankiewicz (2000), where pine growth was threatened by a water deficit in the summer season. Increased pine demand for water occurs in June and July, the months of the most intense growth (Obmiński, 1970). At the same time, these are the months when droughts have become more frequent in recent years (Łabędzki, 2004; Spinoni et al., 2018). Our results confirm that within the temperature and monthly precipitation values typically observed in central Europe, the primary environmental factor influencing the diversity of species growth in the near future will be the availability of water (Boczoń et al., 2017; Taeger et al., 2013). This availability is determined by the precipitation level and losses caused by evapotranspiration (Boczoń and Wróbel, 2015; Zajączkowski et al., 2013).

The higher climatic sensitivity of pines at the Woziwoda site was manifested also by a higher number of pointer years. The pointer years identified in this study are confirmed by earlier studies performed on pine trees in northern Poland for 1910–2014 (Matulewski et al., 2019; Zielski et al., 1998; Zielski and Barankiewicz, 2000). The years 1911, 1940, 1950 and 1982 attract particular attention. These are years in which dry and hot summers were recorded (Matulewski et al., 2019; Zielski, 1996).

Our data show that *Pinus sylvestris* has been under critical climatic pressure and is responding negatively to a warming climate and changing precipitation regime. Models predict a severe decline in coniferous species in the next 50 years, including *Pinus sylvestris* in the temperate zone of Europe (Dyderski et al., 2018; Hanewinkel et al., 2013; Schueler et al., 2014). The disappearance of the currently dominant species in the forests of central and eastern Europe will result in the profound disruption or disappearance of ecosystems functionally related to them, such as peatlands (Dyderski et al., 2018).

Peatlands are also affected by accelerating climate change, and on top of that they are at risk of losing their favourable environment, especially in *Pinus sylvestris* monoculture forests, which are particularly vulnerable to increasing extreme events. Studies conducted by various researchers confirm that remote sensing data provide a valuable source of information about peatlands and help in monitoring their condition (Czapiewski and Szumińska, 2021; Kaplan et al., 2019; Lees et al., 2021; Rapinel et al., 2023). The analyses conducted in this study have demonstrated that multi-sensor airborne data can be successfully utilized to assess the current state of peatland vegetation. The application of simple remote sensing indices enabled the detection of spatial differences in the condition and water stress of vegetation in the Okoniny (Jezierzba) peatland. According to Rastogi et al. (2019), NDVI values for peatland vegetation may decrease in areas affected by stress factors such as warming and reduced precipitation. Moreover, NDVI values for healthy *Sphagnum* moss in peatland usually range from 0.8 to 0.9 during the summer, but they are also species-dependent (Harris, 2008; Letendre et al., 2008; Péli et al., 2015). Consequently, the values of NDVI observed in this study (averaging 0.65) may indicate a prevailing drought situation in certain areas of the Okoniny (Jezierzba) peatland. Comparable findings can be drawn from the spatial variation in MSI values presented in this study. Harris et al. (2006, 2005) demonstrated that MSI is significantly correlated with the near-surface moisture condition of *Sphagnum* moss. Despite the wide application of optical data and spectral indices in assessing peatland conditions, Gerhards (2018) found that spectral indices may only be useful under conditions of severe or prolonged water stress. For the pre-visual detection of initial vegetation water stress symptoms, temperature-based indices are most suitable, exemplified by the LST index used in this study. Although aerial thermal data have been previously applied in peatland research (Kopeć et al., 2016), further research into the potential use of airborne thermal data in assessing peatland vegetation conditions is recommended. To date, there has been little research in Poland using spectral data in peatland monitoring (Bandopadhyay et al., 2019, 2021), and none of this research has attempted to collate palaeoecological, dendrochronological and remote sensing data.

5 Conclusions

Our data show that peatlands are highly sensitive to the progressive rise in Earth's temperatures and changing precipitation regimes. Groundwater levels have dropped dramatically in recent years, causing intense heating of the peatland surface in summer and stressing peat-forming vegetation due to water scarcity. The pine monocultures surrounding the peatlands are also sensitive to climate change. They are currently responding very strongly to summer precipitation deficiency, and these data fit into dendrological predictive models. Planned forest management has permanently changed the composition of the forest. Deciduous tree species such as *Quercus*, *Fagus*, *Carpinus* and *Corylus avellana* have almost disappeared. Forest management has also contributed to increased acidity in the peatland and thus to the rapid development of *Sphagnum* specialized for life in acidic conditions. After the expansion of *Sphagnum*, the water level in the peatland stabilized. Peatlands are also valuable archives of past climatic anomalies and catastrophic events. Pest infestations are recorded, among other things, by the presence of *Pinus* stomata and periods of drought by an increase in the values of coprophilous fungi. These events correspond with dendrochronological records. There is a strong correlation between the first years after hailstorms and smaller increments of tree rings. Our study shows that the combination of different data (palaeoecological, dendrochronological, remote sensing and historical) can be complementary, can create a more complete picture of past environmental changes, and can expand knowledge of best practices for local (Konczal et al., 2024) and global (Joosten, 2021) recommendations for peatland conservation in forests. Healthy wetlands could be key to protecting forests and slowing the transformation of forests caused by climate change (Marcisz et al., 2024). The results are essential for peatland conservation in planned forest management.

Data availability. All data associated with this article are openly available on Mendeley Data at https://doi.org/10.17632/prdgmjcg69.3 (Bąk et al., 2024).

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Twentieth-century ecological disasters in central European monoculture pine plantations led to critical transitions in peatlands

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Abstract. The frequency of extreme events worldwide is steadily increasing. Therefore, it is crucial to recognize the accompanying response of different ecosystems. Monoculture tree plantations with simplified ecosystem linkages in food webs are particularly vulnerable to catastrophic events like fires, wind throws, droughts, and insect outbreaks. These events threaten forests and other associated ecosystems, including peatlands, which are extremely important in regulating the global carbon cycle and, thus, mitigating the effects of a warming climate. Here, we traced a 2000-year history of the Miały peatland, which is located in one of Poland's largest pine plantation complexes, and we examined how this peatland responded to some of the largest environmental disasters observed in the 20th century across central Europe: the 1922–1924 *Panolis flammea* outbreak and the 1992 fire. As a disturbance proxy, we used a multi-proxy palaeoecological analysis (plant macrofossils, testate amoebae, pollen, non-pollen palynomorphs, and micro- and macrocharcoal) supported by a neodymium isotope record. We showed several critical transitions in the peatland associated with extreme events and anthropogenic impacts, which triggered significant changes in the peatland's ecological status.

1 Introduction

In recent decades, peatlands have been subjected to intense and ever-increasing climatic and anthropogenic pressures (Zhang et al., 2022). Hydrologically unstable due to diverse anthropogenic impacts, they are becoming extremely susceptible to various types of disturbances and extreme phenomena, which are a threat to human health, cause economic losses, and contribute to the amplification of the global warming effect (Kiely et al., 2021; Page et al., 2002). Peatlands have evolved from being net CO_2 sinks to CO_2 emitters in every climate zone – from tropical regions (Deshmukh et al., 2021; Page et al., 2022) to the boreal realm (Ofiti et al., 2023; Turetsky et al., 2011; Wilkinson et al., 2023). This is particularly important because peatlands are valuable ecosystems accumulating a third of the world's soil carbon stocks (Parish et al., 2008), twice the entire biomass of the world's forests (Beaulne et al., 2021).

Hundreds of thousands of hectares of peatlands in Poland are located in forests, as forests cover 31 % of Poland's area, equivalent to 94 770 km^2 (Statistical Office in Białystok, 2023). More than half of this forest cover comprises coniferous forests dominated by Scots pine (*Pinus sylvestris* L.). It is mainly the result of planned forest management in modern-day Poland in the 19th and 20th centuries (Broda, 2000). Pine monocultures were easier to manage and grew faster on poor soils, securing a continuous supply of raw material for the growing timber industry (Broda, 2000). Such an environment is particularly dangerous for Poland's peatlands, as monoculture tree plantations have simplified linkages in food webs and are therefore more sensitive to fires, strong winds, droughts, and insect outbreaks (Chapin et al., 2012), which also poses a threat to peatlands. It should be strongly emphasized here that such extreme phenomena have become

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more common in recent years around the world (Seidl et al., 2014; Westerling, 2016). These negative impacts have been recorded for various peatlands, including those in central and eastern Europe (Leonardos et al., 2024; Łuców et al., 2021).

It is essential to recognize how peatlands at different latitudes respond to a warming climate and how they respond to changes resulting from the management of their surroundings (land use change), including planned forests and monoculture tree plantations. Thanks to their anaerobic and acidic conditions, peatlands are excellent preservers of various types of micro- and macrofossils (Rydin and Jeglum, 2013; Tobolski, 2000). Thus, peatlands serve as valuable archives of both internal (autogenic) changes within the peatland itself and external (allogenic) changes in the surrounding environment (Marcisz et al., 2024).

Multi-proxy palaeoecological studies (including analyses of several proxies, such as testate amoebae, plant macrofossils, pollen, charcoal, and others) are an excellent tool for reconstructing the peatland development (Birks and Birks, 2006; Mitchell et al., 2000). Particularly broad insight can be provided when dendrological (Bąk et al., 2024) or geochemical methods (Fiałkiewicz-Koziełet al., 2018; Gałka et al., 2019; Marcisz et al., 2023b) are included. In recent years, the neodymium (Nd) isotope composition of the peat-hosted mineral matter has been increasingly used in palaeoecological studies. Among various applications, the method has been used to determine distant sources of atmospheric dust (Allan et al., 2013; Fagel et al., 2014; Pratte et al., 2017) and the signal associated with anthropogenic pollution (Fiałkiewicz-Koziełet al., 2016). Marcisz et al. (2023b) used this method to identify local disturbances in peat, such as fires or deforestation.

The environmental past of the largest European forest complexes, including the Noteć Forest area in Poland studied here, is insufficiently understood. These forests were affected by some of the most severe environmental disasters of the 20th century that took place in pine-dominated forests across central and eastern Europe: the 1922–1924 *Panolis flammea* outbreak and the 1992 fire. The only palaeoecological data documenting these events in the Noteć Forest were derived from two cores taken from the Rzecin peatland (Barabach, 2014; Lamentowicz et al., 2015; Milecka et al., 2017). However, the interpretation of these extreme events based solely on these two cores appears to leave many questions unanswered and highlights the need for further research into the impact of insect outbreaks and fires on peatland ecosystems. The changes caused by extreme events can lead a peatland to reach a critical transition, i.e. to cross a tipping point after which it does not return to its previous hydrological and trophic conditions (Dakos et al., 2019; Lenton et al., 2008, 2019). So far, peatland research has focused chiefly on the tipping points associated with changes in groundwater levels due to a warming climate, fires, pollution, carbon sequestration, or opening landscape caused by agricultural development (Fiałkiewicz-Koziełet al., 2015; Jassey et al., 2018; Lamentowicz et al., 2019a, b; Loisel and Bunsen, 2020). Except for these issues, there is a need for a broader recognition of the consequences of insect outbreaks in forest areas and the accompanying forest management.

In this article, we focus on the impact of catastrophic events on the ecosystem of the Miały peatland in the Noteć Forest (local scale) and the broad context of such disturbances for pine plantations in central and eastern Europe (regional scale). Our aims were as follows: (1) reconstruct the environmental history of the Miały peatland using multi-proxy palaeoecological analyses (including analyses of pollen, non-pollen palynomorphs, testate amoebae, plant macrofossils, and charcoal) and geochemical analyses (neodymium isotope signatures) and, through this reconstruction, identify peat layers corresponding to severe environmental catastrophic events; (2) assess the impact of such disturbances on the peatland ecosystem and understand the relation between disturbances occurring in the surrounding forest and the peatland. We hypothesized that catastrophic events in pine plantations, including insect outbreaks and fires, cause significant changes in the peatlands located in their area and even a complete change in trophic and hydrological conditions, leading to a critical transition.

2 Materials and methods

2.1 Study site

The Miały peatland is located in western Poland, about 65 km northwest of Poznań (Fig. 1). It is located within the boundaries of the Noteć Forest, one of the largest forest complexes in Poland, covering an area of about 1370 km^2 (Statistical Office in Białystok, 2023). The Noteć Forest is a monoculture dominated by Scots pine (*Pinus sylvestris*, 95 % of the tree stand) (Sukovata, 2022). A large part of the pine forest, including our research site, is located in the "Puszcza Notecka" protected landscape area. It is also a special protected area, "Puszcza Notecka" (PLB300015, since 2007), and a special area of conservation, "Dolina Miały" (PLH300042, since 2023), under Natura 2000. According to the physical geographical regionalization, the peatland is located in the Gorzów Basin mesoregion, in the Warta and Noteć inter-river sub-mesoregion. It is a high glacial–alluvial terrace covered with dunes with a relative height of 20–40 m (Kondracki, 2001). It has a temperate transitional climate. From 1981 to 2010, the average annual air temperature was 8.4 °C. The warmest month was July, with an average temperature of 18.8 °C, and the coolest month was January, with an average temperature of −1.1 °C. Average annual precipitation for 1981–2010 equalled 563 mm, with the precipitation maximum in July (69 mm) and the minimum in April (31 mm) (Institute of Meteorology and Water Management, 2025).

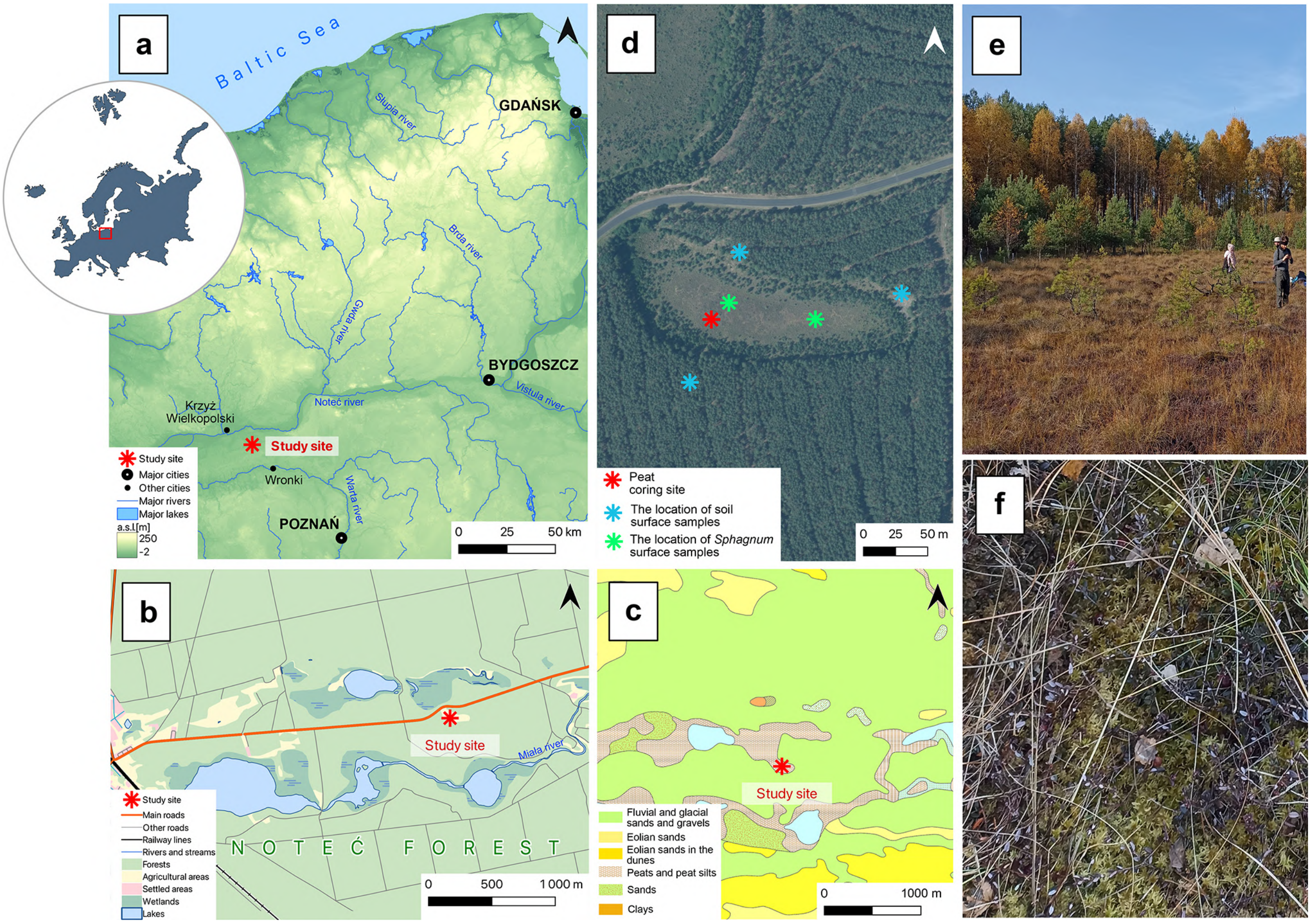

Figure 1. (a–c) The location of the study site on topographic **(a, b)** and geological **(c)** maps. **(d)** Orthophoto of the Miały peatland with sampling points (asterisks): red – peat core sampling site; blue – soil surface sampling sites for the neodymium isotope analyses; green – *Sphagnum* surface sampling sites for the neodymium isotope analyses. **(e)** Photograph of the peatland and its forest surroundings. **(f)** *Sphagnum* mosses covered the peatland surface.

2.2 Fieldwork and sampling

The peat core was collected from the western part of the peatland in October 2021 using a Wardenaar corer (chamber dimensions: 10 cm × 10 cm × 100 cm) (Wardenaar, 1987). The entire length of the sampled peat core – a 97 cm long monolith – was analysed. The core was subsampled continuously every 1 cm, except for the first sample (0–2 cm), which contained a living layer of peat-forming vegetation. A total of 96 samples were obtained for multi-proxy analyses, including the water content in fresh material, organic matter content in dry material, ash-free bulk density, peat accumulation rate, peat carbon accumulation rate, plant macrofossils, testate amoebae, macroscopic and microscopic charcoal, pollen, and neodymium isotopes. Moreover, five surface samples of *Sphagnum* mosses (two samples) and soil (three samples) were taken as a reference for downcore neodymium measurements (Fig. 1), following the approach of Marcisz et al. (2023b).

2.3 Radiocarbon dating, absolute chronology, and peat accumulation rates

Twelve samples containing *Sphagnum*, brown moss stems, charcoal, and *Carex* achenes were used for accelerator mass spectroscopy (AMS) ^{14}C dating of the entire length of the core, conducted at the Poznań Radiocarbon Laboratory in Poland (laboratory code marked Poz; Table 1).

The absolute chronology of the core was based on a Bayesian age–depth model using OxCal v4.4.4 (Bronk Ramsey, 2025). The `P_Sequence` command with a parameter k of 0.75 cm^{-1} calculated the model, assuming $\log_{10}(k/k_0) = 2$ and interpolation = 1 cm. The IntCal20 (Reimer et al., 2020) and Bomb21NH1 (Hua et al., 2021) atmospheric curves were used as calibration sets. The most pronounced changes in peat composition, as manifested by changes in pollen concentration, testate amoeba species composition, and species composition of plant macrofossils, which may signal changes in peat accumulation rates, were inputted using the `Boundary` command. In this model, the `Boundary` command was input at a depth of 26 cm, with a pronounced change in pollen concentration. Two dates (laboratory code Poz-150636 and Poz-150390) were rejected because they were outside the main trajectory of the model. Peat accumulation rates were retrieved from the age–depth model using the OxCal software.

2.4 Peat properties and peat carbon accumulation rates

The water content in a wet sample (WC, %), organic matter content in a dry sample (ORG, %), ash content (ASH, g, %), ash-free bulk density (BD, $\mathrm{g\,cm^{-3}}$), peat accumulation rate (PAR, $\mathrm{mm\,yr^{-1}}$), and peat carbon accumulation rate (PCAR, $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) were calculated for each of the 96 samples. For these analyses, the volume of each sample was accurately measured using calipers. Next, each sample was placed in separate crucibles, weighed, dried, and weighed again to determine the percent WC. The dried samples were burned in a muffle furnace at 550 °C for 5 h and reweighed according to the protocol of Heiri et al. (2001) to determine ASH. BD was calculated by dividing the weight of the dry sample by the volume of the fresh sample and multiplied by ORG, according to Chambers et al. (2010). PAR was calculated based on core chronology and then multiplied by the BD value obtained earlier and by 50 % to obtain PCAR, according to Loisel et al. (2014).

2.5 Plant macrofossil analysis

The plant macrofossils were analysed using the modified protocol of Mauquoy et al. (2010). Each sample of approximately 5 $\mathrm{cm^3}$ underwent wet sieving (mesh diameter: 200 µm). The generalized content of the sample was estimated as a percentage using a binocular microscope. Fruits, seeds, achenes, perigynia, scales, whole preserved leaves, sporangia, and opercula were counted as total numbers in each sample. The tissues of monocotyledon species and moss leaves (brown and *Sphagnum* mosses) were identified on slides using ×200 and ×400 magnification. The material was compared with the guides (Anderberg, 1994; Berggren, 1969; Bojňanský and Fargašová, 2007; Mauquoy and van Geel, 2007). The diagram for the analysed proxy was plotted using the “riojaPlot” package for R (Juggins, 2025).

2.6 Testate amoeba analysis

Peat samples for testate amoeba analysis were washed under 300 µm mesh following Booth et al. (2010). Testate amoebae were analysed under a light microscope with ×200 and ×400 magnification until the sum of 100 tests per sample was reached (Payne and Mitchell, 2009); however, in peat layers below 27 cm, the testate amoeba sums were lower (between 5 and 50) due to the very low concentration of tests. Several keys, including taxonomic monographs (Clarke, 2003; Mazei and Tsyganov, 2006; Meisterfeld, 2001) and online resources (Siemensma, 2025), were used to achieve the highest possible taxonomic resolution. The results of the testate amoeba analysis were used for the quantitative depth to water table (DWT) and pH reconstructions. Both reconstructions were performed in C2 software (Juggins, 2007) using the European training set (Amesbury et al., 2016). In layers with low testate amoeba sums, water table reconstruction should be viewed with caution (Payne and Mitchell, 2009).

2.7 Pollen and non-pollen palynomorph analyses

Samples for palynological analysis (volume: 3 $\mathrm{cm^3}$ for 0–21 cm and 1 $\mathrm{cm^3}$ for 21–97 cm) were prepared using standard laboratory procedures (Berglund and Ralska-Jasiewiczowa, 1986). To remove the carbonates, samples were treated with 10 % hydrochloric acid. This step was followed by digestion in hot 10 % potassium hydroxide (to remove humic compounds) and soaking in 40 % hydrofluoric acid for 24 h (to remove the mineral fraction). Next, acetolysis was carried out. Three *Lycopodium* tablets (Batch 280521291, containing 18 407 spores per tablet; produced by Lund University) were added to each sample during the laboratory procedures for the calculation of microfossil concentration (Stockmarr, 1971). Pollen, spores, and selected non-pollen palynomorphs (NPPs) were counted under an upright microscope (Zeiss Axio SCOPE A1) until the number of total pollen sum (TPS) grains in each sample reached at least 500, apart from 10 samples in which pollen concentrations were very low. Two of them (depths: 19–18 and 17–16 cm) were excluded due to an extremely low pollen concentration, and it was impossible to reach 100 grains included in TPS. Sporomorphs were identified with the assistance of atlases, keys (Beug, 2004; Moore et al., 1991), various publications, and the image database in the case of NPPs, for which there are no atlases (Miola, 2012; Shumilovskikh et al., 2022; Shumilovskikh and van Geel, 2020). The results of the palynological analysis were expressed as percentages, and calculations are based on the ratio of an individual taxon to the TPS, i.e. the sum of AP (arboreal pollen) and NAP (non-arboreal pollen), excluding aquatic and wetland plants (together with Cyperaceae and Ericaceae), cryptogams, and fungi. A pollen diagram was drawn using the Tilia program (Grimm, 1991).

2.8 Macro- and microcharcoal analyses

Microscopic charcoal particles (size: > 10 µm) were analysed from the same slides as pollen following the standard protocol, and the number of charcoal particles and *Lycopodium* spores counted together exceeded 200 (Finsinger and Tinner, 2005; Tinner and Hu, 2003). Microscopic charcoal influx or accumulation rates (particles $\mathrm{cm^{-2}\,yr^{-1}}$) were calculated by multiplying the charcoal concentrations by the peat accumulation rate (PAR) (Davis and Deevey, 1964; Tinner and Hu, 2003).

Table 1. The list of radiocarbon dates from Miały peatland with calibration. The outliers are marked with asterisks (*). The IntCal20 (Reimer et al., 2020) and Bomb21NH1 (Hua et al., 2021) atmospheric curves were used to calibrate the dates. pMC represents percent modern carbon. 2σ presents the confidence interval that encompasses a 95.4 % probability.

Laboratory code – sample number	Depth (cm)	^{14}C date (^{14}C BP)	Calibrated dates (cal CE (2σ – 95.4 %))	Dated material
Poz-150634	10.5	114.23 ± 0.28 pMC	1958–1962 (9.7 %) 1986–1996 (85.7 %)	*Sphagnum* stems
Poz-150451	20.5	153.88 ± 0.4 pMC	1964–1974 (95.4 %)	*Sphagnum* stems
Poz-150635	30.5	110 ± 30	1682–1738 (25.7 %) 1754–1762 (1.1 %) 1801–1938 (68.6 %)	*Sphagnum* stems, seeds
Poz-150681	40.5	370 ± 40	1448–1530 (48.7 %) 1540–1635 (46.7 %)	*Sphagnum* and brown moss stems
Poz-156989	45.5	750 ± 30	1224–1290 (95.4 %)	Brown moss stems
Poz-150389	50.5	830 ± 30	1166–1269 (95.4 %)	*Sphagnum* and brown moss stems
Poz-156994	55.5	840 ± 30	1162–1266 (95.4 %)	Brown moss stems
Poz-150636*	60.5	470 ± 30	1407–1460 (95.4 %)	*Sphagnum* and brown moss stems
Poz-150390*	70.5	1730 ± 30	248–298 (32.6 %) 306–406 (62.8 %)	Brown moss stems
Poz-156773	75.5	1595 ± 30	417–546 (95.4 %)	Brown moss stems
Poz-150637	80.5	1530 ± 30	434–467 (11.3 %) 472–519 (15.6 %) 526–603 (68.5 %)	*Sphagnum* and brown moss stems, charcoal, *Carex* achenes
Poz-150682	96.5	1910 ± 30	28–44 (2.9 %) 58–214 (92.5 %)	*Sphagnum* and brown moss stems

A total of 96 contiguous samples (2 cm^3) were prepared for macroscopic charcoal analysis. Bleaching was used to create a more visible contrast between the charcoal and the remaining organic matter, following the method described by Whitlock and Larsen (2001). The samples were sieved through a 500 µm mesh and analysed with a binocular microscope under ×60 magnification. Only charcoal fragments > 600 µm were analysed to obtain the local fire signal (Adolf et al., 2018). Macroscopic charcoal influx or accumulation rates (particles cm^{-2} yr^{-1}) were calculated using the charcoal concentrations and the PAR.

2.9 Neodymium isotopes

We used neodymium isotopes to assess the impact of disturbances on the Miały peatland. This method helps determine the sources of mineral matter in peat profiles, including whether it was washed into the peatland basin (i.e. the peatland had a connection to groundwater and was of minerotrophic origin) or was primarily of atmospheric origin (meaning the peatland functioned more as an ombrotrophic, rain-fed system) (Marcisz et al., 2023b). Isotopic measurements were performed from peat samples taken along the peat core as well as from reference material from the surface of the peatland and soil around it (Fig. 1). All analytical procedures and isotopic measurements were performed in the Poznań Isotope Laboratory, Poland, on a Finnigan MAT 261 multi-collector thermal ionization mass spectrometer. Details of the analytical procedures are provided by Marcisz et al. (2023b). 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 3 d) in closed perfluoroalkoxy 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. Neodymium was separated using the miniaturized chromatographic techniques described by Pin et al. (1994) and Dopieralska (2003). The analytical precision was monitored by analysing the USGS reference material BHVO-2 ($^{143}Nd/^{144}Nd = 0.512986 \pm 0.000006$ (2σ; $n = 2$)). Neodymium (loaded as phosphate) was measured on Re in a double-filament configuration. Isotopic ratios were collected in a dynamic mode. Nd isotope ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Repeated measurements of the AMES standard yielded $^{143}Nd/^{144}Nd = 0.512118 \pm 10$ (2σ, $n = 12$). Nd isotope data are reported in the standard ε notation:

$$\varepsilon_{\mathrm{Nd}} = \frac{\left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)\text{sample} - \left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)\text{CHUR}}{\left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)\text{CHUR}} \times 10^4, \qquad (1)$$

where CHUR denotes the present-day Chondritic Uniform Reservoir ($^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$) (Jacobsen and Wasserburg, 1980).

2.10 Statistical analyses

To quantify periods of rapid vegetation change in the forest (regional scale) and on the peatland (local scale), as well as hydrological and trophic shifts on the peatland (local scale), we apply principal response curves (PrCs) to the data, as outlined by Burge et al. (2023) in their "baselines" R package. This approach allows for the identification of directional shifts and when these begin to accumulate beyond the level expected from random variation. The multivariate palynological data (pollen data and NPPs; individual taxa only) were Hellinger-transformed and reduced to a one-dimensional curve using PrCs. Thus, PrC results trace changes in the relative abundance of pollen and NPPs over time. While most rate-of-change (RoC) studies rely on a single proxy, the combination of multiple proxies, including pollen and algae, has been applied in previous research (e.g. Abrook et al., 2020).

This method is useful for detecting changes in data with a strong underlying gradient in palaeoecological studies (Van Den Brink and Ter Braak, 1999; De'ath, 1999). Generalized additive mixed models (GAMMs) were then fitted to the data, with a smoothing term accounting for temporal autocorrelation. A cubic regression spline was used as the smoothing basis, with $k = 20$. A range of values for k was tested to ensure that the model avoids overfitting or underfitting the data. Likewise, maximum likelihood (ML) was used for consistency with Burge's framework, instead of restricted maximum likelihood (REML). However, REML was used to reanalyse the data in place of ML as a smoothing parameter, although it did not make an appreciable difference to the results.

When poor GAMM fits occurred, adaptive splines with generalized additive models (GAMs) were compared with the GAMM to assess model fits. Adaptive spline GAMs provide better fits to data exhibiting abrupt changes but cannot yet be incorporated into the GAMM framework (Simpson, 2018). Periods of significant change were identified in the GAMM models by calculating the time intervals during which the confidence intervals surrounding the first derivative did not include zero. PrCs were derived from constrained ordination of the time series palynological data, which use the "`prcurve()`" function ("analogue" package) in R.

The phases in the palaeoecological analyses were distinguished based on changes in plant communities obtained from palynological and plant macrofossil data.

3 Results

3.1 Chronology, peat accumulation rates, and peat properties

The age–depth model shows the agreement index (A_{model}) of 61 %, just above the recommended minimum of 60 % (Bronk Ramsey, 2008) (Fig. 2). The model has the highest uncertainty, with a 95.4 % confidence interval – 80 calibration years – at depths between 65.5 and 64.5 cm (ca. 840–870 cal CE; Fig. 2). The age of the oldest layer – 96.5 cm – was modelled at 130 ± 45 (confidence interval: 1σ) cal CE (Fig. 2).

The water content of the wet sample ranged from 77.0 % (22–21 cm, ca. 1965 cal CE) to 95.0 % (20–19 cm, ca. 1970 cal CE), averaging 89.4 % throughout the core (Fig. 2). Organic matter content of the dry sample ranged from 83.6 % (33–32 cm, ca. 1755–1785 cal CE) to 99.2 % (22–21 cm, ca. 1965 cal CE), with an average of 94.5 % in the entire core (Fig. 2). Bulk density ranged from 0.04 g cm^{-3} (15–14 cm, ca. 1980 cal CE) to 0.28 g cm^{-3} (21–20 cm, ca. 1965–1970 cal CE), with an average of 0.12 g cm^{-3} across the core (Fig. 2). Average PAR throughout the core was relatively slow at 1.3 mm yr^{-1}, while it was fastest at 4.8 mm yr^{-1} (20–19 cm, ca. 1970 cal CE) and slowest at 0.2 mm yr^{-1} (43–42 cm, ca. 1395–1440 cal CE) (Fig. 2). The average PCAR had a value of 73.4 $\text{g C m}^{-2}\,\text{yr}^{-1}$, with the largest value being 590.6 $\text{g C m}^{-2}\,\text{yr}^{-1}$ (21–20 cm, ca. 1965–1970 cal CE) and the smallest being 10.2 $\text{g C m}^{-2}\,\text{yr}^{-1}$ (71–70 cm, ca. 665–700 cal CE) (Fig. 2). Higher PAR and PCAR values were associated with an undecomposed acrotelm zone.

3.2 Palaeoecological analysis

3.2.1 Phase 1 (97–76 cm, ca. 130–520 cal CE): very wet peatland with a dominance of monocots surrounded by mixed forest

The local vegetation (Fig. 3) for most of this period is dominated by monocots (max 96 % of plant macrofossil content), including *Carex*, whose achenes are found in the peat profile. Cyperaceae pollen makes up max 6.0 % (Fig. 4). Short periods of *Sphagnum* dominance (max 80 %), mainly *Sphagnum* subgenus *Cuspidata* (max 40 %), occur (Fig. 3). This phase is also characterized by a high content of unidentified organic matter, reaching up to 10 % (Fig. 3).

The low sums of testate amoebae do not allow for a statistically significant reconstruction of water and pH levels in this phase (full data in the open dataset, Bąk et al., 2025). However, among the testate amoeba taxa, *Centropyxis aculeata* dominates quantitatively. There is a high percentage of cyanobacteria and algae (Zygnemataceae, *Botryococcus*) (Fig. 4) and a maximum of the *Utricularia* curve in the pollen data (max 0.5 %; Fig. 4).

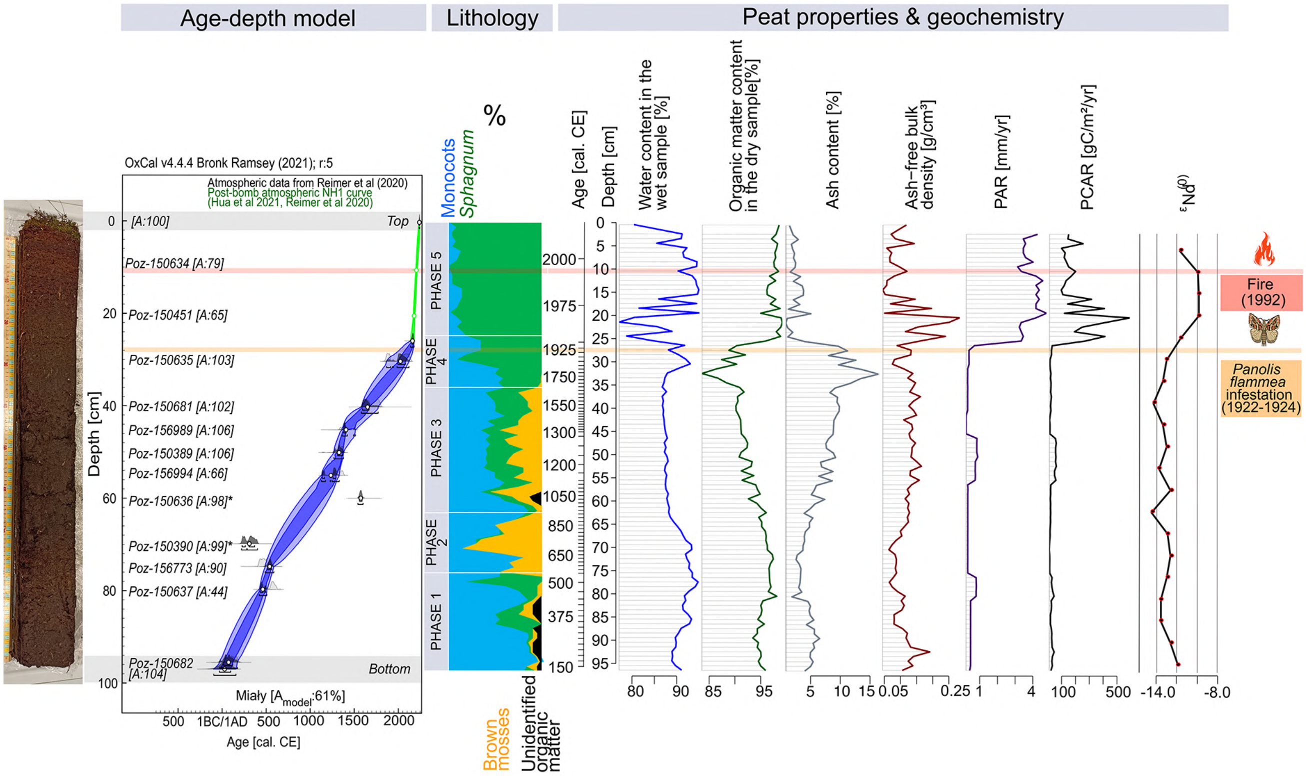

Figure 2. Bayesian age–depth model (based on ^{14}C dating) and lithology (based on plant macrofossils analysis) with palaeoecological phases of the peat profile in Miały (on the left side). Changes in the physical peat properties (water content in the wet sample, organic matter content in the dry sample, ash content, ash-free bulk density, PAR, and PCAR) and neodymium isotope signatures – $\varepsilon_{\mathrm{Nd}}$ – are marked. The timing of the most critical catastrophic disasters in the 20th century is also marked.

Pinus sylvestris-type (39.0 %–65.8 %) grains are the most frequent, but the pollen of deciduous trees is relatively common as well (Fig. 4): *Betula alba* type (7.4 %–26.4 %), *Alnus glutinosa* type (max 17.0 %), *Quercus* (max 15.6 %), *Carpinus betulus* (max 5.8 %), *Corylus avellana* (max 4.6 %), and *Fagus sylvatica* (max 3.5 %). Remains of *Betula* (achenes and catkin scales) are present in the plant macrofossils (Fig. 3).

The highest fire activity is recorded for ca. 310–330 cal CE, with a macroscopic charcoal concentration of ca. 70 particles cm^{-3} (Fig. 3) and a microscopic charcoal concentration of ca. 420 000 particles cm^{-3} (Fig. 4), and for ca. 430–455 cal CE, with 90 particles cm^{-3} of macroscopic charcoal (Fig. 3).

3.2.2 Phase 2 (76–64 cm, ca. 520–890 cal CE): moderately wet peatland and landscape closure – increase in forestation and decrease in ruderal species

The *Sphagnum* content decreases in favour of brown moss (max 85 %) and monocot remains (max 80 %), including *Carex* (achenes and perigynia of this taxon are found; Fig. 3). Cyperaceae pollen (Fig. 4) make up between 3.4 % and 8.4 %. This is the only phase in which seeds of *Menyanthes trifoliata* are found (Fig. 3), and the pollen curve maximum of this taxon is observed (0.3 %; Fig. 4).

Reconstructions of the DWT and trophic conditions imply a low abundance of testate amoebae, with a continuation of the quantitative dominance of *C. aculeata* (full data in the open dataset, Bąk et al., 2025). The share of freshwater bacteria and algae decreases significantly at this time (Fig. 4). Cyanobacteria reach a maximum of 5.9 % (Fig. 4).

This period has the highest forest cover in the peatland's surroundings. Arboreal pollen accounts for over 90 % of total pollen throughout this phase (Fig. 4). Compared to phase 1, the share of *Betula alba*-type pollen decreases (5.1 %–19.1 %), while the share of *Pinus sylvestris*-type pollen slightly increases (44.6 %–65.2 %) (Fig. 4). Admixture species – *Alnus glutinosa* type (max 17.9 %), *Quercus* (max 9.2 %), *Carpinus betulus* (max 6.8 %), *Corylus avellana* (max 5.2 %), and *Fagus sylvatica* (max 2.7 %) – continue to be relatively important (Fig. 4).

For the first half of phase 2, fire activity is low, but it increases in the second half. The concentration of both microscopic and macroscopic charcoal increases markedly towards

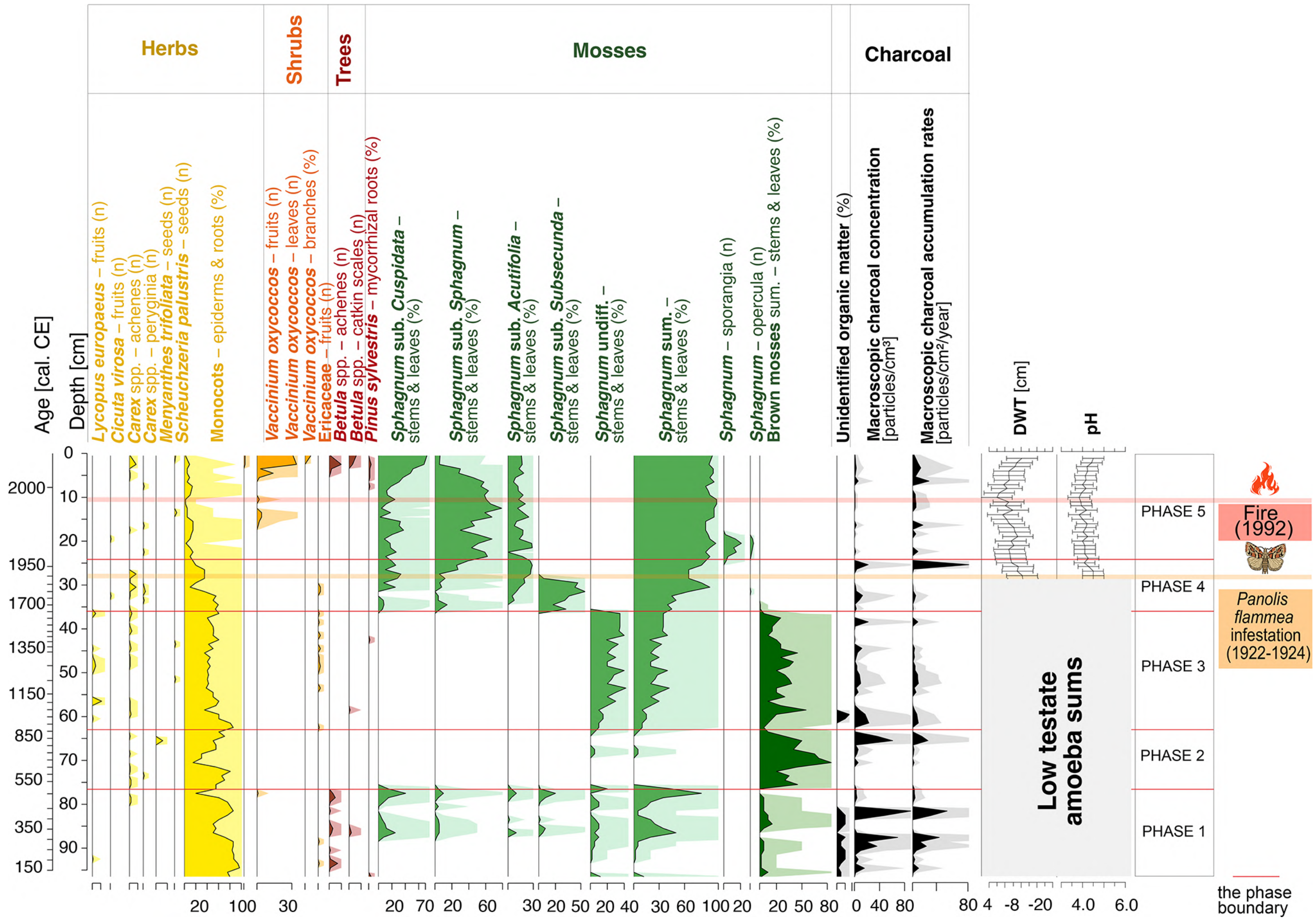

Figure 3. A diagram showing macrofossil percentages and macroscopic charcoal concentrations and influx as a local fire proxy. Testate amoeba-based DWT and pH curves for the 27–0 cm layers are also presented. The timing of the most critical catastrophic disasters in the 20th century is also marked. Ten times exaggeration is presented.

the end of this phase, reaching a maximum of 61 particles cm^{-3} for macroscopic charcoal (Fig. 3) and ca. 293 600 particles cm^{-3} for microscopic charcoal (Fig. 4).

3.2.3 Phase 3 (64–36 cm, ca. 890–1660 cal CE): very wet peatland, expansion of *Sphagnum* mosses, development of agriculture, and gradual decrease in deciduous trees

Sphagnum mosses (max 42 %) appear again, although, due to the significant degree of the material decomposition, it was not possible to determine lower taxonomic ranks in the plant macrofossil analysis (Fig. 3). The content of the remains of monocots (max 85 %) and brown mosses (max 55 %) remains high (Fig. 3). *Carex* achenes are also present (Fig. 3). The percentage of Cyperaceae pollen is relatively high (2.0 %–7.0 %; Fig. 4). This is the only phase in which fruits of *Lycopus europaeus* are found (Fig. 3). Seeds of *Scheuchzeria palustris* are also present (Fig. 3).

The concentration of testate amoebae remains low; thus, the reconstruction of water levels and trophic conditions should again be treated with caution (full data in open dataset, Bąk et al., 2025). Species of the genera *Centropyxis* sp., *Cyclopyxis* sp., and *Difflugia* sp. dominate quantitatively. The increase in cyanobacteria (max 82.6 %) and freshwater algae, especially *Tetraëdron* (max 24.6 %) and *Botryococcus* (max 2.5 %), is significant (Fig. 4).

The share of arboreal pollen is high, ranging from 86 % to 94 %, although with a slightly decreasing trend, compounded by declines in admixture species (Fig. 4). *Pinus sylvestris* type represented 51 %–68 % and *Betula alba* type represented 6 %–15 % of total pollen. At the end of this phase, the share of *Alnus glutinosa* type, *Quercus*, *Carpinus betulus*, *Corylus avellana*, and *Fagus sylvatica* with respect to total pollen was 11.6 %, 5.5 %, 2.0 %, 1.1 %, and 1.6 %, respectively. The declines in the percentage of these taxa may be related to the increased contribution of cereal pollen (Fig. 4). Among cereal pollen, *Secale cereale* dominates, reaching a maximum of 2.2 %. The percentages of Poaceae, *Artemisia*,

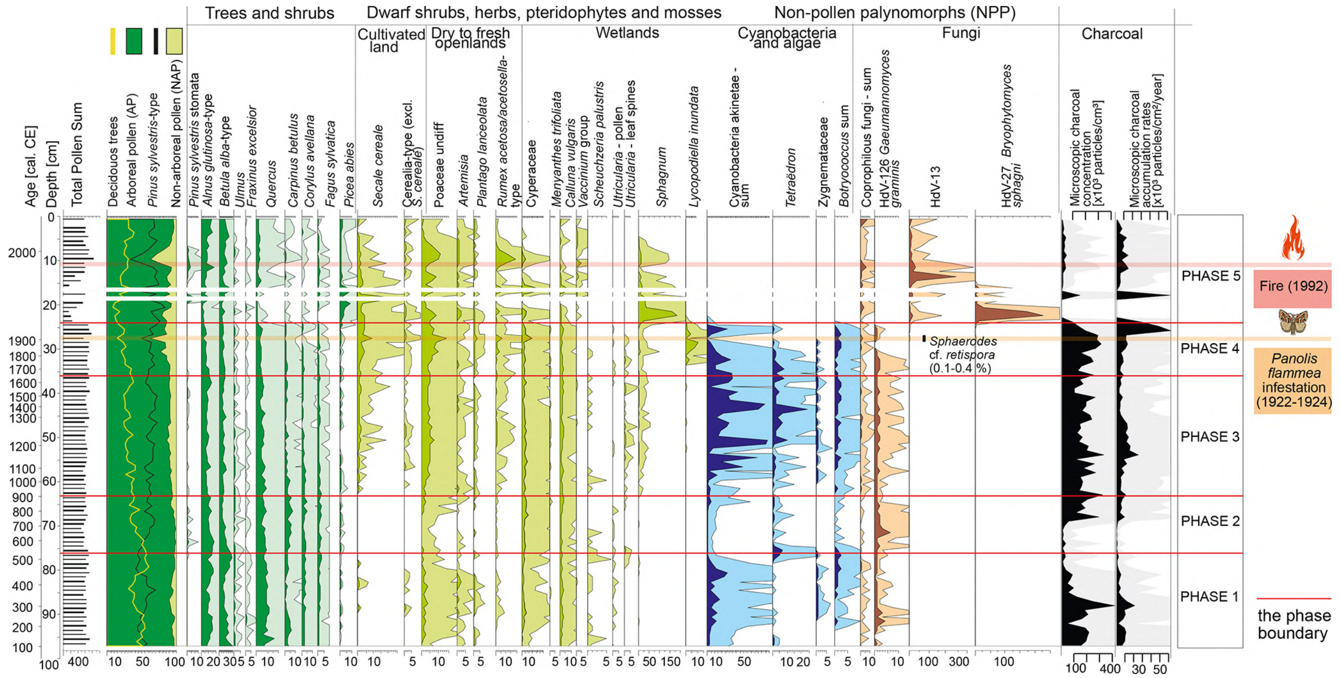

Figure 4. Pollen diagram with selected taxa presented (full list of taxa is provided in the associated open dataset). Pollen percentages are shown in black, and 10 times exaggeration is marked. Microscopic charcoal concentrations and influx as an extra-local fire proxy are also presented. Two samples (depths: 19–18 and 17–16 cm) were excluded from the diagram due to an extremely low pollen concentration (no data are shown for these depths).

Plantago lanceolata, and *Rumex acetosa/acetosella* type also increased (Fig. 4).

3.2.4 Phase 4 (36–24 cm, ca. 1660–1960 cal CE): the further expansion of *Sphagnum* mosses and an increase in *Pinus sylvestris*-type pollen with an episodic extreme decrease in it

The expansion of *Sphagnum* is continued. The percentage of monocot remains decreases to 15 % by the end of this phase. However, the number of achenes and perigynia of *Carex* is higher than in any other part of the profile (Fig. 3). The percentage of Cyperaceae pollen ranges from 2.7 % to 13.0 % (Fig. 4). The initial part of the phase is dominated by the *Sphagnum* subgenus *Subsecunda* (Fig. 3). At the same time, *Lycopodiella inundata* appears (Fig. 4). The brown mosses completely disappear.

At the end of phase 4, the abundance of testate amoebae increases (with *Galeripora discoides*, *Nebela tincta*, and *Phryganella acropodia* as dominant species), which allows for statistically significant reconstructions of the water table level and pH level (Fig. 3). The abundance of cyanobacteria and algae decreases distinctly; most of them disappear entirely at the end of this phase (Fig. 4).

In the pollen dataset (Fig. 4), a further decrease in the percentage of deciduous species is observed. In the upper part of phase 4, the share of *Alnus glutinosa*-type, *Quercus*, *Carpinus betulus*, *Corylus avellana*, and *Fagus sylvatica* pollen with respect to total pollen is 3.4 %, 1.9 %, 1.2 %, 1.3 %, and 0.6 %, respectively. The share of *Betula alba*-type pollen with respect to total pollen remains at about the same level (5.9 %–12.2 %). A significant decrease in *Pinus sylvestris*-type pollen percentages and an increase in the percentages of *Secale cereale*, Poaceae, *Plantago lanceolata*, and *Rumex acetosa/acetosella*-type pollen occur in ca. 1900–1926 cal CE.

Analysis of the macroscopic charcoal data (Fig. 3) shows one local fire event (macroscopic charcoal concentration of 22 particles cm^{-3} and macroscopic charcoal accumulation rate of 7 particles $\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$; 1952–1956 cal CE). The regional fire activity (Fig. 4) remained quite high (microscopic charcoal concentration of ca. 127 000–312 000 particles cm^{-3} and microscopic charcoal accumulation rate of ca. 3900–61 000 particles $\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$).

3.2.5 Phase 5 (24–0 cm, ca. 1960–2021 cal CE): the dominance of *Sphagnum* mosses and the disappearance of cyanobacteria and algae, the development of microscopic fungi, and the episodic extreme collapse of the arboreal pollen curve

The uppermost part of the profile records further development of *Sphagnum*, initially *Sphagnum* subgenus *Sphagnum* and later *Sphagnum* subgenus *Cuspidata*. The proportion of *Sphagnum* subgenus *Acutifolia* remains stable. *Sphagnum* capsule remains – sporangia and opercula – appear; we link their presence with spores of the parasitic fungus *Bryophytomyces sphagni* (see Sect. 4). Tree remains (*Betula* achenes and catkin scales and *Pinus sylvestris* mycorrhizal roots) are abundant. *Vaccinium oxycoccos* leaves appear in large numbers.

At the beginning of this phase, cyanobacteria and algae disappear completely. Testate amoeba species such as *G. discoides*, *Galeripora catinus*, and *N. tincta* are abundant. *G. discoides* dominates for most of phase 5, and the abundance of *N. tincta* increases towards its end. The groundwater level remains constant, except for one marked fluctuation (ca. 1990–1995 cal CE), whereas the pH level increases gradually from ca. 1995 cal CE (Fig. 3). Both phenomena can be linked to the effect of the 1992 fire (see Sect. 4).

Pinus sylvestris type remains the dominant species in this phase of the profile (32.6 %–78.9 %). Compared to the previous phase, the percentage of *Betula alba*-type pollen increases (5.6 %–20.3 %). One significant decrease in the share of tree pollen, in particular *Pinus sylvestris* type, is recorded in ca. 1995 cal CE. We interpret this as decreased forest cover after the 1992 fire (see Sect. 4). At the same time, a higher share of *Pinus sylvestris* stomata typifies ca. 1980–2000 cal CE layers (0.2 %–3.9 %). We associate this with massive needle falls associated with the fire (see Sect. 4). *Rumex acetosa*/*acetosella* type – a taxon characteristic of open and ruderal areas (Behre, 1981) – reaches its maximum at 19.6 % (ca. 1995 cal CE), which we also interpret as an effect of the fire. The shares of other deciduous trees – *Quercus* (max 3.9 %), *Carpinus betulus* (max 1.6 %), *Corylus* (max 1.3 %), and *Ulmus* (max 0.7 %) – decrease.

3.3 Neodymium isotope analysis

The $\varepsilon_{\mathrm{Nd}}$ values measured in the mineral matter extracted from the analysed peat samples range from -14.5 to -9.8. Most samples show a relatively low variability in the strongly negative Nd isotope ratios ($\varepsilon_{\mathrm{Nd}} < -12$), including the most negative values in layers 61–60 and 41–40 cm. Less negative $\varepsilon_{\mathrm{Nd}}$ values (ranging from -9.9 to -9.8) are only observed in the upper part of the profile, most notably in the 21–20, 16–15, and 11–10 cm layers.

Among the reference surface samples, the mineral material from the peatland surface yielded moderately negative $\varepsilon_{\mathrm{Nd}}$ signatures (-12.1 and -11.7), whereas the soil taken from the slopes of the peatland catchment display a strongly unradiogenic Nd isotope composition ($\varepsilon_{\mathrm{Nd}} = -18.9$ to -16.5; Fig. 2, Table 2). The study site is covered by young glacial material dominated by clay and sand derived from Scandinavia, transported and accumulated during the last glaciation (Marks, 2012). Previously, Nd isotope measurements in the young glacial sediments of another outwash plain covered by a pine monoculture were measured by Marcisz et al. (2023b), who reported $\varepsilon_{\mathrm{Nd}}$ similar negative signatures ($\varepsilon_{\mathrm{Nd}} = -26.5$ to -16.6) to those in Miały.

3.4 Statistical analyses

The PrC explained 73 % of the variance in the palynological data. However, the GAMM provided a relatively poor fit to the data. An adaptive spline GAM provided a better explanation of the data, with the differences between the two models primarily related to the improved fit with the more recent samples. This suggests a possible return to previous conditions, although these samples are more likely to be influenced by temporal autocorrelation. Despite this, the GAMM effectively captures the general trends in the data and provides a better fit for the earliest samples (Fig. A1). Therefore, we can proceed to use these data.

The PrC analysis revealed that changes over time occurred between the beginning of the record and 1720 cal CE. However, there is no substantial evidence of significant or rapid changes until after this time. From approximately 1000 cal CE until the 1700s, the PrC scores exhibited high variability. A significant increase in the RoC was identified for the period ca. 1725–2005, as shown in Fig. 5.

4 Discussion

4.1 Combining ecological, palaeoecological, geochemical, and historical data to understand long-term environmental changes

Present-day pine monoculture plantations of Poland are often perceived as typical of this region by the local population, whereas these are highly modified forests that are significantly different from the natural ones. Compared to natural potential vegetation maps, these areas should possess a large proportion of deciduous taxa, e.g. oak–hornbeam forests (*Querco-Carpinetum medioeuropaeum*) (Matuszkiewicz, 2008). The relatively high percentages of deciduous tree pollen compared to the percentages of *Pinus sylvestris*-type pollen in historical times were recorded at many sites from present-day pine monocultures in northern Poland (Bąk et al., 2024; Czerwiński et al., 2021). The development of the Polish state and agriculture in the early Middle Ages, in our data manifested by the high percentages of cereal pollen grains (including *Secale cereale*) and taxa characteristic for open and ruderal areas (Poaceae, *Artemisia*, *Plantago lanceolata*, and *Rumex acetosa-acetosella* type), caused a decline in deciduous species in the forest composition (Fig. 4). These changes in the forest structure were distinct but gradual; when planned management was introduced in 18th century, however, the contribution of admixture trees started to decrease rapidly. In 1772 CE, the area of the Noteć Forest was included in the borders of the Kingdom of Prussia as a result of the First Partition of Poland. At that time, some of the first legal regulations for planned forest manage-

Table 2. Reference $\varepsilon_{\mathrm{Nd}}$ values measured in surface samples taken from the studied peatland and its surrounding (sample nos. 1–5) and $\varepsilon_{\mathrm{Nd}}$ values measured in peat samples.

No.	Sample code	$^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{(0)}$	Uncertainty	$\varepsilon_{\mathrm{Nd}}$ $(t=0)$
1	MŁY01	0.512016	±0.000011	−12.1
2	MŁY02	0.511791	±0.000010	−16.5
3	MŁY03	0.511671	±0.000012	−18.9
4	MŁY04	0.511727	±0.000012	−17.8
5	MŁY05	0.512036	±0.000011	−11.7
6	MŁY5.5	0.512036	±0.000012	−11.7
7	MŁY10.5	0.512129	±0.000010	−9.9
8	MŁY15.5	0.512134	±0.000010	−9.8
9	MŁY20,5	0.512133	±0.000009	−9.9
10	MŁY25.5	0.512042	±0.000009	−11.6
11	MŁY30.5	0.511969	±0.000010	−13.1
12	MŁY35.5	0.511952	±0.000015	−13.4
13	MŁY40.5	0.511905	±0.000010	−14.3
14	MŁY45.5	0.511952	±0.000010	−13.4
15	MŁY50.5	0.511973	±0.000010	−13.0
16	MŁY55	0.511932	±0.000010	−13.8
17	MŁY60	0.511991	±0.000010	−12.6
18	MŁY65	0.511895	±0.000017	−14.5
19	MŁY70	0.511975	±0.000008	−12.9
20	MŁY75.5	0.511992	±0.000011	−12.6
21	MŁY80.5	0.511972	±0.000010	−13.0
22	MŁY85.5	0.511940	±0.000010	−13.6
23	MŁY90.5	0.511941	±0.000010	−13.6
24	MŁY95.5	0.511992	±0.000009	−12.6
25	MŁY97.5	0.512028	±0.000012	−11.9

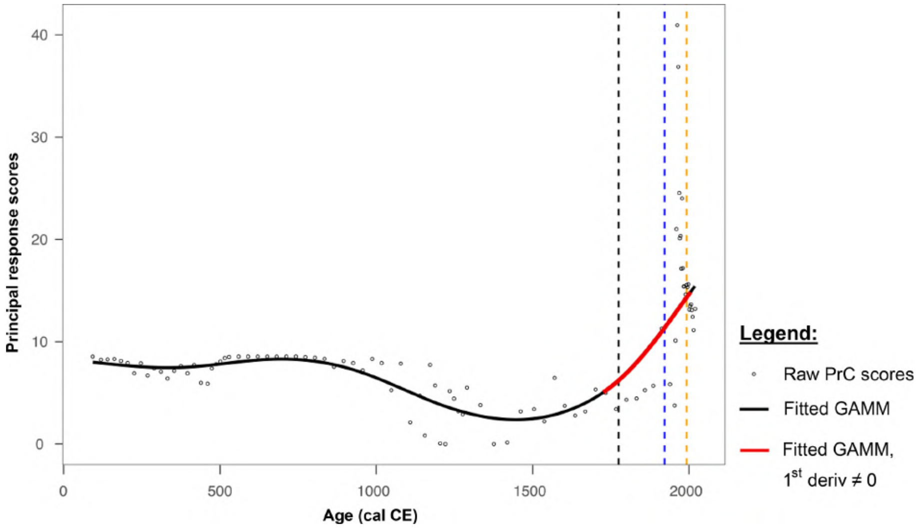

Figure 5. Changes in the principal response curve derived from pollen count data (circles) fit with a GAMM fit (solid black and red lines). The red line indicates periods of rapid change. Dashed vertical lines indicate historical periods of forest management change affecting the site: the 1775 decree by Frederick the Great (black); infestation by *Panolis flammea* (1922–1924; blue); and the 1992 fire period (yellow).

ment in the area appeared, including the 1775 CE decree of Frederick the Great regarding government forests in Prussia and the preference for planting pines instead of deciduous species (Bąk et al., 2024; Jaszczak, 2008). Around this time, the PrC analysis began to reveal periods of significant and rapid change in the palynological record. Since then, both the forest and, even more so, the Miały peatland within it have continued to undergo substantially rapid changes, unlike the preceding changes. The results of the PrC analysis indicated a significant RoC, confirming the occurrence of critical transitions in the peatland on a scale that was not observed in the older part of the core. The trend in the PrC aligns broadly with the patterns seen in the data, as shown by the correspondence between the PrC scores and the relative contributions of deciduous trees, arboreal pollen, *Pinus sylvestris*-type pollen, and NPPs.

It is commonly assumed that outwash plains or aeolian sandy dunes, remnants of the Weichselian glaciation (to 11 700 BP), which are currently covered by extensive Scots pine monoculture in northern Poland (e.g. the Noteć Forest and the Tuchola Forest) are not conducive to the growth of other species and that *Pinus* is a natural main forest-forming species (Magnuski, 1993; Miś, 2003). Although pollen data suggest the dominance of *Pinus sylvestris* type since the 2nd-century CE, a distinct admixture of *Quercus*, *Carpinus betulus*, and *Corylus avellana* was recognized in our study. Previous multi-proxy palaeoecological studies from the Noteć Forest exist; however, they were unable to provide information on the proportion of admixture tree species in the forest composition prior to the onset of planned forest management. The cores collected from the Rzecin peatland covered only the last 200 years and did not capture the entire background of the changes related to human activity and subsequent forest management (Barabach, 2014; Lamentowicz et al., 2015; Milecka et al., 2017; Słowiński et al., 2019). Knowledge of the historical background is essential for the interpretation of the complex response of the peatland ecosystem to a change in forest management, as it allows for the long-term tracing of reference conditions relating to both the composition of the forest and the trophic and hydrological variants of the peatland (Bąk et al., 2024). In this study, we recorded the presence of hydrophytes and later also helophytes and hygrophytes (e.g. *Utricularia*, *Menyanthes trifoliata*, *Lycopus europaeus*, *Scheuchzeria palustris*, and *Cicuta virosa*) in the first four phases of the peatland development (up to ca. 1960 CE; Fig. 4). Combined with the high percentages of cyanobacteria and algae (Zygnemataceae, *Botryococcus*, and *Tetraëdron*) and dominance of *Centropyxis* sp., *Cyclopyxis* sp., and *Difflugia* sp. among the testate amoebae, this indicates the existence of a shallow waterbody supplied not only by rainwater and runoff but also by groundwater (Figs. 3 and 4). All of these taxa disappeared in phase 5, after ca. 1960 CE.

The relative stability of the ecosystem until the 20th century appears to be in line with the moderately variable, unradiogenic neodymium isotope signatures of the mineral matter extracted from the peat samples ($\varepsilon_{\mathrm{Nd}} = -14.5$ to -11.6). These data are similar to the results from other peatlands in the Tuchola Forest, Poland: the Stawek peatland (-15.3 to -12.7) and Głęboczek peatland (-13.7 to -12.6) (Marcisz et al., 2023b). The notably consistent $\varepsilon_{\mathrm{Nd}}$ values in the pre-infestation part of the studied profile point to the dominance of local sources of the mineral matter. Strongly unradiogenic $\varepsilon_{\mathrm{Nd}}$ values are generally characteristic of the surface clastic sediments that dominate the young post-glacial landscape of northern Poland (Marcisz et al., 2023a, b).

The instability of the ecosystem witnessed after the 20th century is a consequence of the introduction of planned forest management and the planting of monoculture plantations in the late 18th century. Indeed, such forests are more sensitive to disturbance and extreme phenomena than mixed forests. The Noteć Forest fell victim to such management and faced two massive ecological disasters in the 20th century: the *Panolis flammea* outbreak in 1922–1924 and a fire in 1992. The consequences of the *Panolis flammea* outbreak were particularly severe, as they directly caused a complete change in the trophic and hydrological conditions of the peatland in the following decades, i.e. in the period around 1925–1960.

Nevertheless, all three above-mentioned disturbance factors (introduction of planned forest management, 1922–1924 outbreak, and 1992 fire) affected the condition of the peatland and were recorded as significant RoCs in the GAMM model, which can be interpreted as critical transitions (Fig. 5).

4.2 *Panolis flammea* outbreak (1922–1924) and its impact on peatland and pine plantations

One of the most harmful documented insect outbreaks in Poland happened in 1922–1924 CE (Broda, 2003) and covered vast areas of central and eastern Europe (today's area of Germany, Poland, Lithuania, Belarus, and part of European Russia), progressing from west to east (Ziółkowski, 1924). It was caused by *Panolis flammea*, one of the most dangerous primary pests of pine trees (Szmidt, 1993). As a result of the 1922–1924 *Panolis flammea* infestation, over 500 000 ha of forest was defoliated in Europe (Głowacka, 2009). In the Noteć Forest, the first caterpillars (found in 1921 CE) did not herald an ecological disaster (Broda, 2003). However, over the next 2 years, between 1922 and 1923, ca. 64 000 ha of the forest was destroyed (Hernik, 1979). In the Potrzebowice forest district, where our site is located, the outbreak destroyed over 90 % of the forest area (ca. 8000 ha) (Broda, 2003).

This outbreak is evidenced in our pollen record, marked by a sharp decrease in the percentage of *Pinus sylvestris*-type pollen (48.0 %) compared to the neighbouring layers – ca. 1875–1900 cal CE (60.6 %) and ca. 1925–1950 cal CE (62.8 %). After almost all the pine trees were destroyed and the caterpillars had nothing to eat, they attacked the deciduous trees, on which they do not usually feed (Anon, 1929). In our data, a manifestation of this shift is probably the decrease in the proportion of *Betula alba*-type, *Alnus glutinosa*-type, and *Quercus* pollen. This layer also shows the highest share of Poaceae (14.7 %), cereal (10.4 %), and *Plantago lanceolata* (2.7 %) pollen in the entire peat core. The share of *Rumex acetosa/acetosella*-type pollen (6.6 %) is also high. The presence of taxa characteristic of open and ruderal areas indicates that the landscape has opened up due to logging activities in the destroyed forest stands. However, in the Rzecin peatland, 8 km southeast of our site, a significant decrease in *Pinus* pollen has not been observed (Barabach, 2014). According to Barabach (2014), as a result of immediate human activities, heliophytes did not develop, and a natural secondary succession did not occur in the Rzecin bog's surroundings. Barabach (2014) argued that a single pine that stands alone will produce more pollen than the same pine in a compact forest stand, referring to the individual trees that survived the disaster. Later, along with wind and water, the pollen was deposited in natural depressions, including the Rzecin peatland. However, an increase in Poaceae pollen percentages has been recorded, confirming the opening of the landscape in the Rzecin bog's surroundings.

The layers corresponding to ca. 1900–1950 cal CE are the only portions of the core in which spores of *Sphaerodes retispora* (also known as *Microthecium retisporum*) were identified. This taxon occurs on other fungus (*Trametes hirsuta*), which inhabits dead trees and their branches, as well as recently dead and decaying wood (Bhatt et al., 2016). It mainly attacks deciduous trees, although reports of attacks on coniferous trees are known (Szwałkiewicz, 2009). Perhaps the appearance of the *S. retispora* spores in these layers reflects the presence of *T. hirsuta* on dead wood after the *Panolis flammea* outbreak. We also observed higher percentages of coprophilous fungi (including HdV-55 A *Sordaria*-type fungi) in the layer corresponding to ca. 1900–1925 cal CE (2.7 %) compared to neighbouring layers – ca. 1875–1900 cal CE (0.4 %) and ca. 1925–1950 cal CE (0.9 %). *Sordaria*-type coprophilous fungi can indicate the presence of open land, the presence of livestock, and wood detritus or wood burning (Lageard and Ryan, 2013; Lundqvist, 1972; Mighall et al., 2008; Wheeler et al., 2016). We point out, however, that *Sordaria*-type spores can also occur on the faeces of wild herbivores and are predominantly coprophilous, meaning that this taxon may include non-coprophilous species (Shumilovskikh and van Geel, 2020). Kołaczek et al. (2013), at the Jesionowa mire in southern Poland, noted the co-occurrence of a high percentage of *Sordaria*-type spores and a high percentage of Poaceae, cereal, *Rumex acetosa*/*acetosella*-type, and *Plantago lanceolata* pollen, i.e. taxa characteristic of open areas that we observed in our pollen dataset during and after the outbreak. However, in the surroundings of the Jesionowa mire, the landscape has not opened up due to deforestation, but the grazing of livestock has intensified. Synchronously, Barabach (2014) reported a massive emergence of Glomeromycota spores, which can be widely considered an indicator of soil erosion (Ejarque et al., 2010; Van Geel et al., 1989). Indeed, the deforestation associated with the outbreak resulted in increased water and wind erosion. However, Kołaczek et al. (2013) argue that Glomeromycota spores can be considered indicators of soil erosion only in lacustrine deposits. In peatlands, there is a high risk of the presence of plant species capable of forming arbuscular mycorrhizae. Glomeromycota spores then come from fungi that have colonized the roots of plants growing on the surface of the peatland.

In their study of the Rzecin peatland, Milecka et al. (2017) reported an increase in charcoal in ca. 1910–1925 cal CE. The authors linked this increase to the fires occurring in the Noteć Forest in the 1920s and 1930s. Still, it could also result from cleanup activities after the *Panolis flammea* outbreak, such as raking and burning litter with dead caterpillars. Barabach (2014) reported a higher content of ash and a higher charcoal concentration in the concerned interval. We did not observe increased micro- or macroscopic charcoal concentrations in the Miały peatland. It is possible that the redistribution of charcoal particles to the edges of the peatland occurred due to high water levels. A core taken closer to the edge could, therefore, give a complete answer as to the extent of burning.

Following the outbreak, an increase in the proportion of *Picea abies* until the early 1970s is observed in our dataset. After the outbreak, initial management plans included diversification of species composition in the newly planted forest's forest stands. Still, *P. sylvestris* was selected as the primary species. Other planted species included *Betula* (mainly along the roads), *Pinus strobus*, *Pinus banksiana*, *Pinus rigida*, *Alnus glutinosa*, *Robinia pseudoacacia*, and *Prunus serotina* (Mroczkiewicz, 1933). Considering that *P. abies* reaches sexual maturity after 20–30 years in open areas (Skrøppa, 2003) or even later in closed areas (ca. 40 years) (Matthias and Giesecke, 2014; Rispens, 2003), we conclude that the observed increase in *P. abies* pollen is an echo of the 1922–1924 outbreak.

Recognizing the ecology of past *Panolis flammea* outbreaks in central and eastern Europe can help model and predict its risk of occurrence in northern Europe, which is warming due to climate change. Pulgarin Díaz et al. (2022) report that, between 1970 and 2020, the range of *Panolis flammea* in Finland shifted nearly 5° northward, 50 years earlier than assumed. The remains of these moths could help determine the scale and ecology of historical outbreaks in central and eastern Europe and, thus, better predict their future effects in northern Europe. Unfortunately, they do not preserve well in the sediments (Bąk et al., 2024). However, we emphasize that we did not use advanced extraction methods that could potentially preserve the delicate structures of the moth wing remains (Montoro Girona et al., 2018); rather, we only undertook observation under light and stereoscopic microscopes when viewing the samples in the analyses used. We also have not encountered *Panolis flammea* at Miały peatland. Palaeoecological analyses such as pollen and testate amoeba analyses can support the recognition of the results of such historical outbreaks, but they cannot confirm that an outbreak occurred. There are, however, palaeoecological reconstructions of outbreaks caused by other pests whose remains are better preserved in the sediment. For example, Schafstall et al. (2022) showed the usefulness of subfossil bark beetles for reconstructing disturbances occurring in *Picea abies* forests in Slovakia.

4.3 Changing trophic and hydrological conditions as an effect of post-outbreak forest management

The effect of the *Panolis flammea* outbreak was tens of thousands of hectares of damaged forests. Damaged forests were cleaned, and the land was prepared for new planting. However, the opportunity to rebuild the forest's species structure was not seized. Easy-to-manage and fast-growing pine trees were used for forest regeneration (Ankudo-Jankowska, 2003), which caused a change in the trophic conditions of the peatland manifested by the decline in pH in our data (Fig. 3). After the infestation, in our dataset, we also notice the expansion of *Sphagnum* mosses, which tolerate more acidic conditions. *Sphagnum* content reaches 65 % for ca. 1900–1925 cal CE and 85 % for ca. 1955–1960 cal CE, further increasing in the upper part of the section (Fig. 3) and almost completely displacing monocot plants and brown mosses. We assume that more acidic conditions in the peatland after the *Panolis flammea* outbreak are the result of monoculture planting regimes after this devastating event, as many studies have documented the ability of various pine species to acidify the soil (Berthrong et al., 2009; Cifuentes-Croquevielle et al., 2020; Hornung, 1985; Turner and Lambert, 1988). This is confirmed by the highest percentages of *Pinus sylvestris*-type pollen at Miały between 1950 and 1960. This is because *Pinus sylvestris* in dense forest complexes begins flowering at an age of about 25–30 years (Mátyás et al., 2004).

The process of peatland acidification is a natural manifestation of peatland development over time, as long as it occurs gradually. We noted a gradual transition from a moderately rich fen to a poor fen in phase 4 (ca. 1660–1960 cal CE). However, further changes in local plant communities and hydrological and trophic conditions toward acidification occurred abruptly, characteristic of external interference. Bąk et al. (2024) pointed out that such changes are a result of forest management activities and can be caused by drainage and transformation in forest species composition. In this study, we emphasize the importance of the consequences of vulnerability and poor resilience of monoculture plantations to disturbances and extreme phenomena such as insect outbreaks.

The change in trophic conditions at this time, as well as the concomitant change in hydrological conditions, are also documented by the complete disappearance of cyanobacteria and algae (Fig. 4), indicating that the peatland was cut off from the groundwater supply. Among testate amoebae, *G. discoides*, *N. tincta*, and *P. acropodia*, species that tolerate unstable hydrological conditions became dominant, suggesting a lowering of the water table and substantial water table fluctuations (Lamentowicz and Mitchell, 2005; Sullivan and Booth, 2011).

This observation is supported by the concurrent change in the Nd isotopic signatures (Fig. 2). The deforestation caused by the *Panolis flammea* infestation is followed by an increase in the Nd isotope ratios, reaching $\varepsilon_{\mathrm{Nd}}$ values notably higher than those observed in any of our reference samples from the peatland catchment. Therefore, the elevated $\varepsilon_{\mathrm{Nd}}$ values, coinciding with the notably decreased ash contents, most likely reflect a decreased supply of local sediments from surface runoff and groundwater flow. This interpretation is in agreement with the acidification of the peatland; the transition in the hydrological regime likely resulted in an increased relative role of extra-local, aeolian sources of the sedimentary material (Allan et al., 2013; Fagel et al., 2014; Marcisz et al., 2023a). A specific source of such ^{143}Nd-enriched sediments cannot, however, be identified based on the $\varepsilon_{\mathrm{Nd}}$ record alone.

In the period of the transition of trophic and hydrological conditions in a Miały peatland (ca. 1925–1960 CE cal CE), we observed the appearance of *Bryophytomyces sphagni* (HdV-27). Some studies have specified that this fungus is an indicator of the change from minerotrophic to ombrotrophic conditions in a peatland, especially in association with the appearance of *Sphagnum* spores (van Geel et al., 2020). Although we observe numerous spores of this fungus in the narrow period of changing trophic and hydrological conditions in our dataset (ca. 1925–1960 CE cal CE), we also note that the massive number of *B. sphagni* spores does not necessarily indicate sudden ombrotrophication of the peatland. There are many studies in which the appearance of *B. sphagni* does not correlate with the ombrotrophication of the peatland (van der Linden et al., 2008; McCarroll et al., 2017; Yeloff et al., 2007). Thus, we emphasize the need for better recognition of the ecology of *B. sphagni*. With the appearance of *B. sphagni*, *Gaeumannomyces caricis* (HdV-126) disappears. *G. caricis* is a fungus associated with *Carex* (van Geel and Aptroot, 2006; Pals et al., 1980). In our plant macrofossil data, *Sphagnum* mosses, as we mentioned above, have almost completely displaced monocots, including *Carex*, which dominated the peatland in phases 3–5. A coincident disappearance of *G. caricis*, the appearance of *B. sphagni*, and the development of *Sphagnum* have been noted in the past in southwest France (Aoustin et al., 2022). These authors, among others, based on the large number of spores of *B. sphagni*, decided to separate the developmental phase of the object they studied, which they referred to as *Sphagnum* bog (Aoustin et al., 2022).

Sudden changes in trophic conditions, resulting in subsequent changes in the vegetation cover in the catchment, are one of the most common causes of critical transitions in peatlands (Lamentowicz et al., 2019b).

4.4 Fire in 1992 – the second-largest fire in the post-World War II history of Poland

Potential high and medium modern fire danger concerns 83 % of forests in Poland (65 % in Europe) (Szczygieł, 2012). This is mainly due to poor habitats and a homogeneous forest structure, with *Pinus sylvestris* as the dominant species. *Pinus*, in turn, favours the accumulation of a significant amount of dry biomass on the surface. Fire danger is also a result of the young age of the tree stands, which have not yet developed stable ecosystem links in food webs. The young stands result from planned forest management involving rapid wood harvesting and 20th-century ecological disasters (particularly insect outbreaks). Industrial pollution, increasing accessibility to the public, and climate change, resulting in prolonged droughts and water deficits, amplify the problems of forest composition and management.

The 1992 droughts were marked by fires in many regions of Poland (Polna, 2005) and other countries in central Europe (Kula and Jankovská, 2013; Somsak et al., 2009). Almost 12 000 forest fires were recorded in Poland alone, and nearly 48 000 ha of forest area burned. The largest fire in Poland's post-war history, which burned more than 9000 ha of forest (Szczygieł, 2012), occurred near the town of Kuźnia Raciborska (Silesia, southern Poland) between 26 and 30 August 1992. Two weeks prior to this event, the second-largest fire in Poland's post-war history had affected the Noteć Forest.

In the 1970s, Hernik (1979) and Ratajszczak (1979) signalled that the tree stands of the Noteć Forest were weakened by repeated insect outbreaks (*Panolis flammea*: 1956; *Lymantria monacha*: 1947 and 1964; *Barbitistes constrictus*: 1964; *Diprion pini*: 1961; *Bupalus piniarius*, 1966; and *Dendrolimus pini*: 1970). Compared to the 1922–1924 *Panolis flammea* outbreak, however, they were smaller, less severe, and covered different locations of the Noteć Forest, rather than a larger area. The authors stressed the need to introduce admixture species to change the age structure of the forest and reduce the fire threat. Their predictions soon turned out to be very accurate. On 2 June 1992, a fire covered about 700 ha of the Noteć Forest (Bugaj, 1992), and on 10 August of the same year, the fire consumed more than 5000 ha of forest in just 8 h (Fabijański, 1996). The total area affected was mapped in detail by the foresters (Fig. 6). Only an enclave of several hectares of deciduous old-growth forest resisted the fire.

Macroscopic charcoal concentrations did not register this fire event as we expected. Although the concentrations of microscopic charcoal in ca. 1989–1991 cal CE (ca. 30 800 particles $\mathrm{cm^{-3}}$) and ca. 1991–1994 cal CE (ca. 27 500 particles $\mathrm{cm^{-3}}$) are higher than those in ca. 1986–1989 cal CE (ca. 10 000 particles $\mathrm{cm^{-3}}$) and ca. 1994–1997 cal CE (ca. 16 300 particles $\mathrm{cm^{-3}}$), these values do not reflect the actual scale of the forest destruction, especially because the fire also took place on the peatland (Fig. 6). A smaller-than-expected signal from the 1992 fire in charcoal analysis was also obtained by Barabach (2014) in the nearby Rzecin peatland. The small amount of macroscopic charcoal may be explained by the fact that more intense fires produce smaller charcoal particles (Schaefer, 1973). Additionally, before the particles are deposited, their dispersion by wind and water plays an important role (Patterson et al., 1987). Shortly after the fire reached the peatland, heavy rain had fell, reaching a value of 31.5 mm (Institute of Meteorology and Water Management, 2025). This rain stopped the fire from spreading further and significantly limited the movement of charcoal by wind.

The events are, however, well recorded by other proxies. Directly after the fire – ca. 1991–1994 cal CE and ca. 1994–1997 cal CE – a substantial decrease in the percentage of arboreal pollen, especially of Scots pine, is observed in the pollen dataset. At the same time, *Pinus sylvestris* stomata appear, which may indicate a fall of needles to the surface. However, we recommend a cautious approach to interpreting the presence of *Pinus sylvestris* stomata. While burnt *Pinus sylvestris* stomata would give certainty to the occurrence of fire, needle fall due to other processes should also be considered. High water levels may also have contributed to the shedding of needles by *Pinus* in the peatland (which we explain below). The water table rose to ground level, probably due to inundation. The rise in the groundwater level shortly after increased fire activity is a well-known phenomenon observed at other sites (Marcisz et al., 2015). The rise in water level is correlated with a high concentration (72 %) of the testate amoeba *Galeripora discoides*, which tolerates hydrologically unstable conditions and is abundant in disturbed ecosystems (Lamentowicz and Mitchell, 2005). *Rumex acetosa/acetosella*-type pollen reaches its maximum percentage, which is accompanied by an increase in the percentage of Poaceae pollen, a taxon characteristic of open areas, indicating the landscape's opening due to the forest's reduction. In their study of the Tuchola Forest peatlands, Marcisz et al. (2023b) observed pronounced decreases in the $\varepsilon_{\mathrm{Nd}}$ values following major fire events, attesting to an increased supply of locally sourced sedimentary material favoured by forest removal. Analogously, some decrease in the $\varepsilon_{\mathrm{Nd}}$ values following the 1992 fire is observed in the peat profile in this study. Therefore, we note that it is not always possible to unambiguously identify local fire events, even using high-resolution charcoal analysis, and that historical sources can validate the data. This is a crucial finding regarding the interpretations of palaeofire reconstructions, pointing out that even catastrophic fires can go unnoticed in the sedimentary record.

The scale and frequency of catastrophic fires, including forest and peatland fires, have been increasing for decades worldwide due to climate change (Sayedi et al., 2024). In terms of the total area burned, the year 2022 was the second-worst year ever recorded in the European Union (San-Miguel-Ayanz et al., 2023). Nearly 900 000 ha of natural area was burned, 43 % of which was located in Natura 2000 regions. In Poland, almost 7000 fires in natural areas (including more than 4800 forest fires) were recorded, resulting in approximately 2850 ha of area burned (including 2210 ha in forests). In terms of the number of fires in natural areas, more fires were recorded in France (22 800 fires; 70 300 ha), Spain (10 500; 268 000 ha), and Portugal (10 400; 110 000 ha). Therefore, forest fires in Poland were frequent but covered small areas (0.4 ha per fire on average). Most of the fires in Poland occurred in May (more than 25 %),

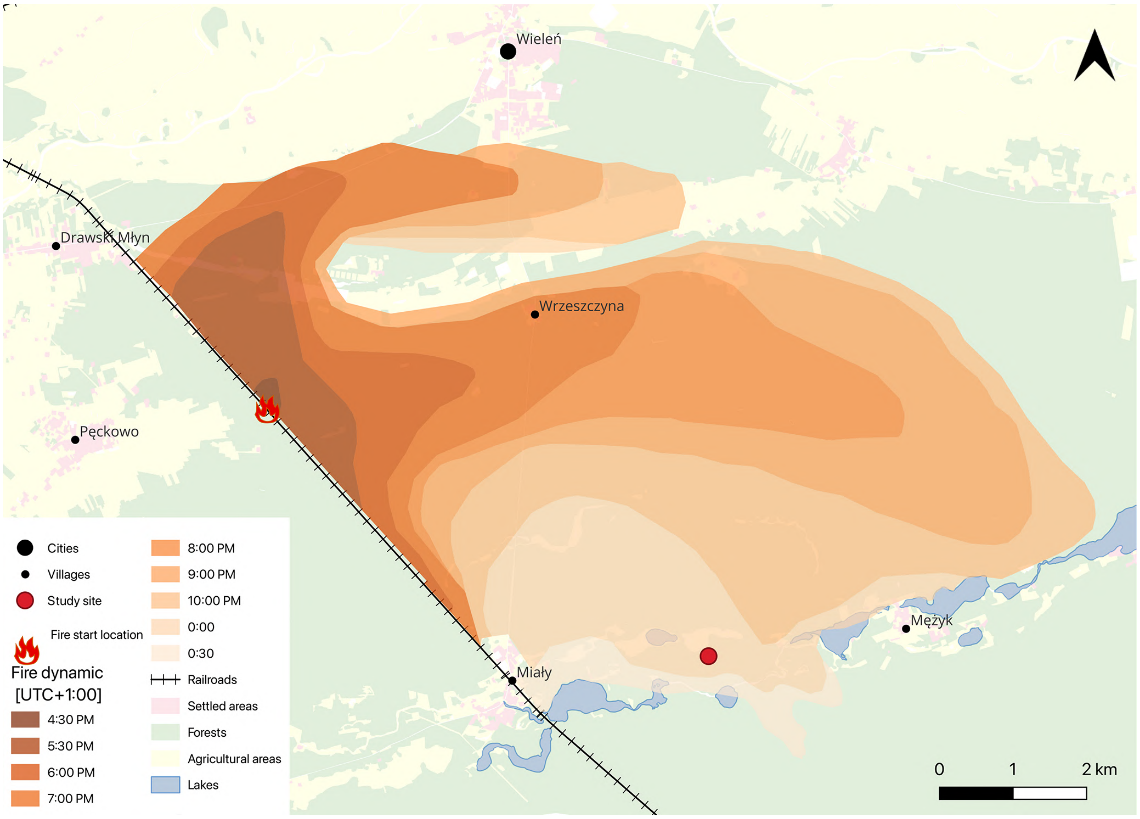

Figure 6. The rate of fire spread in the Noteć Forest in 1992 (author's own work based on data provided by the State Forests, Potrzebowice forest district).

a significant percentage of which were caused by drought. A recent study from the pine-dominated Tuchola Forest in Poland revealed a negative correlation between Scots pine growth and rainfall in May (Bąk et al., 2024), which indeed indicates a water deficit in that month. In 2022, there were 84 fire incidents in the Noteć Forest that resulted in 8.4 ha of burnt area. From 2007 to 2022, there were more than 1170 fire incidents that covered 96.7 ha. Hence, the Noteć Forest is a high-fire-risk area and, as a large monoculture forest complex, requires continuous monitoring, including within EU structures.

5 Conclusions

Understanding the functioning of peatlands that are under severe climatic pressure and have been exposed to extreme events in recent decades is crucial for their conservation and monitoring. Peatlands, as archives of environmental change, are sources of valuable information about past ecological disasters, recorded in both the palaeoecological and geochemical records. Combining these two approaches gives a complete picture of environmental changes due to fires or insect outbreaks. The conclusions of such studies can be successfully used to predict the consequences of contemporary phenomena. Particularly severe disasters can even lead to peatland ecosystems reaching critical transitions, after which there is an irreversible change in hydrological and trophic conditions, followed by a change in vegetation. We have identified many palaeo-indicators that allow a comprehensive assessment of the peatland's response to catastrophic events, both at the time of these events and on a long-term scale (Fig. 7).

We have shown that the Miały peatland has rapidly acidified as a result of *Panolis flammea* infestation and forest restoration activities. We reported a significant decrease in *Pinus sylvestris*-type pollen during catastrophic events. Competition among plants in the peatland was won by those adapted to acidic conditions, *Sphagnum* mosses, which displaced monocotyledonous plants. We point out that it is difficult to identify past *Panolis flammea* outbreaks, as the remains of these moths do not preserve well in sediments. We emphasized a cautious approach to fungi as bioindicators of environmental change due to many ambiguous interpretations in studies. Charcoal analysis can provide information on localized fires, but it should be emphasized that not every fire is recorded in this way. For this reason, adequate validation of the data with historical sources or, if these do not exist, multi-proxy palaeoecological analyses are essential. How-

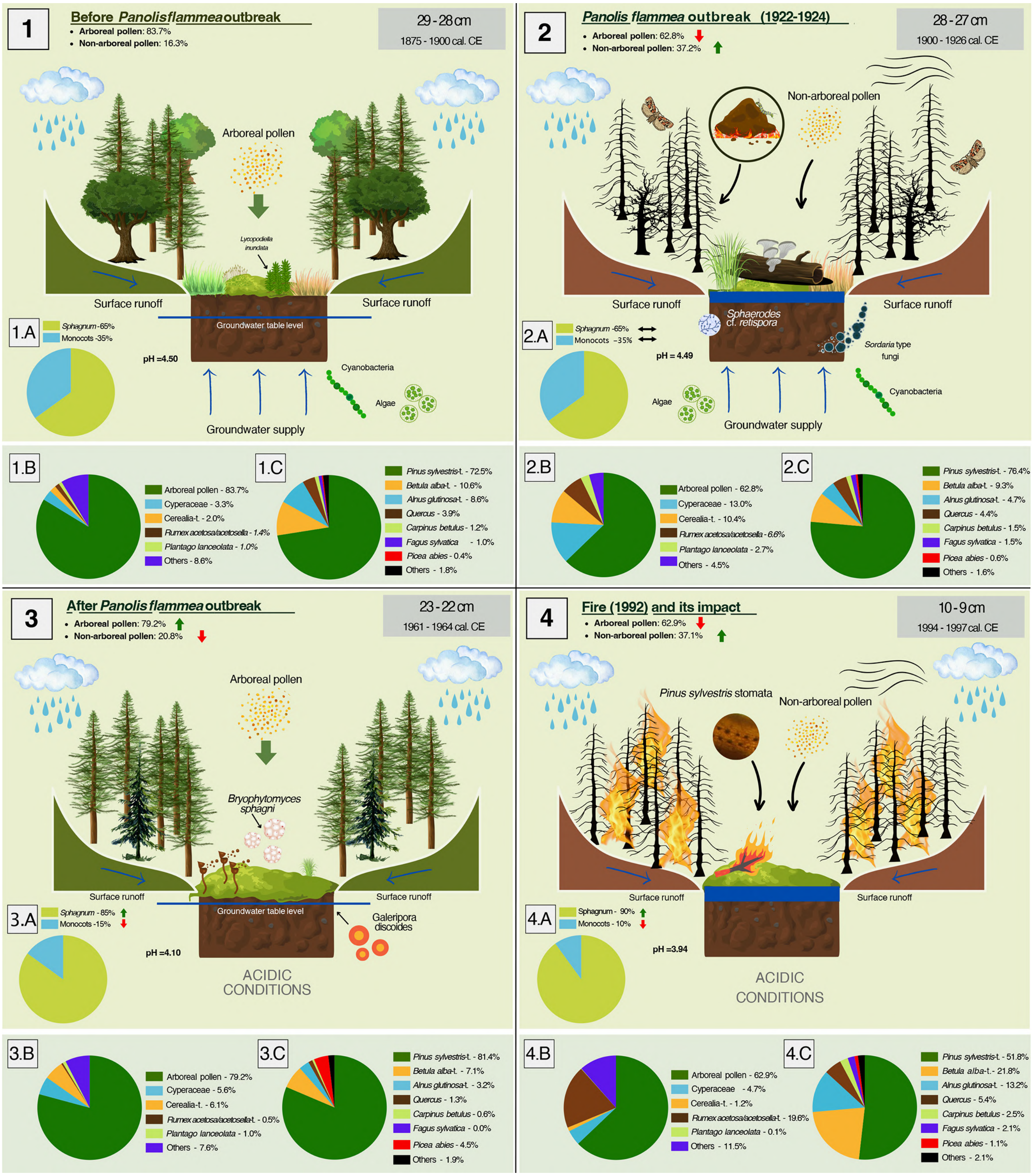

Figure 7. Diagram showing environmental changes in the Miały peatland and the forest surrounding it as a result of the *Panolis flammea* outbreak (1922–1924; panel nos. 1 and 2), leading to a change in forest structure to a *Pinus sylvestris* monoculture (panel no. 3) and the consequences of poorly resilient monocultures in the form of the 1992 fire (panel no. 4). The percentages of taxa in the pie charts were taken from palynological data. Each of the four large panels corresponds to one specific layer in the peat profile – the depth of the layer and the calibrated period are marked in the upper-right corners of the panels in a grey box.

ever, we point out that other palaeo-recordings, treated cautiously, can help identify past fires, such as *Pinus sylvestris* stomata. To understand current or recent changes in peatlands and their surroundings, it is often not enough to analyse the recent history covering the last 100–200 years; rather, the background going back hundreds or thousands of years must be considered. Only such a combination gives a complete overview of changes due to human activity, climate change, or ecological disasters. We observed that there has been no catastrophic deforestation for more than 1800 years. Major deforestation occurred only after changes in forest management. The peatland was also hydrologically and trophically stable for most of the time analysed. Drastic changes in trophic and hydrological conditions of the Miały peatland began after the introduction of planned forest management in the late 18th century, weakening forests' resilience to environmental disasters. Particularly extreme changes occurred with the 1922–1924 *Panolis flammea* outbreak period and the subsequent approach to forest restoration after 30–40 years. Moreover, keeping the forest structure homogeneous led to a huge fire in 1992 (Fig. 7).

Appendix A

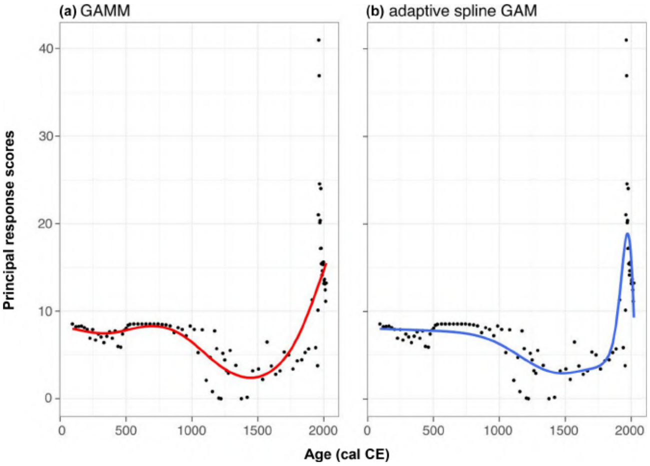

Figure A1. PrC **(a)** GAMM and **(b)** GAM with adaptive spline – raw scores and fitted relationships.

Data availability. The open dataset that supports the findings of this study is available from Mendeley Data: https://doi.org/10.17632/cv5t59wf24.1 (Bąk et al., 2025).

Author contributions. MB: fieldwork, laboratory analyses (bulk density, carbon accumulation, plant macrofossils, and selection of plant macrofossils for AMS radiocarbon dating), age–depth modelling, data interpretation, visualization, and writing (original draft). ML: fieldwork, support with plant macrofossil analysis, data interpretation, and writing (commented on and edited the manuscript). PK: laboratory analyses (pollen and spores), age–depth modelling, data interpretation, visualization, and writing (commented on and edited the manuscript). DW: laboratory analyses (testate amoebae), testate amoeba-based reconstructions, and data interpretation. MJ: fieldwork, data interpretation, and writing (commented on and edited the manuscript). LA: statistical analyses, data interpretation, and writing (commented on and edited the manuscript). KM: funding acquisition, conceptualization, fieldwork, laboratory analyses (charcoal), data interpretation, visualization, and writing (commented on and edited the manuscript)

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Substantial changes in land and forest management led to critical transitions in peatland functioning over the last 700 years

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Over the last 300 years, many European forests have been progressively modified toward monoculture ecosystems, with preference given to coniferous forests. These forests, often dominated by Scots pine (*Pinus sylvestris*), are currently impacted by various disturbance factors, e.g., more frequent windthrows, droughts, fires and insect infestations. Peatlands located in these monocultures are also significantly impacted, enhancing their vulnerability to drying and burning. Here, we investigate how the functioning of a *Sphagnum*-dominated peatland has changed during the last ca. 700 years along with the introduction of new forest management strategies–modification of a mixed-forest complex into a Scots pine monoculture. Multi-proxy, high-resolution palaeoecological analyses include AMS radiocarbon dating, pollen and spores, plant macrofossils, testate amoebae and historical data. Direct peatland fire disturbance was reconstructed using a wide range of charcoal analyses: charcoal counts and morphological types to reconstruct past fire activity, and Raman spectroscopy to reconstruct past fire intensity. The results obtained confirm that introduction of new management techniques impacted the functioning of the peatland, leading to critical transitions in vegetation composition and hydrology. Detailed analyses of a distinct charcoal layer present in the peat show that increased fire activity as recorded by charcoal accumulation does not necessarily equate to burning intensity. Therefore, we recommend the use of charcoal-derived wildfire intensity reconstructions in tandem with charcoal abundance studies.

Keywords Palaeoecology, Palaeofire, Fire activity, Fire intensity, Monoculture, *Pinus sylvestris*

The functioning of peatlands, once a common feature across the Northern Hemisphere, has been drastically impacted by human activity over decadal and centennial timescales[1,2]. As a result, many peatlands have been destroyed or severely disturbed, recording a gradual decrease in area across a number of countries[3]. For example, several studies from Europe assessing the number of wetlands and/or peatlands subject to significant disturbance or destruction have determined ca. 85%, 98%, and 94% of peatlands have been drained in Poland[4], Germany, and the Netherlands[5], respectively.

Most peatland disturbance originates with the ever-growing influence of human activity on the landscape. Such pressures may comprise direct or indirect actions, operating independently or in tandem, which in turn influence peatland ecosystem functioning. Direct anthropogenic pressures include peatland drainage[3,6,7] or deliberate peat extraction (e.g., gardening, fuel, building materials[8–10]). Indirect impacts are often associated with the expansion of agriculture adjacent to the peatland[9,11], or an implementation of changes in forest management techniques to the nearby forest complexes[12,13]. As a consequence, these disturbances most often perpetuate lowering of the water table, with a myriad of consequences for subsequent peatland functioning. By lowering the water table in a peatland ecosystem, the encroachment of surface vascular vegetation (e.g., dwarf shrubs, tree saplings) is often promoted, in turn, outcompeting mosses[14–16]. Pervasive hydrological disturbances lead to droughts and further increase the vulnerability of peatlands to fires and dramatic carbon losses[17–19].

The impact of disturbances on peatlands and their subsequent regeneration have been studied thus far through observational and experimental studies[20–22], and the use of palaeoecology[8,23–25]. Research to date has

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shown that regeneration efforts do not always lead to the reappearance of pre-disturbance vegetation[10], and novel ecosystems may be created, possessing similar ecosystem functions but varying species compositions[26]. Hydrological conditions are crucial for peatland recovery[27,28], including post-fire recovery[29,30]. Similarly, restoration is vital in protecting peatland carbon stocks and mitigating emissions[31,32]. There exists, however, a shortage of research regarding the impact of forest management on peatlands, specifically regarding complex interplays of multi-phase co-interactions of disturbance factors[33]. As most peatlands have been disturbed in the past by various factors, more attention needs to be paid to the understudied effects that local fire disturbance and vital large-scale forest structure modifications have had on *Sphagnum*-dominated peatland ecosystems.

Our aim is to reconstruct how peatland ecosystem functioning has changed over the last ca. 700 years as a result of this unification in forest stands, in particular, the influence of forest management on peatland vegetation, hydrology, and fire activity. To achieve this, we have applied high-resolution contiguous sampling and multi-proxy reconstruction to an inter-forest peatland record, based on pollen and spores, plant macrofossils, testate amoebae, and a wide range of charcoal analyses (charcoal counts and morphological types, and Raman spectroscopy). We support our interpretations with historical and geopolitical data. We hypothesise that the establishment of monoculture forest has suppressed fire activity and stabilized hydrological conditions in the studied peatland (Fig. 1).

Results and interpretation

Chronology and peat and carbon accumulation rates

The investigated sequence spans ca. 695 years between 1327 ± 60 cal. CE and 2022 cal. CE. The age-depth model revealed a model agreement index (A_{model}) equal to 49% (Fig. 2) which is below the recommended minimum

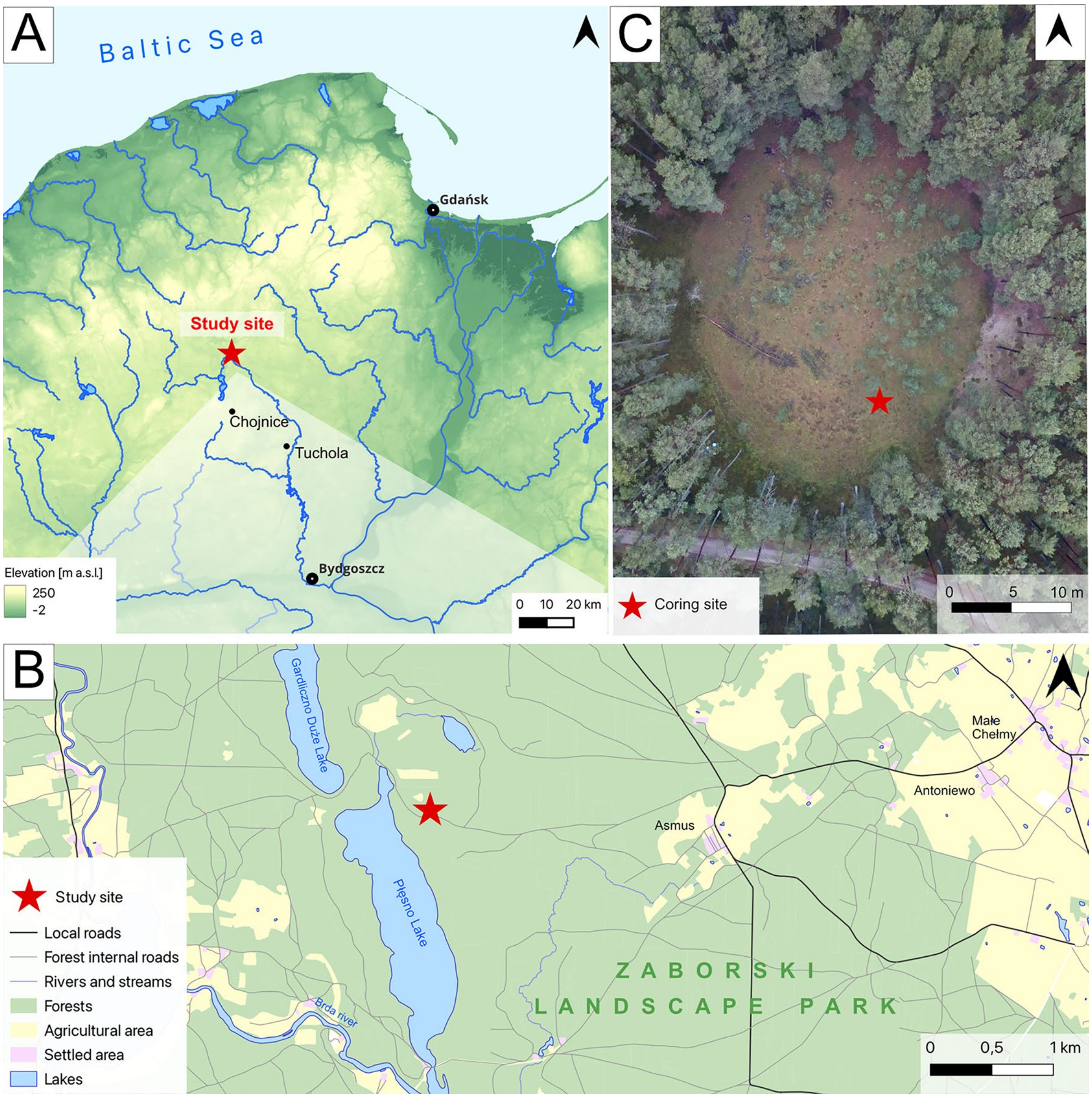

Fig. 1. Study site location.

(60%; Bronk Ramsey[34]). However, we accepted this model as only one date (Poz-152923) revealed an individual date agreement to the model < 60%. All other dates have an individual agreement > 60%. The temporal resolution of samples was dependent upon their position in the peat profile. This ranged between 1–3 years/cm in the section between 0–30 cm (2022–1969 cal. CE) to 18–38 years/cm in the section between 91 and 96 cm (1478–1327 cal. CE). However, for the majority of the peat profile it did not exceed 11 years/cm. The 1 σ error of the modelled age ranged between ca. 0 and 60 years. The sediment accumulation rate (SAR) ranged between 0.03 and 0.06 (1478–1327 cal. CE) to 0.9 cm/year (2022–2011 cal. CE).

Environmental changes in Stawek peatland

The Stawek record, as studied here, presents three distinct phases of peatland development across the study period, associated with fire activity (Phase 1), human occupation of the area (Phase 2), and land and forest management (Phase 3).

Phase 1 – Fire disturbance and post-fire regeneration (ca. 1400–1630 CE, 96–70 cm)

Phase 1 in the development of Stawek peatland is associated with a prominent charcoal layer, visible in the core between ca. 1400–1580 CE (96–80 cm), characterised by a predominance of charcoal and *Substantia humosa* (i.e., highly decomposed organic material), exceeding 80% abundance in some layers (Fig. 3). Among the identifiable plant macrofossils, the peat was dominated by *Sphagnum* sub. *Cuspidata,* alongside other unidentifiable *Sphagnum* spp. Numerous monocot remains, fragments of *Pinus*, and wood were also present. Above the charcoal layer, between ca. 1600–1630 CE (80–70 cm), macrofossil evidence suggests a period of post-disturbance regeneration and a succeeding stabilisation of the peatland. This coincides with a fall in the proportion of *Substantia humosa*, a paucity of *Pinus* remains, and an increase in *Sphagnum* counts.

Among testate amoebae present during this phase, the most common species include: *Cryptodifflugia oviformis*, *Hyalosphenia subflava*, *Phryganella acropodia*, *Schoenbornia humicola* and *Trigonopyxis arcula* (Fig. 4). The presence of *H. subflava* and *T. arcula* has previously been associated with fire/post-fire regeneration in moorland[35], while *C. oviformis* and *S. humicola* are common in dry and disturbed habitats[36], including within charcoal horizons and disturbed layers throughout other peat cores[37]. All aforementioned species incorporate mineral material from the environment to form their shells. A high abundance, as observed here, indicates increased mineral deposition into the peatland during this phase[23]. Notably, all of these species disappear from the testate amoeba communities at the end of phase 1, indicating a substantial environmental shift.

Quantitative reconstructions show that the mean depth-to-water table (DWT) in this phase equated to 23.2 cm (14.6–33.5 cm), with a sharp rise in water table depth from 22.2 cm to 14.6 cm in 1620 s CE. A mean pH value of 4.7 at this time, marked a fall from 5.6 early-phase, to 3.9 end-phase. (Fig. 4).

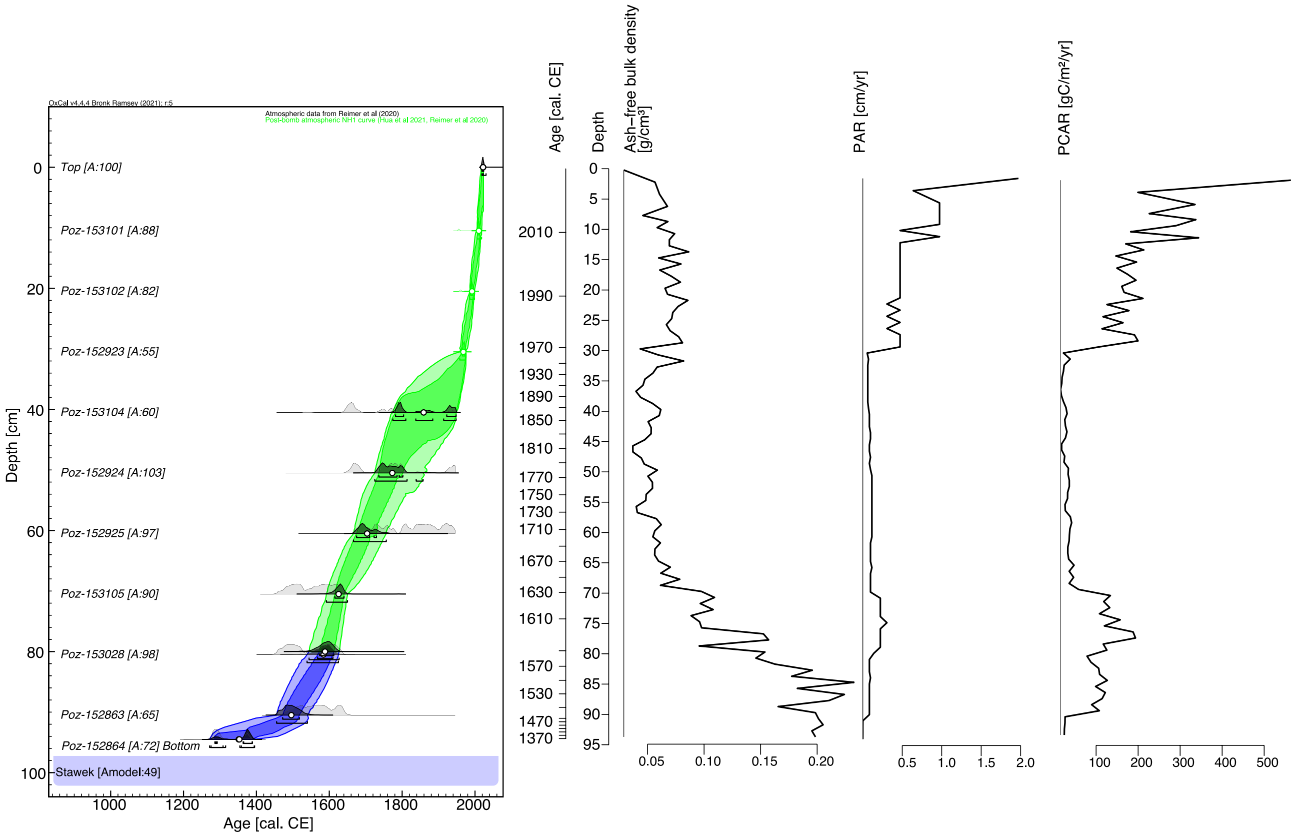

Fig. 2. Age-depth model for the Stawek peat core and changes in bulk density and carbon accumulation rates.

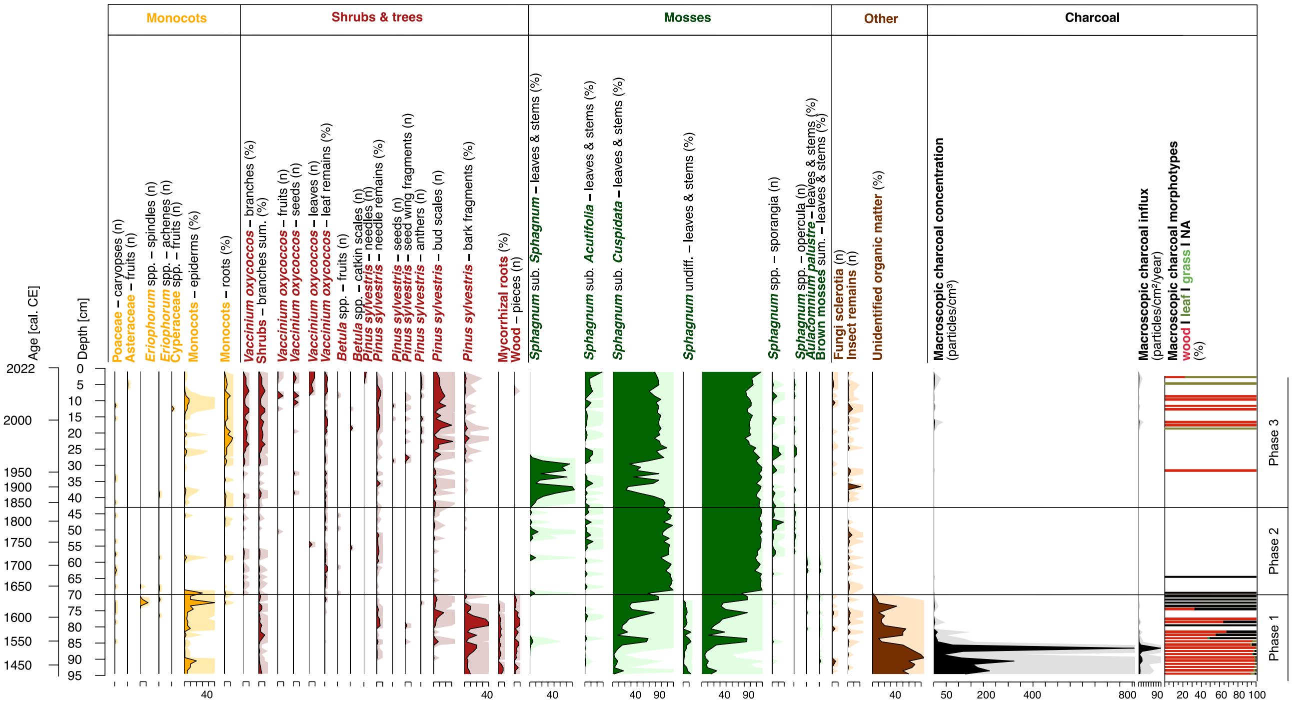

Fig. 3. Plant macrofossil and macroscopic charcoal diagram (5 times exaggeration is marked).

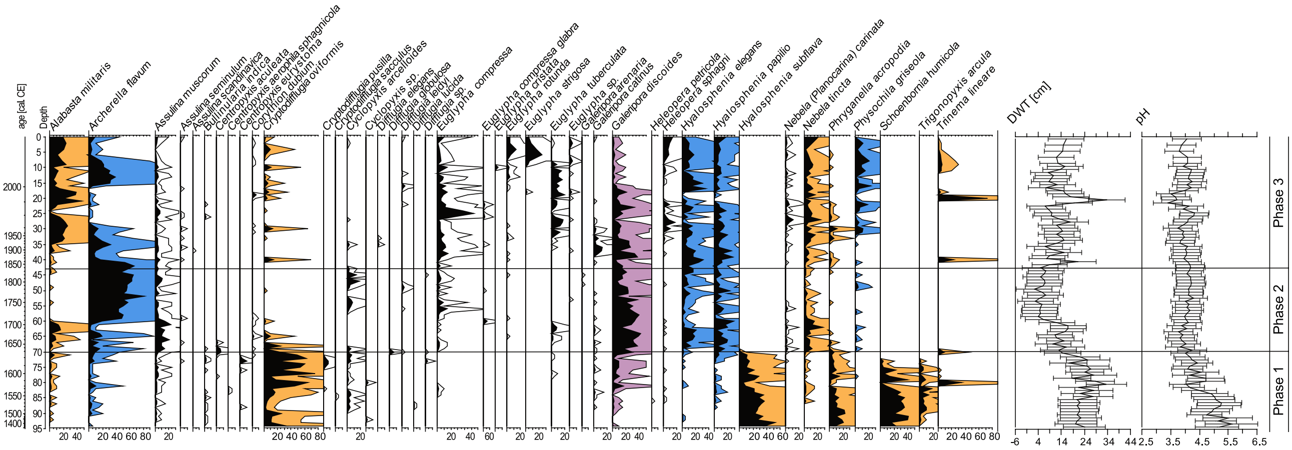

Fig. 4. Testate amoeba diagram (5 times exaggeration is marked) and quantitative reconstructions of depth-to-water table (DWT) and pH. Dry indicator testate amoebae are marked in orange, wet indicators in blue, and disturbance indicator in purple.

Pollen records suggest a closed canopy forest within the area at this time, dominated by *Pinus sylvestris* and an admixture of *Betula*, *Alnus glutinosa*, *Corylus avellana*, *Quercus*, *Fagus sylvatica* and *Carpinus betulus* (Fig. 5). At ca. 1535 CE (86.5 cm) a sharp drop in deciduous tree pollen – particularly *Betula*, *A. glutinosa*, *C. avellana* and *C. betulus* – accompanied a marked increase in *P. sylvestris* pollen frequency, exceeding 80% abundance toward the end of the phase. During this period, the loss of deciduous canopy supported an increase in cereal populations, primarily *Secale cereale*.

As mentioned previously, this phase in peat accumulation was dominated by charcoal, with overall abundance remaining very high up to ca. 1580 CE (81 cm). This is contrasted by a significant reduction in charcoal toward the end of this phase, between 1600–1630 CE (80–70 cm). Mean macroscopic charcoal influx (MAC) across this charcoal horizon totalled 11.3 particles/cm^2/year, a considerable figure for peatlands (Figs. 3, 6), with peak MAC (89.9 particles/cm^2/year) recorded at ca. 1530 CE (86.5 cm). With respect to charcoal morphology, most of the analysed macroscopic charcoal pieces were wood fragments, with a few leaves, and some indeterminable fragments (Fig. 6). Some of the charcoal pieces were large enough (> 1 cm) to permit species identification, all of which corresponded to burnt *Pinus sylvestris* (Fig. 6). Some charcoal pieces also displayed evidence of

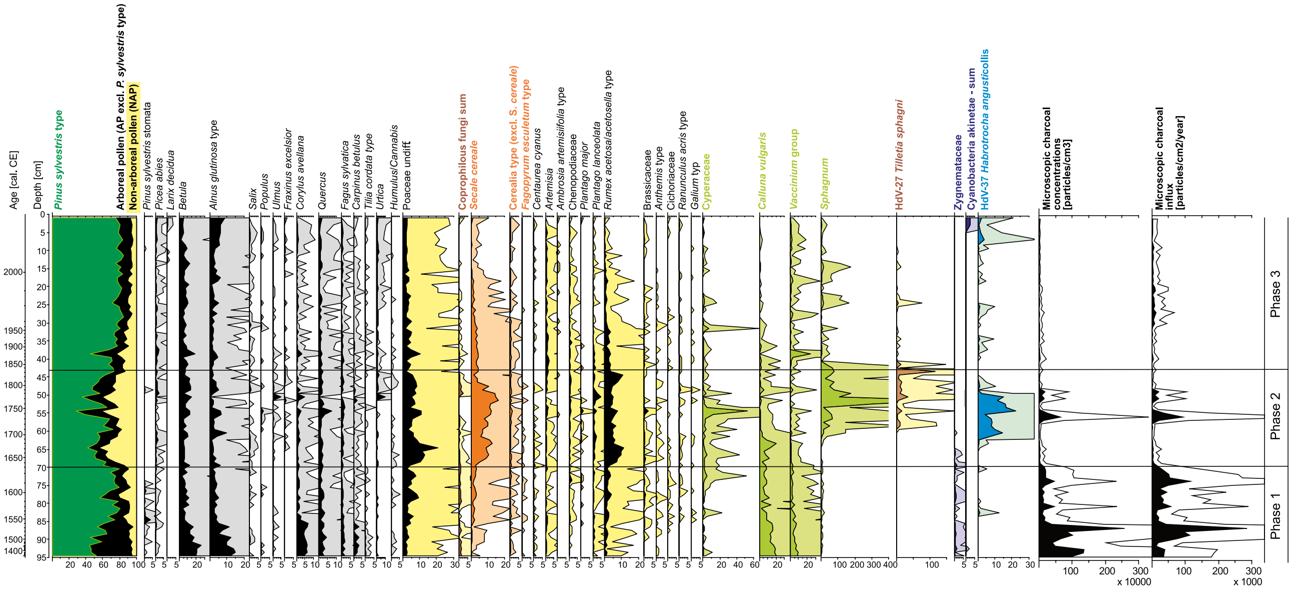

Fig. 5. Palynological diagram including pollen, spores, selected non-pollen palynomorphs, and microscopic charcoal (5 times exaggeration is marked).

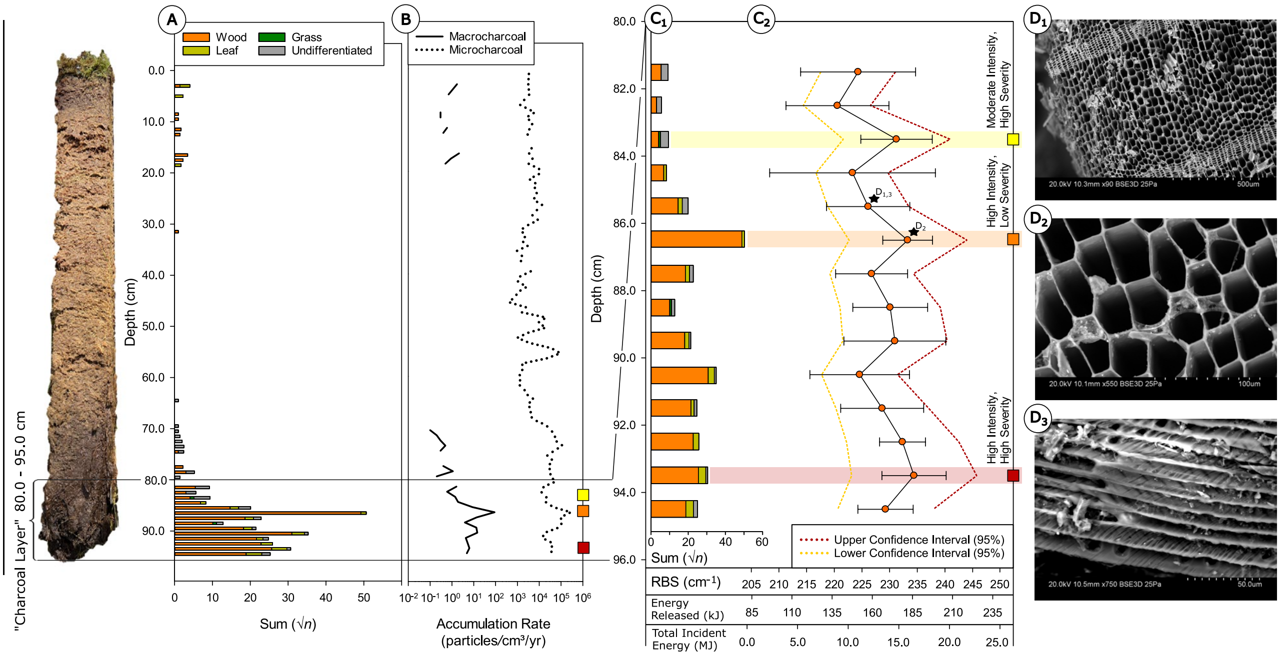

Fig. 6. Detailed diagram presenting the Stawek charcoal layer: [A] macroscopic charcoal morphotype data (square-root transformed); [B] macro- and microscopic charcoal accumulation rates (logarithmic scale); [C1]—charcoal count and morphotype data with [C2] comparative results for the Raman spectroscopy of charcoal samples between core depths 80.0 – 96.0 cm. Values for median RBS are shown here alongside equivalent metrics for fire intensity reconstruction, including 'energy released' (kJ) and 'total incident energy' (MJ) after Eqs. (1) and (2), respectively[77]. Dotted lines indicate upper and lower confidence intervals (95%) for fire intensity reconstruction; and [D] SEM photographs of the largest found charred wood fragments of *Pinus sylvestris* presenting: [D1] wood cell structure, [D2] hyphae penetrating cell walls, and [D3] compression wood.

compression wood, commonplace in pines growing on peatlands[38], as well as cell wall-penetrative fungal hyphae, suggesting one source of the charcoal included decomposing *Pinus* wood at the peatland surface[39]. This is further evidence for localised *Pinus* encroachment and peatland drying during this phase.

In contrast, mean microscopic charcoal influx (MIC) across this layer totalled 59,107 particles/cm^2/year, demonstrating substantial regional fire activity (Figs. 5, 6). Coinciding peaks in MAC and MIC (285,309 particles/cm^2/year) at ca. 1535 CE (86.5 cm) suggest the representation here of a single or several fire events, or that fire activity was commonplace throughout the entire region at this time. Regional fires represented by MIC were still active during the regeneration phase of Stawek peatland (ca. 1600–1630 CE, 80–70 cm depth), with a mean influx of 44,005 particles/cm^2/year.

Randomised macrocharcoal pieces, isolated between 81.0 and 95.0 cm (ca. 1580–1370 CE), offer median Raman band separation (RBS) values and equivalent wildfire intensity metrics (i.e., energy released and total incident energy) indicative of a general trend in fire intensification with depth (Fig. 6). This intensification appears to occur with an approximate cyclicity, as peak intensification occurs every ~ 3–4 samples (1.5–2 units). Troughs in intensification immediately follow periods of cyclical peak intensity, suggesting a 'rapid' reversal of fire-promotive conditions. Broadly, wildfire intensity as reconstructed here shows an inverse relationship with standard deviation at each interval, suggesting an increase in sample variability (i.e., fire system variability) during periods of low intensity. This may reflect a variability in the degree to which material is charred, due to increased material preservation under lower fire intensity conditions (i.e., less material is combusted away). This coincides with an observation of brown colouration, indicative of partial charring in samples of lower median RBS (e.g., STA_81.5). Partial charring is also evident in poorly resolved D- and G-bands, with spectra that exhibit an increased distance between the horizontal axis and the righthand tip of the spectrum. This feature is representative of 'fluorescence angle' and typically denotes heterogeneous physiochemistry (e.g., lignocellulosic[40]) that has not been removed fully under progressive charcoalification[41]. This variability may also be related to the dominant or constituent mix of fuels charred, and their inherent physiochemical differences, in turn responding differently to wildfire conditions.

Phase 2 – Thriving agricultural activities (ca. 1630–1840 CE, 70–43 cm)

Sphagnum abundance increases (Fig. 3), peaking at almost 100% between ca. 1645–1685 CE (67.5–63.5 cm depth). In this instance, the dominant *Sphagnum* species were those from sub. *Cuspidata*, however, some leaves and stems of *Sphagnum* sub. *Acutifolia* and sub. *Sphagnum* were also present, alongside remains of vascular plants, mainly those of *Vaccinium oxycoccos* and *Pinus sylvestris*. The domination of *S.* sub. *Cuspidata* points to acidification and formation of lawn microforms typical for poor fens.

The testate amoeba community composition also changed in this phase (Fig. 4), with the replacement of fire-related taxa by common dry indicator species, for example *Alabasta militaris* and *Nebela tincta*. At the same time, *Galeripora discoides* appeared in greater numbers–a species that is common in hydrologically unstable habitats[36,42]. It was soon followed by an encroachment of wet indicator mixotrophic taxa, namely, *Hyalosphenia elegans* and *Hyalosphenia papilio*.

At the beginning of the eighteenth century CE, wet indicator species *Archerella flavum* dominated the recorded testate amoeba communities, coinciding with quantitative DWT reconstructions and an indication of a substantial rise in water tables. A mean DWT value of 8.5 cm (16.9 cm to 2.2 cm) was accompanied by a sharp increase in depth-to-water table from 11.9 cm to 6.2 cm at the beginning of eighteenth century CE (ca. 1700–1715 CE, at 60.5–59.5 cm depth). Additionally, pH values ranged between 4.2 and 3.8 (mean pH: 4.0) which indicates high acidity in the peatland at this time.

Pollen analysis indicates a change in local vegetation composition and an opening of the landscape (Fig. 5), represented by a substantial drop in arboreal pollen ('AP' *herein*) – falling to 55% at ca. 1670 CE (64.5 cm; Fig. 5). Increases in Poaceae (≤ 20%), *Rumex acetosa/acetosella* type (≤ 11%) and crops, principally *S. cereale* (> 16%), indicate deforestation and a rapid increase in agricultural activity within the study area at this time[43]. Relative abundance of *S. cereale* remained elevated for much of phase 2, up to ca. 1800 CE (47.5 cm), later falling below 4.5%.

A particularly low abundance of macroscopic charcoal preserved during this phase suggests little to no local fire activity (Fig. 3), or an intrinsic constraint on charcoal preservation. The absence of evidence for fire activity suggests successful suppression efforts by local populations, during active management of the land in the region. With respect to regional fire activity, two peaks in MIC – 94,139 (55.5 cm) and 20,500 (48.5–50.5 cm) particles/cm^2/year, at ca. 1740 CE and 1770–1790 CE, respectively – coincide with short-term drops in AP indicative of deforestation.

Phase 3 – The establishment and impact of Pinus monoculture (ca. 1840–2022 CE, 43–0 cm)

The top section of the Stawek core presents as *Sphagnum*-dominated peatland, comprised primarily of *S.* sub. *Cuspidata*, with a short-term dominance of *S.* sub. *Sphagnum* between ca. 1885–1970 CE (37.5 and 29.5 cm), and the presence of *S.* sub. *Acutifolia* (Fig. 3). A large number of vascular plant remains were also present, mainly those of *V. oxycoccos* and various fragments of *P. sylvestris*. The presence of *S.* sub. *Sphagnum* may indicate a change in the microtopography of the peatland surface, specifically to the formation of hummocks with dwarf shrubs common for ombrotrophic peatlands.

Testate amoeba compositions during this phase were characterised by a fall in the abundance of *A. flavum*, while *A. militaris* and *N. tincta* became more abundant (Fig. 4). Within the final 20 years of accumulation, the abundance of *G. discoides* fell, alongside a re-appearance of *A. flavum* in greater numbers, together with the mixotrophs *H. elegans*, *H. papilio* and *Physochila griseola*. Quantitative reconstructions indicate a substantial rise in water tables, including a mean DWT value of 12.8 cm (21.3–4.9 cm). Two transient periods of falling water tables at ca. 1860 CE and 1990 CE (40.5 and 20.5 cm, respectively) correspond to the appearance of *Trinema lineare* and the re-appearance of *C. oviformis* as small, dry habitat indicators[44]. The increase in DWT at ca. 1860 CE is similarly related to a change in dominant *Sphagnum* species under the encroachment of *S.* sub. *Sphagnum*. Moderate drying can be observed in the uppermost peat layers, and pH values range between 3.5 and 4.3 (mean pH: 3.9), indicating continued high acidity.

In this phase, pollen compositions suggest an ecosystem dominated by trees, supported by a peak in AP abundance of 95% in the 2010s, and a mean AP value for this phase of 90.5%. Forest composition was, at this time, comprised primarily of *Pinus* and an admixture of *Betula* and *A. glutinosa* (Fig. 5). A reduction in the abundance of Poaceae, cereals and ruderal taxa such as *Rumex acetosa/acetosella* type indicate reforestation of the area, with a substantial decrease in localised agricultural activities.

Fire activity was very low in this phase (Figs. 3, 5), with only a few small, charred wood fragments and leaves present in this phase of peat accumulation. Charcoal counts remained low (mean MAC: 0.2 particles/cm^2/year), indicative of limited (if any) localised burning, with some evidence of regional burning (mean MIC: 4269 particles/cm^2/year). Microcharcoal accumulation rates at this stage are, however, lower than any other period through the Stawek profile, raising questions as to the true extent of regional fire activity.

Discussion

Management practices as a proponent of critical transitioning in peatlands

Numerous natural and anthropogenic factors substantially impact peatland functioning, leading to modifications in various peatland ecosystem components, including vegetation, microbial food webs, hydrology, peat/carbon accumulation rates, and others[1,27]. The stronger and more pervasive the disturbance, the greater its impact on peatland functioning[19]. Many examples show critical transitions in wetlands as a source of transformation in certain ecosystems–modifying their functioning due to the crossing of tipping points[27,45]. In the Stawek record, we have distinguished two critical transitions in ecosystem functioning, visible in plant macrofossil, testate amoeba, and charcoal data. By correlating high-resolution pollen and historical data, we have further identified the causes and effects of these substantial changes in peatland functioning.

At the onset of the seventeenth century CE, the first critical transition in Stawek is marked by a sharp change in the sediment type–from highly decomposed peat, rich in charcoal, to the appearance of *Sphagnum* and heightened peat accumulation rates. Between the fourteenth and seventeenth centuries CE this peatland experienced a subsequent drying with surface fire activity, as evidenced by the analysis of charcoal particles and the presence of hyphae in the wood cells (Fig. 6). Though substantial at that time, the frequency of fire activity during this period is indistinguishable with contemporary methods in charcoal analysis. An abrupt reduction in fire activity, as observed, is possibly attributable to the activity of local communities present in the area at the time, utilising this region for agricultural purposes.

An increase and decrease in cereal and arboreal pollen, respectively, implies the opening of forest canopies with moderate rapidity, expansion of farming, and suppression of natural fire activity. It is likely that a number of the broadleaf species (e.g., oak, hornbeam) were used by local communities to establish villages and households–well documented in Polish archaeological and palaeoecological studies[46,47]. The opening of the forest and the establishment of agricultural land at this time is further observed in the sharp increase in cereal pollen types typically grown in this region (e.g., *Secale cereale, Fagopyrum*), often coupled with the drainage of wetlands[33]. The expansion of farming and intensification of land use, as observed here, represent 'tipping points' in peatland development, recorded previously, e.g., in Pawski Ług peatland, where in the mid-fourteenth century a rapid transition from a lake to a *Sphagnum*-dominated peatland took place[12]. In the case of Pawski Ług, significant alterations to land management were brought about by the Knights of the Order of St. John (Joannites), who controlled estates in Brandenburg and Pomerania. Consequently, German settlers were introduced to the former Slavic territories in 1350[12]. The introduction of a feudal economy on less-developed lands centred around landscape opening for the establishment of agriculture and was a common practice in the Middle Ages across Europe[47–50].

The landscape opening around Stawek peatland was later facilitated by more invasive activities related to the growing economy. In the seventeenth and eighteenth centuries CE, tar and glass factories were principal industry sectors in the region, from which goods were exported to various European locations until the 1st World War[51]. Charcoal, produced in numerous hearths across the Tuchola Forest, represented another significant export commodity[51]. Two temporary reductions in cereal pollen abundance in the eighteenth century CE may correspond to periods of civil and political unrest, e.g., the 'Third Northern War' (1700–1725) or the 'Seven Years War' (1756–1763), the effects of which have been noted in the pollen record of Lake Czechowskie (Northern Tuchola Forest)[52]. This perturbation in cereal pollen is similarly noted with the first partition of Poland in 1772, and the annexation of Pomerelia (incl. the Tuchola Forest) to Prussia[33,53,54].

A contrasting process marks the second critical transition, namely, the closing of the forest and plantation of pine within the Stawek study area. This abrupt change in forest management strategy was the result of Prussian administrative decisions, as defenders of land inclusive of the Tuchola Forest, subsequent to the partition of Poland in 1772. In the first decades of the Prussian administration, private lands were still used by peasants for agriculture[55]. However, the liquidation of state forests had declined in the 1830s, and ceased in 1860[56]. The introduction of new management strategies focussed on timber production, resulting in a substantial modification of forest composition. This was characterised by a shift from a 40% broadleaf to 60% Scots pine mix to almost 100% *Pinus sylvestris* forests[24,33].

According to historical sources, by as early as 1893, *Pinus* had been planted in up to 99% of forests in the Tuchola Forest District[33,54]. Moreover, the *Pinus sylvestris* saplings planted during this period were non-native, transported from Germany (primarily Schwarzwald) and thus ill-adapted to the local climatic and edaphic conditions. Subsequently, German *Pinus sylvestris* have been gradually replaced with native Polish *Pinus sylvestris* saplings, to strengthen the forest stands (Local Forester, *personal communication*).

This change in forest composition was also associated with a division of the forest into clear-cut, squared/rectangular districts. Domination of coniferous species increased soil acidity, creating a so-called "sea-salt effect"[54,57,58]. Management by Prussians involved not only a substantial change in forest stands, but also water management, characterised by the introduction of melioration and drainage and, in consequence, the drying of various types of wetlands[51] (see Bąk, et al.[54] for a detailed historical background). Deliberate lake and pond desiccation, and progressive soil acidification, created a suitable acid habitat for the encroachment of *Sphagnum* and finally the terrestralisation of water bodies, still observed today[59–62]. Bagno Stawek Nature Reserve offers another appropriate analogue, located ca. 500 m from our study site. This alkaline fen, possessing endangered flora such as *Saxifraga hirculus*, *Cinclidium stygium* and *Paludella squarrosa,* is now suffering from *Sphagnum* encroachment (personal observation), leading to its gradual degradation.

The closure of forest stands is visible in the Stawek palynological record, and a highly acidic environment is evident in both plant macrofossil and testate amoeba records (Figs. 3, 4, 5). The presence of diverse *Vaccinium oxycoccos* macroremains and an increase in abundance of *S.* sub. *Sphagnum* points to ombrotrophication and formation of hummock-hollow microtopography on the surface of the peatland. It is evident that the introduction of monoculture led to minor hydrological disturbances in the peatland but did not significantly impact its acidity–most likely due to the influence of *Pinus sylvestris*. A similar process was observed in the Noteć Forest in north-western Poland, which has a similar history to the Tuchola Forest – it was annexed into Prussia (1772) and modified to a *Pinus sylvestris* monoculture[63]. These actions resulted in an acidification of the area, lowering of the water table, and the encroachment of *Sphagnum* into existing water bodies, thus creating many new peatlands. This transformation is best represented by the *Sphagnum* encroachment and colonisation of Lake Rzecin, currently forming the largest peatland in the Noteć Forest[63,64].

Monoculture forests, as unified forest stands dominated by one tree species, are notably susceptible to various disturbances, such as droughts, forest fires or insect infestations[33,65–67]. Surprisingly, however, there has been no observable increase in fire activity (*as per* the charcoal record) across the Tuchola Forest within the last 200 years. Though few forest fires have been reported within historical sources, these were located elsewhere in the forest complex, and seemingly had no influence over the studied peatland area.

The Tuchola Forest also experienced several insect outbreaks (mainly caused by *Panolis flammea* and *Lymantria monacha* that feed on *P. sylvestris*) in the twentieth century, particularly in the years 1922–1924, 1962–1963 and 1978–1982[24,33,53]. Again, there was no discernible record of this disturbance, typically characterised by insect remains in the macrofossil record. This may be countered, only, by a minor decrease in *P. sylvestris* abundance, visible in the pollen record during the 1980s (Fig. 5). A similar palynological signal was recorded in the Martwe peatland, ca. 50 km from Stawek[24].

Evaluating multi-proxy trends in fire activity and intensity

Among high-resolution peatland charcoal records, studied in northern Poland over the last decade (e.g[6,12,13,24,68–72].,, only Stawek peatland, as investigated here, and Głęboczek (also located in the Tuchola Forest) possessed distinct and substantial charcoal layers ([37,73]; Fig. 6).

Relative to Stawek, the Głęboczek charcoal layer was substantially thinner and its presence was associated with a ca. 500-year hiatus[73]. Whilst radiocarbon dating and age-depth modelling offer no evidence of significant inversion in the Stawek peat record (Fig. 2; Marcisz, et al.[37]), it may be fair to assume that a number of short-term hiatuses, undetectable by sediment dating, are present. This offers a considerable opportunity to investigate the Stawek charcoal layer at high resolution, and determine the correlation, if any, between several complementary fire proxies, including Raman spectroscopy as a novel method in fire intensity reconstruction[74–77].

It is apparent under preliminary study that, as a result of heightened charcoal volume and proportions of highly decomposed peat (determined as *Substantia humosa*, Fig. 3), it is not possible to identify plant macrofossils in the bottom charcoal layer, excluding a few *Sphagnum* fragments. Reconstructed water tables were low (< 20 cm), and almost no mixotrophic testate amoeba species were present, suggesting that the site was not highly acidic. An increase in charcoal quantity from the base of the peat profile to 86 cm (ca. 1535 CE) further coincides with an increase in NAPs. Furthermore, immediately following the layer in which the highest charcoal sum was recorded (86.5 cm) we observe a substantial decrease in AP and deciduous pollen taxa: *Alnus, Corylus, Quercus* and *Carpinus*. It may be assumed, therefore, that these were selectively harvested by local populations to obtain timber for housing and/or everyday use[46].

Larger charcoal pieces (> 1 cm) found within this layer were all identified as *Pinus* fragments, burned when the trees were dead and decomposing, as indicated by the presence of hyphae in the charcoalified wood cells[39] (Fig. 6). This suggests that pine trees burnt in situ and confirms that the peatland was dry in this fire period, facilitating the burning of surface biomass that may have otherwise been waterlogged under wet peatland conditions. Dead *Pinus* wood situated on the surface of the peatland likely produced a considerable amount of charcoal and formed this layer.

Above the layer with the highest charcoal sums, the record indicates a simultaneous decrease in charcoal and an increase in cereal pollen, indicative of a reduction in fire activity and intensification of agricultural activities in the region. At the same time, *Pinus* pollen sums increase, in this instance, a likely artefact of high pollen production by *Pinus* rather than an expansion in *Pinus* extent. Therefore, it may be assumed that deciduous trees were selectively felled to obtain wood, the forest was opened to establish agricultural space, and local populations suppressed natural fires.

Several methods have been applied across the field of palaeoecology to reconstruct past fire intensity. For example, the trait approach has been used to group tree species into various fire trait categories (e.g., resister, avoider), with an assumption of past fire intensity predicated upon pollen sums and traits associated with certain species[78]. However, this method is limited by the potential for a species to burn in low and high-intensity fires, irrespective of fire resistance, assuming fire is present in the natural environment. Therefore, species composition alone cannot unequivocally inform about the level of fire intensity. Similar caution is necessary for interpretations based on the morphology of fossil charcoal fragments (e.g., length-to-width ratio), as applied to fire intensity reconstructions from ocean and lake sediments (e.g[79,80].,,). The morphological and morphometrical features of individual charcoal fragments can be strongly altered by taphonomic processes during deposition as well as chemical processing of the sediment and sieving during sample preparation. The assumptions as to what morphotype of charcoal is produced in certain environments may, therefore, be inaccurate and a simplification of otherwise complex fire behaviour in various ecological systems.

A range of factors influence the amount of charcoal produced during wildfires. Fuel types are important, as charcoal production varies between[81] and within a range of plant species[82]. In woodlands, if abundant understorey tree saplings are present a wildfire will produce more charcoal compared to a stand with fewer saplings. Saplings are highly susceptible to combustion due to their small diameter stems and thin bark (bark thickness is an important trait controlling the potential for charcoal production). Fine fuels (graminoids, leaves, needles, ferns, mosses and small twigs) with low fuel moisture are likely to record the opposite response, as charcoal is more likely to be consumed into ashes and gases during combustion. Given this, it is simplistic to assume a direct correlation between the number, volume and/or concentration of charcoal fragments, and fire intensity (e.g[83,84].,,). Whilst the hypothesis 'more equals more' may seem intuitive, contemporary observations in the experimental replication of wildfire suggest higher intensity fires consume (i.e., combust) a greater proportion of fuel mass at a higher rate, though this remains dependent upon the characteristics of the fuel (e.g[85,86].,,). As a result, the available fuel for preservation as charcoal is limited. Hence, less charcoal should be preserved in the sediment/peat resulting from combustion under high intensity fires, and vice versa. Similar assumptions are made under calculations of 'Fire Radiative Power' (FRP), as determined by a transfer function model[87] whereby FRP is calculated from charcoal sums. This suggests a close association between charcoal sums and FRP[69,88]that may not, in fact, reflect true fire intensity as reconstructed here by application of Raman spectroscopy. This has been emphasised in further studies, including the application of a variety of methods to reconstruct fire intensity in sediment records (e.g[89].,) and via Fourier Transform Infrared spectroscopy (FT-IR)[90–94].

Raman spectroscopy, applied to the physiochemical analysis of wildfire charcoals, represents a rapid, versatile, and non-destructive method of palaeofire intensity reconstruction[74–77]. In studying changes to nanoscopic crystalline structures within experimental charcoals, generated through laboratory pyrolysis at increasing temperatures, trends in spectral band-derived parameters have formed a robust basis for thermometry. The application of experimental pyrolysis in this instance yields 'pyrolysis intensities' as an approximate measure of wildfire intensity[95]. However, the temperature of pyrolysis has limited applicability in understanding the complex energy fluxes that occur during flaming combustion as experienced in a natural wildfire[96,97]. Recent efforts have, instead, developed measures of true wildfire intensity from calorimetric experimentation and Raman spectroscopy in tandem, considering the combined role of pyrolysis, flaming combustion, residual heating, and char oxidation in modifying the physiochemistry of charcoal[77]. From this, accurate reconstructions of fire intensity, as a function of energy release, are possible over different timescales, consistent with modern methods in wildfire characterisation[98].

The application here of Raman spectroscopy to Stawek charcoals suggests no definitive correlation between Raman-derived fire intensity and charcoal sums. Samples from which the most intense fires have been reconstructed were seldom associated with the greatest sum of charcoal (Fig. 6), countered only by measurements at 86.5 cm (ca. 1535 CE). Instead, samples at depths 83.5, 93.5, and 92.5 cm (ca. 1560, 1405, and 1440 CE, respectively) presented reduced charcoal sums alongside high intensity fires. This suggests instances of an inverse relationship between charcoal sum and Raman-derived intensity, as previously hypothesised. This is supported by samples at 90.5 cm depth (ca. 1500 CE), recording the second-highest charcoal abundance and low fire intensity. It is apparent, however, that this association is inconsistent. As a result, the comparison of charcoal abundance and reconstructed intensity may yield further insight into the nature and behaviour of past fire activity, specifically as a measure of fuel consumption, ecosystem disturbance, and fire severity[97]. For instance, reduced charcoal abundance coinciding with high-intensity fire reconstructions may represent pervasive, high-intensity localised burning. This would likely result in the consumption of greater masses of available fuel, and a reduction in charcoal production. In contrast, high-intensity fires recorded alongside high charcoal sums may indicate ephemeral fire events. Dependent upon the intended purpose and outcomes of Raman-derived palaeofire reconstructions, intensity reconstructions are therefore recommended in tandem with charcoal abundance studies. This research, however, reiterates the inapplicability of charcoal abundance studies as a sole measure of fire behaviour.

Conclusions

This study focused on a high-resolution, multi-proxy reconstruction of environmental change within a *Sphagnum*-dominated peatland, affected by seven centuries of substantial change in land and forest management strategies. Two critical transitions, recorded in the peat profile, were related to an introduction of agriculture and modification of forest stands from mixed-forest to coniferous monoculture. A rapid development of agricultural activities–as confirmed by palynological, plant macrofossil and testate amoeba data–resulted in a reduction in fire activity, perpetuating the dominance of *Sphagnum* and an increase in peat accumulation rates. Further afforestation and the establishment of *Pinus* monoculture impacted the peatland, stabilizing *Sphagnum* growth and acidity levels.

Peatland fire disturbance, reconstructed using a wide range of charcoal analyses, has given us an insight into a number of key fire characteristics. We show that increased fire activity, as recorded by charcoal morphotypes and accumulation rates, does not necessarily equate to Raman-derived burning intensity. Indeed, the relationship between charcoal counts and thermometric intensity reconstructions can instead provide essential insight into fire severity, for which no direct proxy exists to date. We therefore recommend the use of charcoal-derived intensity reconstructions in tandem with charcoal abundance studies for greater accuracy and insight when reconstructing and interpreting peatland fire records. These results can be highly useful for the development of accurate future multi-proxy reconstructions of fire activity and the interpretation of past fire regime changes, especially debunking simplified interpretations of charcoal sums as direct evidence for high-intensity fires.

Moreover, as ongoing efforts in peatland conservation and restoration under anthropogenic climate change are becoming more challenging for foresters and forest managers, we are convinced that the results of this study will underline the necessity of wetland protection. Priority should be given to protecting peatland hydrology because high water tables provide water retention and fire protection for not only peatlands, but also the neighbouring forest, at the same time protecting carbon stored in peat for millennia.

Methodology

Study site

The studied site–Stawek peatland–is located in the Tuchola Forest, a *Pinus sylvestris* monoculture forest located in Northern Poland (53°53′22′′N, 17°33′06′′E, 138 m a.s.l.; Fig. 1). Stawek is a small (< 1 ha) *Sphagnum*-dominated kettle-hole peatland, encompassed by birch and pine to the north, with numerous collapsed dead trees on the surface[37]. The study area is located close to the Pomeranian ice margin of the Vistulian Glaciation, dated to ca. 17,000–16,000 cal. BP[99]. The Tuchola Forest thereby represents a young glacial landscape covered by till and sandur, rich in glacial landforms originating from the melting of dead ice[100], including depressions, within one of which Stawek peatland formed.

The Tuchola Forest represents one of the largest forest complexes in Poland, covering an area of ca. 300,000 ha[101]. Historically, this region was populated by Scots pine-dominated (*Pinus sylvestris*) mixed forest, as an admixture with many deciduous taxa such as birch (*Betula pendula*, *B. pubescens*), alder (*Alnus glutinosa*), hornbeam (*Carpinus betulus*), beech (*Fagus sylvatica*), oak (*Quercus robur*) and hazel (*Corylus avellana*)[24,102,103]. Within the last six centuries, the region encompassing the Tuchola Forest has experienced complex political change, including administrative affiliations[33,104]. Following the accession of this region to Prussia at the end of the eighteenth century, administrative decisions made by successive governments included the modification and repurposing of these forests into a Scots pine monoculture[33,53,104]. A detailed description of these forest modifications due to administrative decisions can be found in Bąk, et al.[54].

The study area is characterized by a transitional climate, the coldest and warmest months comprising January (− 1.7 °C) and July (18.2 °C), respectively, while annual precipitation averages 699 mm (mean values for the 1991–2021 period recorded at Swornegacie village located ca. 5 km from the site[105]).

Fieldwork

The choice of the site was determined by a previous study performed from the Stawek peatland where we reconstructed environmental disturbances in the deeper peat layers (90–110 cm) using the multi-proxy approach, exploring the potential of neodymium isotopes in peat as a past local disturbance proxy[37]. The coring campaign in 2020 (survey included several coring locations across the site using a gouge auger and sampling of a peat core using a small Instorf corer – 50-cm long with 5 cm diameter chamber) revealed distinct charcoal layers present in Stawek peat which we decided to explore in detail. A single one meter-long undisturbed peat monolith utilised in this study was extracted in April 2022 with a Wardenaar sampler (100 × 10 × 10 cm[106]) from the centre of Stawek peatland. This time we sampled with a larger corer to obtain more material for multi-proxy analyses. Even though investigations based on a single core are standard practice in palaeoecological research[107], we are aware of their limitations, specifically when it comes to drawing broad conclusions related to the spatial variability of peat layers. The obtained peat monolith was packed into a plastic tube and wrapped in plastic to ensure minimal disturbance and contamination during transport.

Laboratory work

In total, 91 contiguous peat sub-samples were obtained at 1 cm resolution (2 cm resolution was applied to the uppermost 8 cm, an undecomposed *Sphagnum* layer) across a 95 cm undisturbed peat monolith. Multi-proxy analyses applied to all of the 91 sub-samples included: bulk density, peat and carbon accumulation rates, pollen and spores, plant macrofossils, testate amoebae, and charcoal analyses.

Radiocarbon dating and age-depth modelling

A Bayesian age-depth model was constructed to determine the absolute chronology for the profile based upon 10 ^{14}C AMS dates (Table 1). The age-depth model was constructed using the *P_Sequence* function in the OxCal 4.3 software with parameters: $k_0 = 0.5$, $log_{10}(k/k_0) = 1$ and $interpolation = 0.5$ cm[34,108,109]. The IntCal20[110] and Bomb21NH1[111] ^{14}C atmospheric curves were used as the calibration sets. All dates were included in the model. The sections of the profile with potential changes in the accumulation rate of deposits ($AR_{deposits}$) were introduced to the model as boundaries (*Boundary* command). Based on the stratigraphy, we placed the boundaries at depths of: (i) 96 cm—the base of the model, (ii) 80 cm—the boundary between a decomposed layer rich in charred fragments of plants (below) and undecomposed peat, and (iii) 0 cm—the top of the profile. In the following text mean (μ) values of modelled dates were rounded to the nearest decade. The ages are expressed as 'CE' (Common Era). The $AR_{deposits}$ was calculated using OxCal 4.3 software and presented as cm yr^{-1}.

Bulk density and carbon accumulation

For each of the 91 samples, the water content in the wet sample (WC, %), organic matter content in the dry sample (ORG, %), ash content (ASH, g), ash-free bulk density (BD, g/cm^3), peat accumulation rate (PAR, cm/yr), and peat carbon accumulation rate (PCAR, gC/m^2/yr) were calculated. The volume of each sample was accurately measured using calipers. Each sample was then placed in separate crucibles, weighed, dried, and weighed again to determine the percent of WC. The dried samples were burned in a muffle furnace at 550 °C for 12 h and reweighed following the protocol by Heiri, et al.[112] to determine ASH. BD was calculated by dividing the weight of the dry sample by the volume of the fresh sample and multiplied by ORG according to Chambers,

No	Laboratory code –sample number	Depth (cm)	^{14}C date (^{14}C BP)	Calibrated dates [cal. CE (2σ–95.4%)	Dated material
1	Poz-153101	10.5	104.25 ± 0.32 pMC	1952–1958 (12.9%) 2006–2014 (82.5%)	*Sphagnum* stems
2	Poz-153102	20.5	114.32 ± 0.38 pMC	1957–1962 (10.0%) 1986–1996 (85.5%)	*Sphagnum* stems, charcoal
3	Poz-152923	30.5	154.53 ± 0.4 pMC	1964–1974 (95.4%)	Vascular plant remains
4	Poz-153104	40.5	225 ± 30	1636–1688 (41.2%) 1730–1806 (47.6%) 1925–… (6.6%)	Vascular plant remains
5	Poz-152924	50.5	195 ± 30	1646–1695 (24.1%) 1724–1812 (54.0%) 1838–1844 (0.5%) 1853–1877 (1.3%) 1916–… (15.5%)	Vascular plant remains
6	Poz-152925	60.5	140 ± 30	1672–1778 (37.2%) 1798–1944 (58.3%)	Vascular plant remains
7	Poz-153105	70.5	345 ± 30	1470–1637 (95.4%)	Charcoal
8	Poz-153028	80.5	360 ± 30	1456–1529 (45.5%) 1540–1635 (50.0%)	Charcoal
9	Poz-152863	90.5	325 ± 30	1483–1642 (95.4%)	Charcoal
10	Poz-152864	94.5	695 ± 30	1270–1316 (69.4%) 1360–1388 (26.1%)	Charcoal

Table 1. ^{14}C Radiocarbon dates for the Stawek profile.

et al.[113]. PAR was calculated based on the core chronology and then multiplied by the BD value obtained earlier and by 50% to obtain PCAR, following Loisel, et al.[114].

Plant macrofossils

The analysis of plant macrofossils was based on a modified protocol of Mauquoy, et al.[115]. Each sample of approximately 5 cm^3 was wet sieved (mesh diameter: 200 µm). The content of monocot epidermis, mosses, leaf and needle remains, shrub branches, bark fragments, monocot and shrub roots was determined as percentages. Fruits, seeds, seed wing fragments, anthers, caryopses, spindles, scales, wholly preserved leaves and needles, sporangia, opercula, fungal sclerotia, and wood pieces were counted as total numbers in each sample. In addition, the percentage of non-identifiable organic matter (*Substantia humosa*) was also determined. Moss leaves (brown and *Sphagnum* mosses) were identified on slides using a magnification of × 200 and × 400. The classification of *Sphagnum* mosses was based on the publication of Laine, et al.[116]. All material was compared with several identification guides[116–120]. Insect remains (unidentifiable to the species level) were also found.

Testate amoebae and quantitative reconstructions

Peat samples for testate amoeba analysis (size: 3 cm^3) were washed under 0.3 mm sieves following a standard method[121]. Testate amoebae were analysed under a light microscope between × 200 and × 400 magnification until the sum of 100 tests per sample was reached[122]. Several keys and taxonomic monographs[123–125] and online resources[126] were used to achieve the highest taxonomic resolution. The results of testate amoeba analysis were used for the quantitative depth-to-water table (DWT) and trophy (pH) reconstructions. Both reconstructions were performed in C2 software[127] using the European training set[128].

Pollen, spores, and non-pollen palynomorphs

Samples for palynological analysis (size: 1 cm^3) were prepared using standard laboratory procedures[129], followed by acetolysis. A single *Lycopodium* tablet (containing 18,407 spores per tablet; produced by Lund University) was added to each sample during the laboratory procedures for the calculation of microfossil concentration[130]. Pollen, spores, and selected non-pollen palynomorphs (NPPs) were counted under an upright microscope (Zeiss Axio SCOPE A1) until the number of total pollen sum (TPS) grains in each sample reached at least 500, apart from 13 samples in which pollen concentrations were very low. Sporomorphs were identified with the assistance of atlases, keys[131,132], various publications[133,134], and an image database of NPPs (https://non-pollen-palynomorphs.uni-goettingen.de). The results of the palynological analysis were expressed as percentages, calculations are based on the ratio of an individual taxon to the TPS, i.e., the sum of AP (arboreal pollen) and NAP (non-arboreal pollen), excluding aquatic and wetland plants (together with Cyperaceae and Ericaceae), cryptogams, and NPPs. The palynological diagrams were generated using Tilia software[135].

Charcoal

Microscopic charcoal particles (> 10 µm) were counted from depth-respective palynological slides until the combined total of charcoal particles and *Lycopodium* spores exceeded 200[136,137]. Sub-samples 14.5 and 38.5 cm were not analysed in this instance due to lack of appropriate material. Microscopic charcoal concentrations (particles/cm[3]) were calculated in relation to the number of *Lycopodium* spores counted in each sample. Microscopic charcoal influx or accumulation rates (MIC, particles/cm^2/year) were calculated by multiplying microscopic charcoal concentrations by peat accumulation rates (PAR)[136].

For macroscopic charcoal analysis, samples (size: 3 cm^3) were sieved through a 0.5 mm mesh. To obtain a local fire signal, independent of the distal wind-blown fraction, only charcoal fragments exceeding 600 µm were analysed as part of this study[87], using a binocular stereomicroscope with × 60 magnification. Whenever possible, macroscopic charcoal morphotypes (wood, grass, or leaf) were determined following a standard methodology[69,138,139]. Macroscopic charcoal concentrations (particles/cm^3) were calculated by dividing the charcoal sum by sample volume. Macroscopic charcoal influx or accumulation rates (MAC, particles/cm^2/year) were calculated using the macroscopic charcoal concentrations and PAR.

Scanning electron microscopy (SEM) and binocular stereomicroscopy was applied to the largest charred wood fragments (sampled at 86.5 and 85.5 cm) to assess taxonomy, micromorphology, and evidence of biological alteration. The morphology and chemical compositions were studied using an S-3700N Hitachi scanning electron microscope (SEM) coupled with a Thermo Scientific Energy Dispersive Spectrometer (EDS) detector and the Noran System 7 (NSS) analytical software. The observations were carried out at the Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań, Poland, using BSE mode at an accelerating voltage of 20–30 kV, a working distance of 10 mm and a vacuum of 15–30 Pa.

Raman spectroscopy

The carbonaceous microstructures of macrocharcoal fragments, isolated from the peat monolith sub-samples (Σ14) between 81.0 and 95.0 cm, were analysed for this study by applying µ-Raman spectroscopy ('Raman' *herein*). This was with the intention of assessing energy-dependent physiochemical changes that occurred during the formation of the charcoal in historic Stawek peatland wildfires, as a proxy for wildfire intensity established in Mauquoy, et al.[76], Theurer, et al.[74], Theurer, et al.[75], and Theurer, et al.[77].

To ensure all Raman spectra were robust, repeatable, and temporally comparable, charcoal sub-samples did not undergo any form of chemical preparation or treatment (e.g., bleaching), the influence over the carbonaceous microstructure, of which, remains uncharacterised. Instead, charcoals were isolated manually via randomised selection under a binocular stereomicroscope, ensuring a variety of fragment sizes and morphologies were analysed, and the inherent heterogeneity of natural fire activity was accounted for in selection.

During spectroscopic analysis, individual surface measurements (i.e., spectra) were spot-collected at random from up to 25 charcoal fragments per sample, where possible. Sites were selected for spectral acquisition according to their evident cellular structure and reflectivity, indicative of flat surfaces under incident light microscopy that are particularly conducive for a balanced signal–noise ratio.

Spectra were collected using a *Renishaw* 'InVia Reflex' Raman spectrometer at the University of Aberdeen. A green diode-pumped 514.5 nm laser (VIS, 24,000 l/mm) was applied through a *Leica* DM2700M incident light microscope, implementing × 50 objective magnification. Applied power did not exceed 0.3 mW (1% total output). This remains in accordance with protocols established to preserve sample integrity[140]. Calibration to a silicon reference peak (~ 520.5 cm^{-1}) was conducted prior to spectral acquisition, and reference offsetting utilised as and when appropriate. A laser spot size of 1–2 µm was applied during acquisition. Spectra were generated between ~ 1100–1700 cm^{-1}, centred at ~ 1400 cm^{-1}, comprising three consecutive accumulations over 15 s total exposure (5 s/accumulation) at a scan resolution of ~ 3 cm^{-1}. A cosmic ray removal function was also applied during each acquisition.

In order to generate spectral band separation values ('RBS', cm^{-1}) for charcoal materials, from which the measure of wildfire intensity is derived[77], a standardised method of automated deconvolution was applied in this study. This coded method, incorporates a 'peak fit' base code[141,142] into a (modified) secondary deconvolution code, as developed in Schito and Corrado[143] and utilised in[144]. This was conducted within MATLAB (v. R2021a) and the code applies a smoothing function and linear baseline to input spectra, anchored between 1050 and 1150 cm^{-1} and 1650–1750 cm^{-1}. Following this, two pseudo-Voigt (50% Gaussian–Lorentzian) bands shapes are fit automatically to Raman bands 'D' (~ 1350 cm^{-1}) and 'G' (~ 1585 cm^{-1}). From this, a series of parametric outputs are generated based on the band application, including Raman band separation ('RBS' *herein*) values. RBS, generated by the progressive separation of bands 'D' and 'G' with increasing thermal maturation of the carbon microstructure, has shown a consistent and robust direct proportionality with pyrolysis-intensity (Schito, et al.[145] *and references therein*), as an (experimental) proxy for wildfire intensity[75]. Raman Band Separtation values, as derived here, have been applied to Eqs. (1) and (2) after Theurer, et al.[77], enabling the reconstruction of equivalent values for 'energy released' (kJ) and 'total incident energy' (MJ) for fire activity in which this charcoal was generated. These values represent measures of true wildfire intensity[97], corresponding to energy release and radiative absorption as experienced by vegetation under fire front progression[96,146], respectively. The reader is directed to Theurer, et al.[77] for further details as to the development of this reconstruction method.

$$Energy\ Released\,(kJ) = 3.448 \times [RBS] - 621.762 \tag{1}$$

$$Total\ Incident\ Energy\,(MJ) = 0.514 \times [RBS] - 104.04 \tag{2}$$

Acquisition and deconvolution protocols applied here remain consistent with established practices in the Raman spectroscopic study of charcoal (e.g[74–77,147–149].,).

Data availability

The datasets generated and/or analysed during the current study are available in the Mendeley Data repository, https://data.mendeley.com/datasets/c43j5cm2c4/2.

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Additional amendment

1. When reporting experiments and field studies on wild plants (i.e. uncultivated), authors must provide the following information in their manuscript: a. If plant(s) or seeds have been collected, a statement that relevant permits/permissions/licenses were obtained. b. A statement in the manuscript naming the person who identified the plant. c. A statement in the manuscript saying that a voucher specimen was stored and where it was stored. The authors should also provide the voucher ID number for the voucher specimen if this is available. a. The studied site is not under protection, therefore it was not obligatory to obtain any coring permits. Moreover, except for the topmost sample, the entire peat core is composed of decomposed material, not living plants. When it comes to uncultivated species, seeds of Vaccinium oxycoccos have been reported in the topmost sample–this species is of least concern according to the IUCN Red List. Seeds of Pinus sylvestris have also been reported, however, the study site is located in the Pinus sylvestris-dominated managed monoculture forest. b. Plant macrofossil analysis was undertaken by Mariusz Bąk (as stated in Authors contribution statement). c. Palaeoecological studies do not require voucher specimens to be stored.

Author contributions

KM – funding acquisition, conceptualization, fieldwork, laboratory analyses (testate amoebae, charcoal), data interpretation, visualization, writing (original draft preparation) MB – laboratory analyses (bulk density, carbon accumulation, plant macrofossils, selection of plant macrofossils for AMS radiocarbon dating), age-depth modelling, data interpretation, visualization, writing (review & editing) PK – fieldwork, laboratory analyses (pollen and spores), age-depth modelling, data interpretation, visualization, writing (review & editing) ML – fieldwork, support in plant macrofossil analysis, data interpretation, writing (review & editing) TT – Raman spectroscopy, data interpretation, visualization, writing (review & editing) PM – fieldwork, laboratory analyses (charred wood identification), writing (review & editing) DM – Raman spectroscopy, data interpretation, visualization, writing (review & editing).

Competing interests

The authors declare no competing interests.

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- wybór makroskopowych szczątków roślin do datowania radiowęglowego ^{14}C,
- współtworzenie modelu wiek-głębokość,
- wykonanie analizy makroskopowych szczątków roślin,
- przeprowadzenie analizy materiałów historycznych oraz archiwalnych map i zobrazowań lotniczych,
- interpretacja i synteza danych paleoekologicznych, dendrochronologicznych, dendroklimatycznych, teledetekcyjnych oraz historycznych,
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- Interpretacja danych teledetekcyjnych.
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- wykonanie analiz teledetekcyjnych,
- interpretacja danych teledetekcyjnych,
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- udział w laboratoryjnej obróbce rdzenia torfowego,
- wykonanie analizy makro- i mikroskopowych fragmentów węgielków,
- współwykonanie rekonstrukcji poziomu wody i pH opartej o analizę ameb skorupkowych,
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1. Bąk, M., **Lamentowicz, M.**, Kołaczek, P., Wochal, D., Jakubowicz, M., Andrews, L., and Marcisz, K.: Twentieth-century ecological disasters in central European monoculture pine plantations led to critical transitions in peatlands, Biogeosciences, 22, 3843-3866, 2025, https://doi.org/10.5194/bg-22-3843-2025

był następujący:

- udział w pracach terenowych związanych z pozyskaniem rdzenia torfowego do analiz paleoekologicznych,
- wsparcie merytoryczne analizy makroskopowych szczątków roślin,
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był następujący:

- współtworzenie modelu wiek-głębokość,
- wykonanie analizy palinologicznej,
- współtworzenie rycin nr 2 i 4,
- interpretacja danych paleoekologicznych,
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był następujący:

- przeprowadzenie analizy ameb skorupkowych,
- wykonanie rekonstrukcji poziomu wody i pH opartej o analizę ameb skorupkowych,
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I declare that my contribution to the article:

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był następujący:

- koncepcja badań oraz zapewnienie środków na ich realizację; kierownik grantu Narodowego Centrum Nauki SONATA 16 nr 2020/39/D/ST10/00641,
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- udział w laboratoryjnej obróbce rdzenia torfowego,
- wykonanie analizy makro- i mikroskopowych fragmentów węgielków,
- interpretacja danych paleoekologicznych i danych izotopowych,
- komentowanie i edytowanie manuskryptu.

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- koncepcja badań oraz zapewnienie środków na ich realizację; kierownik grantu Narodowego Centrum Nauki SONATA 16 nr 2020/39/D/ST10/00641,
- udział w pracach terenowych związanych z pozyskaniem rdzenia torfowego do analiz paleoekologicznych,
- udział w laboratoryjnej obróbce rdzenia torfowego,
- wykonanie analizy ameb skorupkowych i rekonstrukcji poziomu wody i pH,
- przeprowadzenie analizy makro- i mikroskopowych fragmentów węgielków,
- interpretacja i synteza danych,
- stworzenie ryciny nr 4 oraz współtworzenie rycin nr 3, 5, 6.
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był następujący:

- udział w laboratoryjnej obróbce rdzenia torfowego,
- przeprowadzenie analiz gęstości objętościowej, tempa akumulacji torfu, tempa akumulacji węgla w torfie,
- wybór makroskopowych szczątków roślin do datowania radiowęglowego ^{14}C,
- współtworzenie modelu wiek-głębokość,
- wykonanie analizy makroskopowych szczątków roślin,
- stworzenie ryciny nr 1 oraz współtworzenie ryciny nr 2 i 3,
- interpretacja danych paleoekologicznych,
- komentowanie i edytowanie kolejnych wersji manuskryptu.

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był następujący:

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- współtworzenie modelu wiek-głębokość,
- przeprowadzenie analizy palinologicznej,
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- conducting Raman spectroscopy,
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- commenting on and editing the manuscript.

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Inne publikacje

Artykuły naukowe:

1. Andrews, L. O., Marcisz, K., Kołaczek, P., Amon, L., Veski, S., Heinsalu, A., Stivrins, N., **Bąk, M.**, Aquino-Lopez, M. A., Cwanek, A., Łokas, E., Karpińska-Kołaczek, M., Czerwiński, S., Słowiński, M., Lamentowicz, M.: Response and recovery of a *Sphagnum* peatland from long-term human-induced alkalinisation, Biogeosciences [preprint], 2025, *w recenzji*. https://doi.org/10.5194/egusphere-2025-1351
2. Wochal, D., Marcisz, K., Barabach, J., **Bąk, M.**, Lamentowicz, M.: The Fen that vanished: The untold story of drainage and peat extraction in Bagno Chlebowo peatland with implications for nature conservation, Global Ecology and Conservation, 61, e03647, 2025, *opublikowany*. https://doi.org/10.1016/j.gecco.2025.e03647

Rozdziały w monografiach:

1. Konczal, S., Lamentowicz M, **Bąk, M.**, Czerwiński, S., Kołaczek, P., Wochal, D., Marcisz, M., Chojnicki, B., Harenda, K., Poczta, P., Gąbka, M., Jaster, D., Matulewski, P., Jedliński, J., Niedzielko, J., Wylazłowska, J., Żmuda, M., Żmuda, D., Kopeć, D., Rosadziński, S., Wietecha, M., Landowska, J., Landowski, J.: Rekomendacje dla ochrony mokradeł w lasach, [w]: Jak chronić torfowiska w lasach?, [red.]: Lamentowicz, M. and Konczal, S., ArchaeGraph, Łódź, 161–165, 2024, *opublikowany*.
2. Marcisz, K., **Bąk, M.**, Kołaczek, P., Lamentowicz, M., Wochal, D.: Historia lasu i mokradeł zapisana w torfowiskach, [w]: Jak chronić torfowiska w lasach?, [red.]: Lamentowicz, M. and Konczal, S., ArchaeGraph, Łódź, 29–45, 2024, *opublikowany*.

Publikacje popularnonaukowe:

1. Sanderson, N. K., Loisel, J., Gallego-Sala, A., Anshari, G., Novita, N., Marcisz, K., Lamentowicz, M., **Bąk, M.**, Wochal, D.: Setting a new research agenda for tropical peatlands, recent carbon accumulation and ecosystem. Past Global Changes Magazine 31(2). https://doi.org/10.22498/pages.31.2.121, s. 12, 2023.

2. **Bąk, M.**: Dendrochronologia – historia zapisana w drzewach. „Geografia w Szkole. Czasopismo dla Nauczycieli”: 3/2023, s. 4–8, ISSN: 0137-7566, 2023.

3. **Bąk, M.**: Torfowiska – namiastka pierwotnej natury. „Geografia w Szkole. Czasopismo dla Nauczycieli”: 2/2022, s. 4–8, ISSN: 0137-7566, 2022.

Staże naukowe i pobyty badawcze

1. 04.04.2025-17.04.2025: **Uniwersytet Azorów**, Wydział Nauk Rolniczych i Środowiskowych, Angra do Heroísmo, w ramach realizacji autorskiego projektu: „Development and functioning of peatland in Azores Islands”.
   Finansowanie: Program Erasmus+, umowa nr UAM24-0478.

   > Podczas stażu realizowałem projekt, którego celem jest pierwsza wielowskaźnikowa rekonstrukcja paleoekologiczna historii rozwoju jednego z torfowisk na wyspie Terceira, a dzięki temu ocena wpływu kolonizacji portugalskiej w XV wieku na ekosystem wyspy (skala regionalna) oraz warunki troficzne i hydrologiczne samego torfowiska (skala lokalna). Projekt ma służyć także pierwszej ocenie współczesnej różnorodności taksonomicznej ameb skorupkowych na Terceirze. Działania realizowane są we współpracy z naukowcami Uniwersytetu Azorów – prof. Eduardem Manuelem Ferreirą Diasem, dr Cândidą Margaridą Ferreirą Mendes i José Azevedem. Zebrany materiał stanowił podstawę do napisania wniosku pt. „Ocena wpływu kolonizacji portugalskiej na archipelag Azorów z wykorzystaniem wielowskaźnikowej rekonstrukcji paleoekologicznej” w konkursie NCN PRELUDIUM-24, który jest w ocenie.

2. 06.03.2025-19.03.2025: **Uniwersytet Helsiński**, Pracownia Badań nad Zmianami Środowiska (ECRU), w ramach realizacji autorskiego projektu: „Taxonomic diversity of plant macrofossils in the Estonian and Finnish peat deposits and their applicability for reconstructing plant communities in the past”.
   Finansowanie: Inicjatywa Doskonałości-Uczelnia Badawcza (ID-UB), decyzja nr 158/13/UAM/0036.

   > W trakcie stażu zrealizowałem projekt, którego celem była identyfikacja taksonomiczna makroskopowych szczątków roślin w osadach torfowych z wybranych torfowisk estońskich i fińskich. Działanie podejmowane było we współpracy z dr Minną Väliranta, jedną z czołowych na świecie naukowczyń zajmujących się analizą makroskopowych szczątków roślin. Aktywność zaowocowała wspólną pracą nad artykułem.

3. 01.07.2024-14.07.2024: **Danau Girang Field Centre**, (University of Cardiff i Departament Dzikiej Przyrody Stanu Sabah), Borneo, Malezja. Wyjazd będący nagrodą w konkursie „Wielkopolska dla Planety” organizowanym przez Urząd Marszałkowski Województwa Wielkopolskiego dla młodych naukowców działających na rzecz realizacji celów zrównoważonego rozwoju.
   Finansowanie: Urząd Marszałkowski Województwa Wielkopolskiego.

   > Podczas pobytu uczestniczyłem w badaniach nad bioróżnorodnością Rezerwatu Dolnej Kinabatangan na Borneo, w tym w obrączkowaniu i pomiarach morfometrycznych ptaków, znakowaniu i pomiarach morfometrycznych gryzoni, badaniu wzorców aktywności kotków bengalskich (*Prionailurus bengalensis*) oraz łuskowców jawajskich (*Manis javanica*).

4. 07.05.2024-18.05.2024: **University of Aberdeen**, School of Geosciences, w ramach realizacji autorskiego projektu pn. „Identification and documentation of plant macrofossils from peatland in Pinus sylvestris plantations”.

Finansowanie: Inicjatywa Doskonałości-Uczelnia Badawcza (ID-UB), decyzja nr 115/13/UAM/0007.

> Celem pobytu było wykonanie wysokiej jakości fotografii makroskopowych szczątków roślin zdeponowanych w torfowiskach położonych w plantacjach sosnowych w północno-zachodniej Polsce i ich właściwa identyfikacja taksonomiczna. Opiekunem pobytu był dr Dmitri Mauqouy, czołowy specjalista w zakresie identyfikacji makroskopowych szczątków roślin. Zdjęcia posłużą do stworzenia artykułu prezentującego różnorodność taksonomiczną szczątków roślinnych z wybranych torfowisk w Polsce. Wykonałem ponad sześćdziesiąt wysokiej jakości zdjęć w ujęciach mikroskopowych, które stanowią trzon przygotowywanego artykułu.

5. 14.11.2023-13.12.2023: **Instytut Geografii i Przestrzennego Zagospodarowania Polskiej Akademii Nauk** w Warszawie, w ramach realizacji autorskiego projektu: „Wpływ przemysłowej eksploatacji torfu na rozwój torfowiska wysokiego typu bałtyckiego *Wieliszewskie Bagna* w świetle wielowskaźnikowej analizy paleoekologicznej”.
   Finansowanie: Inicjatywa Doskonałości-Uczelnia Badawcza (ID-UB), decyzja nr 102/13/SNP/0007.

> Podczas stażu zrealizowałem projekt, którego celem była rekonstrukcja rozwoju torfowiska „Wieliszewskie Bagna” ze szczególnym uwzględnieniem wpływu działalności kopalni torfu na ekosystem tegoż torfowiska. Pod opieką prof. dr. hab. Michała Słowińskiego przeprowadziłem analizę makroskopowych szczątków roślin dla pobranego z torfowiska rdzenia. Obecnie trwają prace nad przygotowaniem manuskryptu.

6. 18.10.2023-27.10.2023: **Uniwersytet Techniczny w Tallinie**, w ramach realizacji projektu dot. antropogenicznych zaburzeń torfowisk w Estonii realizowanego we współpracy z Polską Akademią Nauk.
   Finansowanie: Porozumienie pomiędzy Polską Akademią Nauk a Estońską Akademią Nauk

> W trakcie pobytu wygłosiłem referat w Instytucie Geologii Uniwersytetu Technicznego w Tallinnie pn „Integrating palaeoecological and dendrochronological data to explore the impact of climate and land-use changes on *Sphagnum* peatlands in the pine monoculture areas”. Uczestniczyłem w badaniach terenowych we wschodniej części Estonii, na torfowiskach Liivjärve i Puhatu.

Konferencje międzynarodowe[2]

1. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Jakubowicz, M., Andrews, L., Marcisz, K.: 20th-century ecological disasters led to peatland critical transitions in central European pine monoculture forest; EGU General Assembly 2025, Vienna,

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[2] Lista obejmuje wyłącznie konferencje międzynarodowe, w których doktorant uczestniczył jako główny prezentujący.

Austria, 27 kwietnia–2 maja 2025, EGU25-985, https://doi.org/10.5194/egusphere-egu25-985, 2025.

2. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Jakubowicz, M., Andrews, L., Marcisz, K.: 20th-century ecological disasters in central European monoculture pine plantations led to critical transitions in peatlands; Yorkshire Paleo Group, University of Salford, Manchester, UK, 23 kwietnia 2025, 2025.

3. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Matulewski, P., Kopeć, D., Wietecha, M., Marcisz, K. (2024). Integrating palaeoecological, dendrochronological and remote sensing data to explore the impact of climate and forest management on a Sphagnum peatland (Tuchola Pinewoods, N Poland); EGU General Assembly 2024, Vienna, Austria, 14–19 kwietnia 2024, EGU24-546, https://doi.org/10.5194/egusphere-egu24-546, 2024.

4. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Jakubowicz, M., Andrews, L., Marcisz, K.: 20th-century ecological disasters led to peatland critical transitions in central European pine monoculture forest; EGU General Assembly 2024, Vienna, Austria, 14–19 kwietnia 2024, EGU24-546, https://doi.org/10.5194/egusphere-egu24-546, 2024.

5. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Fiutek, P., Jakubowicz, M., Marcisz, K.: Palaeoecological reconstruction of a 2000-year-long history of *Sphagnum* peatland development in the context of the transition from a mixed forest to a pine plantation; XXI INQUA Congress 2023 (International Union for Quaternary Research), Sapienza University of Rome, Rome, Italy, 2023.

6. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Matulewski, P., Marcisz, K.: Integrating palaeoecological and dendrochronological data to explore the past impact of climate and land-use changes on *Sphagnum* peatlands in the temperate climate of Central and Eastern Europe; XXI INQUA Congress 2023 (International Union for Quaternary Research), Sapienza University of Rome, Rome, Italy, 2023

Wybrane konferencje krajowe[3]

1. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Jakubowicz, M., Marcisz, K.: XX-wieczne katastrofy ekologiczne w Puszczy Noteckiej i ich wpływ na rozwój torfowiska Miały; Pakt dla Mokradeł – Konferencja o ochronie obszarów wodno-błotnych z okazji Światowego Dnia Mokradeł 2025, Uniwersytet im. Adama Mickiewicza, Uniwersytet Przyrodniczy w Poznaniu, Poznań, Polska, 3-5 lutego 2025, 2025.

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[3] Lista obejmuje wybrane konferencje krajowe, w których doktorant uczestniczył jako główny prezentujący.

2. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Matulewski, P., Kopeć, D., Wietecha, M., Jaster, D., Marcisz, K.: Historia rozwoju torfowiska wysokiego w warunkach planowej gospodarki leśnej w świetle integracji danych paleoekologicznych i dendrochronologicznych; XIV Sesja Paleolimnologiczna: Ekosystemy wodne – przemiany i presje na osi czasu, Uniwersytet Pomorski w Słupsku, Słupsk, Polska, 21-22 marca 2024, 2024 – **II nagroda w konkursie na najlepsze wystąpienie młodego naukowca.**

3. **Bąk, M.**, Lamentowicz, M., Marcisz, K.: Makroszczątki roślinne w analizie rozwoju torfowiska na przykładzie stanowiska Miały w Puszczy Noteckiej; XIII Sesja Paleolimnologiczna, Uniwersytet im. Kazimierza Wielkiego w Bydgoszczy, Bydgoszcz, Polska, 23-24 marca 2023, 2023.

4. **Bąk, M.**, Lamentowicz, M., Kołaczek, P., Wochal, D., Fiutek, P., Jakubowicz, M., Marcisz, K.: Rekonstrukcja paleoekologiczna dwutysiącletniej historii rozwoju torfowiska wysokiego; Pakt dla Mokradeł – Konferencja o ochronie obszarów wodno-błotnych z okazji Światowego Dnia Mokradeł 2023, Centrum Ochrony Mokradeł, Wydział Biologii Uniwersytetu Warszawskiego, Warszawa, Polska, 4-7 lutego 2023, 2023.