Integrating palaeoecology and dendrochronology to explore the impact of climate and forest management on a peatland in Scots pine monoculture

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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 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

37 and a decrease in the water table over the last few decades that led to the lake-peatland transition. These
38 changes progressed with the strongest agricultural activity in the area in the 19th century. However, the 20th
39 century was a period of continuous decline in agriculture and an increase in the dominance of Scots pine in
40 the landscape as the effect of afforestation. Dendroclimatic data indicate a negative effect of temperature on
41 Scots pine and pressure from summer rainfall deficiency. Additional remote sensing analysis, using
42 hyperspectral, LiDAR and thermal airborne data, provided information about the current condition of the
43 peatland vegetation. With the application of spectral indices and the analysis of land surface temperature,
44 spatial variations in peatland drying have been identified. Considering the context of forest management
45 and the protection of valuable ecosystems in monocultural forests, the conclusions are relevant for peatland
46 and forest ecology, palaeoecology and forestry.

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

51

52 **1. Introduction**

53 ~~Recognizing how different ecosystems function under a changing climate and increasing human impact is~~

54 ~~crucial for their conservation and management.~~ Peatlands are vulnerable to various types of change, which

55 play an important role in the global carbon cycle and whose destabilization can create catastrophic positive

56 feedback for climate warming (Gallego-Sala et al., 2018; Wilson et al., 2016). Peatlands, although they only

57 cover about 3% of the Earth's total land area (Parish et al., 2008; Rydin and Jeglum, 2013), store more than

58 30% of the organic carbon (C) (Freeman et al., 2004; Gorham, 1991; Harenda et al., 2018), which is far

59 more carbon than the entire biomass of the world's forests (Beaulne et al., 2021b). Their advantage over

60 forests is not only due to their ability to accumulate C but also to the fact that they do not emit decomposed

61 carbon from the so-called rapid C cycle for up to thousands of years (Blodau, 2002; Gorham, 1991). The

62 estimation of C content accumulated in peatlands is challenging (Sanderson et al., 2023), although some

63 studies indicate ca. 600 Gt of C in the Northern Hemisphere alone (Yu et al., 2010). It has recently been

64 shown that even the smallest kettle-hole peatlands effectively accumulate of C and serve as important C hot

65 spots (Karpińska-Kołaczek et al., 2024).

66 Insufficient awareness of the ecological importance of peatlands has led to them being treated as

67 wastelands and drained for hundreds of years to obtain land for agriculture, and forestry or exploited

68 commercially as an energy resource (Joosten et al., 2012; Łuc6w et al., 2022; Paavilainen and Päivänen,

69 1995). Many of these areas have also had to adapt to a changing environment resulting from the use of

70 various forest management techniques, e.g., the replacement of mixed forests with more easily managed

71 monoculture forests (plantations) (Lee et al., 2023; Łuców et al., 2021; Słowiński et al., 2019). Mixed

72 forests, through greater biodiversity, are more resilient and better able to adapt to environmental change

73 (Bauhus et al., 2017; Messier et al., 2022), providing a more comprehensive range of ecosystem services

74 (Felton et al., 2016; Huuskonen et al., 2021).

75   Despite being more straightforward to manage, forest monocultures are characterized by simplified

76 ecosystem linkages (Chapin et al., 2012). As a result, they are more susceptible to various extreme events

77 and disturbances, both natural and anthropogenic, including droughts, fires, strong winds, and pest

78 gradations (Grondin et al., 2014). This is particularly important as disturbances of these types of forests are

79 becoming more common (Seidl et al., 2014; Westerling, 2016). Natural disturbance regimes in forests are

80 mainly a response to climate change (Hanson and Weltzin, 2000; Pureswaran et al., 2015; Seidl et al., 2017;

81 Trumbore et al., 2015), therefore they are expected to increase in frequency and severity in the coming years

82 (Gregow et al., 2017; Moritz et al., 2012; Wotton et al., 2010). Moreover, the problem applies to all kinds

83 of monoculture forests regardless of the dominant species and climate zones (Booth, 2013; Guariguata et

84 al., 2008; McNulty et al., 2013; Spiecker, 2000), including pine plantations in the temperate climate zone of

85 Central and Eastern Europe (Łuców et al., 2021; Schüle et al., 2023). Thus, peatlands, which are so crucial

86 in terms of their impact on global climate change, located in the area of forest monocultures are even more

87 vulnerable to extreme phenomena and disturbance, despite the already high climatic and anthropogenic

88 pressure.

89   The history of peatlands' development can be traced using palaeoecological analyses, which allow

90 numerous reconstructions of past environmental conditions, including climate change (Lamentowicz et al.,

91 2015; Mauquoy and Yeloff, 2008). These include reconstructions of vegetation changes in the peatland and

92 its surroundings, changes in the water table, and reconstructions of past fire activity (Gałka et al., 2022;

93 Kołaczek et al., 2018; Marcisz et al., 2020b, 2017; Mroczkowska et al., 2021). This is because peat

94 preserves, plant remains, pollen, spores, microbial remains, and charcoal are deposited in situ and brought

95 in by wind or water, collectively called peat archives (Godwin, 1981). While paleoenvironmental

96 reconstructions based on peat records have become common, few studies still integrate palaeoecological

97 data with other methods. For example, studies that combine palaeoecological and dendrochronological

98 records, including dendroclimatic reconstructions based on analysis of the annual growth of tree rings, are

99 still relatively rare (Ballesteros-Cánovas et al., 2022; Beaulne et al., 2021a; Dinella et al., 2021; Edvardsson

100 et al., 2022, 2019, 2016; González de Andrés et al., 2022; Kuosmanen et al., 2020; Lamentowicz et al.,

101 2009b). Yet, combining peat records with dendrochronological data can benefit interpretations of trees and

102 forest resilience and resistance to disturbances compared to local environmental changes recorded in peat.

103 Such a view of past environmental changes through several proxies and other archive types is fundamental

104 and will be helpful for forest management and nature conservation in the future. To assess the current state

105 of the peatland, we also included remote sensing data in the analysis. Remote sensing methods have been

106 applied to study wetland conditions for over 50 years and are currently regarded as one of the most useful

107 methods in this research area (FAO, 2020; Guo et al., 2017). Remote sensing technologies enable the remote

108 and non-invasive acquisition of information about the research object using specialized sensors, typically

109 mounted aboard satellites or aircraft. In this study, data obtained from a multisensor aerial platform were

110 used to assess the extent of peatland, the identification of drainage ditches and the current vegetation

111 condition.

112 Our study aims to assess the impact of the introduction of pine monoculture on the development of

113 *Sphagnum* peatlands in central and eastern Europe. We reconstructed hydrological conditions caused by

114 changing climate and forest management, identified peat layers corresponding to the occurrence of extreme

115 phenomena known from historical sources, and integrated palaeoecological and dendrochronological

116 (dendroclimatic) data developed from annual growths of Scots pine (*Pinus sylvestris*). We also explored

117 how peatland responded to extreme phenomena, such as outbreaks or fires, in situ and in the immediate

118 environment.

119 We have assumed that the introduction of pine monoculture has led to significant changes in peatland

120 species composition in favour of peat mosses and a stabilization of the groundwater table. We also undertook

121 to confirm that peatlands record and respond to extreme phenomena, both occurring in situ and in the

122 immediate environment. We assumed that disturbance events that happened in the monoculture forest

123 throughout the years would be recorded in the pine tree ring record and would validate and complete

124 peatland reconstruction.

2. Materials and methods

2.1. Study site

128 The Okoniny peatland (53°40'52″–53°41'21″N 18°03'09″–18°03'40″E according to standard WGS

129 84) is located in northern Poland, about 60 km north of Bydgoszcz and about 20 km northeast of Tuchola

130 (Fig. 1). The study area is located within the Tuchola Pinewoods mesoregion (Kondracki, 2001), close to

131 the Pomeranian ice margin of the Vistulian Glaciation dated to ca. 17,000–16,000 cal. BP (Marks, 2012).

132 The entire area of the Tuchola Pinewoods is a young glacial landscape covered by glacial till, sand, and

133 numerous depressions and other forms originating from melting dead ice (Błaszkiewicz et al., 2015). Based

134 on the analysis of remote sensing data, it was determined that the surface area of the peatland is 27.08

135 hectares, with approximately 7.00 hectares designated as non-forested area. The direct catchment area of

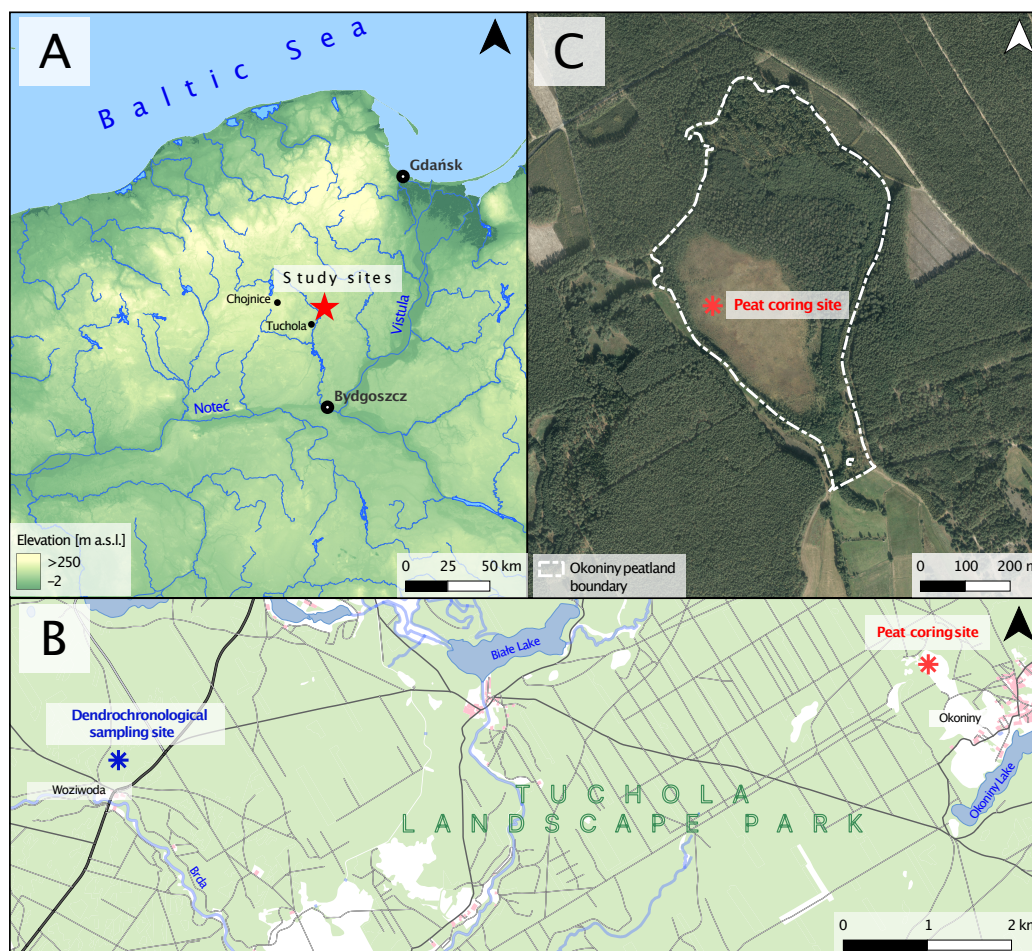
136 the peatland covers a surface of 33.23 hectares. The current elevation of the peatland is around 119 m asl,

137 with the highest elevated area within the direct catchment reaching around 128 m asl. It is part of a protected

138 area (Regulation No. 64/97, 1997), included within the boundaries of the Tuchola Landscape Park (created

139   in 1985). Moreover, since 2008 the entire complex of the Tuchola Pinewoods has been included on the

140   Natura 2000 list as a Special Protection Area. Since 2010, it has been listed as a UNESCO Biosphere

141   Reserve (UNESCO, 2024).

142

143   Figure 1. Location of the study area. (A) Location on a map of north-western Poland. (B) Location of the

144   two study sites – dendrochronological sampling site and peat coring site. (C) Okoniny peatland sampling

145   site with current peatland boundaries.

146

147   The Okoniny peatland is located in a temperate latitude zone, with a transitional climate influenced

148   by continental air masses from eastern Europe and oceanic air masses from the Atlantic Ocean (Beck et al.,

149   2018). According to climate data obtained from the Institute of Meteorology and Water Management for the

150   meteorological station in Chojnice (35 km west of the study area) for the thirty years 1991-2020, the coldest

151 month is January with an average temperature of -1.5 °C, the warmest month is July with an average

152 temperature of 18.0 °C. In the thirty years 1961-1990, both January and July were cooler by 1.6 °C compared

153 to 1991-2020. The average annual temperature increased from 6.9 °C in 1951-1990 to 8.1 °C in 1991-2020.

154 In terms of precipitation, February has the least amount with an average of 31.1 mm for the period 1991-

155 2020, and July has the most with an average of 80.7 mm for the period 1991-2020. Compared to 1951-1990,

156 the average precipitation for February increased by 7.7 mm and for July decreased by 4.1 mm. Mean annual

157 rainfall increased from 558.1 mm for 1951-1990 to 612.4 mm for 1991-2020.

158 Samples for dendroclimatic analysis were taken from forest division no. 91 in the Woziwoda

159 Forestry, Woziwoda Forest District, about 9.5 km west of the study site (Fig. 1). The oldest pine trees in the

160 forest district were selected for the study according to the indications of the forest survey and taxonomic

161 descriptions.

162

163 **2.2. Peat and tree core sampling**

164 A peat core was taken from the north-western part of the peatland in February 2022 using a Wardenaar corer

165 (chamber dimension: 10 cm × 10 cm × 100 cm) (Wardenaar, 1987). The entire length of the sampled peat

166 core – 96 cm-long monolith – was analyzed. The core was sampled continuously every 1 cm, except for the

167 top 10 cm, which contained a living *Sphagnum* layer. The first sample covered 4 cm of the surface layer (0-

168 4 cm), and the following three samples were taken every 2 cm (4-6, 6-8 and 8-10 cm). 90 samples were

169 obtained and analyzed for bulk density, ash content, peat and carbon accumulation rates, plant macrofossils,

170 testate amoebae, macroscopic and microscopic charcoal, and pollen.

171 The research tree stem material was taken in April 2023 from 23 living and healthy trees at the Woziwoda

172 site, ca. 9.5 km west of the Okoniny peatland. From each tree, a minimum of two cores were taken (from

173 the east and west sides) at a breast height (1.3 m) with a Pressler increment corer. In total, 50 cores were

174 acquired from the Scots pine tree stems.

175

176 **2.3. Radiocarbon dating and chronology**

177 Ten samples containing *Sphagnum* stems and leaves were used for accelerator mass spectroscopy (AMS)

178 ^{14}C dating of the entire length of the profile. The survey was conducted at the Poznan Radiocarbon

179 Laboratory in Poland (laboratory code marked Poz; Tab. 1). The IntCal20 (Reimer et al., 2020) and

180 Bomb21NH1 (Hua et al., 2021) atmospheric curves were used to calibrate the dates.

181

182 Table 1. The list of radiocarbon dates from Okoniny peatland with calibration in the OxCal v4.4.4 software

183 using 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

184

185 The absolute chronology of the entire core was based on a Bayesian age-depth model using OxCal v4.4.4

186 (Bronk Ramsey, 2021). The *P_Sequence* command with a parameter *k* of 0.1 cm^{-1} was used to calculate the

187 model, assuming $log_{10}(k/k_0) = 2$, and interpolation = 1 cm. The most pronounced change in peat composition,

188 as manifested by changes in pollen concentration, testate amoeba species composition and species

189 composition of plant macrofossils, which may signal changes in peat accumulation rates, was input using

190   the *Boundary* command at a depth of 66 cm. For better readability of the age-depth model, mean values (μ)

191   were introduced and used to illustrate the modeled age.

192

2.4. Peat properties and carbon accumulation rate

194   Analyses of bulk density, loss on ignition, and peat carbon accumulation rate (PCAR) were carried out for

195   each of the ninety samples. Each sample's volume [cm^3] was carefully and cautiously measured beforehand

196   using calipers to avoid compressing the material. Each sample was then placed in a separate crucible and

197   dried to determine the percentage of water content. The weighed and dried samples were incinerated at 550

198   °C for 12 hours and reweighed according to the protocol of Heiri et al. (2001) to determine the ash mass

199   [g]. Bulk density [g/cm^3] was obtained by dividing the dry sample mass by the volume of the fresh sample

200   according to Chambers et al. (2010). Loss on ignition [g] was obtained by subtracting the ash mass from the

201   dry sample mass. Accumulation rates obtained from the peat core chronologies were multiplied by

202   measuring the bulk density without ash and by 50% to obtain the PCAR, following the protocol of Loisel et

203   al. (2014). The top eleven centimeters of the core (0-11 cm) were discarded for PCAR assessment due to

204   the unrepresentative nature of the results obtained, as increased values of carbon accumulation in near-

205   surface peat cannot be used for inference (Young et al., 2019).

206

2.5. Plant macrofossils analysis

208   The analysis of plant macrofossils was carried out using the modified protocol of Mauquoy et al., 2010.

209   Each sample of approximately 5cm³ was wet sieved (mesh diameter: 200 µm). The generalized content of

210   the sample was estimated in percentage using a binocular microscope. Fruits, seeds, caryopses, achenes,

211   perigynia, bud scales, catkin scales, whole preserved leaves, whole preserved needles, cones, anthers,

212   sporangia, opercula, fungi sclerotia, and wood pieces were counted as total numbers in each sample. The

213   tissues of monocotyledon species and moss leaves (brown and *Sphagnum* mosses) were identified on slides

214   using a magnification of ×200 and ×400. The material was compared with the guides (Anderberg, 1994;

215   Berggren, 1969; Bojňanský and Fargašová, 2007; Mauquoy and van Geel, 2007).

216

2.6. Testate amoebae analysis

218   Samples for testate amoeba analysis (volume: ca. 5cm³) were washed under 300 µm sieves following the

219   method described by Booth et al. (2010). Testate amoebae were analyzed under a light microscope with

220   ×200 and ×400 magnifications until the sum of 100 tests per sample was reached (Payne and Mitchell,

221   2009). Several keys and taxonomic monographs (Clarke, 2003; Mazei and Tsyganov, 2006; Meisterfeld,

222   2001; Ogden and Hedley, 1980) as well as online resources (Siemensma, 2023) were used to achieve the

223   highest possible taxonomic resolution. The results of a testate amoebae analysis were used for the

224   quantitative depth-to-water table (DWT) and pH reconstructions. Both reconstructions were performed in

225   C2 software (Juggins, 2007) using the European training set (Amesbury et al., 2016).

226

227   **2.7. Pollen and non-pollen palynomorphs (NPPs)**

228   Samples for palynological analysis (volume: 2 cm^3) were prepared using standard laboratory procedures

229   (Berglund and Ralska-Jasiewiczowa, 1986). To remove the carbonates, samples were treated with 10%

230   hydrochloric acid. This step was followed by digestion in hot 10% potassium hydroxide (to remove humic

231   compounds) and soaking in 40% hydrofluoric acid for 24 h (to remove the mineral fraction). Next, acetolysis

232   was carried out. Three *Lycopodium* tablets (Batch 280521291, containing 18407 spores per tablet; produced

233   by Lund University) were added to each sample during the laboratory procedures for the calculation of

234   microfossil concentration (Stockmarr, 1971). Pollen, spores, and selected non-pollen palynomorphs (NPPs)

235   were counted under an upright microscope (Zeiss Axio SCOPE A1) until the number of total pollen sum

236   (TPS) grains in each sample reached at least 500, apart from 23 samples in which pollen concentrations

237   were very low. Sporomorphs were identified with the assistance of atlases, keys (Beug, 2004; Moore et al.,

238   1991), various publications, and the image database in the case of NPPs, for which there are no atlases

239   (Miola, 2012; Shumilovskikh et al., 2022; Shumilovskikh and van Geel, 2020). The results of the

240   palynological analysis were expressed as percentages, calculations are based on the ratio of an individual

241   taxon to the TPS, i.e., the sum of AP (arboreal pollen) and NAP (non-arboreal pollen), excluding aquatic

242   and wetland plants (together with Cyperaceae and Ericaceae), cryptogams, and fungi.

243

244   **2.8. Macro- and microcharcoal analysis**

245   Microscopic charcoal particles (size: > 10 μm) were counted from the same slides as pollen until the number

246   of charcoal particles and *Lycopodium* spores counted together, exceeded 200 (Finsinger and Tinner, 2005;

247   Tinner and Hu, 2003). Microscopic charcoal influx or accumulation rates (MIC) were calculated by

248   multiplying charcoal concentrations by peat accumulation rates (PAR) (Davis and Deevey, 1964; Tinner and

249   Hu, 2003).

250   For macroscopic charcoal analysis, samples (volume: 2 cm^3) were prepared by bleaching to create a more

251   visible contrast between the charcoal and the remaining organic matter following the method described by

252   Whitlock and Larsen (2001). Samples were sieved through a 500-μm mesh and only large charcoal

253   fragments > 600 μm were analyzed to obtain a local fire signal (Adolf et al., 2018). Samples were analyzed

254   with a binocular under 60× magnification. Macroscopic charcoal influx or accumulation rates (MAC,

255   particles/cm^2/year) were calculated using the charcoal concentrations and PAR.

256

257   **2.9. Visualization of the palaeoecological results**

258 Palaeoecological diagrams for the analyzed proxies were plotted using Tilia/Tilia graph software (pollen)
259 (Grimm, 1992, 1991), C2 software (testate amoebae) (Juggins, 2007) and riojaPlot package for R (plant
260 macrofossils) (Juggins, 2023). Quantitative reconstructions of testate amoebae-based depth to water table
261 (DWT) and pH changes were done in C2 software (Juggins, 2007), using the European training set
262 (Amesbury et al., 2016).

263

264 **2.10.   Tree core chronology construction**

265 Tree cores underwent a standardized dendrochronological procedure (Zielski and Krąpiec, 2004). Polished
266 cores were scanned between 1200 - 2400 DPI using an Epson Perfection V700 Photo scanner. Annual
267 growth rings were measured on digital images with an accuracy of 0.01mm using CooRecorder. This
268 facilitated the selection of individual growth sequences, which were utilized to form a chronology for each
269 plot. Visual comparisons were made between individual sequences, and the significance of correlations was
270 assessed using Student's t-test (Baillie and Pilcher, 1973). Subsequently, cross-dating was conducted using
271 COFECHA software (Grissino-Mayer, 2001), which evaluates each data series concerning the reference
272 chronology created and compares the correlation coefficients obtained. Raw chronologies were derived by
273 employing an arithmetic mean. For climate-growth analysis standardized chronologies were used, obtained
274 by fitting a spline function (i.e., the "n-year spline" was set at 2/3 of the wavelength of n years of single
275 growth series) using the 'dplR' package (Bunn, 2008) package version 1.7.6 (2023) in the software R version
276 4.3.0 (R Core Team, 2022). By using this standardization method, random variation in the radial growth was
277 removed (Cook et al., 1990). For the obtained chronologies i.e., raw (TRW) and standardized (RWI), values
278 for the following descriptive statistics were computed: the mean correlation between series (inter-series
279 correlation or Rbar), the GLK index (Gleichläufigkeit; Eckstein and Bauch, 1969), and EPS (express
280 population signal) (McCarroll and Loader, 2004).

281

282 **2.11.   Dendroclimatological and pointer years analysis**

283 The 'chron' function from 'dplr' package allowed for the making of a residual chronology, which was used
284 for climate-growth analysis. The 'dcc' function and its moving response (25-yrs window) function method
285 were used to determine the effects of climate conditions on the growth of Scots pine using the 'treeclim'
286 package (Zang and Biondi, 2015) version 2.0.6.0 in R (R Core Team, 2022). This package allows the use
287 of the bootstrap procedure to test the significance and stability of the coefficients of determination (r^2) over
288 a set period (Guiot, 1991). Monthly mean air temperature (TEMP) and total monthly precipitation (PREC)
289 were used to analyze climate-growth for the period 1920-2022 (Klein Tank et al., 2002). Climate data were
290 acquired via Climate Explorer (Trouet and van Oldenborgh, 2013) and calculated from the monthly gridded

291   observational dataset E OBS v. 25.0e (Haylock et al., 2008) obtained for the 17.75-18.00°E and 53.50-
292   53.75°N grid.

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

300

301   **2.12.   Acquisition and post-processing of remote sensing data**

302   The analysis of the current state of Okoniny peatland was conducted using airborne remote sensing data.
303   The data were acquired through a multisensor aerial platform by the MGGP Aero company on March 25,
304   2022 (leaf-off collection) and July 20, 2022, one of the warmest days of the year, which was particularly
305   important for acquiring thermal data (leaf-on collection). Multispectral images (acquired with the IXM-100
306   camera) and Airborne Laser Scanning data (ALS; acquired with the Riegl VQ780-II scanner) were obtained
307   in the leaf-off season. Subsequently, during the vegetation season, the dataset was enhanced by acquiring
308   hyperspectral data (collected using the HySpex VS-725 scanner) and thermal data (obtained with the
309   InfraTEC 9400 camera). Based on the multispectral images, an orthophotomap was generated with a Ground
310   Sampling Distance (GSD) of 10 cm. Hyperspectral data were used to create a mosaic consisting of 430
311   bands (in the range from 400 to 2500 nm), ALS data were applied for the development of a Digital Terrain
312   Model (DTM), and thermal data were used to produce a land surface temperature (LST) mosaic. Thermal
313   and hyperspectral mosaics and DTM were prepared with GSD = 1 m.

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

325

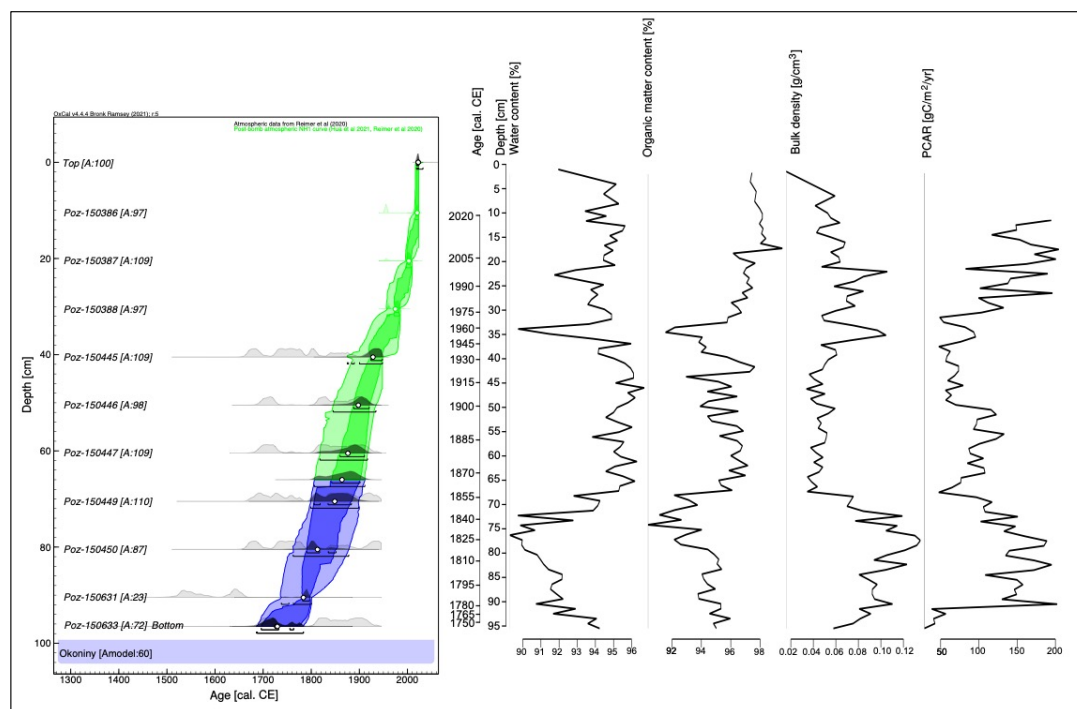
2.13.   Historical maps and cartographic information

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).

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 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.

358

359   Figure 2. Age-depth model of the peat profile in Okoniny based on ^{14}C dating. Water content, organic matter

360   content, bulk density, and PCAR are also marked.

361

362   **3.2. Palaeoecological analyses**

363   **3.2.1. Phase 1 (~1726–1838, 96–74 cm): wet conditions and low human impact**

364   The high concentration of non-pollen palynomorphs (NPPs) such as cyanobacteria and the algae *Tetraëdron*

365   *minimum*, *Scenedesmus*, *Botryoccocus*, and *Pediastrum* point to the presence of a shallow water body in

366   this time (Fig. 5). This was also confirmed by the plant macrofossils and pollen analyses. Plant macrofossil

367   analysis (Fig. 3) showed that the peatland vegetation in this phase was strongly dominated by vascular

368   vegetation, mainly monocotyledons with *Carex* spp. Shallow waters and edges of the water body were

369   overgrown by sedge communities (Cyperaceae pollen) (2.8-14.5%) (Fig. 5). Additionally, this was indicated

370   by the presence of macrophytes represented by pollen of *Potamogeton* subgen. *Eupotamogeton* (0-0.9%),

371   *Nymphaea* (0-0.4%), and *Utricularia* (0-0.3%) (Fig. 5).

372   This phase was also characterized by the brown moss *Straminergon stramineum* (max. 9% of the subsample

373   content) (Fig. 3). This species occurs in a wide range of habitats (Hedenäs, 1993) but is most common in

374   wet, moderately acidic habitats (Blockeel, 2010). *Straminergon stramineum* is usually found as scattered

375   stems or small patches among other mosses but occasionally forms scattered mats, sometimes partially

376   submerged in water, next to lakes, on the edges of peat bogs or in lakeside marshes (Hill and Blockeel,

377   2014).

378   This phase of peatland development was characterized by a very low concentration of testate amoebae in

379   the samples. *Centropyxis aculeata* was the most abundant species (Fig. 4). The dominance of plagiostomic

380   species from the genus *Centropyxis* may point to the presence of mineral input into the peatland

381   (Lamentowicz et al., 2009a; Marcisz et al., 2020a). The water level in the peatland was quite unstable and

382   fluctuated between 4.3 and 16.5 cm below the ground and the pH value ranged between 4.5 and 5.2, but due

383   to the low number of identified tests, these reconstructions should be taken suggestively (Fig. 4).

384   The surrounding vegetation was characterized by the dominance of forests, as evidenced by the high

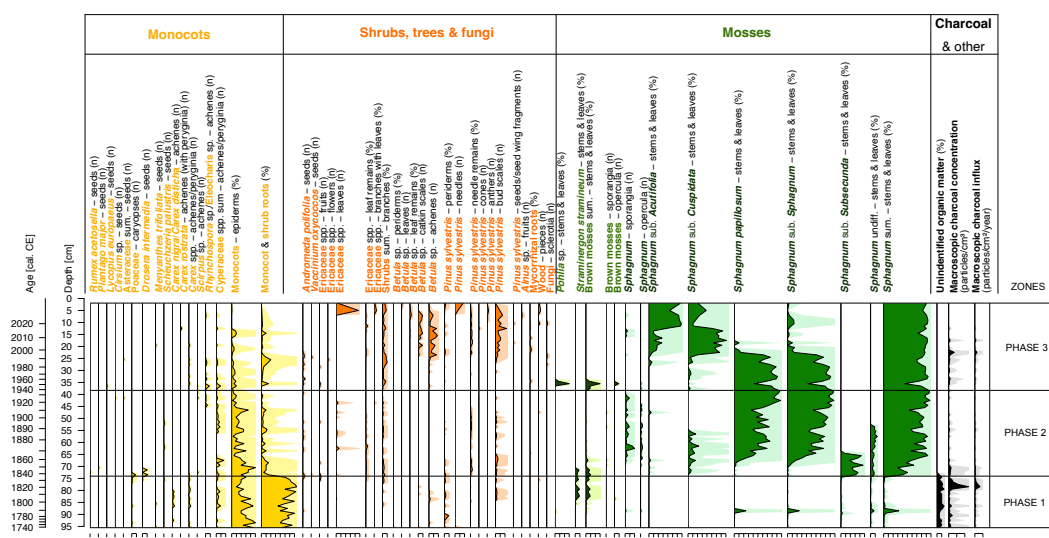
385   proportion of arboreal pollen (AP) (83.6-91.1%) in total pollen content (TP) (Fig. 5). Main species was

386   *Pinus sylvestris* (62.6-81.3% AP) and *Betula* (6.8-16.0% AP), with admixtures of *Alnus* (2.5-7.7% AP),

387   *Quercus* (1.8-8.1% AP), *Corylus avellana* (0.6-3.8% AP), *Carpinus betulus* (0-3.4% AP) and *Fagus*

388   *sylvatica* (0.4-3.3% AP). Values of Cerealia pollen sum (0-7.8% TP) with *Centaurea cyanus*, a crop weed,

389   indicated a stable presence of cultivated fields.

390

392   Figure 3. Diagram showing macrofossil percentages, macroscopic charcoal concentrations, and influx as a

393   local fires proxy. 10 times exaggeration is marked.

394

395   This phase also had the highest influx of macroscopic charcoal (MAC) of all three distinguished

396   phases (Fig. 3). Towards the end of the phase, at depths of 79.5 and 78.5 cm (1st half of the 1820s according

397   to calibrated dates), influx reached the highest values throughout the core and equaled 24.5 and 11.5

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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).

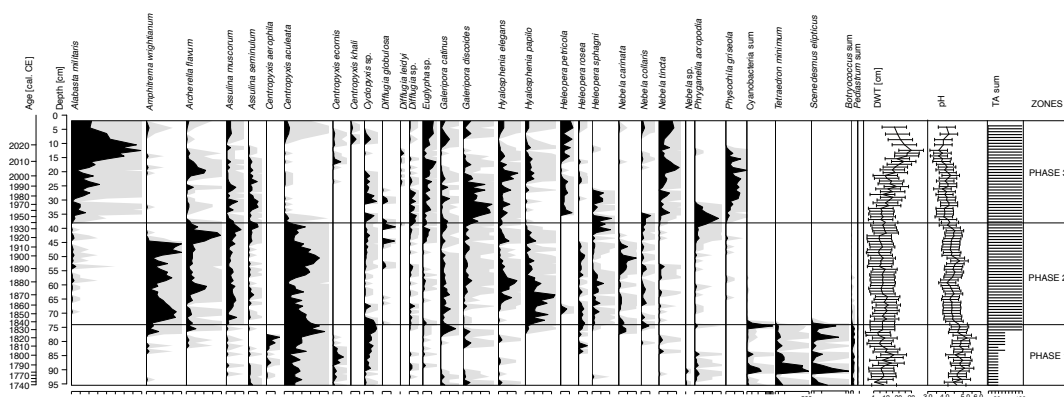



Figure 4. Testate amoebae and non-pollen palynomorphs (Cyanobacteria, *Tetraëdron minimum*,

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.

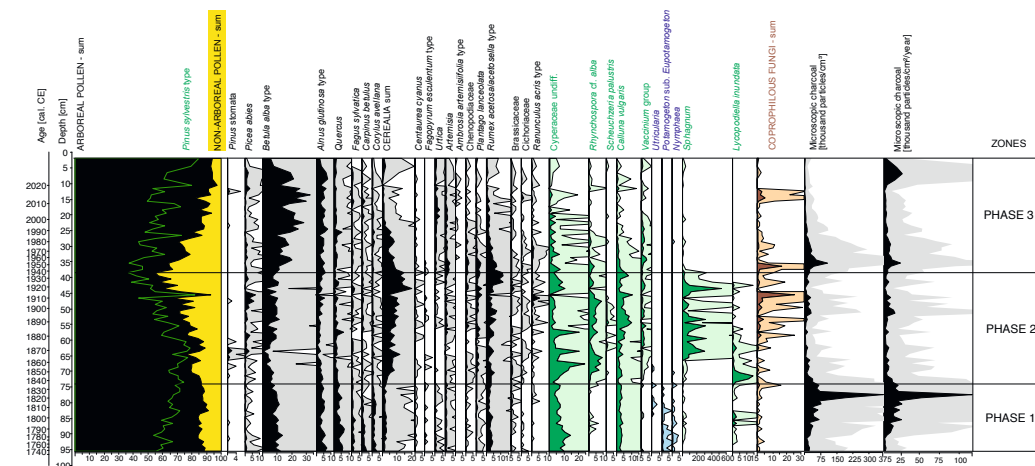



Figure 5. Pollen diagram with selected taxa presented (list of taxa presented in the associated open dataset). Pollen percentages are shown in black, and 5 times exaggeration is marked. Microscopic charcoal concentrations and influx as an extra-local fires proxy are also presented.

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%

444   in the second phase, with a peak in the late 1910s and early 1920s, indicating the development of agriculture
445   in the vicinity of the peatland (Fig. 5). Around the same time, the proportion of *Rumex* also increases
446   significantly (0-11.5%). The low values of MAC (Fig. 3) and MIC (Fig. 5) indicate a low fire activity in the
447   studied area.

448

449   **3.2.3. Phase 3: (~1945–present, 37–0 cm): Lowering of the groundwater table ~~as a result of climate~~**
450   **~~change,~~ further afforestation with *Pinus sylvestris*, a succession of *Betula***

451

452   The local vegetation (Fig. 3) underwent several changes during this phase. Although *Sphagnum* dominated
453   for the entire time, the subgenus *Sphagnum* receded in favour of first the subgenus *Cuspidata* and then the
454   subgenus *Acutifolia*. The beginning of the phase was marked by *Pohlia nutans*, which can win the
455   competition in unstable habitat conditions, such as during the dry season (Boulc'h et al., 2020). Its
456   occurrence correlated with the presence of Phryganella acropodia among testate amoebae (Fig. 4), which is
457   an indicator of low water levels in Sphagnum peatland (Diaconu et al., 2017; Lamentowicz and Mitchell,
458   2005b).
459   This was followed by *Alabasta militaris* ($\overline{x}$ = 25.5%), *Galeripora discoides* ($\overline{x}$ = 10.5%) and *Nebela tincta*
460   ($\overline{x}$ = 8.2%) beginning to dominate (Fig. 4). *G. discoides* is typically present in acidic sites with unstable
461   hydrological conditions (Lamentowicz and Mitchell, 2005b; Sullivan and Booth, 2011). *N. tincta* tolerates
462   dry, highly acidic conditions with mineral matter supply (Booth, 2002; Koenig et al., 2018; Lamentowicz et
463   al., 2011). *A. militaris*, dominant in recent years, is indicative of dry and markedly acidic conditions
464   (Amesbury et al., 2016; Booth, 2002; Lamentowicz et al., 2011; Marcisz et al., 2020a; Sullivan and Booth,
465   2011). Based on testate amoebae, this phase was distinguished by a significant drop in the groundwater
466   table, from an average level of 9.6 cm below the ground surface in the second phase to 15.7 cm. In the last
467   decade, the most significant decline was observed, with an average level of 21.9 cm, with a maximum of
468   27.5 cm, 1983 cal. CE. The pH continued to decrease – from 4.4 to 4.0 (Fig. 4).
469   On a regional scale, there is an increase in the relative abundance of *Pinus* pollen in the TP, from about 46%
470   at the beginning of the phase to about 85% today as an effect of afforestation (Fig. 5). Betula pollen
471   concentration has an apparent increase, from 0,7-11,3% in the second phase to 5,6-32,5%. The increased
472   concentration of *Betula* pollen, combined with macroscopic remains in the form of achenes and catkin scale,
473   indicates the intensive succession of this species on the peatland surface. The ruderal species *Urtica* and
474   *Artemisia* were also more strongly manifested. The average proportion of *Urtica* pollen in the TP increased
475   almost 8 times (from 0-0.7% to 0-2.9%). The percentage of Cerealia in TP has decreased significantly, from
476   nearly 20% in the early 1920s to just over 1% today.

477   Local (Fig. 3) and regional (Fig. 5) fire activity continued to be low, although two slightly more intensive

478   periods of regional fires were marked – ca. 1945-1963 and the early 2020s.

479

480   **3.3. Dendrochronological and pointer years analysis**

481   A total of 50 tree-ring series of 23 *Pinus sylvestris* L. trees from the Woziwoda site were successfully cross-

482   dated. Based on the well-synchronized tree-ring series TRW (Fig. 6) and RWI site chronologies spanning

483   222 years (1801-2022) were developed. The statistical characteristics of the ring-width series and the

484   statistical parameters indicating the signal strength of the regional RWI chronology are shown in Tab. 2.

485   The mean EPS was 0.93, which is well above the threshold value (EPS = 0.85) required to produce a

486   statistically robust RWI chronology. Mean series inter-correlation, MS, SNR, and other statistical

487   parameters indicating the strength of chronology signals were also high, indicating the suitability of

488   chronology for climate-growth analysis.

489   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

490

491   Across the study period (1920-2022) significant positive relationship between growth and February mean

492   temperature was identified (Fig. 7). The moving correlation analysis showed an increasing trend in the

493   sensitivity of tree growth to climatic factors (Fig. 8). The positive response of tree growth to February mean

494   temperature remained constant throughout the study period (1920-2022) (Fig. 8). However, the sensitivity

495   of tree growth to summer temperature increased. The relationship between annual growth and summer

496   temperature was not stable during the period 1920-2022. Nevertheless, in the last 30 years, a significant

497   negative relationship between annual growth and June mean temperature was observed.

498   Climate-growth analysis for monthly data did not show a statistically significant relationship between

499   growth and precipitation (Fig. 7). However, moving response analysis revealed significant short-term

500   relationships between tree growth and precipitation. Furthermore, it was demonstrated that the influence of

501   precipitation in the current year's months on tree growth calculated for the years 1960-2022 was more

502   significant than the relationships calculated for the years 1921-1959. In recent years, a particularly positive

503   relationship between tree growth and early-year (February-April) precipitation as well as June precipitation

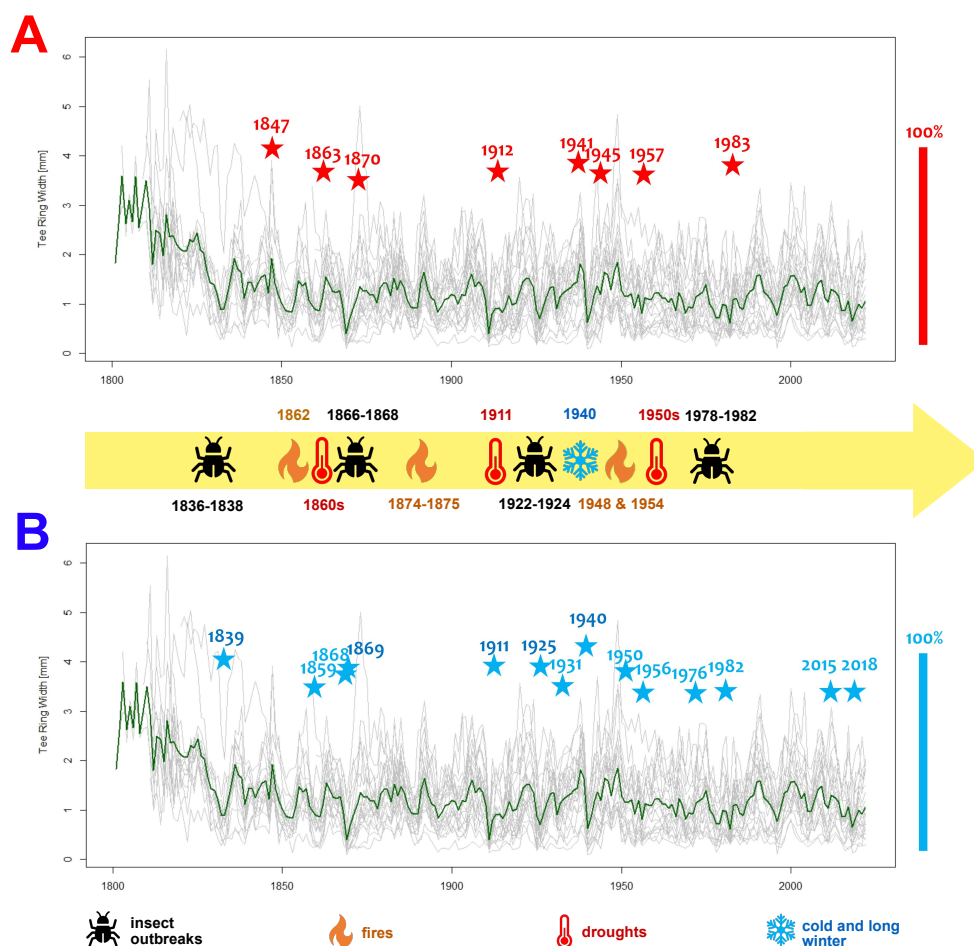
504   has become apparent.

505   For Woziwoda site 8 positive and 13 negative pointer years were identified for the period 1814-2022 (with

506   a minimum sample depth 10 trees) (Fig. 6). The most pronounced positive pointer years with more than

507   90% tree response were as follows: 1847, 1863, 1912, 1941, 1945, 1957, and 1983. The most pronounced

508   negative pointer years were: 1839, 1868, 1869, 1911, 1925, 1940, and 1950. Figure 6 provides marks of

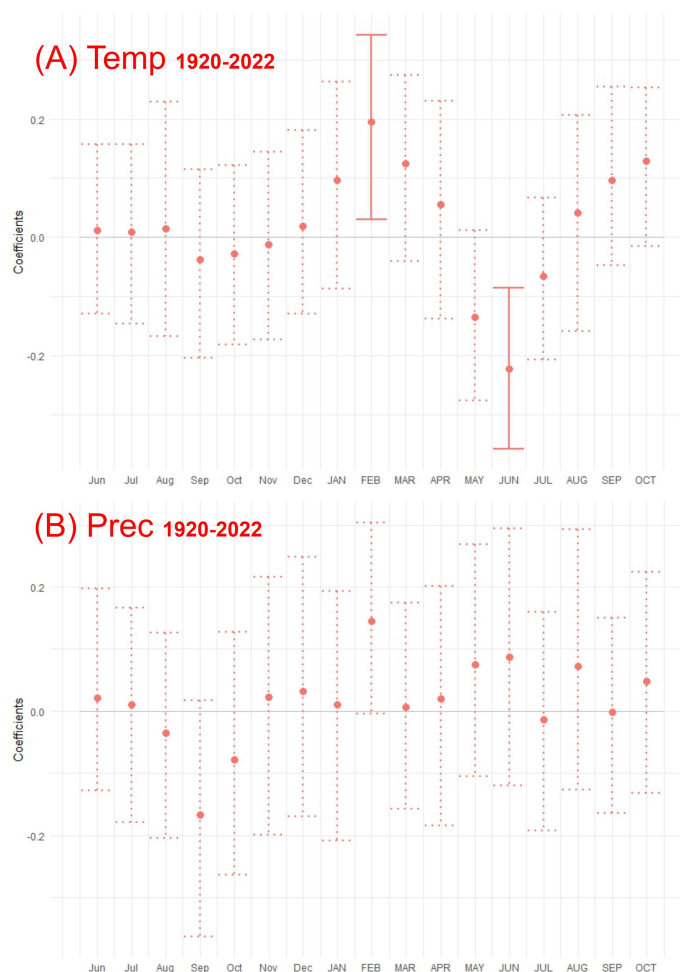
509   pointer years together with meteorological and ecological characteristics.

510

511   Figure 6. The grey lines depict the individual tree ring series of each tree, while the green line represents

512   the average raw chronology of *Pinus sylvestris* L. at the Woziwoda site. Identified within the Scots pine

513   chronology from Woziwoda are pointer years, categorized as negative (NEG) (A) and positive (POS) (B).

514   These pointer years are highlighted with colored asterisks: red for positive pointer years and blue for

515   negative pointer years. The position of the asterisks refers to a scale of 0-100%.

516

517   Figure 7. Response function coefficients between residual *Pinus sylvestris* L. chronology residual *Pinus*

518   *sylvestris* L. chronology and climate variables: (A) mean air temperature (TEMP), and (B) precipitation for

519   the period 1920–2022. Names of the previous year's months start with a lowercase letter. Solid lines

520   represent significant coefficients at $p < 0.05$.

521

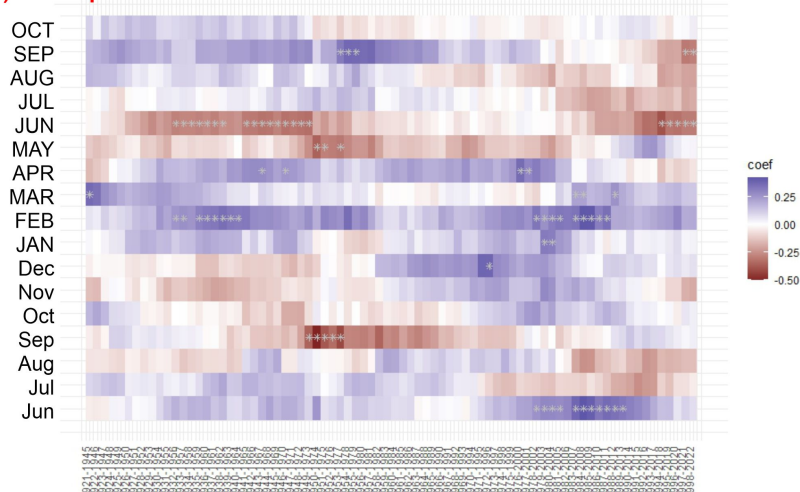
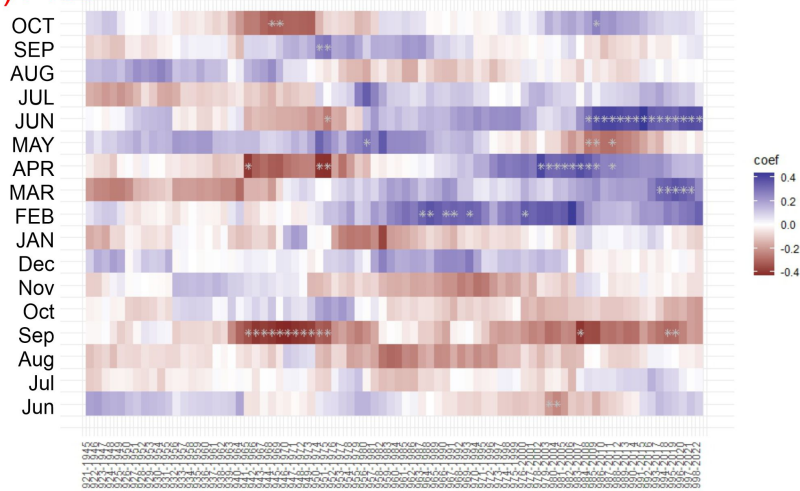



Figure 8. Moving response correlations (25-year window) between residual *Pinus sylvestris* L. chronology
and climate variables: (A) mean air temperature (TEMP), and (B) precipitation for the period 1920–2022.
The color code represents the correlation coefficient. Significant correlations are indicated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

526

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

528   Presently, the non-forest part of the peatland is drained by two parallel ditches. One is located in
529   the northern, and the other is in the southern non-forested part of the peatland. The analysis of thermal data

530   obtained on a torrid midsummer day indicates that the average LST for the non-forested part of the peatland

531   is approximately 34.29 °C, with a temperature range extending from 19.22 °C to 46.37 °C. There is a distinct

532   internal variability in LST values within the studied area. Higher values, indicative of more significant

533   dehydration, were identified in the eastern part of the peatland, while lower values were observed in the

534   western part. A repeating spatial pattern of their values was observed in the analysis of vegetation indices

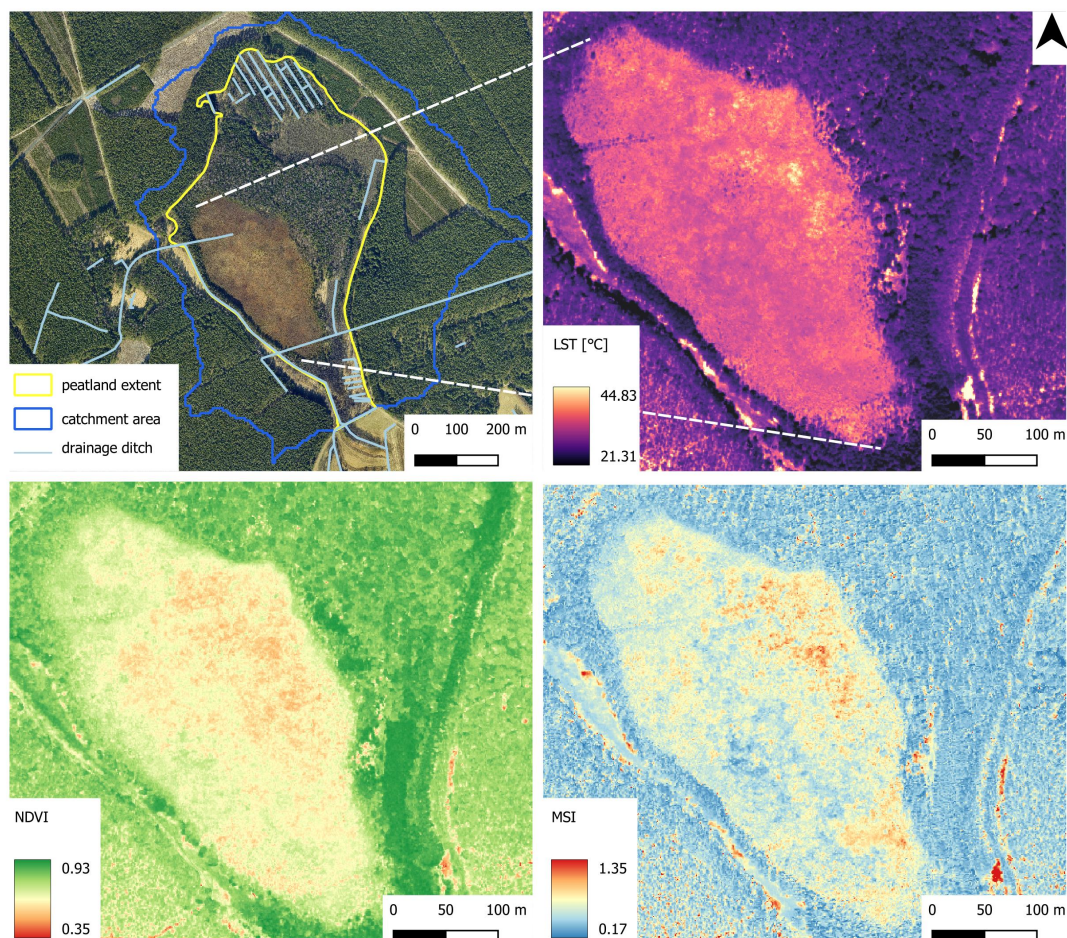
535   (NDVI and MSI). High NDVI values and low MSI values, indicative of good vegetation condition and low

536   water stress, were observed in the western and southwestern parts of the peatland (Fig. 9). The average

537   NDVI value in these areas is 0.71, and MSI is 0.6. Conversely, low NDVI values and high MSI values,

538   indicative of significant dehydration of the peatland and low vegetation vigor, were observed in the eastern

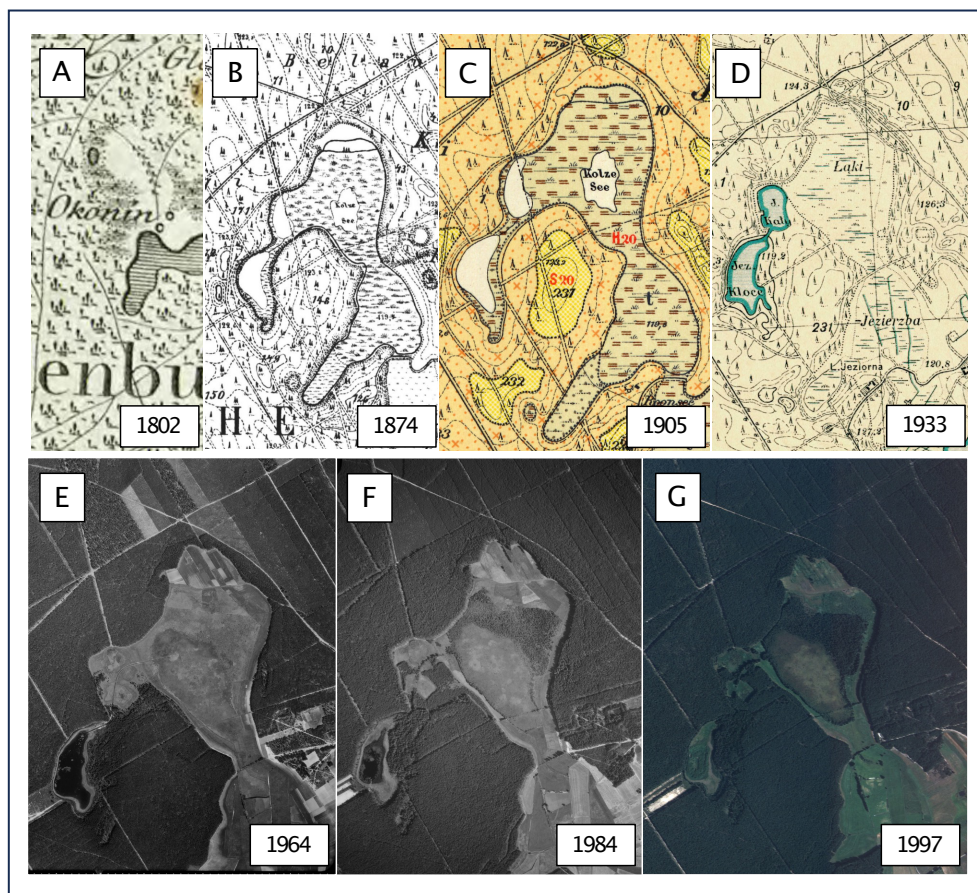
539   part of the object (Fig. 9), where NDVI averages 0.63, and MSI is around 0.69. The overall average NDVI

540   for the object was 0.65, and for MSI, it was 0.68.

541

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

543 in 2022.

544

545 **3.5. Historical maps and airborne images as confirmation of changes shown in palaeoecological data**

546

547 Figure 10. Changes in the peatland and its surroundings since the beginning of the 19th century based on

548 historical maps and aerial images. (A) Schrötter-Engelhardt map 1:150 000 (1802), (B) Messtischblatt map

549 no. 982 1:25 000 (1874), (C) Prussian geological and agricultural map no. 2374 1:25 000 (1905), (D)

550 Detailed Map of Poland 1:25 000 (1933), (E) Aerial photograph from 1964, (F) Aerial photograph from

551 1984, (G) Aerial photograph from 1997. Maps no. A, B, C, and D are in the public domain. Aerial

552 photographs were obtained from © Central Office of Geodesy and Cartography in Poland, license no.

553 DIO.7211.457.2023_PL_N.

554

555   Analysis of historical materials (Fig. 10), including maps and airborne images, confirms the results of the

556   palaeoecological analysis. Both the Schrötter-Engelhardt map of 1802 and the Messtischblatt of 1874

557   indicate the existence of a small lake in the coring area. Again, however, it should be noted that the Schrötter-

558   Engelhardt map is a highly generalized study and does not give much information about the surroundings

559   of today's peatland, other than that we are dealing with an area with the character of a dense forest complex

560   with wetlands in isolated places. Messtischblatt allows us to better interpret the surroundings of the analyzed

561   modern peatland at the time in which the map was prepared. A small lake named "Kolze See" is observed

562   in an advanced stage of development, i.e., progressive overgrowth. This lake is located in the surroundings

563   of wetlands (Bruch in German) somewhat distant heathland (Heide in German) and wasteland (Ödland in

564   German) (the original nomenclature of the map legend was adopted). This lake and two other lakes close

565   by are enclosed within a single catchment area. To the south, the area of the current peatland was adjacent

566   to an open, extensive meadow.

567   Even more information is provided by a 1905 geological-agricultural map prepared on the topographic base

568   Messtischblatt map of 1874. In addition to land use, it shows the type and thickness of alluvial and diluvial

569   deposits. According to this map, the area around the lake was covered by alluvial sediments – humus with

570   peat subsoil and shallow groundwater (org. in German: Humus (Peat) mit Torf-Untergrund und nahem

571   Grundwasser). The thickness of the peat was marked at two meters. However, it should be noted that drilling

572   surveys at that time only covered a maximum depth of two meters, so the maps do not provide information

573   on the total thickness of the sediments (Jasnowski, 1962). Places that were used as heathland and wasteland

574   on the topographic map are covered by sandy humus on a sandy substrate with shallow groundwater (org.

575   in German: Sandiger Humus mit Sand-Untergrund und nahem Grundwasser) and by humic sands on a

576   substrate of permeable sands with shallow groundwater (org. in German: Humoser Sand mit durchlässigen

577   Sand-Untergrund und nahem Grundwasser).

578   A Detailed Map of Poland from 1933 documents the change in an ecosystem from lake to land. The area,

579   which on Prussian topographic maps was a lake with a surrounding bog, is described as a meadow on this

580   map. Moreover, the meadows adjacent to the south were marked with drainage ditches, which were not on

581   the Prussian maps. The area's surroundings, as before, were dominated by coniferous forests.

582   Aerial photos document subsequent changes in the ecosystem. The 1964 photo shows the northern part of

583   today's peatland's agricultural use (regular surface layout). Lake Kały, located nearby, became completely

584   overgrown, and its area was later dug by a drainage ditch, brought to the studied peat bog. The surrounding

585   area of the peatland is dominated by dense forest with occasional open clear-cutting areas. A photo from

586   1984 documents the succession of trees in the north-central part of the peatland. In the surrounding area,

587   open forest areas have entirely disappeared. A photo from 1997 clearly shows the development of trees on

588   the peatland, which have formed a dense block in its north-central part. A distinct area of *Sphagnum-*

589   dominated peatland with a well-marked edge has also emerged. Currently, the northernmost part of the

590   peatland is overgrown by pine; it is almost impossible to identify the maximum extent of the peatland surface

591   in the field (Fig. 1).

592

593   **4. Discussion**

594   **4.1. Exceptionally high peat accumulation rate**

595   ~~Peat accumulates when vegetation production exceeds organic losses under high water levels and anaerobic~~

596   ~~conditions (Tobolski, 2000).~~ In the Okoniny peatland, a rapid rate of peat accumulation is observed,

597   averaging 3.56 mm/yr, with a maximum value of 7.1 mm/yr at a depth between 11 and 12 cm. There are

598   several peatlands in Poland for which higher accumulation rates were reported. In the Tuchola Pinewoods,

599   the faster average rate of peat accumulation was recorded at Dury – 10 mm/yr (Pawlyta and Lamentowicz,

600   2010) and Mukrza – 4.6 mm (Lamentowicz and Obremska, 2010). At Jelenia Wyspa mire the accumulation

601   rates reached 0.4 mm/yr for the first 3000 years but accelerated to 3 mm/yr in the last 150 years

602   (Lamentowicz et al., 2007). A much slower rate was on the Tuchola kettle-hole bog – 1.2 mm and after ca.

603   1320 cal. yr BP the accumulation rate dropped to 0.4 mm/yr (Lamentowicz et al., 2008b). In other pine

604   monocultures, such as the Noteć Forest, the Rzecin peatland stands out for its high accumulation rate – an

605   average of 6.8 mm/yr in one profile and 7.5 mm/yr in the other one (Milecka et al., 2017). Peatlands in

606   Tuchola Pinewoods, including Okoniny peatland, generally have a faster accumulation rate than peatlands

607   located in other parts of Pomerania. The small kettle-hole peatland characteristic of Tuchola Pinewoods

608   accumulates carbon the fastest of all peatland types (Karpińska-Kołaczek et al., 2024). For the Stążki mire,

609   the highest accumulation rates were reported for the period between ca. 150-1230 AD and reached 2.2

610   mm/yr (unfortunately, the more recent, topmost material was not analysed) (Lamentowicz et al., 2008a).

611   Peat accumulation was even slower on Słowińskie Błota raised bog – 1.38 mm between 1830 and 2006,

612   although the highest accumulation rate was 5 mm/yr (during AD 840-860) (Lamentowicz et al., 2009b). At

613   the Gołębiewo sites the maximum accumulation rate was 1.85 mm/yr for the first site and 0.36 mm/yr for

614   the second site (Pędziszewska and Latałowa, 2016). The average 2 mm/yr accumulation rate for the

615   Kusowskie Bagno bog was in its 4000-year history (Lamentowicz et al., 2015). At Gązwa bog, the

616   accumulation rate was estimated at 1.46 mm/yr, more than twice as slow as at Okoniny peatland (Gałka et

617   al., 2015). In other regions of Poland, Jaczno bog (Suwałki Lakeland) stands out where peat accumulation

618   rate in this peatland was very rapid, averaging 2.76 mm/yr, with the highest values recorded in

619   undecomposed and uncompacted acrotelm – up to 12.7 mm/yr (Marcisz et al., 2020b). At the Pawski Ług

620   bog PAR was similar – 2.6 mm/yr (Lamentowicz et al., 2020). Such high accumulation rate values are also

621   rare in other parts of the temperate climate zone of Europe. Teici bog (Latvia) showed similar accumulation

622   rates - 3.5 mm/yr - from 1835 to 1965 AD and 10 mm/yr after 2000 (Stivrins et al., 2018). Okoniny peatland

623   after 2000 (between 21.5 and 11.5 cm) recorded an accumulation of 5.7 mm/yr. Saxnäs mosse in Sweden

624   showed an almost linear peat accumulation rate of 2-2.5 mm/yr (van der Linden et al., 2014). The maximum

625   accumulation was recorded at around 2310-2250 cal on the Estonian Hara bog. BP (31-15 cm) reaching 2.4

626   mm/yr (Łuców et al., 2022).

627

628   **4.2. Relationships between forest management and pollen analysis**

629   **4.2.1. The complex history of the Tuchola Pinewoods and its influence on the forest**

630   The results of pollen analysis of the collected core enabled us to illustrate how the forest was managed over

631   the past 300 years. Due to political changes and several administrative decisions, the management strategies

632   of the Tuchola Pinewoods underwent vital changes. The consequences of the implementation of forest

633   management techniques were visible in the palaeoecological record.

634   In 1772, the area of Gdansk Pomerania with the Tuchola Pinewoods was included in the borders of the

635   Kingdom of Prussia as a result of the First Partition of Poland (Wilson, 2012). At that time, some of the first

636   legal regulations for planned forest management in the area appeared (Jaszczak, 2008a). Nevertheless, in

637   1775, Frederick II the Great (1740-1786) issued a decree regarding government forests in Prussia, and later

638   state forests in Poland. It proposed the division of the forest into districts consisting of 50 man-made

639   clearings. However, this method of forest management worked well in the area of small forests in western

640   Prussia, but not for large forest complexes like the Tuchola Pinewoods. In 1782 Frederick II the Great issued

641   a special decree "On the development of the Tuchola Forest," in which it was written that the area of the

642   Tuchola Pinewoods was to be divided into eight districts of about 6000 hectares and 60 cutting areas in each

643   district. Only one man-made clearing in each district was provided for economic use, so no more than 100

644   hectares of forest per district (Jaszczak, 2008b). However, despite the introduction of many regulations

645   relating to forest management, the first decades of the 19th century brought devastating and predatory

646   deforestation on a large scale. For most of the 19th century, progressive deforestation was a problem in the

647   region, making the already poor conditions for agricultural development much worse (Wilson, 2012). With

648   each successive partition of Poland (1772, 1793, 1795), the Prussian government took over the state forests,

649   first the royal table estates (in Polish: dobra stołowe), and then also royal land (in Polish: królewszczyzny).

650   After the second partition, state forests were separated from agricultural land and transferred to separate

651   administrations (Nienartowicz, 2012). In 1810, the Prussian government issued the so-called Secularization

652   Act, under which forests were removed from churches and monasteries and attached to state forests. A law

653   had been in effect in Prussia since 1713, which prohibited the selling of state-owned property, but the

654   approach was different in Prussia.

655   To carry out the fastest possible Germanization of these lands, the local state property was sold off to the

656   Prussian nobilities, inviting them to settle in the area. Prussia's defeat of Napoleon's forces at the Battle of

657   Jena-Auerstedt in 1806 and the contribution Napoleon imposed in 1808 also contributed to the selling off
658   of the state forests. In December 1808, the government in Berlin passed an edict (published in November
659   1809) allowing the sale of state land, including forests, to cover the national debt (Broda, 2000; Kozikowski,
660   1911). Only large, compact forest complexes of a protective nature and economic importance were excluded
661   from this regulation (Broda, 2000). An additional reason for the loss of state forest area was the need to
662   redeem the servitude rights vested in peasants when selling property. The government compensated the
663   peasants for their rights to use the forest by transferring other forests without looking at area losses. The
664   peasants most often cut down all the forest given to them and turned the land into agricultural land. The
665   cause for such action was provided by the 1807 edict that removed state supervision of private forests, which
666   was later extended in 1811 (Broda, 2000; Kozikowski, 1911). Private forests could be freely managed from
667   then on, including dividing into smaller parcels, converting to agricultural land and selling.
668   This period was also a time of intense social and economic change, marked by the collapse of feudalism in
669   favour of a capitalist economy. The end of these transformations in Prussia was the enfranchisement of
670   peasants in 1811-1823. Economic development entailed a considerable demand for timber, and this, in turn,
671   became the basis for the robbery economy in forests. The selling off of state forests slowed down only in
672   the 1830s largely due to the efforts of G.L. Hartig, the general director of state forests in Prussia, and stopped
673   entirely in 1860.
674   Exploited forest areas were restored mainly with pine and spruce, either artificially or naturally. Because of
675   this, deciduous admixture species with entirely different life requirements began to disappear over time
676   (Broda, 2000). The introduction of easier-to-maintain coniferous species was driven by the growing demand
677   for wood in industry. The trend toward introducing pine monocultures intensified from the 1830s onward.
678   Since forest management in Prussia's state forests served mainly fiscal purposes, the concept of monoculture
679   plantations did well for several more decades. This situation persisted until the 1860s when a devastating
680   pest gradation occurred (Broda, 2000). At that time, the first steps were taken regarding the introduction of
681   admixtures into restoration.
682   Our data confirm an increase in the proportion of pine pollen in the forest composition and a decrease in the
683   proportion of pollen of other species. From the 1730s to the mid-1860s, the share of pine pollen in the pollen
684   of all trees increased from about 60% to about 90%. Our pollen diagram shows the rapid increase in *Pinus*
685   *sylvestris* pollen concentration after 1850. It can, therefore, be assumed that this resulted from *Pinus*
686   *sylvestris* introduced by mass monoculture plantings in the early 1830s reaching reproductive capacity. Pine
687   usually reaches sexual maturity between 10 and 15 years (Sullivan, 1993), although the threshold age has
688   been set at 25 years (Matthias and Giesecke, 2014). The decline in the share of deciduous species and the
689   increase in the share of Scots pine in the landscape began in Poland with the formation of the state. However,
690   at that time, it was associated with the expansion of agriculture and the harvesting of preferred species such

691 as *Carpinus betulus* (Czerwiński et al., 2021) Nevertheless, in the Prussian partition, planned forest

692 management permanently changed the composition of Poland's largest forest complexes, which were

693 dominated by easy-to-grow pine (Broda, 1993). A dynamic increase in the share of pine pollen until the

694 1860s in the Tuchola Pinewoods was also recorded at the Czechowskie Lake (Słowiński et al., 2019). An

695 increase in pine pollen concentration since the 19th century was also shown in pollen diagrams of other sites

696 from Pomerania – Stążki (Lamentowicz et al., 2008a), Słowińskie Błota (Lamentowicz et al., 2009b) – and

697 in other monoculture plantation complexes from Prussian partitioning area – Rzecin peatland in the Noteć

698 Forest (Milecka et al., 2017).

699 Although attempts were undertaken to correct earlier mistakes, this did not stop the massive deforestation.

700 Until the 1870s, the feudal system was still mixed with capitalist components, but from the 1870s onward,

701 under monopoly capitalism, timber trade and processing began to reach a significant size (Broda, 2000).

702 However, it has been noted that forests regulate air temperature, store water in the soil more efficiently, and

703 reduce wind speed, preventing soil erosion, which can help local agriculture face difficult environmental

704 conditions (Wilson, 2012). For this reason, as early as the 1870s, the state administration encouraged

705 landowners to protect forest stands on their lands and establish forestry cooperatives. The government also

706 guaranteed funds for the reforestation of private and municipal lands. In the mid-1870s, the Landtag set

707 aside a budget for the purchase and reforestation of wasteland by the state. However, these funds were used

708 to a small extent, although this somewhat reduced the share of forested private property (Broda, 2000;

709 Wilson, 2012). In 1886, the Royal Settlement Commission (in German: Königliche

710 Ansiedlungskommission) was established to buy up the estates of impoverished Polish nobility to acquire

711 agricultural land for German settlers (Wilson, 2012).

712 At the end of the 19th century, Tuchola Pinewoods became the largest timber production hub in the Prussian

713 partition. The Bydgoszcz timber industry region also played a major role in wood processing. The first steam

714 sawmill in the Bydgoszcz region was built in 1873, and by 1913, there were 20 of them, processing some

715 500,000 m^3 of wood and employing more than 1,600 people (Broda, 2000). All this resulted in a significant

716 decline in the concentration of tree pollen in the total pollen concentration in our diagram, to less than 60%

717 by the late 1920s and early 1930s. At the same time, we have seen intensive agricultural development. At

718 Okoniny, the proportion of Cerealia pollen doubled between ca. 1900-1920. This trend is also confirmed by

719 pollen data from the site in Okoniny Nadjeziorne, on the other side of Okonińskie Lake (Tipton, 2023), as

720 well as from Czechowskie Lake, about 25 km northeast of our site (Słowiński et al., 2019). Despite intensive

721 deforestation in general, further afforestation with pine was also progressing. In 1893, pine forests accounted

722 for 99% of all forests in Tuchola County (Szwankowski, 2005). Intense changes in forest management (pine

723 dominance) and agricultural development (high concentration of Cerealia pollen) in the 19th century are also

724   evident in records of profiles outside large, dense forest complexes – Kusowskie Bagno (Gałka et al., 2014),

725   Linje mire (Marcisz et al., 2015).

726

727   **4.2.2.Impact of forest management on peatland vegetation**

728   As a result of changes related to forest management, lake to peatland transition occurred rapidly. We assume

729   that this was primarily the result of drainage, which was undertaken in the area at the end of the 19th century

730   (see drainage ditches on the southern side and a dike in the middle part of the site on maps in Figure 6), and

731   secondly, to a lesser extent, the transition from mixed forests to pine monoculture. These activities

732   contributed to an increase in the acidity of the peatland. Forest drainage is often associated with the

733   acidification of surface waters (Miller et al., 1990). The introduction of forest drainage, on or near peatlands,

734   to improve tree growth has been quite common in northern and northeastern Europe (Westman and Laiho,

735   2003). The oxidation of organic sediments and the detachment of hydrogen ions H+ increase acidity (Ulrich,

736   1980). In addition, the supply of alkaline cations to the peat is impeded by drainage ditches (Minkkinen et

737   al., 2008). However, the long-term consequences of drainage are devastating to peatlands, as they initiate

738   vegetation succession, in which species typical of peatlands are replaced by forest vegetation (Laine et al.,

739   1995). In the example of our palaeoecological data, the dynamic succession of pine and birch in the Okoniny

740   peatland is evident, which is also supported by aerial imaging. As already mentioned, the successive decline

741   in pH is also the result of the impact of pine plantations growing in catchments. A drop in pH in Okoniny

742   has likely enabled the rapid growth and expansion of *Sphagnum* and the peatland initiation. The crowns of

743   forests, especially the needles, can increase the uptake of atmospheric pollutants such as sulfur and nitrogen

744   components, contributing to the acidification of surface waters (Nisbet, 2001; Reynolds et al., 1994).

745   Conifers also can capture ions of marine origin - Na and Mg cations. These, in turn, displace hydrogen and

746   aluminium cations from the soil, leading to acid runoff from the forests along with surface runoff, which is

747   known as the "sea-salt effect" (Drinan et al., 2013; Harriman et al., 2003; Reynolds et al., 1994). We

748   observed the presence of *Pinus* needles at the beginning of phase 2 (from 1838 cal. CE), at the transition

749   from pond to peatland ecosystem. Moreover, Pinus stomata were also present in palynological samples at

750   that time, pointing to more frequent needle falls. More pine trees in the Tuchola Pinewoods resulted in much

751   higher amounts of needles and other pine fragments accumulating on the forest ground, leading to soil

752   acidification. This, together with drier conditions, could quickly lead to acidification around the pond,

753   forming perfect conditions for *Sphagnum* to encroach – first as a floating mat that successively overgrown

754   the pond. We sampled the peat core close to the edge of the peatland, thus in the place where moss

755   encroachment on the open water body began; therefore, we were able to track this succession in our record.

756   This succession and disappearance of Lake Kolze are also clearly visible in historical maps (Figure 10).

757   Other examples of quick encroachment of floating mats on the surface of the lake have been observed and

758   mapped in other open water bodies in the Tuchola Pinewoods (Kowalewski, 2003; Kowalewski and

759   Milecka, 2003) and other regions (Warner, 1993).

760

761   **4.3. Anomalies and extreme events**

762   **4.3.1. The impact of droughts and fires on the forest and peatland**

763   Historical sources indicate that in the 18th and 19th centuries, the Tuchola Pinewoods were relatively often

764   affected by droughts resulting in fires (Wilson, 2012). In 1781, there was a fire in Tuchola (ca. 16 km SW),

765   during which a large part of the city with the church and town hall burned down, and in 1792, Starogard

766   Gdański (ca. 42 km NE) burned almost to the ground (Orłowicz, 1924). Major fires also occurred in 1794,

767   and 1807, when more than 34,000 hectares of forest burned (Orłowicz, 1924; Schütte, 1893). Fires in 1809,

768   1810, 1812, 1813 and 1828 in the Świt forest district about 15 km from the study site were also recorded

769   (Cyzman, 2008). Palaeoecological data, especially MIC, confirm high fire activity in the first decades of the

770   19th century (a rapid increase). Słowiński et al. (2019) emphasized that data on fires before the 1830s,

771   especially regarding their area, should be treated with caution due to the lack of accurate measurement

772   techniques. In the Woziwoda Forest District, within which the Okoniny peatland is located, the forests of

773   the Biała and Barłogi forest districts also burned in 1842 (Cyzman, 2008). Intense fires also appeared in the

774   Tuchola Pinewoods between 1846 and 1848 (Orłowicz, 1924; Schütte, 1893).

775   Later, numerous fires were also reported in the Woziwoda Forest District. Between 1860 and 1889, 310 fires

776   were observed, destroying 4206 hectares of the forest (Orłowicz, 1924; Schütte, 1893). The highest number

777   of fires in this period was registered in 1862-1864 and 1874-1875 when 3565 hectares of forest burned;

778   altogether, nearly 85% of the area burned in 1860-1889 (Schütte, 1893). The largest area burned in 1863

779   equaled 2333 hectares, including more than 1250 hectares in the Woziwoda forest district; altogether, 25%

780   of all the forest burned in 1860-1889 (Orłowicz, 1924; Schütte, 1893). Meteorological data confirm dry

781   years in the period from 1862 to 1865. In 1862 and 1863, the annual precipitation in Bydgoszcz was only a

782   little over 450 mm (Kirschenstein, 2005), and it was then that the largest number of hectares of forest in the

783   known history of the Tuchola Forest burned (Dietze et al., 2019).

784   However, contemporary linked the number of fires with political events and nationalist sentiment among

785   the Polish population (Orłowicz, 1924; Schütte, 1893; Wilson, 2012). In 1901, in the nearby Trzebciny and

786   Gołąbek Forest Districts, a fire consumed 663 hectares of forest (there was a parallel children's strike in

787   Września Province) (Orłowicz, 1924; Wilson, 2012). Fires could also be caused by agricultural activities

788   and land preparation for crops (Poraj-Górska et al., 2017). By the 1830s, charcoal production was

789   widespread (McGrath et al., 2015), and forest burning was used to create heathlands for beekeeping

790   (Bienias, 2009).

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

797 In 1948, about 450 hectares of forest were burned near Osieczna, and in 1954, 80 hectares were burned near
798 Ocypel (Cherek, 2007). Palaeoecological data record an increased MIC supply during this period. The first
799 of these fires was also recorded in the sediments of Czechowskie Lake (Słowiński et al., 2019). The summer
800 drought of 1921 occurred over a larger area of Europe, from Poland and the Czech Republic to the UK (van
801 der Schrier et al., 2021). Summer droughts also affected the Tuchola Pinewoods in 1951 and 1959. In 1959
802 Bydgoszcz received only 37 mm of precipitation from August to October (Mitosek, 1960), and from 1950
803 to 1958 Bydgoszcz received less than 500 mm of rain per year (Kirschenstein, 2005). Our palaeoecological
804 data confirm droughts in the 1950s. There is a sharp increase in the proportion of *Phryganella acropodia*
805 among the testate amoebae, an indicator of dry conditions (Diaconu et al., 2017), and a high concentration
806 of coprophilous fungi and an expansion of brown mosses in the form of *Pohlia nutans* (up to 30% of the
807 peat sample composition) are also marked. Dendroclimatic data recorded the negative impact of climatic
808 conditions on pine, especially strongly in 1950 and 1956.

809 Studies show that particle size illustrates the distance of the fire from the site, the heavier the particles, the
810 shorter distances they travel (Clark, 1988; Peters and Higuera, 2007). However, many factors determine the
811 particles' transport–the fire's intensity, the burning areas and the wind direction. Adolf et al. (2018) point out
812 that the charcoal source area of occurrence of both MIC and MAC can reach a radius of 40 km. However,
813 it is often assumed that MAC indicates fires that occurred up to 1-3 km (Clark, 1990; Higuera et al., 2007;
814 Oris et al., 2014). The distances to which particles move are also determined by terrain and vegetation. They
815 move longer distances on flat terrain covered with grasses (Woodward and Haines, 2020), while they move
816 shorter distances in dense forests (Kelly et al., 2013; Oris et al., 2014). In this context, it should be assessed
817 that the local fire activity in the studied peatland was low, with an average of 0.36 particles/cm^3/year,
818 although from historical sources, fires are known to have occurred nearby.

819

820 **4.3.2. Insect outbreaks and their impact on pine monoculture**
821 The earliest information on insect outbreaks from the forests of the Tuchola Pinewoods under planned forest
822 management dates back to 1836-1838. A gradation of the *Panolis flammea* occurred at that time (Schütte,
823 1893). The insects also attacked between 1866 and 1868. As a result of this gradation, 1380 hectares of
824 forest were destroyed in the Woziwoda forest district alone (Schütte, 1893). The pollen diagram from the

825   Okoniny peatland documents the phenomenon in the 1860s with a decrease in *Pinus sylvestris* pollen and

826   an increased presence of *Pinus* stomata that may indicate the event of the insect outbreak (Barabach, 2015).

827   The needles that fell were partially decomposed and carried downwind to the peatland, where they were

828   preserved (Słowiński et al., 2019). The same effect was noted in another closely located peatland in Okoniny

829   Nadjeziorne, where the 1866-1868 gradation also corresponds with increased numbers of *Pinus* stomata

830   (Tipton, 2023). In 1855, *Lymantria monachal* appeared in large numbers but damaged only some of the

831   younger stands (Schütte, 1893).

832   A serious incidence of *Panolis flammea* gradation also occurred in 1922-1924 (Kiełczewski, 1947;

833   Mokrzecki, 1928). Between 1978 and 1985, with a peak in 1982, the forests of the northern part of the

834   country were overrun by *Lymantria monacha*, and this was the largest gradation since the establishment of

835   the National Forests in 1924, with salvage treatments covering more than 6.3 million hectares of forest over

836   seven years (Broda, 2000; Jabłoński, 2015; Śliwa, 1989, 1987). Both major gradations are reflected in

837   palynological data, manifested by declines in pollen percentage of trees, primarily *Pinus* and *Picea*. A

838   decrease in conifer pollen during the gradation period has also been shown by studies of other sites in the

839   Tuchola Pinewoods (Łucόw et al., 2021; Tipton, 2023). Other pine monoculture in Poland, the Noteć Forest

840   was also affected by gradation in 1922-1924, and this event manifested itself in palaeoecological data

841   (Barabach, 2015; Lamentowicz et al., 2015; Milecka et al., 2017). Among other things, Barabach (2015)

842   noted an increase in *Glomeromycota* fungal spores, which according to this author may indicate intense soil

843   erosion caused by the felling of dead trees and a marked increase in *Calluna* and Poaceae indicating an

844   increase in the openness of the landscape. Lamentowicz et al. (2015) noted an increase in mineral content

845   in the sediment as indicated by *Centropyxis platystoma*, which was confirmed by XMT analysis of the peat.

846   Milecka et al. (2017) described higher ash content and higher charcoal content in the sediments. Although

847   the Tuchola Pinewoods and the Noteć Forest are in the region of highest risk of outbreaks, other areas of

848   Poland were also affected, such as the Kampinos Forest in 1972 (Śliwa, 1974), or over the last decade, the

849   Białowieża Primeval Forest (Grodzki, 2016; Kamińska et al., 2021).

850   Palaeoecological studies based on the presence of insect head capsules and/or feces, as well as other insect

851   remains could be helpful, but these methods are rarely used (Bhiry and Filion, 1996; Lavoie et al., 2009;

852   Simard et al., 2006; Waller, 2013). Often the main obstacle to performing this method is bad preservation

853   of insect remains in peat. In the Okoniny peatland, we did not find any insect remains, even though quite a

854   large sample volume has been analyzed for the plant macrofossil analysis. Therefore, we can interpret the

855   effect of insect outbreaks using other sources of evidence.

856   It's difficult to assess unequivocally whether the gradations affected the immediate vicinity of the peatland,

857   or whether this is a regional signal. Historical maps could be helpful, but these usually do not show the

858   difference between old and new plantings (Barabach, 2012). However, dendrochronological data obtained

859   from pine trees could help to reconstruct the extent of the outbreak. The main problem in monoculture
860   forests though is that the forest is successively cut and new trees are planted regularly. However, for our
861   dendrochronological record, we were able to obtain samples from the oldest pine trees in the area. The oldest
862   trees in the region analyzed in this study were planted over 200 years ago in the close vicinity of the
863   Woziwoda Forest District, after the introduction of the Prussian forest management strategies, and have
864   been kept there by foresters for obtaining tree saplings and for monitoring. The influence of insect outbreaks
865   has been recorded in these pine trees and we were able to track all the outbreak events in the wood. The first
866   years after the gradations - 1839, 1869, 1925 and 1982 - manifested very strongly in the dendrochronological
867   data as negative indicator years.

868

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

870   The assessed growth reactions of pine trees to climate factors at the Woziwoda site may be considered
871   typical. The effect of February air temperatures on Scots pine growth in northern Poland was previously
872   noted (Cedro, 2001; Cedro and Lamentowicz, 2011; Feliksik and Wilczyński, 2009; Koprowski et al., 2012,
873   2011; Matulewski et al., 2019; Zielski, 1996; Zielski et al., 2010; Zielski and Sygit, 1998). Although the
874   studied pines from Woziwoda showed a similar growth response to climate as other pines from northern
875   Poland, their climate sensitivity was greater. The highest negative correlation for pine radial growth from
876   the Woziwoda site was found with July's mean air temperature.
877   Another factor commonly affecting the radial growth of Scots pine, according to the literature, is pluvial
878   conditions in February. This linkage was identified by Cedro (2001), Feliksik and Wilczyński (2009),
879   Koprowski et al. (2011) in the Pomeranian region (Northern Poland). The present study confirmed a short-
880   term relationship between pine radial growth and precipitation sums in February (Fig. 7). Late February and
881   early March are when additional water is required due to the initiation of biochemical processes in trees
882   (Przybylski, 1993). Additionally, in our study, a stronger dependence of pine radial growth on precipitation
883   was demonstrated in June. A similar result for pine from northern Poland was obtained by Matulewski et al.
884   (2019), Zielski and Barankiewicz (2000), where pine growth was threatened by a water deficit in the summer
885   season. Increased pine demand for water occurs in June and July, which are the months of the most intense
886   growth (Obmiński, 1970). At the same time, these are the months when droughts have become more frequent
887   in recent years (Łabędzki, 2004; Spinoni et al., 2018). Our results confirm that within the temperature and
888   monthly precipitation values typically observed in Central Europe, the primary environmental factor
889   influencing the diversity of species growth in the near future will be the availability of water (Boczoń et al.,
890   2017; Taeger et al., 2013). This availability is determined by both the level of precipitation and losses caused
891   by evapotranspiration (Boczoń and Wróbel, 2015; Zajączkowski et al., 2013).

892 The higher climatic sensitivity of pines at the Woziwoda site was manifested also by a higher number of

893 pointer years. The pointer years identified in this study are confirmed by earlier studies performed on pine

894 trees in northern Poland for the period 1910-2014 (Matulewski et al., 2019; Zielski et al., 1998; Zielski and

895 Barankiewicz, 2000). The years 1911, 1940, 1950 and 1982 attract particular attention. These are years in

896 which dry and hot summers were recorded (Matulewski et al., 2019; Zielski, 1996). Moreover, the years

897 1925 and 1982 are marked by insect outbreaks.

898 Our data show that *Pinus sylvestris* has been under critical climatic pressure and is responding negatively

899 to a warming climate and changing precipitation regime. Models predict a severe decline in coniferous

900 species in the next 50 years, including *Pinus sylvestris* in the temperate zone of Europe (Dyderski et al.,

901 2018; Hanewinkel et al., 2013; Schueler et al., 2014). The disappearance of species currently dominant in

902 the forests of Central and Eastern Europe will result in the profound disruption or disappearance of

903 ecosystems functionally related to them, such as peatlands (Dyderski et al., 2018).

904 Peatlands are also affected by accelerating climate change and on top of that they are at risk of losing their

905 favourable environment, especially in *Pinus sylvestris* monoculture forests particularly vulnerable to

906 increasing extreme events. Studies conducted by various researchers confirm that remote sensing data,

907 provide a valuable source of information about peatlands and help in monitoring their condition (Czapiewski

908 and Szumińska, 2021; Kaplan et al., 2019; Lees et al., 2021; Rapinel et al., 2023) The analyses conducted

909 in this study have demonstrated that multisensor airborne data can be successfully utilized to assess the

910 current state of peatlands vegetation. The application of simple remote sensing indices enabled the detection

911 of spatial differences in the condition and water stress of vegetation in the Okoniny peatland. According to

912 Rastogi et al. (2019), NDVI values for peatland vegetation may decrease in areas affected by stress factors

913 such as warming and reduced precipitation. Moreover, NDVI values for healthy Sphagnum moss in peatland

914 usually range from 0.8 to 0.9 during the summer, but they are also species-dependent (Harris, 2008; Letendre

915 et al., 2008; Péli et al., 2015). Consequently, the values of NDVI observed in this study (averaging 0.65)

916 may indicate a prevailing drought situation in certain areas of the Okoniny peatland. Comparable findings

917 can be drawn from the spatial variation of MSI values presented in this study. Harris et al. (2006, 2005)

918 demonstrated that MSI is significantly correlated with near-surface moisture condition of Sphagnum moss.

919 Despite the wide application of optical data and spectral indices in assessing peatland conditions, Gerhards

920 (2018) found that spectral indices may only be useful under conditions of severe or prolonged water stress.

921 For the pre-visual detection of initial vegetation water stress symptoms, temperature-based indices are most

922 suitable, exemplified by the LST index used in this study. Although aerial thermal data has been previously

923 applied in peatland research (Kopeć et al., 2016), further research into the potential use of airborne thermal

924 data in assessing peatland vegetation conditions is recommended. To date, there have been few works in

925   Poland using spectral data in peatland monitoring (Bandopadhyay et al., 2021, 2019). However, none has

926   attempted to collate palaeoecological, dendrochronological, and remote sensing data.

927

5. Conclusions

929   Our data show that peatlands are highly sensitive to the progressive rise in Earth's temperatures and changing

930   precipitation regimes. Groundwater levels have dropped dramatically in recent years, causing intense

931   heating of the peatland surface in summer and stressing peat-forming vegetation to water scarcity. The pine

932   monocultures surrounding the peatlands are also sensitive to climate change. They are currently responding

933   very strongly to summer precipitation deficiency, and these data fit into dendrological predictive models.

934   Planned forest management has permanently changed the composition of the forest. Deciduous tree species

935   such as *Quercus*, *Fagus*, *Carpinus*, and *Corylus avellana* have almost completely disappeared. Forest

936   management has also contributed to an increase in acidity in the peatland, and thus the rapid development

937   of *Sphagnum* specialized for life in acidic conditions. After the expansion of *Sphagnum*, the water level in

938   the peatland stabilized. Peatlands are also valuable archives of past climatic anomalies and catastrophic

939   events. Pest gradations are recorded, among other things, by the presence of *Pinus* stomata, and periods of

940   drought by an increase in the concentration of coprophilous fungi. These events correspond with

941   dendrochronological records. There is a strong correlation between the first years after hailstorms and

942   smaller increments of tree rings. Our study shows that palaeoecological and dendrochronological data can

943   complement each other and create a more complete picture of past environmental changes and expand

944   knowledge of best practices for local (Konczal et al., 2024) and global (Joosten, 2021) recommendations

945   for peatland conservation in forests. Healthy wetlands could be key to protecting forests and slowing the

946   transformation of forests caused by climate change (Marcisz et al., 2024). The results are important for

947   peatland conservation in the context of planned forest management.

948

Competing interests

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

951

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962

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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