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

Mariusz Bąk[1], Mariusz Lamentowicz[1], Piotr Kołaczek[1], Daria Wochal[1], Paweł Matulewski[2], Dominik Kopeć[3,4], Martyna Wietecha[3,5], Dominika Jaster[2], Katarzyna Marcisz[1]

[1]Climate Change Ecology Research Unit, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań, Poland
[2]Anthropocene Research Unit, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań, Poland
[3]Department of Biogeography, Paleoecology and Nature Conservation, University of Lodz, Łódź, Poland
[4]MGGP Aero Sp. z o. o., Tarnów, Poland
[5]Doctoral School of Exact and Natural Sciences, University of Lodz, Łódź, Poland

Correspondence to: Mariusz Bąk, mariusz.bak@amu.edu.pl

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 peatland located within the Tuchola Pinewoods 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 macrocharcoal 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 analyzed period and a decrease in the water table over the last few decades that led to the lake-peatland transition. These changes progressed 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 effect 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.

Keywords: palaeoecological data, palaeoecology, dendrochronology, dendroclimatic data, climate change, monoculture forests, plantation, historical data, historical maps, multi-proxy, high-resolution, airborne data, thermal data, vegetation indices, remote sensing

1. Introduction

Peatlands are vulnerable to various types of change, which play an important role in the global carbon cycle and whose destabilization can create positive feedback for climate warming (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 not only due to their ability to accumulate C but also to the fact that they do not emit decomposed carbon from the so-called rapid C cycle for up to thousands of years (Blodau, 2002; Gorham, 1991). The estimation of C content accumulated in peatlands is challenging (Sanderson et al., 2023), although some studies indicate ca. 600 Gt of 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 exploited 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, which are so crucial in terms of their impact on global climate change, located in the area of forest monocultures 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., 2015; 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., 2020b, 2017; 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 paleoenvironmental 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., 2022, 2019, 2016; 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 and 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 one 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, the identification of drainage ditches, and the current vegetation condition.

Our study aims to assess the impact of forest management (introduction of pine monoculture) and changing climate on the vegetation, as well as hydrological, and trophic conditions of a peatland in CE 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 favor 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 rings (annual growths) 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 known from historical sources and compared dendrochronological (dendroclimatic) data with them.

2. Materials and methods

2.1. Study site

The Okoniny peatland (53°40’52″–53°41’21″N 18°03’09″–18°03’40″E according to standard 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 Pinewoods 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 the Tuchola Pinewoods 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 hectares, with approximately 7.00 hectares designated as non-forested area. The direct catchment area of the peatland covers a surface of 33.23 hectares. The current elevation of the peatland is around 119 m asl, with the highest elevated area within the direct catchment reaching around 128 m asl. It is part of a protected area (Regulation No. 64/97, 1997), included within the boundaries of the Tuchola Landscape Park (created in 1985). Moreover, since 2008 the entire complex of the Tuchola Pinewoods has been included on the Natura 2000 list as a Special Protection Area. Since 2010, it has been listed as a UNESCO Biosphere Reserve (UNESCO, 2024).

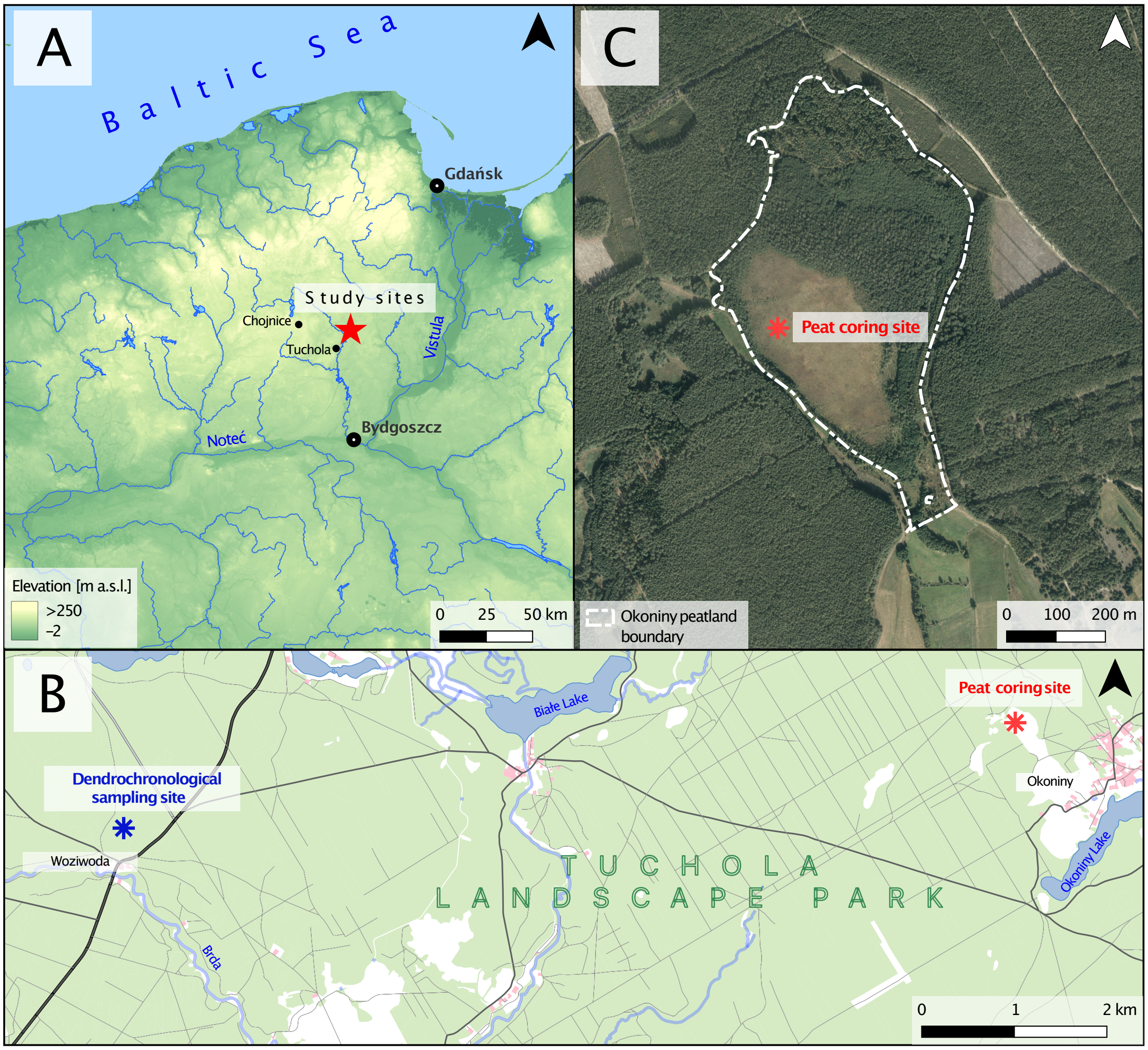


Figure 1. Location of the study area. (A) Location on a map of north-western Poland. (B) Location of the two study sites – dendrochronological sampling site and peat coring site. (C) Okoniny peatland sampling site with current peatland boundaries.

The Okoniny 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 for the meteorological station in Chojnice (35 km west of the study area) for the period between 1991-2020, the coldest month is January with an average temperature of -1.5 °C, the warmest month is July with an average temperature of 18.0 °C. Between 1961-1990, 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 1991-2020, and July has the most with an average of 80.7 mm for the period 1991-2020. Compared to 1951-1990, the average precipitation for February increased by 7.7 mm and for July 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 the Woziwoda Forestry, 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 north-western 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 analyzed. 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). 90 samples were obtained and analyzed 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 peatland. From each tree, a minimum of two cores were taken (from the east and west sides) at a breast height (1.3 m) with a Pressler increment corer. In total, 50 cores were acquired from the Scots pine tree stems.

2.3. Radiocarbon dating and chronology

Ten samples containing *Sphagnum* stems and leaves were used 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; Tab. 1). The IntCal20 (Reimer et al., 2020) and Bomb21NH1 (Hua et al., 2021) atmospheric curves were used to calibrate the dates.

Table 1. The list of radiocarbon dates from Okoniny peatland with calibration 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 – number sample	Depth (cm)	^{14}C date (^{14}C BP)	Calibrated dates [cal. CE (2σ – 95.4%)	Dated material
1	Poz-150386	10.5	100.86 ± 0.33 pMC	1952-1958 (33.9%) 2013-… (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-… (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-… (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

The absolute chronology of the entire core was based on a Bayesian age-depth model using OxCal v4.4.4 (Bronk Ramsey, 2021). 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 interpolation = 1 cm. The most pronounced change 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, 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 modeled age.

2.4. Peat properties and carbon accumulation rate

Analyses of bulk density, loss on ignition, and peat carbon accumulation rate (PCAR) were carried out for each of the ninety 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 hours 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 measuring the bulk density without ash and by 50% to obtain the PCAR, following the protocol of Loisel et al. (2014). The top eleven centimeters of the core (0-11 cm) were 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 5cm^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 a magnification 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 analyzed proxy was plotted using the riojaPlot package for R (plant macrofossils) (Juggins, 2023).

2.6. Testate amoebae analysis

Samples for testate amoeba analysis (volume: ca. 5cm^3) were washed under 300 μm sieves following the method described by Booth et al. (2010). Testate amoebae were analyzed 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 (Siemensma, 2023) were used to achieve the highest possible taxonomic resolution. The results of a 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 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: 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 18407 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 diagram for the analyzed proxy was plotted using Tilia/Tilia graph software (pollen) (Grimm, 1992, 1991).

2.8. Macro- and microcharcoal analysis

Microscopic charcoal particles (size: > 10 μm) 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: 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-μm mesh and only large charcoal fragments > 600 μm were analyzed to obtain a local fire signal (Adolf et al., 2018). Samples were analyzed with a binocular under 60× magnification. Macroscopic charcoal influx or accumulation rates (MAC, particles/cm^2/year) 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 - 2400 DPI using an Epson Perfection V700 Photo scanner. Annual growth rings were measured on digital images with an accuracy of 0.01mm 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 COFECHA software (Grissino-Mayer, 2001), which evaluates each data series concerning 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 at 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 Core Team, 2022). By using this standardization method, random variation in the radial growth was removed (Cook et al., 1990). For the obtained chronologies 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 years analysis

The 'chron' function from ‘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-yrs 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 Core Team, 2022). 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 analyze climate-growth for the period 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 17.75-18.00°E and 53.50-53.75°N 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 peatland was conducted using airborne remote sensing data. The data were acquired through a multisensor aerial platform by the MGGP Aero company on March 25, 2022 (leaf-off collection) and July 20, 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 DTM as a base map. 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 formulas 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 index 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 was used for calculating Land Surface Temperature (LST), measured in degrees Celsius.

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 manuscript 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, 1982, 1981). In this article, the generalized version of the map is interpreted.

The Prussian topographic map Messtischblatt of 1874 on a scale of 1:25 000, sheet No. 982, Zalesie section, was also analyzed. and the 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 on the topographic Messtischblatt of 1874 was considered. The Prussian Geological Survey produced the map (Königlich-Preußische Geologische Landesanstalt) and provides information on alluvial and diluvial deposits covering the area under study. The maps show the changes in the peat bog and its surroundings from the early 19th century to the 1930s. Aerial images from 1964, 1984, and 1997 obtained from the Central 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 a model 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 the period of ca. 282 years, with a maximum uncertainty of ca. 30 years (mostly in the section 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, with the highest values associated with the undecomposed 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 (at 11.5 cm), and the slowest was 0.1 cm/yr (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, undecomposed layer was excluded from the peat carbon accumulation rate (PCAR) analysis. For the rest of the core (11-96 cm), PCAR averaged 112 gC/m^2/yr. The mean water content of the wet sample was 93.8%, and the mean organic matter content of the dry sample was 95.5%.

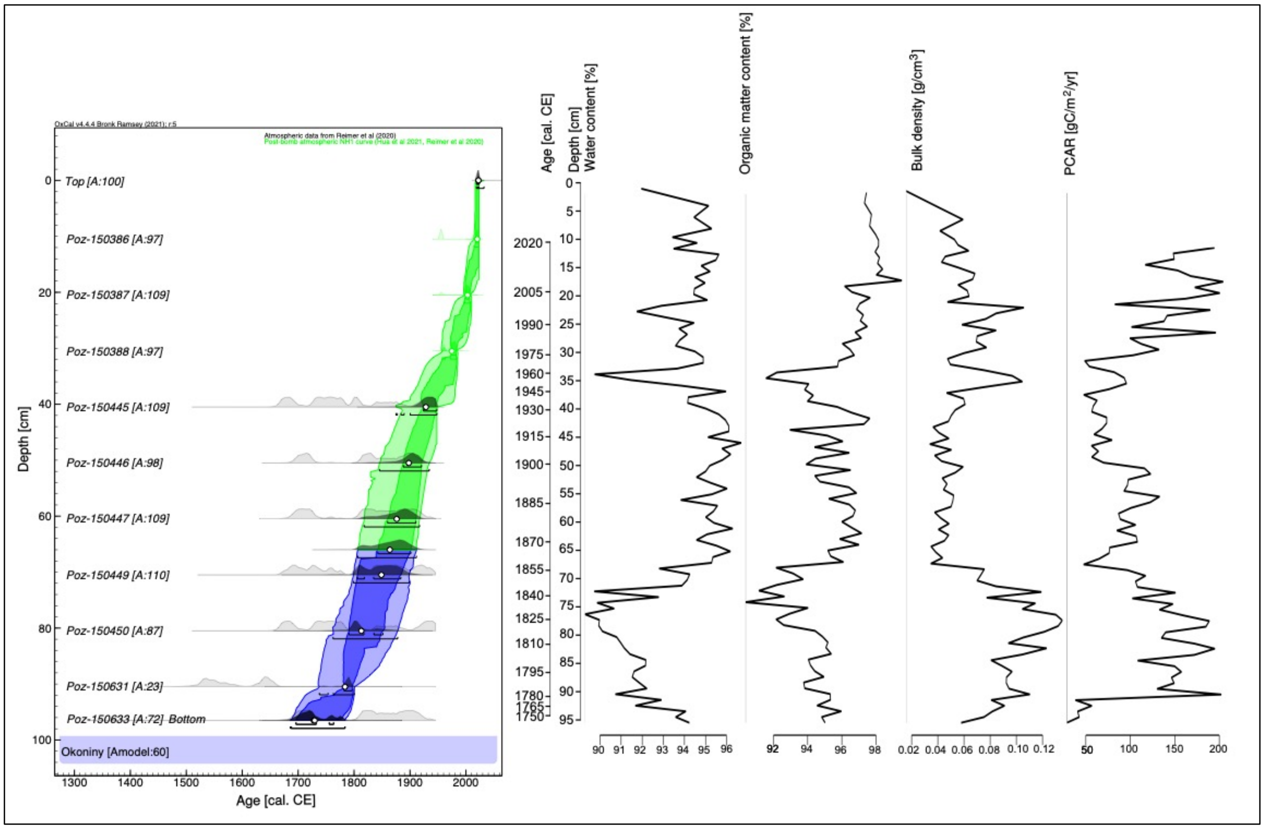


Figure 2. ^{14}C age-depth model of the Okoniny peat profile. Water content, organic matter content, bulk density, and PCAR are also marked.

3.2. Palaeoecological analyses

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

The plant macrofossils 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 monocotyledons with *Carex* spp. Shallow waters 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 shares of aquatic non-pollen palynomorphs (NPPs) such as cyanobacteria and the algae *Tetraëdron minimum*, *Scenedesmus*, *Botryoccocus*, and *Pediastrum* (Fig. 5) confirms results of plant macrofossil and pollen analyses.

This phase was also characterized by 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, 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 peat bogs 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 total pollen content (TP) (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). Values of Cerealia pollen sum (0-7.8% TP) with *Centaurea cyanus*, a crop weed, indicated a stable presence of cultivated fields.

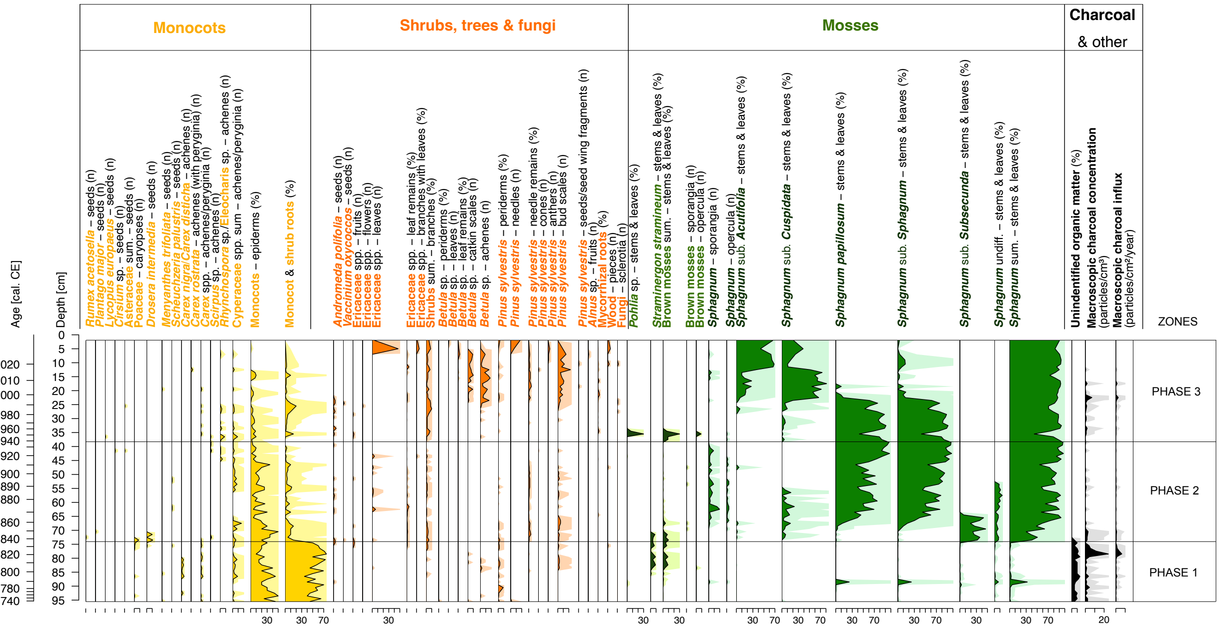


Figure 3. Diagram showing macrofossil percentages, macroscopic charcoal concentrations, and influx as a local fires proxy. 10 times exaggeration is marked.

This phase also had the highest influx of macroscopic charcoal (MAC) of all three distinguished phases (Fig. 3). Towards the end of the phase, at depths of 79.5 and 78.5 cm (1st half of the 1820s according to calibrated dates), influx reached the highest values throughout the core and equaled 24.5 and 11.5 particles/cm^2/year, respectively. The highest influx of MAC in both subsamples corresponded with the influx of microscopic charcoal (MIC), reaching over 53,200 particles/cm^2/year for the 79.5 cm subsample and over 125,000 particles/cm^2/year 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).

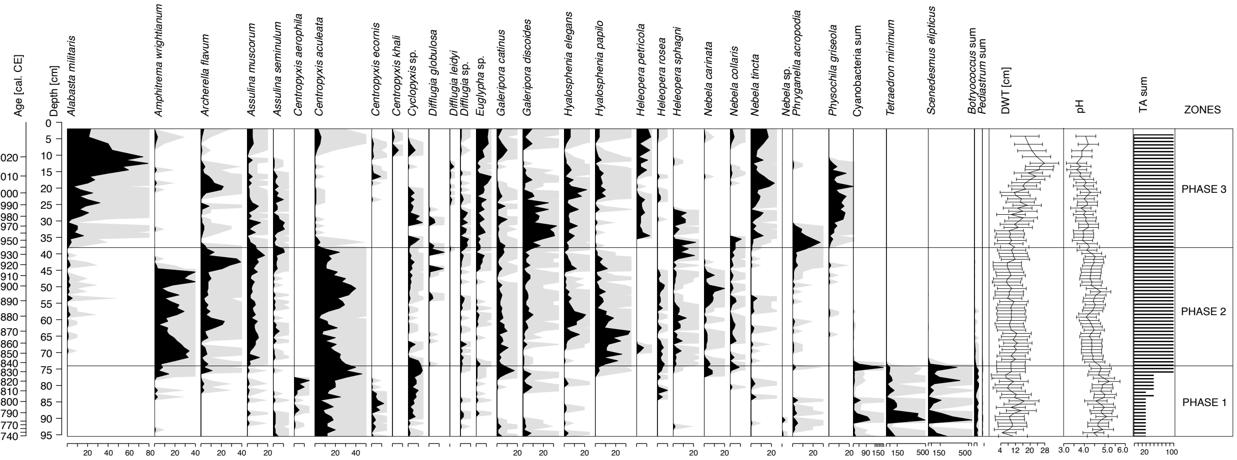


Figure 4. Testate amoebae and selected aquatic non-pollen palynomorphs (Cyanobacteria, *Tetraedron minimum*, *Scenedesmus*, *Botryococcus*, and *Pediastrum*) diagram. Percentages are shown in black and 10 times exaggeration is marked. Testate amoeba-based depth-to-water table (DWT) and pH reconstructions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

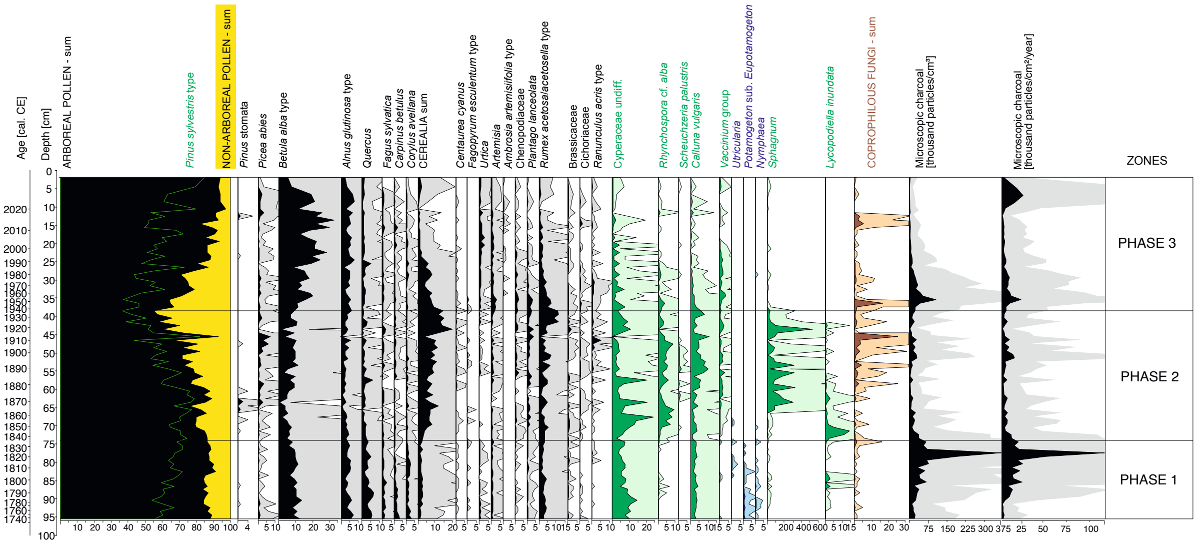


Figure 5. Pollen diagram with selected taxa presented (list of taxa presented in the associated open dataset). Pollen percentages are shown in black, and 10 times exaggeration is marked. Microscopic charcoal concentrations and influx as an extra-local fires proxy are also presented.

3.2.2. Phase 2: (~1838–1945, 74–37 cm): stabilization of 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 space (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 even throughout the season. *Andromeda polifolia* also appeared in this phase. Initially, the presence of *Sphagnum* was accompanied by *Straminergon stramineum* (max. 10%), but later it disappeared completely. By the beginning of the twentieth 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 papilo*, 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. papilo* 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 corresponds 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 their 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 increases significantly (0-11.5%). The low values of MAC (Fig. 3) and MIC (Fig. 5) indicate a low fire activity in the studied area.

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* ($\bar{x}$ = 25.5%), *Galeripora discoides* ($\bar{x}$ = 10.5%) and *Nebela tincta* ($\bar{x}$ = 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 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, 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). Betula pollen share 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 manifested. 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 the early 2020s.

3.3. Dendrochronological and pointer years analysis

A total of 50 tree-ring series of 23 *Pinus sylvestris* L. trees from the Woziwoda site were successfully cross-dated. Based upon the TRW (Fig. 6) and RWI sites, well-synchronised 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 Tab. 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.

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

Chronology length	1801-2022
Mean tree age [yrs]	197
Number of tree/cores	23/50
Mean ring width (mm) ± SD	1.256 ± 0.702
Series intercorrelation	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

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 1920-2022. Nevertheless, in the last 30 years, a significant negative relationship between annual growth and June mean temperature was observed.

Climate-growth analysis for monthly data did not show a statistically significant relationship between growth and precipitation (Fig. 7). However, moving response analysis revealed significant short-term relationships between tree growth and precipitation. Furthermore, it was demonstrated that the influence of precipitation in the current year's months 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 Woziwoda site 8 positive and 13 negative pointer years were identified for the period 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 marks of pointer years together with meteorological and ecological characteristics.

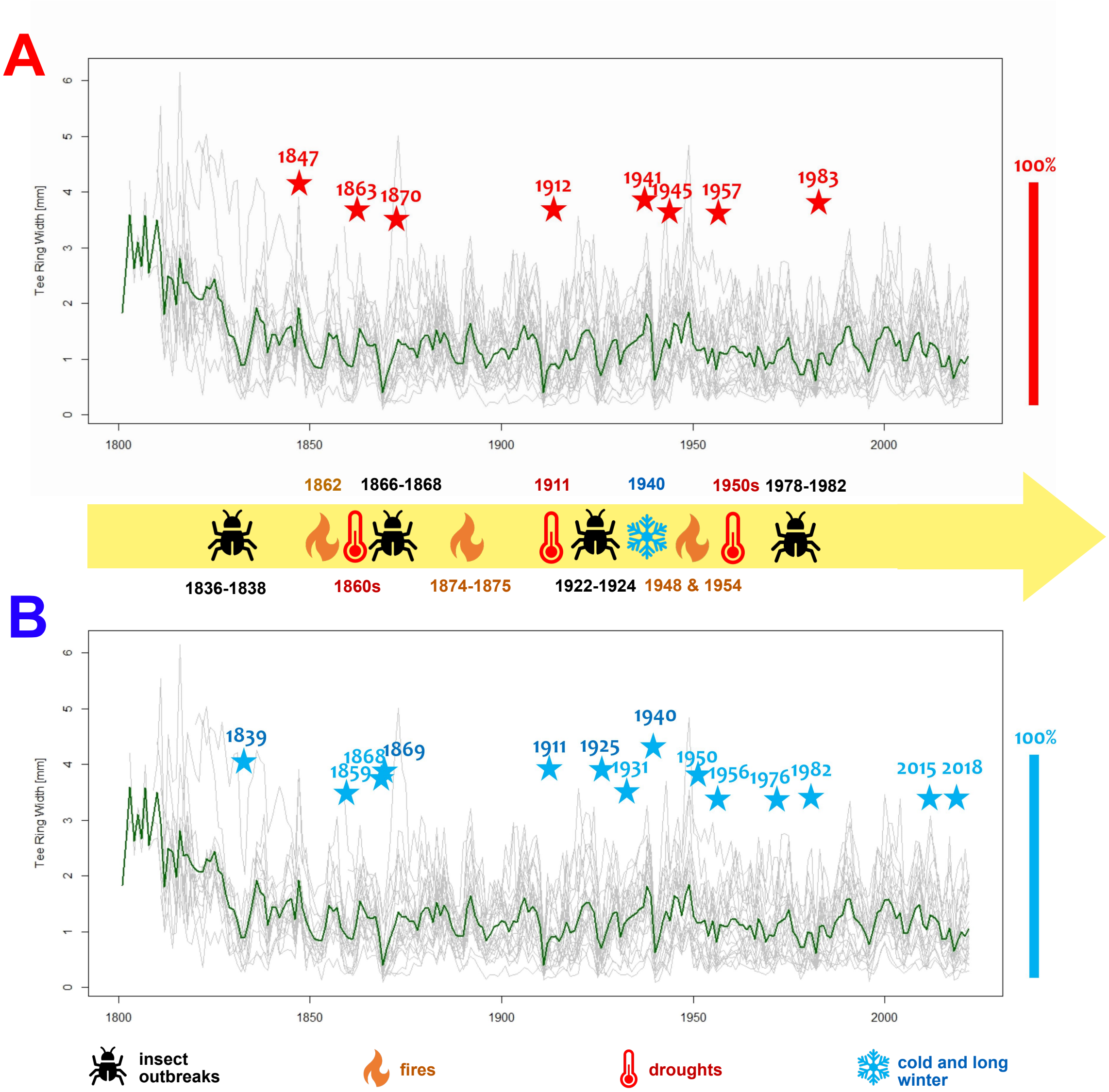


Figure 6. The grey lines depict the individual tree ring series of each tree, while the green line represents the average raw chronology of *Pinus sylvestris* L. at the Woziwoda site. Identified within the Scots pine

chronology from Woziwoda are pointer years, categorized as negative (NEG) (A) and positive (POS) (B). These pointer years are highlighted with colored 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, Wilson 2012.

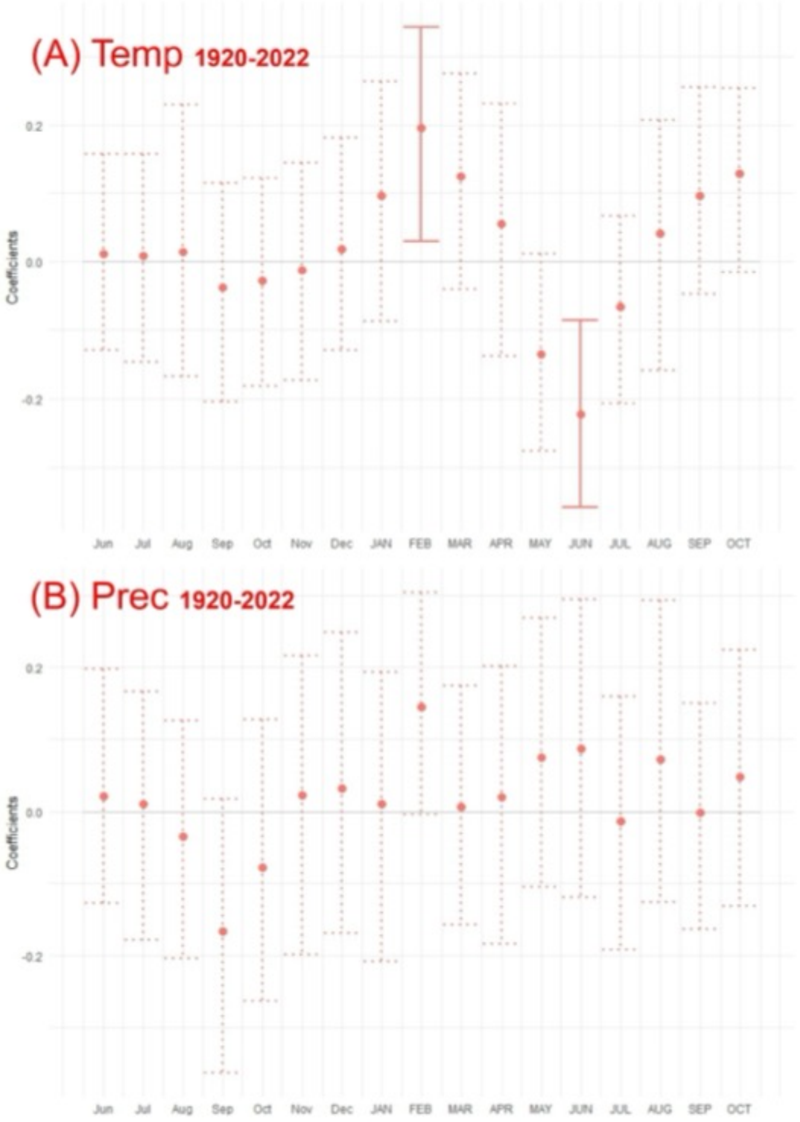
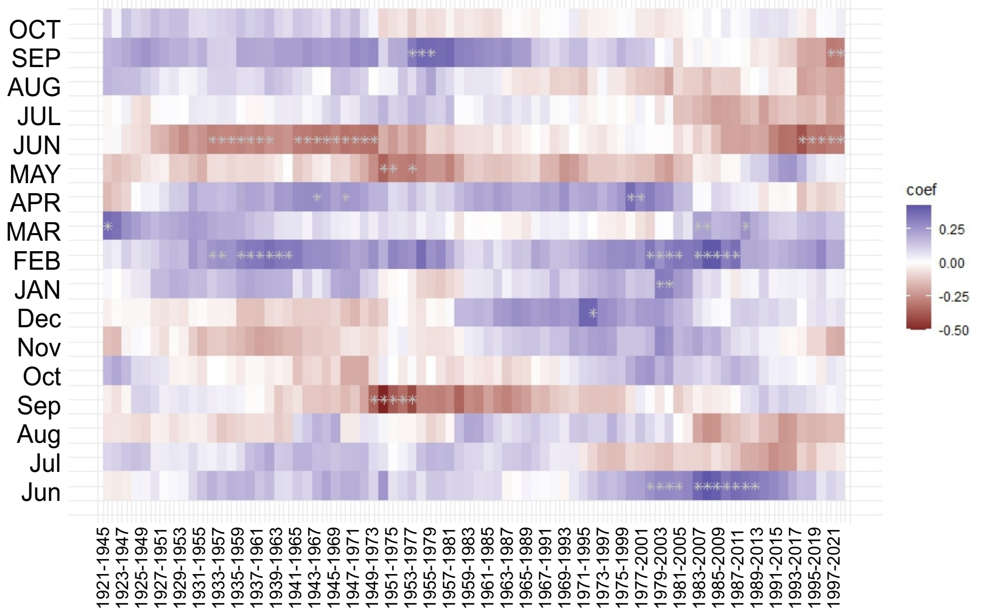


Figure 7. Response function coefficients between residual *Pinus sylvestris* L. chronology and climate variables: (A) mean air temperature (Temp), and (B) precipitation (Prec) for the period 1920–2022. Names of the previous year's months start with a lowercase letter. Solid lines represent significant coefficients at $p < 0.05$.

(A) Temp



(B) Prec

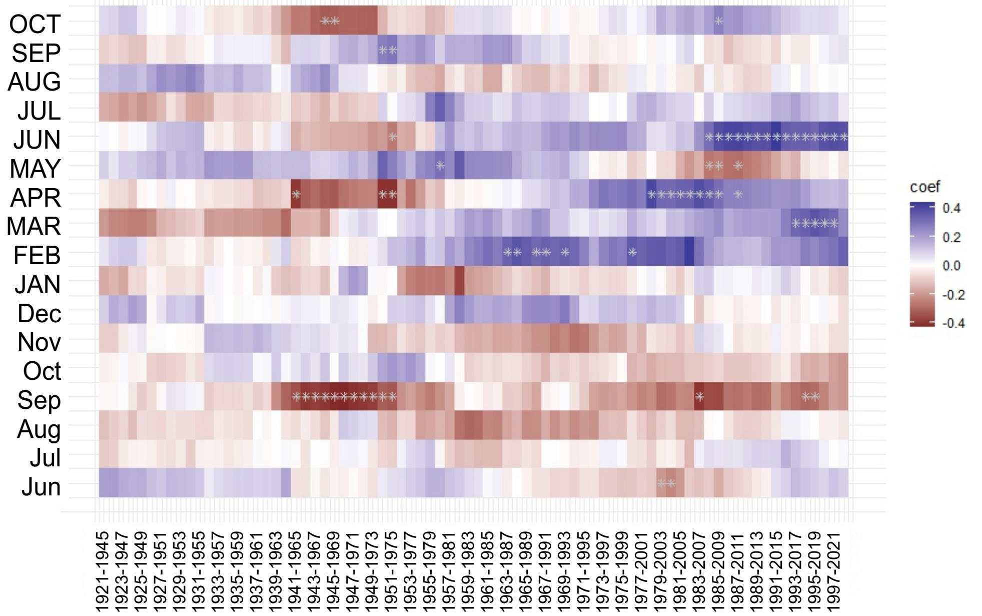


Figure 8. Moving response correlations (25-year window) between residual *Pinus sylvestris* L. chronology and climate variables: (A) mean air temperature (Temp), and (B) precipitation (Prec) for the period 1920–2022. The color code represents the response function coefficients. Significant correlations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

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, 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 °C to 46.37 °C. There is a distinct internal 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 vigor, were observed in the eastern part of the object (Fig. 9), where NDVI averages 0.63, and MSI is around 0.69. The overall average NDVI for the object was 0.65, and for MSI, it was 0.68.

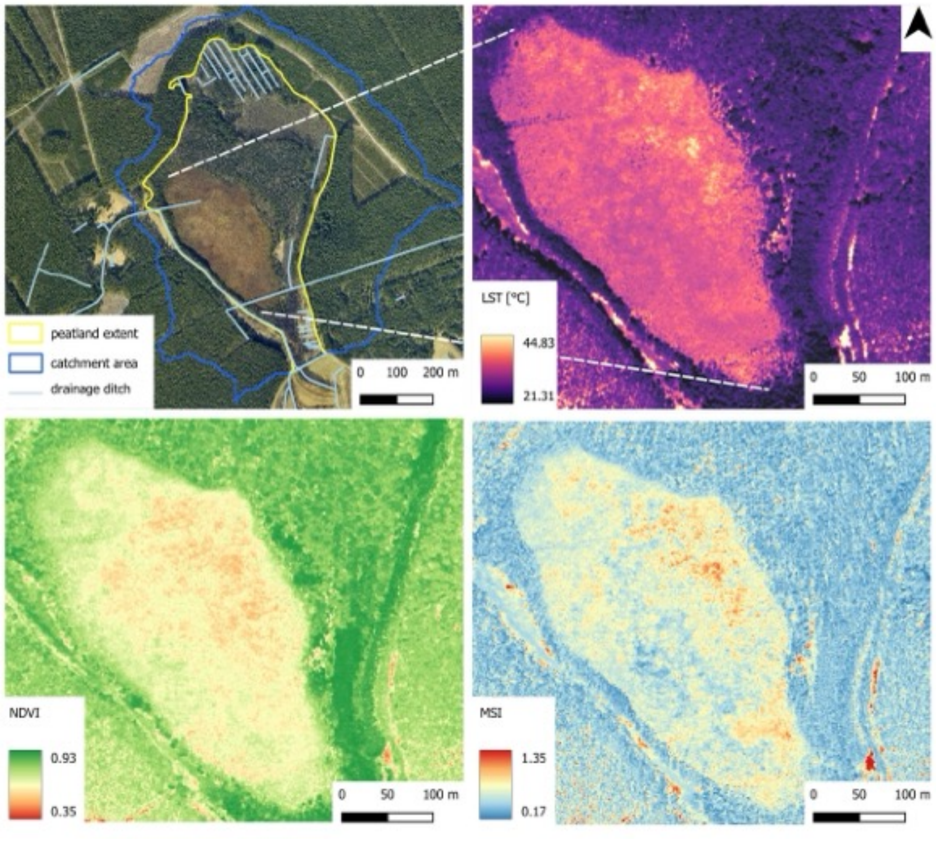


Figure 9. Remote sensing characteristics of Okoniny peatland based on multisensorial airborne data acquired in 2022.

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

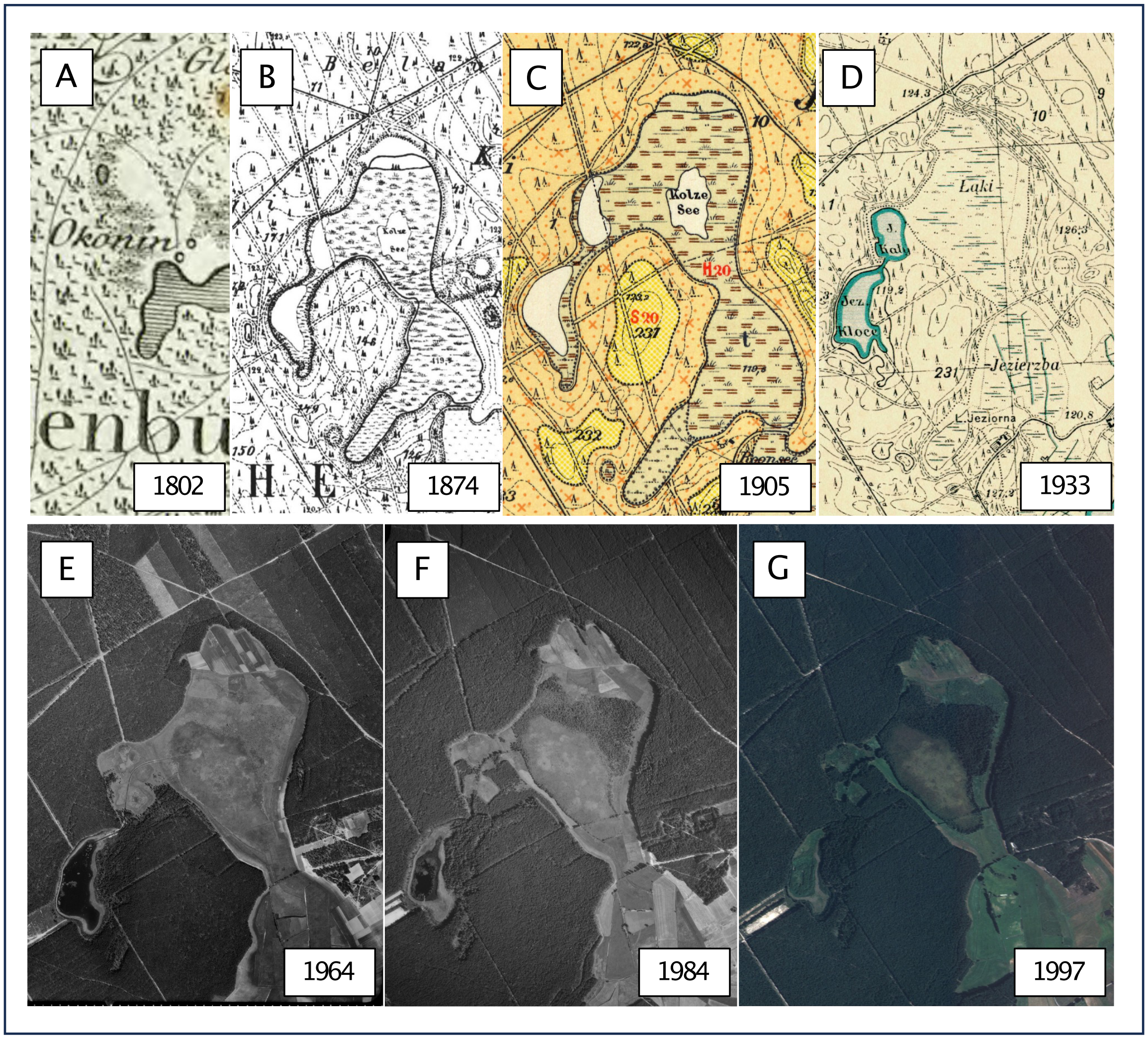


Figure 10. Changes in the peatland and its surroundings since the beginning of the 19th century based on historical maps and aerial images. (A) Schrötter-Engelhardt map 1:150 000 (1802), (B) Messtischblatt map no. 982 1:25 000 (1874), (C) Prussian geological and agricultural map no. 2374 1:25 000 (1905), (D) Detailed Map of Poland 1:25 000 (1933), (E) Aerial photograph from 1964, (F) Aerial photograph from 1984, (G) Aerial photograph from 1997. Maps no. A, B, C, and D are in the public domain. Aerial photographs were obtained from © Central Office of Geodesy and Cartography in Poland, license no. DIO.7211.457.2023_PL_N.

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. Messtischblatt allows us to better interpret the surroundings of the analyzed modern peatland at the time in which the map was prepared. A small lake named "Kolze See" is observed in an advanced stage of development, i.e., progressive overgrowth. This lake is located in the surroundings of 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 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 (org. in German: Humus (Peat) mit Torf-Untergrund und nahem Grundwasser). The thickness of the peat was marked at two meters. However, it should be noted that drilling surveys at that time only covered a maximum depth of two meters, 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 (org. in German: Sandiger Humus mit Sand-Untergrund und nahem Grundwasser) and by humic sands on a substrate of permeable sands with shallow groundwater (org. in German: Humoser Sand mit durchlässigen Sand-Untergrund und nahem Grundwasser).

A Detailed Map of Poland from 1933 documents the change in an 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 meadows adjacent to the south were marked with drainage ditches, which were not 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 today's peatland's agricultural use (regular surface layout). Lake Kały, located nearby, became completely overgrown, and its area was later dug by a drainage ditch, brought to the studied peat bog. The surrounding area of the peatland is dominated 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 peatland, a rapid rate of peat accumulation is observed, averaging 3.56 mm/yr, with a maximum value of 7.1 mm/yr at a depth between 11 and 12 cm. This accumulation rate is not commonly observed. There are only several peatlands in Poland for which higher accumulation rates were reported. In the Tuchola Pinewoods, these were Dury – 10 mm/yr (Pawlyta and Lamentowicz, 2010), Mukrza – 4.6 mm/yr (Lamentowicz and Obremska, 2010), Jelenia Wyspa mire where the accumulation rates reached 0.4 mm/yr for the first 3000 years but accelerated to 3 mm/yr in the last 150 years (Lamentowicz et al., 2007), and the Tuchola kettle-hole bog – 1.2 mm and after ca. 1320 cal. yr BP the accumulation rate dropped to 0.4 mm/yr (Lamentowicz et al., 2008b). In other pine monocultures, such as the Noteć Forest, the Rzecin peatland stands out for its high accumulation rate – an average of 6.8 mm/yr in one profile and 7.5 mm/yr in the other one (Milecka et al., 2017). Peatlands in Tuchola Pinewoods, including Okoniny 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. 150-1230 AD and reached 2.2 mm/yr in Stążki (Lamentowicz et al., 2008a), and 1.38 mm between 1830 and 2006, although the highest accumulation rate was 5 mm/yr (during AD 840-860) in Słowińskie Błota raised bog (Lamentowicz et al., 2009b). At the Gołębiewo sites the maximum accumulation rate were 1.85 mm/yr and 0.36 mm/yr (Pędziszewska and Latałowa, 2016). For many *Sphagnum*-dominated peatlands in other parts of Poland, the average PAR varied between 1.4-2.5 mm/yr (Gałka et al., 2015; Lamentowicz et al., 2020; M. Lamentowicz et al., 2015; Marcisz et al., 2020b). Such high accumulation rate values are also rare in other parts of the temperate climate zone of Europe. Teici bog (Latvia) showed similar accumulation rates - 3.5 mm/yr - from 1835 to 1965 AD and 10 mm/yr after 2000 (Stivrins et al., 2018). Okoniny peatland after 2000 (between 21.5 and 11.5 cm) recorded an accumulation of 5.7 mm/yr. Saxnäs mosse in Sweden showed an almost linear peat accumulation rate of 2-2.5 mm/yr (van der Linden et al., 2014). The maximum accumulation was recorded at around 2310-2250 cal on the Estonian Hara bog. BP (31-15 cm) reaching 2.4 mm/yr (Łuców et al., 2022). A comparison with other regions of Poland and Europe shows that the exceptionally high accumulation rates at the analyzed site are worth highlighting.

4.2. Relationships between forest management and pollen analysis

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

The results of pollen analysis of the collected core 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 the Tuchola Pinewoods underwent vital changes. The consequences of the implementation of forest management techniques were visible in the palaeoecological record.

With the first partition of Poland in 1772 by Prussia, 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. 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 Supplementary File 1.

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 *Pinus sylvestris* pollen percentage after 1850. It can, therefore, be assumed that this resulted from *Pinus sylvestris* introduced by mass monoculture plantings in the early 1830s reaching reproductive capacity. Pine usually reaches sexual maturity between 10 and 15 years (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 Polish largest forest complexes, which were dominated by easy-to-grow pine (Broda, 1993) (see Supplementary File 1). A dynamic increase in the share of pine pollen until the 1860s in the Tuchola Pinewoods was also recorded at the Czechowskie Lake (Słowiński et al., 2019). An increase in pine pollen percentage since the 19th century was also shown in pollen diagrams of other sites from Pomerania – Stążki (Lamentowicz et al., 2008a), Słowińskie Błota (Lamentowicz et al., 2009b) – and in other monoculture plantation complexes from the Prussian partitioning area – Rzecin peatland in the 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 on settlement, more in Supplementary File 1). 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 size (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 face 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 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 (in German: 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 Pinewoods 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 1,600 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, 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 – Kusowskie Bagno (Gałka et al., 2014), 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, 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 Figure 6), and secondly, to a lesser extent, 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, on or near peatlands, to improve tree growth has been 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 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 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. More pine trees in the Tuchola Pinewoods resulted in much higher amounts of needles and other pine fragments accumulating on the forest ground, leading to soil acidification. This, together with drier conditions, could quickly lead to acidification around the pond, forming perfect conditions for *Sphagnum* to encroach – first as a floating mat that successively overgrown the pond. We sampled the peat core close to the edge of the peatland, thus 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 disappearance of Lake Kolze are also clearly visible in historical maps (Figure 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 the Tuchola Pinewoods (Kowalewski, 2003; Kowalewski and Milecka, 2003) and 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, the Tuchola Pinewoods were relatively often affected by droughts resulting in fires (Wilson, 2012). In 1781, there was a fire in Tuchola (ca. 16 km SW), during which a large part of the city with the church and town hall burned down, and in 1792, Starogard Gdański (ca. 42 km NE) burned almost to the ground (Orłowicz, 1924). Major fires also occurred in 1794, and 1807, when more than 34,000 hectares 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 peatland is located, the forests of the Biała and Barłogi forest districts also burned in 1842 (Cyzman, 2008). Intense fires also appeared in the Tuchola Pinewoods 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 hectares 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 hectares of forest burned; altogether, nearly 85% of the area burned in 1860-1889 (Schütte, 1893). The largest area burned in 1863 equaled 2333 hectares, including more than 1250 hectares in the Woziwoda forest district; altogether, 25% of all the forest burned in 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 the 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 hectares 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 of the 1860s provide a regional signal at another site in the Tuchola Pinewoods – 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 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 hectares of forest were burned near Osieczna, and in 1954, 80 hectares were 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 the Czech Republic to the UK (van der Schrier et al., 2021). Summer droughts also affected the Tuchola Pinewoods 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) are also marked. Dendroclimatic data recorded the negative impact of climatic conditions on pine, especially strongly 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 fire's intensity, the burning areas, and the wind direction. Adolf et al. (2018) point out that the charcoal source area of occurrence 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 (Clark, 1990; Higuera et al., 2007; Oris et al., 2014). The distances to which particles move are also determined by terrain and vegetation. They move longer distances on 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, it should be assessed that the local fire activity in the studied peatland was low, with an average of 0.36 particles/cm^3/year, although from historical sources, fires are known to have occurred nearby.

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 peatland, we found no insect remains, even though quite a large sample volume has been analyzed 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 forests of the Tuchola Pinewoods under planned forest management dates back to 1836-1838. An infestation of ~~the~~ *Panolis flammea* occurred at that time (Schütte, 1893). The insects also attacked between 1866 and 1868. As a result of this infestation, 1380 hectares of forest were destroyed in the Woziwoda forest district alone (Schütte, 1893). The pollen diagram from the Okoniny peatland documents the phenomenon in the 1860s with a decrease in *Pinus sylvestris* pollen and an increased presence of *Pinus* stomata that may indicate the event 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 closely located peatland in Okoniny Nadjeziorne, where the 1866-1868 infestation also corresponds with increased numbers of *Pinus* stomata (Tipton, 2023). In 1855, *Lymantria monachal* appeared in large numbers but damaged only some of the younger stands (Schütte, 1893).

A serious incidence of *Panolis flammea* gradation also occurred in 1922-1924 (Kiełczewski, 1947; Mokrzecki, 1928). Between 1978 and 1985, with a peak in 1982, the forests of 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 million hectares of forest over seven years (Broda, 2000; Jabłoński, 2015; Śliwa, 1989, 1987). Both major gradations are reflected in palynological data, manifested by declines in the pollen percentage of trees, primarily *Pinus* and *Picea*. A decrease in conifer pollen during the gradation period has also been shown by studies of other sites in the Tuchola Pinewoods (Łuców et al., 2021; Tipton, 2023). Other pine monoculture in Poland, the Noteć Forest was also affected by gradation in 1922-1924, and this event manifested itself in palaeoecological data (Barabach, 2015; Lamentowicz et al., 2015; 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. (2015) noted an increase in mineral content in the sediment as indicated by *Centropyxis platystoma*, which was confirmed by XMT analysis of the peat. Milecka et al. (2017) described higher ash and charcoal content in the sediments. Although the Tuchola Pinewoods and the Noteć Forest are in the region of highest risk of outbreaks, other areas of 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's difficult to assess unequivocally whether the gradations 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 though 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 analyzed 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 for obtaining 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 gradations - 1839, 1869, 1925, and 1982 - manifested very strongly in the dendrochronological data as negative indicator years.

4.4. 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., 2012, 2011; Matulewski et al., 2019; Zielski, 1996; Zielski et al., 2010; Zielski and Sygit, 1998). Although the studied 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), Koprowski et al. (2011) in the Pomeranian region (Northern Poland). The present study confirmed a short-term relationship between pine radial growth and precipitation sums 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), 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 species currently dominant 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 multisensor airborne data can be successfully utilized to assess the current state of peatlands vegetation. ~~Applying~~ of simple remote sensing indices enabled the detection of spatial differences in the condition and water stress of vegetation in the Okoniny 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 peatland. Comparable findings can be drawn from the spatial variation of MSI values presented in this study. Harris et al. (2006, 2005) demonstrated that MSI is significantly correlated with 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 has 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 have been few works in Poland using spectral data in peatland monitoring (Bandopadhyay et al., 2021, 2019). However, none 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 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 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 gradations 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 combining of different data (palaeoecological, dendrochronological, remote sensing and historical) can complement each other and create a more complete picture of past environmental changes and 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.

Competing interests

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

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Data availability

All data associated with this article are openly available on Mendeley Data repository under the DOI: 10.17632/prdgmjcg69.1

Authors contribution

MB – fieldwork, laboratory analyses (bulk density, carbon accumulation, plant macrofossils, selection of plant macrofossils for AMS radiocarbon dating), age-depth modelling, data interpretation, visualization, writing (original draft)

ML – fieldwork, support in plant macrofossil analysis, data interpretation, writing (commenting and editing)

PK – fieldwork, laboratory analyses (pollen and spores), age-depth modelling, data interpretation, visualization, writing (commenting and editing)

DW – laboratory analyses (testate amoebae), testate amoeba-based reconstructions, data interpretation

PM – fieldwork, laboratory analyses (dendrochronology), data interpretation, visualization, writing (commenting and editing)

DK, MW – fieldwork, remote sensing analyses and interpretation, writing (commenting and editing)

DJ – laboratory analyses (dendrochronology), data interpretation

KM – funding acquisition, conceptualization, fieldwork, laboratory analyses (charcoal), testate amoeba-based reconstructions, data interpretation, visualization, writing (commenting and editing)

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