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Pine Forest Management and Disturbance in Northern Poland: Combining High-Resolution 100-Year-Old Paleoecological and Remote Sensing Data

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Global warming has compelled to strengthen the resilience of European forests. Due to repeated droughts and heatwaves, weakened trees become vulnerable to insect outbreaks, pathogen invasions, and strong winds. This study combines high-resolution analysis of a 100-year-old high-resolution peat archive synthesized from the Martwe peatland in Poland with remote sensing data. We present the first REVEALS based vegetation reconstruction in a tornado-hit area from Poland on the background of previous forest management in monocultural even-aged stands – Tuchola Pinewoods. During the 20th century, the pine monocultures surrounding the peatland were affected by clear-cutting and insect outbreaks. In 2012, a tornado, destroyed ca. 550 ha of pine forest around the peatland. The palynological record reflects these major events of the past 100 years as well as changes in forest practices. Our study showed the strong relationships between the decrease of *Pinus sylvestris* (Scots pine) in palynological record as well as planting patterns after the tornado. Moreover, past forestry practices [such as domination of *Pinus sylvestris*, the collapse of *Picea abies* (Norway spruce), low share of *Betula* spec. (birch) due to *Pinus sylvestris* promotion and probable also to a lesser by removal of *Betula* as a "forest weed," and low plant coverage of tree species due to clear-cutting and cutting after insect outbreaks] were well identified in the proxy record. In monocultures managed over decades, the reconstruction of vegetation may be challenging due to changes in the age composition of the *Pinus sylvestris* stands. We found that through historical, remote sensing, and paleoecological data, the dynamics of disturbances such as insect outbreaks and tornadoes, as well as the changing perceptions of local society about forests, can be determined.

Keywords: tornado, peatland, paleoecology, pollen analysis - REVEALS, monocultures, insect outbreaks

INTRODUCTION

Forest disturbance by storms, including tornadoes, is a rare but important problem that needs to be considered in the development of forest management strategies (Dobrowolska, 2015; Szmyt and Dobrowolska, 2016). Over the past decades, the frequency of extreme events such as storms and tornadoes has increased across Europe (Seidl et al., 2014) and is forecasted to increase further in the future (Senf and Seidl, 2021). Atmospheric phenomena that can damage forests, such as strong winds and tornadoes, are difficult to predict. However, it is important to understand the complex interactions between the damage caused by extreme events, the resilience of forest communities, climate change, and forest management due to the increased extent of forest destruction by the wind in recent years in Europe (Gardiner et al., 2010; Seidl et al., 2014; Gregow et al., 2017). Moreover, observations from the last decades indicate that the future will witness more extreme events that will not just affect the forests. These events include heatwaves, which will increase the possibility of fires (Ummenhofer and Meehl, 2017; Brando et al., 2019). The European monocultures are expected to be more sensitive to drought, and hence, the exposure of forests to pathogens, insect outbreaks, and strong winds (Leuschner and Ellenberg, 2017; Seidl et al., 2017, 2020).

Wind disturbances were more frequent in the European forests in the last decades (Seidl et al., 2017). During 1950–2010, more than 130 separate storms occurred, causing significant damage to forests (Gardiner et al., 2010). Huge economic losses resulted from cyclone Gudrun in 2005 and extratropical cyclones in Sweden in 1969 (wood loss of 42.2 mln m^3), Lothar and Martin storm in 15 European states in 1990 (more than 240 mln m^3), and cyclone Klaus in France, Spain, Portugal, and Italy in 2009 (43.1 mln m^3) (Jantz, 1971; Gardiner et al., 2010). Furthermore, tornadoes of F2 or higher intensity can harm and uproot trees (Fujita, 1971). Across Europe, 9,529 tornadoes have been recorded between 1800 and 2014 CE (Groenemeijer and Kühne, 2014; European Severe Weather Database, 2020), with the actual number predicted to be higher (Shikhov and Chernokulsky, 2018).

Our study is focused on the Tuchola Pinewoods, which are one of the largest forest complexes in Poland. The current forest composition includes pine monocultures (plantations) in even-aged stands, introduced in the second half of the 18th century by Prussian forestry (Gietkowski, 2009). At present, *Pinus sylvestris* (Scots pine) is the dominant species, occupying more than 95% of the forest area, and is accompanied by other species such as *Betula* (birch) (1.8%), *Quercus* (oak) (1.1%), *Alnus glutinosa* (black alder) (1.0%), and *Picea abies* (Norway spruce) (0.5%) (State Forests data, 2020).

Studies report that forests have been affected by fires, insect outbreaks, strong winds, and tornados in the last 100 years (Karasiewicz, 1926; Koziński, 2007; Gietkowski, 2009; Słowiński et al., 2019). The Tuchola Pinewoods showed markedly low resistance to insect outbreaks. The most severe outbreak in this forest and Poland, in general, was that of *Panolis flammea* (pine beauty) in 1922–1924 (Mokrzecki, 1928; Broda, 2000, 2010). Due to the outbreak, most of the Notecka Forest and the Tuchola Pinewoods were cut down (Koehler, 1974; Ankudo-Jankowska, 2003; Broda, 2003). During 1978–1985, weather anomalies with cold winters and changes in water conditions triggered the outbreak of *Lymantria monacha* (black arches), which was the largest recorded in the history of the Polish State Forests (since its founding in 1924) (Sliwa, 1989; Jablonski, 2015). This outbreak affected the northern and western parts of Poland, including the Tuchola Pinewoods.

On 14 July 2012, the Tuchola Pinewoods have been hit by one of the most destructive tornadoes in Poland, which had an intensity of F3 (Taszarek et al., 2016). The tornado caused one fatality and 10 injuries, and within minutes, around 550 ha of the Tuchola Pinewoods in the Trzebciny District and 105 buildings were damaged. The track of the tornado was 20-km long and 800-m wide at maximum. On 11/12 August 2017, a hurricane hit the Tuchola Pinewoods. It destroyed forests up to an area of ca. 80,000 ha (9.8 mln m^3) in 60 forest districts in northwestern Poland (Trębski, 2019).

In Poland, about 350 tornadoes have occurred between 2000 and 2019 (European Severe Weather Database, 2020). Moreover, 37 deadly tornadoes were known from earlier periods, for example, in Turzyn (1829), Tuchola (1871), Rowiska (1926), and Rawa Mazowiecka (1958) (Taszarek, 2016; Taszarek and Gromadzki, 2017). Each year, an average of 8–14 tornadoes hits Poland. The country is also affected by tornadoes of very high intensity (F4 on the Fujita scale) once every one or two decades (Taszarek, 2016).

Martwe peatland, located within the area deforested by the July 2012 tornado, offers the rare opportunity to study the imprint of a tornado in the paleoecological (pollen) record. We moreover use this archive to study the representation of other forest changes during the past 100 years, including further catastrophic events such as large-scale disasters and clear-cutting. To this end we attempt quantitative interpretation of the pollen record using the REVEALS model and compare the results with archival data from the area 4 km radius around the lake.

Here, we used a *Sphagnum* peatland as a natural archive that is often used to reconstruct long-term environmental and climate changes of the past based on paleoecological research (Tobolski, 2000; Charman, 2007; Słowiński et al., 2014). Paleoecological archives, such as peat, provide information about the past landscape changes, regional and local vegetation, climate, fires, and human history (Booth et al., 2004; Mitchell et al., 2007; Lamentowicz et al., 2015; Payne et al., 2015). In particular, pollen analysis serves as a proxy to reconstruct local- and regional-scale vegetation (van Geel, 1978; Słowiński et al., 2015; Kołaczek et al., 2018) and infer the history of forest management (Słowiński et al., 2019; Lamentowicz et al., 2020; Schafstall et al., 2020). Pollen percentage values do not perfectly represent past vegetation composition because pollen production and dispersal differ among plant taxa so strong pollen producers are over-represented while weak pollen producers are under-represented. We applied the REVEALS model (Sugita, 2007) to reduce this bias in the pollen data.

Furthermore, peatlands have been used extensively as archives of the past direct and indirect disturbances such as deforestation, clear-cutting, drainage, land use, pollution, fragmentation, fire, floods, or storms (Ireland and Booth, 2012; Ireland et al., 2012; Marcisz et al., 2019; Swindles et al., 2019; Łuców et al., 2020). However, they have never been used so far to explore past tornado events. Therefore, the aim of this study, is to present the first tornado-related paleoecological record from a monoculture in Poland on the background of previous forest management (clear-cutting, cutting after insect outbreaks), through vegetation reconstruction of a 100-year-old peat core, based on pollen analysis and the REVEALS model (Sugita, 2007) as well as on remote sensing data. We used the pollen analysis for the better understanding disturbances recorded in pine dominated forests in periods that devoid of historical data.

MATERIALS AND METHODS

Study Site

The study site is the Martwe peatland in NW Poland (a partly floating mat on the Martwe lake) and its neighboring area within a radius of 4 km (**Figure 1B**). The peatland, which is located in the middle of a Pine monoculture forest, surrounds a small dystrophic lake. This lake is overgrown by *Sphagnum* floating mat (Martwe peatland) (**Figure 1C**), from which the peat core was obtained. The forest in this area has existed continuously for centuries, however, since after the first partition of Poland (1772 CE), a large-scale transformation of forests to pine monocultures by Prussian forestry was recorded. It was exactly connected with the introduction of the decree "On the management of the Tuchola Forest" issued by King Frederick of Prussia in 1782 (Jaszczak, 2008; Jażdżewski, 2008). As a result, eight administrative areas were created in the forested area of Tuchola Forest, whose first purpose was to make a detailed map of the forest area in order to estimate the potential for timber harvesting. The study site is located in Trzebciny Forest District in the southern part of the Tuchola Pinewoods (53°37′07.0′′N, 18°12′09.0′′E, 109.4 m a.s.l.; **Figure 1**). It is situated in the outwash plain of the Wda River, which developed during the Pomeranian phase of the

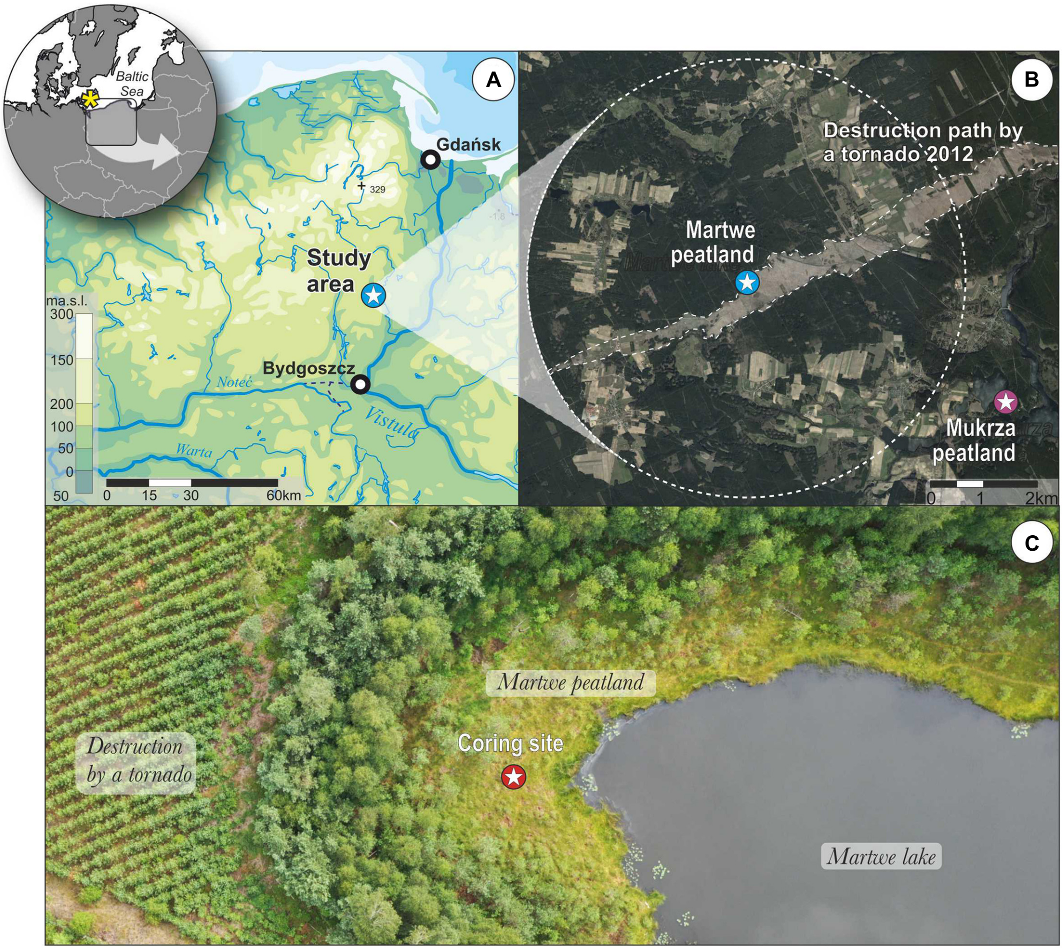


FIGURE 1 | Setting of the study site. **(A)** Location on the Europe and Poland maps. **(B)** Location of the tornado path from 2012 in the southern part of the Tuchola Pinewoods. The Martwe peatland is in the center of map. Its neighboring area within the 4-km radius is marked in a white circle. The Martwe peatland is indicated by blue color, and Mukrza peatland (the nearest well-dated paleoecological site) by magenta color. **(C)** Coring site from the Martwe peatland (*Sphagnum* floating mat on the Martwe lake) and drone picture from July 2020.

Vistulian glaciation (Błaszkiewicz et al., 2015). The Martwe lake was formed by the melting of a buried ice block (Kordowski et al., 2010; Słowiński, 2010; Słowiński et al., 2015). The entire peatland as well as the lake (3.56 ha) is protected at the national level as Nature Reserve. It is assumed that acidification of the lake and the development of floating mat have been triggered by the cultivation of *Pinus sylvestris* monoculture about 200 years ago (Gietkowski, 2009; Kordowski et al., 2010). The maximum depth of the lake in the central part is about 3 m, while the peat layer has a thickness of 20–100 cm (Kordowski et al., 2010). The climate data from the meteorological station in Chojnice (about 45 km from the study site) obtained for the years 1951–2017 reveal that the warmest month is July with a temperature of 17.1°C and the coldest is January with –2.5°C (Institute of Meteorology and Water Management - National Research Institute, 2019). The average annual temperature of the study site is 7.3°C, and the average annual precipitation ranges between 550 and 600 mm.

Current Forest Composition and Potential Vegetation

In the study area, the forests are currently dominated by *Pinus sylvestris* forests (**Figures 2A,C**). The map of potential natural vegetation suggests a greater variety of trees species (**Figure 2B**; Matuszkiewicz et al., 1995), with mixed oak-pine forests being dominant (*Querco-Pinetum*), accompanied by oak-lime-hornbeam forests (*Tilio-Carpinetum*, poor) and swampy ash-alder wood forests (*Frazino-Alnetum* [*Circaeo-Alnetum*]). *Leucobryo-Pinetum*, *Peucedano-Pinetum*, and *Carici elongate-Alnetum* associations occupy a small area of the forests.

Peat Record

Four peat monoliths were extracted from the Martwe peatland in spring 2016 using a Wardenaar sampler (chamber dimension: 10 cm × 10 cm × 100 cm) (Wardenaar, 1987). The most representative peat core was selected for this study. For reconstruction covering the last 100 years, we analyzed a 47-cm-long part of one peat monolith (MAR1, 67 cm) from the southern part of the Martwe peatland, which was affected by a tornado from 2012. Pollen analysis was performed to reconstruct changes in the composition of forests over the last 100 years. Pollen samples (1 cm^3) were collected continuously at 0.5-cm intervals (from 4 to 11 cm) and 1-cm intervals (1–3 and 12–47 cm), and prepared using standard laboratory procedures for palynological analysis (Berglund and Ralska-Jasiewiczowa, 1986). Pollen grains were identified using atlases (Moore et al., 1991; Beug, 2004) under a microscope at 400× and 1,000× magnifications. The figure of the simplified percentage pollen diagram was prepared using the Tilia program (version 2.0.41) (Grimm, 1992; **Supplementary Figure 1**). The pollen records from the Martwe peatland was compared with pollen record from Mukrza peatland, which is ca. 5 km southeast of the Martwe peatland. Original data come from the doctoral dissertation of Milena Obremska (Obremska, 2006; Lamentowicz and Obremska, 2010).

To extract past vegetation cover from pollen data we applied REVEALS using the REVEALSinR function from the discover R package (Theuerkauf et al., 2016). REVEALS is a correction factor approach, i.e., bias in pollen data is removed by dividing pollen counts by two corrections factors, i.e., pollen productivity estimates (PPEs) to account for differential pollen production and

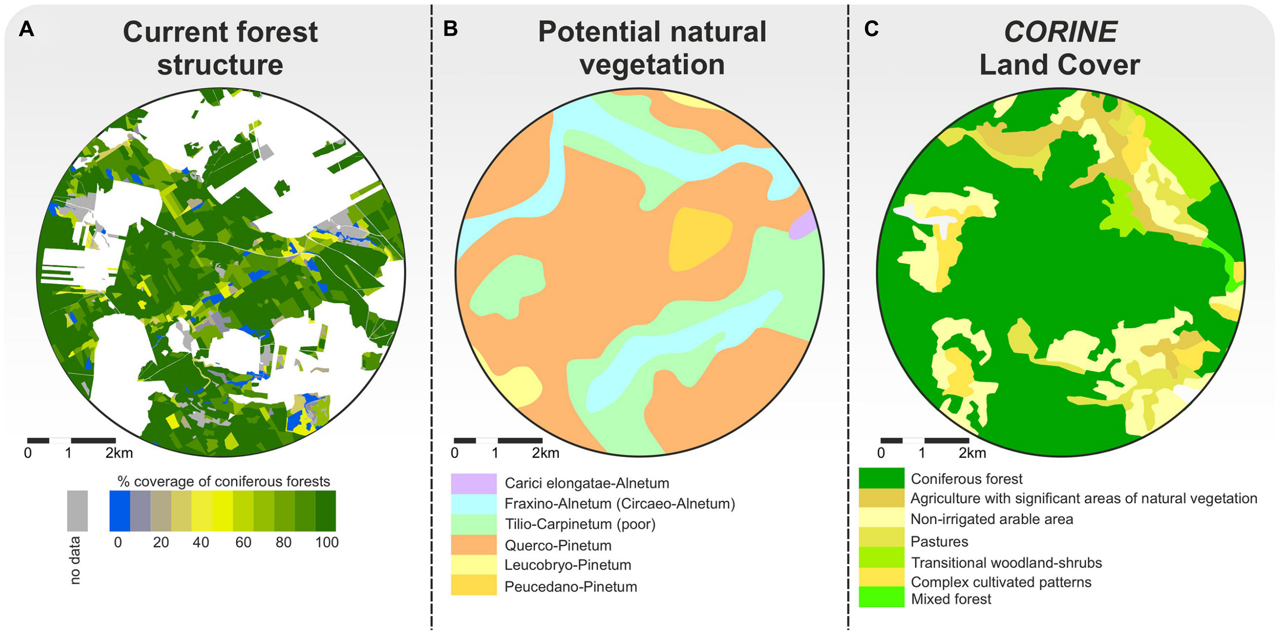


FIGURE 2 | Maps of the area within the 4-km radius from the Martwe peatland (*Sphagnum* floating mat on the Martwe lake). **(A)** Current forest structure. The map was developed for the year 2020. **(B)** Differentiation of potential natural vegetation (Matuszkiewicz et al., 1995). **(C)** CORINE Land Cover. The map was developed for the year 2018. The Martwe peatland is located in the center of each map.

the dispersal-deposition factor K which accounts for differential pollen dispersals. We selected the Lagrangian-stochastic model to calculated K factors. As yet no PPEs are available from Poland, we used a preliminary PPE data set, which is based on the application of the ROPES model on a number of lake pollen records from northern Poland and Germany (**Supplementary Table 1**; Theuerkauf and Couwenberg, 2018). ROPES is a quantitative method for translating single pollen records into past vegetation composition without PPEs as an input parameter. The method requires pollen counts and pollen accumulation rate data. Besides reconstructed vegetation composition, ROPES also estimates PPEs. Stratigraphic diagrams were prepared using C2 (Juggins, 2003).

Chronology

The six samples of *Sphagnum* stems were dated using ^{14}C AMS method in Poznań Radiocarbon Laboratory (laboratory code: Poz; **Table 1**). The Bayesian age-depth model based on these dates was constructed to determine the absolute chronology the age-depth model was constructed using OxCal 4.3 software (Bronk Ramsey, 1995, 2006), by applying the *P_Sequence* function, assuming $k_0 = 0.9$, $\log_{10}(k/k_0) = 1$, and interpolation = 0.5 cm (Bronk Ramsey, 2008; Ramsey and Lee, 2013). IntCal20 (Reimer et al., 2020) and BombNH1 (Hua et al., 2013) ^{14}C atmospheric curves were used as the calibration sets. For better readability, μ (mean) values are used to reflect the modeled age derived from the age-depth model.

The topmost peat profile (53 cm) was dated using the ^{210}Pb method. A samples for the analysis were processed at the Institute of Nuclear Physics, Polish Academy of Sciences, in Kraków. The activity of ^{210}Pb was determined as the activity of its daughter radionuclide ^{210}Po (half-life 138 days), which is in radioactive equilibrium with ^{210}Pb. A total of 52 peat samples, weighing 0.35–0.63 g, were spiked with ^{208}Po as a yield tracer and digested using a concentrated mixture of HNO_3, HCl, and H_2O_2. Then, the solution was treated with 0.5 M HCl. Finally, a thin alpha-spectrometric Po source was prepared by spontaneous electrodeposition onto a silver plate after reduction of Fe^{3+} with ascorbic acid (Flynn, 1968; Fernández et al., 2012; Lee et al., 2014). The ^{210}Po activities were measured using Alpha Duo spectrometer with Ortec detectors.

Excess ^{210}Pb (unsupported) was calculated as the difference between the total activity concentration and supported activity concentration of ^{210}Pb. The supported activity was calculated from the mean ^{210}Pb activity concentration for the bottom layers (56 ± 5 Bq/kg). The age–depth relationships in a part of the peat core were estimated using two alternative dating models: Constant Rate of Supply (CRS) and Constant Flux Constant Sedimentation (CF/CS) (Sanchez-Cabeza and Ruiz-Fernández, 2012). The total unsupported inventory of ^{210}Pb was calculated to be 2,800 ± 350 Bq/m^2. The value was then corrected based on the extrapolation of the exponential equation to eliminate a systematic deviation of CRS dates toward erroneously old ages—the so-called "old-date error" (Binford, 1990; Tylmann et al., 2016).

Remote Sensing Methods

The land-use changes in the study area (neighboring area within a radius of 4 km) were reconstructed using archival material and the following maps: (1) German topographic maps—Messtischblatt (Meßtischblätter) in the scale of 1:25,000 [sheet: Lonsk (2375) from 1932 CE]; (2) Topographic Map of the Military Geographical Institute—Tactical Map of Poland in the scale of 1:100,000 (sheet P34 S26 Tuchola, released in 1933 CE, based on a photo from 1928 CE); (3) postwar topographic maps in the scale of 1:25,000 published in the 1980s CE; (4) overview map of the stands of the Osie Forest District, Szarłata area, in the scale of 1:20,000 (state on 1975); and (5) potential natural vegetation map of Poland in the scale of 1:300,000 (sheet A2) (Matuszkiewicz et al., 1995). All historic maps used for the analysis were calibrated and geo-referenced. Their spatial accuracy was ca. 30 m or better. The current state of the forest was determined using aerial orthophotomaps. Information layers with age, type, and tree species were obtained from the Forest

TABLE 1 | ^{14}C dating results from the Martwe peatland with the calibration and description of the dated plant macrofossils.

Laboratory code - number	Depth (cm)	^{14}C date (14C BP)	Calibrated dates [cal. CE] (2σ - 95.4%)	Dated material
Poz-88711	12.5	107.15 ± 0.35 pMC	1956–1957 (2.7%) 2002–2006 (92.8%)	*Sphagnum* stems
Poz-88710	20.5	115.36 ± 0.36 pMC	1957–1958 (12.8%) 1989–1992 (82.6%)	*Sphagnum* stems
Poz-88709	30.5	132.62 ± 0.4 pMC	1977–1979 (95.4%)	*Sphagnum* stems
Poz-88714	40.5	101.78 ± 0.43 pMC	1955–1956 (95.4%)	*Sphagnum* stems
Poz-88713	50.5	255 ± 30	1520–1587 (22.4%) 1622–1677 (54.4%) 1742–1751 (0.9%) 1764–1800 (17.8%)	*Sphagnum* stems
Poz-88708	56	230 ± 30	1530–1539 (1.2%) 1635–1686 (44.9%) 1732–1805 (44.1%) 1927–undefined limit (5.2%)	*Sphagnum* stems

pMC—the percentage of modern carbon; this unit is applied to modern dates (i.e., after 1950 CE).

Data Bank of the Polish State Forests (pl. Bank Danych o Lasach – Lasy Państwowe), which is part of the Numerical Forest Map. The Forest Data Bank provides detailed information about the modern forest. Data about open land were obtained from CORINE Land Cover, topographic maps in the scale of 1:10,000, and aerial photographs. Private forests were not included in the study. At present, their share in the total forest area is insignificant but it was considerable in the past in Tuchola Pinewoods (Pączewski, 1924). All maps were prepared using ArcGIS software.

RESULTS AND INTERPRETATION

Chronology

The age-depth model revealed that the model agreement (A_{model}) was 59%, which is almost equal to the recommended minimum (60%) (Bronk Ramsey, 2008). As most of the dates showed an individual agreement of >30% and all dates represented the period after the year 1945, we decided to accept the model (**Figure 3** and **Table 1**). The fragment of the profile that was studied (0–47 cm) spanned a period of ca. 1892–2016. For the period after 1945, the maximum error of modeled age reached 4.3 years, whereas for the period between ca. 1891 and 1945 the age uncertainty ranged between 10.6 and 30 years.

The results showed that ^{210}Pb and ^{14}C chronologies were inconsistent for the lower part of the profile after applying the two models (CF/CS and CRS) and correcting for the lower part of the ^{210}Pb date profile (**Supplementary Files**). For the section between 35.5 and 25.5 cm, the chronologies did not overlap even when maximum uncertainties were taken into account and both models differed from each other by ca. 15–20 years. Finally, we chose the absolute chronology based on ^{14}C dates as it spans a longer time interval. However, it must be mentioned that the chronology for the period before the year 1945 (below 41 cm) should be treated with caution as it is encumbered by relatively high uncertainty.

Forest Composition Over the Last Century

The results of the pollen analysis of the 47-cm peat core and descriptions of the maps of plantings in 1900–2016 CE within the 4-km radius of the Martwe peatland are presented together for common zones (A–D) (**Figures 4**, **5**). Zonation was based on changes in regional vegetation between ca. 1900 CE and 2016, data on planting areas (km^2) within the 4-km radius of the peatland, and historical events such as a tornado that occurred on 14 July 2012 in Tuchola Pinewoods and local outbreaks of *Panolis flammea* during 1922–1924 CE and *Lymantria monacha* during 1979–1982 (Mokrzecki, 1928; Sliwa, 1989; Broda, 2000).

For the interval between ca. 1900 and 1922 CE (zone A, 47–44 cm), the pollen-based reconstruction suggested that the forest covered on average ca. 52% of the surroundings of the Martwe peatland (**Figure 4**). *Pinus sylvestris* was found to be the most abundant taxon (ca. 29.7–34.9%), while *Betula* spec. was rarer (ca. 3.8–10.8%). *Picea abies* had covered more than 10% at the beginning of zone A but then its abundance declined to almost zero. *Secale cereale* (11.4–19.7%) and other cereals (5.8–12.8%) were the most abundant open land taxa, followed by *Rumex acetosa/acetosella* (ca. 7.1–12.6%), Poaceae (grasses) (ca. 3.5–5.6%), *Artemisia* (ca. 4.6–5.5%), and *Plantago lanceolata* (ca. 2.2–4.2%). The lower forest cover (pollen data) in the peat core accompanied with an increase in the planting area (**Figure 5A**). The pollen data reflected high openness with simultaneous afforestation, which might be interpreted by the lag between tree planting and the onset of pollen production. Historical map data showed that ca. 5.6 km^2 of the surface area within the 4-km radius of the peatland (i.e., ca. 10% of the area) was afforested between 1900 and 1922 CE (**Figure 5A**). Most plantings were made beyond 1 km from the peatland, and the plantations included ca. 90.2% coniferous, ca. 9.1% deciduous, and ca. 0.7% unidentified trees. The plantings probably suggests previous clear cutting within these areas (assuming the forest has been continuously maintained over the last 100 years in the area) and/or afforestation of new areas (for example, agricultural fields) (Koziński, 2007). Tuchola Forest became the largest center of wood production at the end of the 19th century. Therefore, in the planting area, there may have been felling of trees for industrial purposes in the earlier period and/or afforestation after clear-cutting for war (Broda, 2010).

The reconstructed plant abundances are roughly similar in zone B (1922–1955 CE, 44–40 cm). The forest cover remained at an average of ca. 47% (**Figure 4**), with *Pinus sylvestris* covering ca. 31% and *Betula* spec. covering ca. 6–9% on average. *Picea abies* clearly recovered from the decline in zone A, covering ca. 5% in zone B. The reconstructed cover of *Secale cereale* is ca. 15–22%, that of other cereals ca. 9–16%, that of Poaceae ca. 5%. Between 1922 and 1955 CE, trees were newly planted on ca. 13.3 km^2 (ca. 26.5% of the study area), mainly as large plantations and also in the vicinity of the Martwe lake (**Figure 4B**). Again, more than 93.1% of the trees planted were coniferous, mainly Pinus sylvestris, maintaining pine monocultures (ca. 6.1% deciduous and ca. 0.8% unidentified trees). Much of the plantations likely compensated for clear-cutting following World War II, and especially disturbances caused by insect outbreaks from the beginning of the 20th century (1922–1924 CE) (Stieber and Bartz, 1923; Bartz and Ziółkowski, 1924; Mokrzecki, 1928; Ziółkowski and Bartz, 1928; Andrzejewski and Bartz, 1929; Broda, 2010; Słowiński et al., 2019). Widespread large-scale clear-cutting in the Tuchola Pinewoods was interspersed with insect outbreaks in these times (Fudała, 1985; Sukovata and Kolk, 2000), resulting in high economic losses. Between 1922 and 1925 CE, the influence of the insect outbreaks was the strongest, and the outbreaks mainly included that of *Panolis flammea* (moth and its caterpillars feed on *Pinus* needles), and to a lesser extent *Lymantria monacha*, which affected the Trzebciny Forest District (forest district in which the lake is located) (Mokrzecki, 1928; Fudała, 1985; Broda, 2000; Załoga, 2014). In this case, an increase in plantings was noted (**Figure 5B**). The clear-cutting caused by insect outbreaks led to the removal of trees and reforestation, mainly of *Pinus sylvestris*, in very large areas of Trzebciny Forest District (**Figure 5B**).

In the period 1955 to 1980 CE (zone C, 40–28.5 cm), the reconstructed forest cover increases from ca. 50% to ca. 80%,

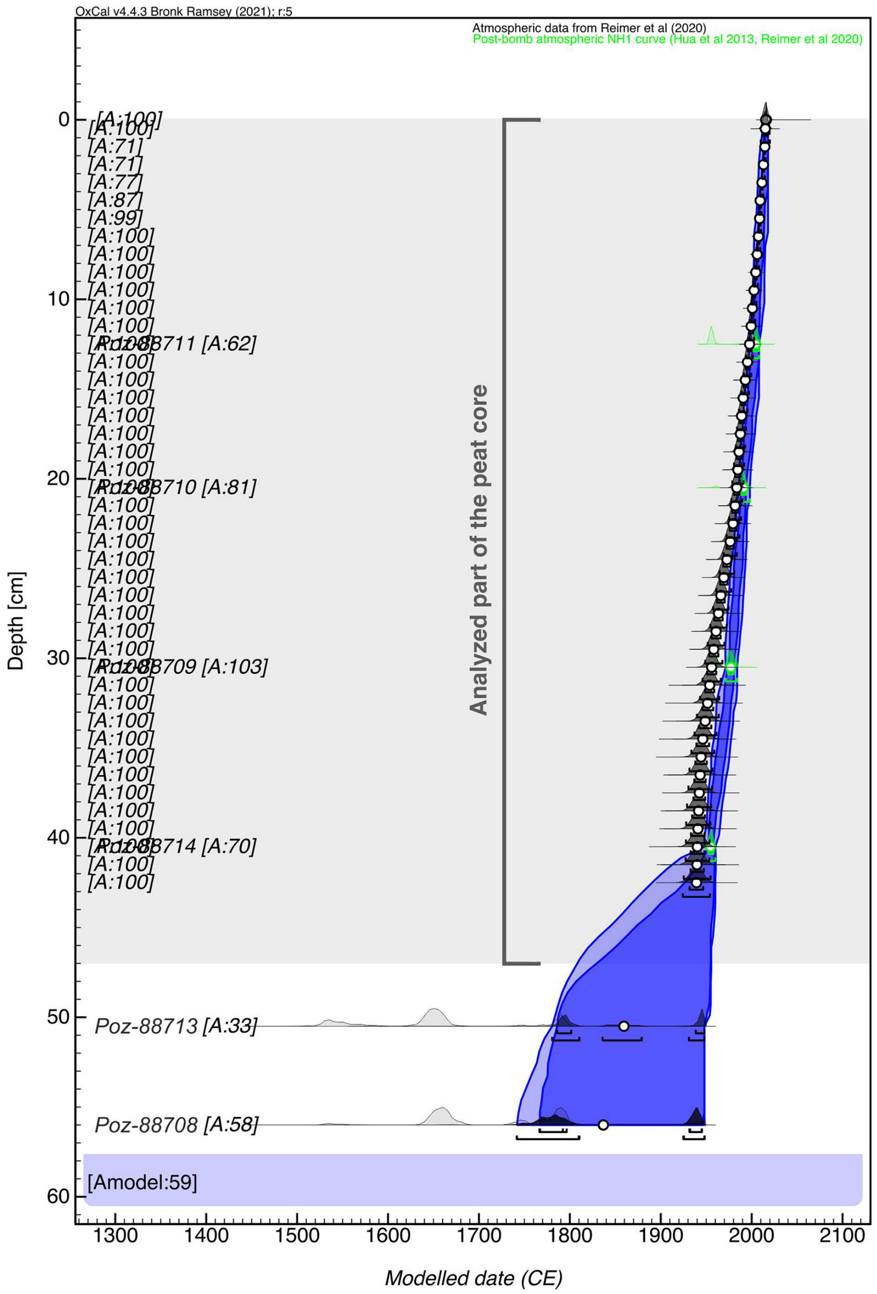


FIGURE 3 | Age–depth model of the peat core (MAR1) from the Martwe peatland.

mainly because of an increase in the cover of *Betula* spec. from ca. 5% to ca. 22%, particularly after 1965 CE (**Figure 4**). The cover of *Pinus sylvestris* remains at about ca. 33%. The reconstructed cover of *Picea abies* shows large variations from ca. 1.4% to ca. 17.4%, and at least periodic higher values than before. For most herbal taxa, including *Secale cereale* and other cereals, the reconstructed cover in zone C is somewhat lower that before. Only the cover of Poaceae is somewhat higher than before, arriving at ca. 4.7% to ca. 8.6%. Between 1955 and 1980 CE, ca. 5 km^2 of the area was afforested, i.e., significantly less than during previous periods (**Figure 5C**). As before, most planted trees have been coniferous (ca. 90%), mainly pine (**Figure 5A**). Although archival data do not indicate prominent changes in forest cover, our pollen-based reconstruction still suggests an increase in forest cover, i.e., particularly a higher cover of *Betula* spec. and *Picea abies*. We consider two likely explanations for this mismatch. First, *Betula* spec. may have truly expanded within existing, pine dominated forests, e.g., due to changes in forest management or nutrient availability. Secondly, *Betul*a spec. may have expanded in the vicinity of the sample site. In this case,

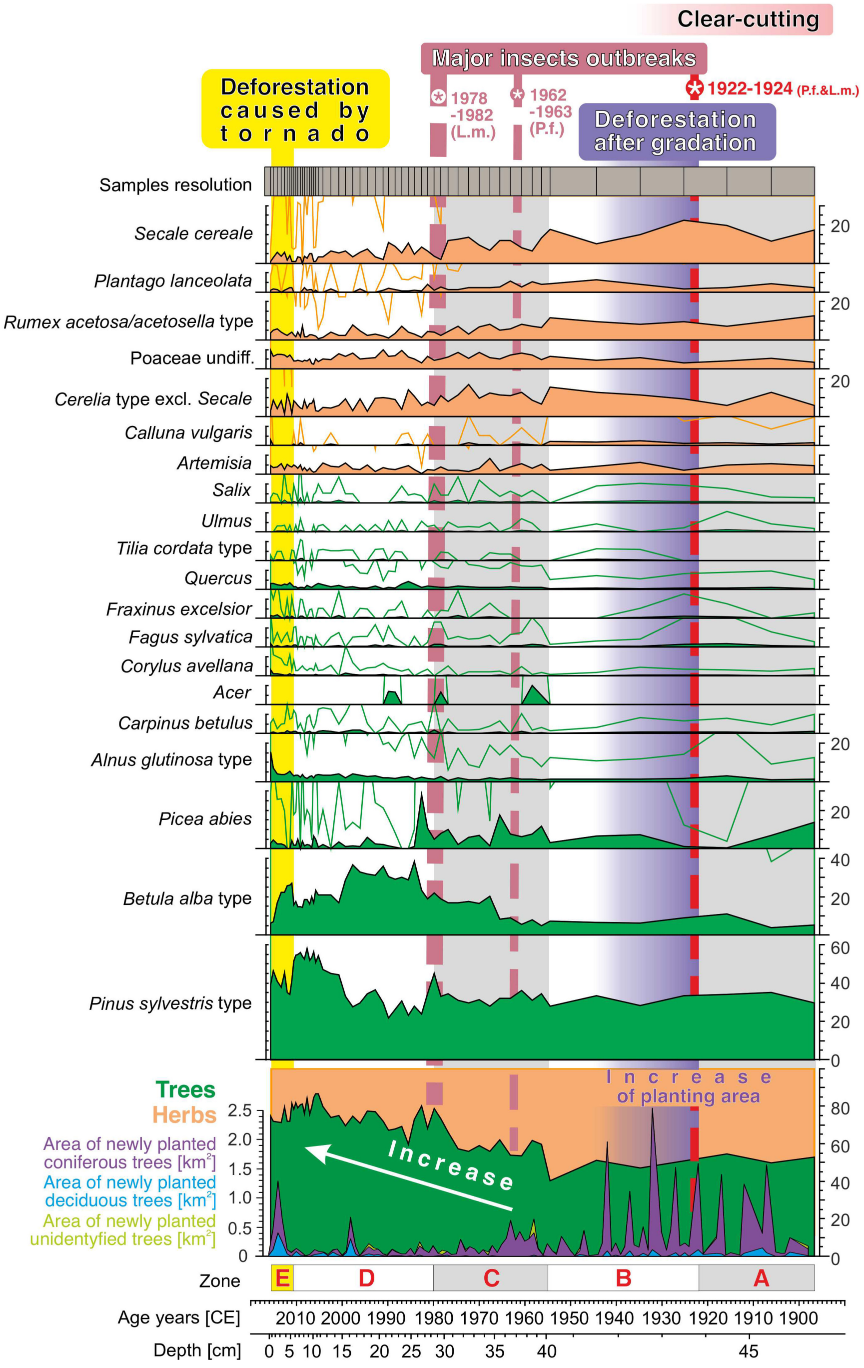


FIGURE 4 | REVEALS-reconstructed abundance of major plant taxa in the surroundings of the Martwe peatland (*Sphagnum* floating mat on the Martwe lake) (×10 magnification). The figure also includes the area of newly planted (km^2) coniferous, deciduous, and unidentified trees within the 4-km radius from the peatland, major local outbreak events (*Lymantria monacha*—L.m.; *Panolis flammea*—P.f.), and a description of the main stages.

higher pollen deposition of *Betula* spec. a is result of high (extra) local pollen deposition.

Zone D (28.5–5.5 cm, 1980 and 2012 CE ± 2 years) is characterized by the highest reconstructed forest cover (ca. 67.2–86.7%, **Figure 4**). Within the zone, the cover of *Betula* spec. is highest between 1980 and 2000 CE (ca. 30%) while the cover of *Pinus sylvestris* is highest between 2000 and 2012 CE (ca. 50%). Moreover, at the beginning of zone D, a peak in the cover of *Picea abies* (ca. 28%) is observed. After ca. 1980, the reconstructed cover remains much lower. This decline likely represents the outbreak of *Lymantria monacha* between 1979 and 1982 in the Trzebciny District (Sliwa, 1989; Załoga, 2014; Jablonski, 2015).

Our reconstruction also suggested some expansion in *Alnus glutinosa* to ca. 2.6% on average. Other deciduous taxa showed only slight changes. The cover of open taxa and, including Cerealia type excl. Secale, *Secale cereale*, *Plantago lanceolota*, and *Rumex acetosa/acetosella*, is lower than before. Between 1980 and 2012 CE, an area of ca. 3.6 km^2 has been afforested within 4 km distance from lake Martwe, i.e., a smaller area than before (**Figure 5C**). Among the newly planted trees, the proportion of deciduous trees is higher than before (>30%) whereas the proportion of coniferous trees is lower (>60%) (**Figure 5A**).

Our reconstruction suggests a prominent role of *Betula* spec. in the forests of the study area at least between 1980 and 2000 CE. Currently the forests in the Trzebciny District are clearly dominated by *Pinus sylvestris* (ca. 91%) whereas *Betula* spec. plays only a minor role (ca. 3%) (Kasprzyk, 2021). The literature/maps indicate that the cover of *Betula* spec. was not substantially higher between 1980 and 2000. The higher reconstructed cover may be an artifact of high (extra)local pollen deposition, i.e., pollen deposition from *Betula* spec. trees growing at or close to the core location. We cannot evaluate whether the increase in the reconstructed cover of *Betula* spec. since 1965 is fully attributable to such effect, or whether it represents some true regional expansion of *Betula* spec. Such expansion may have been triggered by changes in forest management and grazing intensity. *Betula* could be actively removed as a "forest weed" until the mid-20th century (our results) (Grus, 1891, 1897; Dec, 1945). Also, in the past *Betula* was limited by intense grazing (**Supplementary Figures 2, 3**; Mokrzecki, 1928; Broda, 2000) and insect outbreaks. In previous centuries, the forest was used more by humans (**Supplementary Figures 2, 3**).

Finally, our reconstruction indicates very recent changes in forest composition (zone E, 2012 ±1 year to 2016 CE, 5.5–1 cm, **Figure 4**). The cover of *Pinus sylvestris* is somewhat lower (40%), which can be mainly related to forest tornado damage in 2012 CE (**Figure 1**; Taszarek et al., 2016; Kaleta, 2017). For *Betula* spec., a short increase to ca. 26% was observed, followed by a steady decline to ca. 6%. For *Alnus glutinosa*, a distinct increase to ca. 16% is indicated after 2014 CE. Other tree taxa showed no prominent changes. Both the high cover of *Betula* spec. around 2012 CE and the high cover of *Alnus glutinosa* in recent years are unrealistically high, forest inventories show much lower cover. Hence, the high values likely are an artifact of (extra) local pollen deposition at the coring site. Among the herbs, some increase was noted particularly for the grasses, compared to the end of zone D. Between 2012 and 2016 CE, ca. 2.6% of the area within 4 km from the study site was afforested (**Figure 5E**), with ca. 67.3% coniferous and ca. 32.7% deciduous trees (**Figure 2A**). The afforested areas included those bordering the peatland to the south and east. Most trees were newly planted following the tornado in 2012 in the devastated areas (**Figures 1**, **4D**; Stopiński, 2012; Taszarek et al., 2016). The tornado had mostly destroyed ca. 80-year-old *Pinus sylvestris* trees planted after an outbreak of *Panolis flammea* from 1922 and 1924 (**Figure 4**; Mokrzecki, 1928; Broda, 2003).

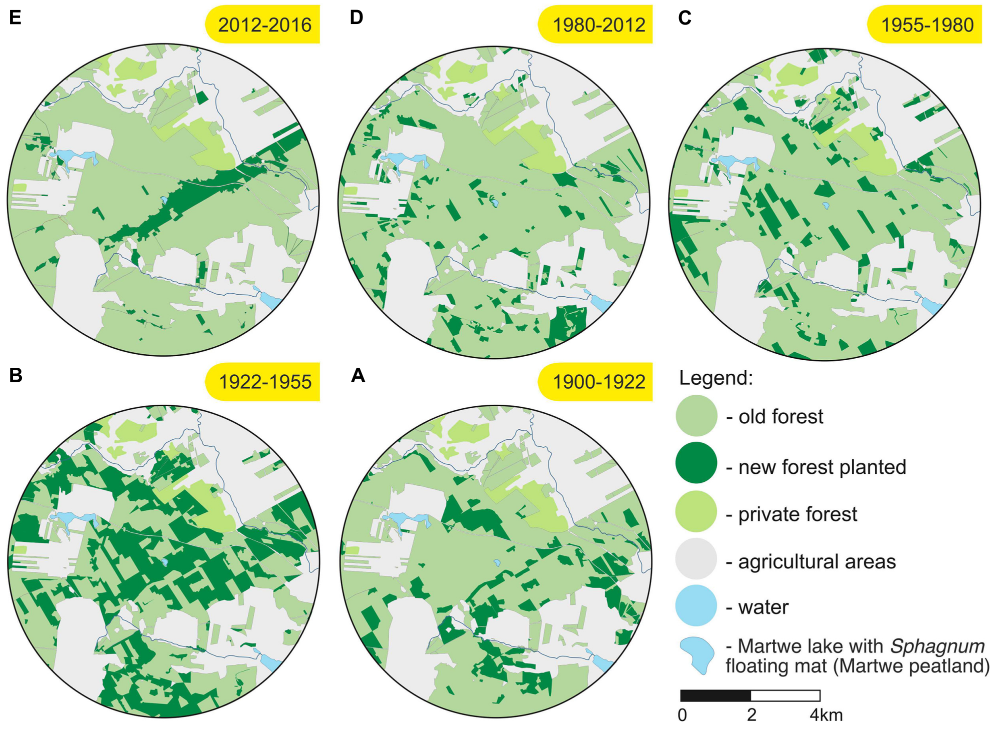


FIGURE 5 | Maps of the subsequent plantings in 1900–2018 CE within the 4-km radius from the Martwe peatland (*Sphagnum* floating mat on the Martwe lake). The peatland is located in the center of each map. The letters **(A–E)** correspond to the palynological zones. The term "old forest" in the map refers to an already wooded area.

DISCUSSION

Legacy of Forest Management

The forests of the study area (**Figures 4**, **5**) are mainly pine monocultures introduced by humans for timber harvesting (Mokrzecki, 1928; Gietkowski, 2009). The current vegetation clearly differs from the potential natural vegetation, which is richer in deciduous tree taxa (**Figure 5**). Human impact on the vegetation in the Tuchola region is well recognizable since the beginning of the Middle Ages (Milecka and Szeroczyńska, 2005; Noryśkiewicz, 2006), whereas the origin of the *Pinus sylvestris* monocultures dates back to the Prussian Partition (Gietkowski, 2009; **Figure 6**). Large-scale transformation of forests was started by Prussia soon after the first partition of Poland in 1772 CE (Gietkowski, 2009; Słowiński et al., 2019). Some effects of this transformation were clear-cutting and introduction of pine monocultures on poor soils developed on Wda and Brda sandy outwash plains (Dysarz, 1998; Gietkowski, 2009; **Supplementary Figure 1**). Paleoecological studies conducted on the lakes and peatlands in the Tuchola forest have confirmed strong human-induced changes in the composition of the forest over the last 300 years (Lamentowicz et al., 2007, 2013; Dietze et al., 2019; Słowiński et al., 2019).

The forest management, as well as the perception of the forest by managers and local communities, has changed through time. This is most clearly visible in the species composition of the forests that were managed before the last centuries in the entire Tuchola Pinewoods (Broda, 2000). Due to changes in the management and transformation of forests into a pine monoculture, the perception of local people and foresters toward pine monoculture and particular tree species has also been affected (Karasiewicz, 1922, 1926; Mokrzecki, 1928; **Supplementary Figures 1, 2**). The most prominent example is *Betula* spec. which has been considered a forest pest (Grus, 1897) and hence was simply removed from the undergrowth (Grus, 1897; Dec, 1945). Correspondingly, our reconstruction showed a low cover of *Betula* spec. until World War II. After the war, *Betula* spec. became more abundant because *Betula* strips were introduced as a so-called green belt surrounding pine monocultures to better control forest fires (Forest Fire Protection Manual). Moreover, in the past, local communities were allowed to use the forest for the grazing of sheep and cows and to collect needles and cones (Mokrzecki, 1928; Broda, 2000). These activities largely removed the forest undergrowth, including *Betula*, and prevented ground fires. However, these activities also removed nutrients, and as a result, caused degradation of forests and increased their susceptibility to insect attacks (Broda, 2000).

Methodological Implications – Archival Materials Meet Paleoecology

The present comparison of a pollen-based land-cover reconstruction with archival data shows similarities but also differences, which points at limitations of either approach. Most importantly, the land-cover reconstruction suggests an increase in forest cover since about 1950 CE, while archival data show a stable pattern of forest and open land. The primary cause for that mismatch may be the changing age structure of pine plantations. Our pollen-based reconstruction assumes that pollen productivity of all taxa is a constant. In reality, however, pollen productivity is variable and influenced, e.g., by the age of a forest stand. Before 1950 CE, the area of newly planted pine forests was high, following large scale harvesting and insect outbreaks. Hence, the area of young pine forests, which still produce low or little pollen was high. After 1950 CE, the situation was more stable and the proportion of older forests with high pollen production likely increased. Besides age, pollen production may also be influenced by nutrient availability. Until the mid 20th century, forest grazing and the removal of organic matter probably has reduced nutrient availability, which may have reduced tree growth and pollen productivity. Moreover, over the past decades, atmospheric fertilization has enabled accelerated tree growth (Pretzsch et al., 2014), and may have also affected pollen production.

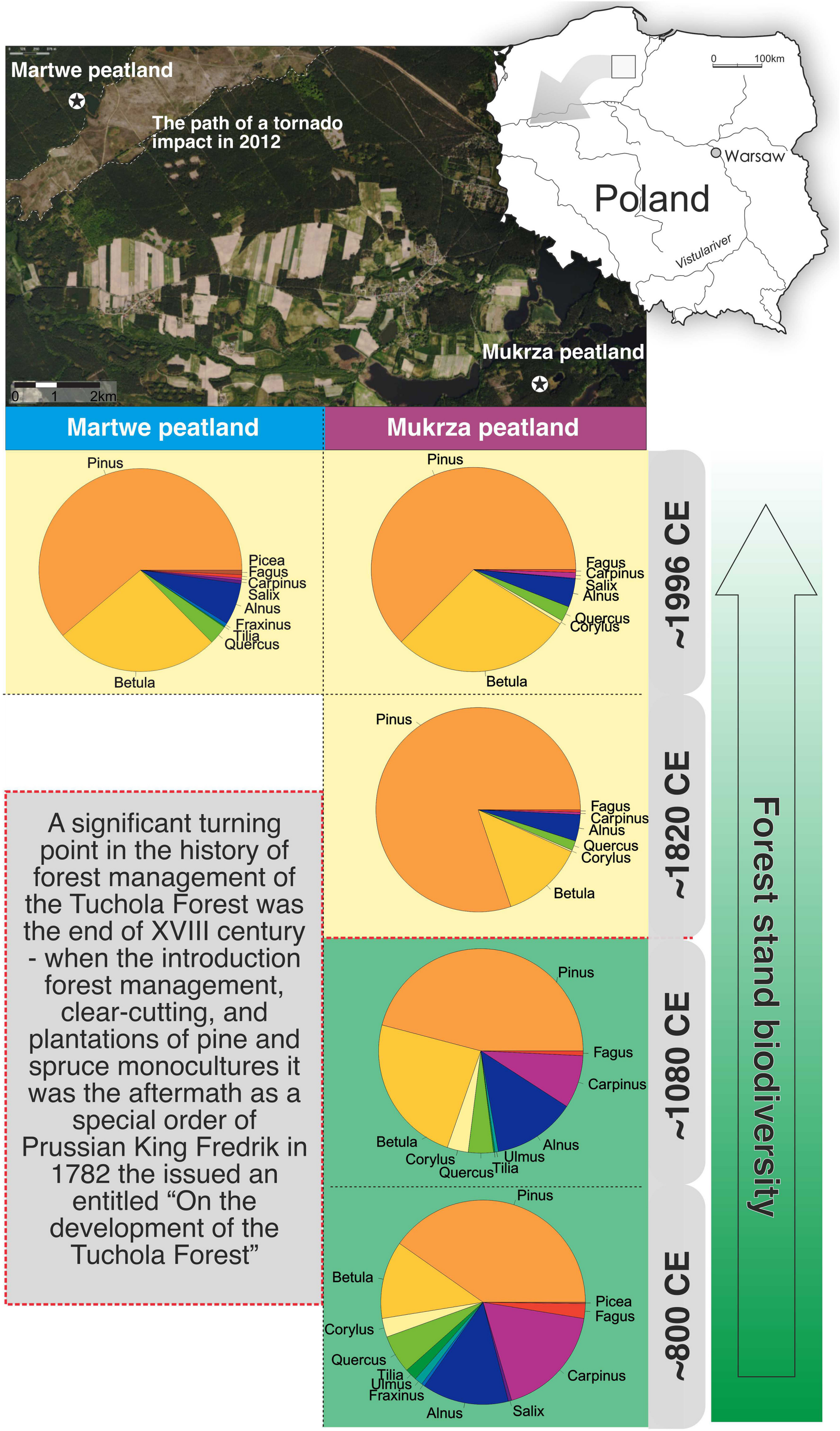
Our reconstruction suggests widespread expansion of *Betula* spec. during the second half of the 20th century, likely because forest grazing ended and more nutrients were available. *Betula* spec. did not expand in previously open areas but obviously in the existing pine forests, as understory element and/or along forest margins. The forests would hence produce, besides *Pinus sylvestris* pollen, an increasing amount of *Betula* spec. pollen. In other words, the pollen deposition of tree taxa, mainly *Pinus sylvestris* and *Betula* spec., increases, although the forest cover is unchanged. Hence, a second cause for the mismatch between the pollen-based forest cover and archival pollen cover may be the expansion of *Betula* spec. in *Pinus sylvestris* forests.

Alternatively, the possibly too high reconstructed cover of *Betula* spec. particularly between 1980 and 2000, may be attributable to (extra) local pollen deposition. The REVEALS approach is suited for pollen records from large lakes, which well represents regional vegetation composition. Pollen deposition in small lakes and peatlands, like lake Martwe, may instead be much influenced by (extra) local pollen deposition from nearby vegetation and hence represent a mixture of regional and local scale vegetation composition. Application of more suited local scale methods, such as LOVE or Marco Polo, was impossible because of a missing regional reference site (Sugita, 2007; Mrotzek et al., 2017).

Overall, our results underline that interpretation of pollen records from the recent past is far from simple, mainly because the pollen production of trees and herbs is variable due to changes in land management, atmospheric fertilization and also the climate. Further comparisons of archival and pollen-based reconstructions would be helpful to better understand the effects. To this end, records of pollen accumulation rates, e.g., from varved lakes, would be particularly useful because they avoid the mutual interdependence of pollen percentage data.

Long-Term Environmental Consequences of the Forest Plantations – Archival Materials Meet Paleoecology

The pollen signal from the Martwe peat core (MAR1), along with the remote sensing data, clearly show the land-use changes that were caused by the clear-cutting of pine monocultures and insect



A significant turning point in the history of forest management of the Tuchola Forest was the end of XVIII century - when the introduction forest management, forest management, clear-cutting, and plantations of pine and spruce monocultures it was the aftermath as a special order of Prussian King Fredrik in 1782 the issued an entitled "On the development of the Tuchola Forest"

FIGURE 6 | Relative abundance of arboreal pollen (AP, standard and untransformed pollen values) in the past based on a pollen record from the Mukrza peatland and comparison of records from the Martwe peatland. The figure present four phases of forest transformation by human activities in the Tuchola Pinewoods: (a) around 800 CE, before the end of the Migration Period, seminatural vegetation forest composition; (b) early Medieval Period, beginning of the 12th century, low human activity; (c) beginning of the 19th century, the period after the introduction of pine monoculture; and (d) current forest vegetation composition, end of the 20th century. The zones are based on a study of the Mukrza peatland by Obremska (2006).

outbreaks in the 20th century as well as a recent disaster—the tornado in 2012 (**Figures 4**, **5**). Especially, a good correspondence was observed between the changes in *Pinus sylvestris* pollen signals with archival materials and the cartographic data of the tornado event. The last dramatic event (and other massive wind throws that occurred in the region) and historical events like insect outbreaks during the last 100 years in Tuchola Pinewoods confirm the high vulnerability of these types of ecosystems to various disturbances like winds, pathogens, and fires (Mokrzecki, 1928; Seidl et al., 2017). Similar changes were observed in the forest composition during the last 100 years in the Mukrza peatland (**Figures 1**, **6**). The pollen records of both peatland are compared in **Figure 6**. It can be noticed that the relative abundance of arboreal pollen was similar—90.8% in Martwe and 87.5 in Mukrza peat—in ca. 1996 CE (standard and untransformed pollen values). The relative abundance of *Pinus sylvestris* was ca. 55.9% and ca. 54.7%, respectively (**Figure 6**). Studies of forest plantations in various regions of the world show that forest homogenization increases the vulnerability of the emerging novel ecosystem (Słowiński et al., 2019; Matusick et al., 2020). Monocultures of *Pinus sylvestris* cause acidification and depletion of soils, which not only results in reduced productivity (Bialy, 1999; Baltodano, 2000; Rutkowska, 2019; Steckel et al., 2020), but also has a negative impact on the biodiversity of forests (Gustafsson et al., 2012; Fedrowitz et al., 2014) and leads to acidification of wetlands (Lamentowicz and Mitchell, 2007). Furthermore, the long-term process of restoration influences soil biodiversity (Fedrowitz et al., 2014) and, as a consequence, the resistance of Scots pine in Tuchola Pinewoods. Due to the transformation of mixed-forest (mainly removal of hornbeam, oak, ash, and alder forests) into pure *Pinus sylvestris* monoculture (**Figure 6**; Miotk-Szpiganowicz, 1990; Boiński, 1993), the Tuchola Pinewoods are more vulnerable to disturbances such as insect outbreaks, fires, or winds (Słowiński et al., 2019).

Across Poland, pine forest monocultures have usually been established on sandy soils (Matuszkiewicz, 1999). The susceptibility of pine forest in our study area represents a climate-related hazard. Due to maintaining pine monocultures, the management of Tuchola Pinewoods is not focused on the natural regeneration of forests (**Figure 6**). The current challenge is to find optimal solutions for forest regeneration and adapt its species composition to changing habitat (Tomaś and Jagodziński, 2019). As a consequence of delay in the adaptation of tree composition to new conditions caused by climate changes due to the long-life cycle of trees (Jagodziński, 2020), *Picea abies* and *Betula* forests die out in many regions of Poland (Boczoń et al., 2018; Skrzecz and Perlińska, 2018). Although the European forest policy and management widely promote the shift from coniferous monocultures to mixed stands of coniferous and broadleaved species, these suggestions are either not introduced in most of the forested areas or not applied appropriately (**Figure 7**; Zerbe, 2002; Kint et al., 2006; Knoke et al., 2008; Zhang et al., 2012; Thurm et al., 2016; del Río et al., 2017). In the last decade, several studies confirmed that the replacement of monocultures by mixed forests increases their resistance to sudden climate shifts (Thurm et al., 2016; Leuschner and Ellenberg, 2017) and disturbances such as insect outbreaks, fires, and pathogen invasion. Nevertheless, it has been highlighted that natural recovery leads to higher biodiversity as well as a more resilient and productive ecosystem (Liang et al., 2016; Leuschner and Ellenberg, 2017). Based on the forecasts of threats to individual tree species in Europe, Dyderski et al. (2018) clearly emphasized that the so-called pioneering tree species like *Betula pendula*, *Larix decidua*, *Picea*

FIGURE 7 | Drone pictures of the forest planted after forest tornado damage from 2012 with characteristic *Betula pendula* islands and *Betula pendula* trees along the roads. In the background – Martwe lake with *Sphagnum* floating matt (Martwe peatland).

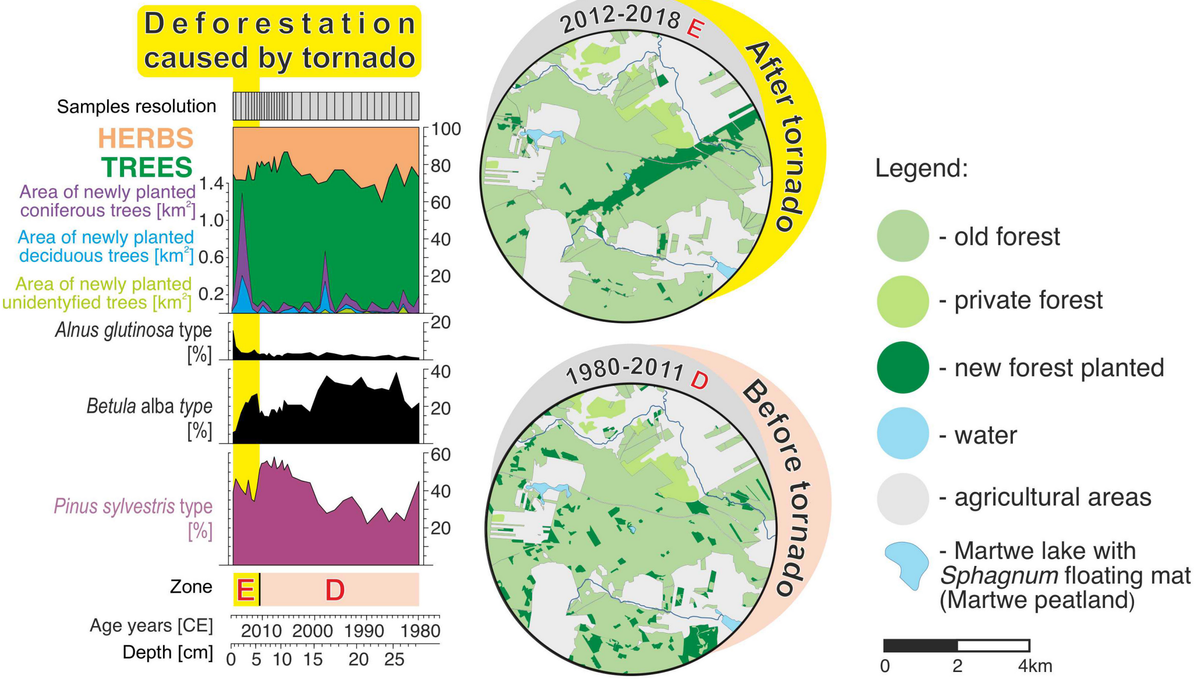


FIGURE 8 | Summary diagram of REVEALS-reconstructed plant abundances and remote sensing data after and before the tornado event from 2012. Maps of the area within the 4-km radius from the Martwe peatland (*Sphagnum* floating mat on the Martwe lake).

abies, and *Pinus sylvestris* will be increasingly affected by climate change-related issues such as increases in disturbances and insect outbreaks (Seidl et al., 2014). The authors underline that this constitutes a serious threat to both forest management and nature conservation due to the fact that *Pinus sylvestris* occupies about 67% of the forest area of the country (Dyderski et al., 2018). The cultivation of *Picea* abies and *Pinus sylvestris* forest was adequate in the past two centuries; however, with progressive global warming, the measurable benefits might be difficult to achieve. Droughts cause permanent changes in forest composition and conditions (Jagodziński, 2020), and thus contribute to the weakening of trees in the forests. Our study documented an increased abundance of deciduous forests (**Figure 4**) in the last two decades. During that time, the planting of deciduous forest accounted for a high percentage, which was not observed earlier (**Figure 4**). However, there is still a large difference in relation to the species composition from the Medieval Period (**Figure 6**; Obremska and Lamentowicz, 2006).

The changes in the structure and composition of the forest during the last 100 years were compared using pollen records and archive maps. The results (**Figures 4**, **5**) showed that the size and location of tree plantings in the last 100 years allowed the reconstruction of considerable land-use changes. We recorded a strong relationship between the pollen spectra of *Pinus sylvestris* and the planting process, and consequently, forest tornado damage by the tornado in 2012 (**Figures 4**, **5**, **8**). Data combination proves that paleoecology with archival materials and cartographic data complement each other well, especially in the case of heavily economically exploited monoculture leading to critical transitions. The pollen pattern of *Pinus sylvestris*, along with the archival materials and cartographic data between 1900 and 1943 CE, indicates clear cutting on a wide scale. Moreover, the location and size of plantings and later clear-cutting suggest dynamic changes in land use until 1965 CE, especially in the first half of the 20th century, while the period between 1965 and 2012 CE was characterized by a clear slowdown in changes. We have planned to use precise data about the location and size of plantings in further paleoecological research to study the impact of deforestation and clear-cutting on the functioning of wetland ecosystems (Słowiński et al., 2017; Łuców et al., 2018).

CONCLUSION

We present the first tornado-related paleoecological record from a monoculture in Poland on the background of previous forest management (clear-cutting, cutting after insect outbreaks), through vegetation reconstruction of a 100-year-old peat core, based on pollen analysis and the REVEALS model as well as on remote sensing data. Results of this study confirm that an event such as a tornado (forest tornado damage) may be recorded in a peat core. The forest tornado damage from 2012 was characterized by a decrease in *Pinus sylvestris* cover as a result of the destruction of the forest by a tornado and the increase of *Betula* spec. cover. The combination of paleoecological and remote sensing data allowed us to present the forest management practices during the last 100 years. The past forestry practices (like clear-cutting and cutting after insect outbreaks, also to a lesser extent an active removal of *Betula* as a “forest weed”) are well identified in the proxy record. Our study shows that the observed monocultural stands lacked resistance to strong winds, but they were weakened most possibly also by droughts, and susceptible to insect outbreaks. Although the monocultures quickly replaced the disturbed stands, they did not result in any change in management, and as a result, only *Pinus sylvestris* was newly planted repeatedly. It is only in the last two decades that a change occurred in management and deciduous species such as oak and hornbeam were introduced into monocultures. This trend should be maintained to achieve the species composition and percentage share as that of 300 years ago to make the forest less sensitive to wind and better adapted to climate change.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

MS contributed to the conception and design of the study. MS, ML, KM, and DŁ collected the peat core. DŁ wrote the first draft of the manuscript. PK performed the pollen analyses. ST performed the maps analysis. MT performed the REVEALS analysis. PK, ML, EŁ, and MS contributed to the chronology. DŁ, MS, and ST contributed to the figures and tables. All authors contributed to edit and revision of the manuscript and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.747976/full#supplementary-material

Supplementary Figure 1 | Simplified percentage pollen diagram from the Martwe peatland (×10 magnification).

Supplementary Figure 2 | A postcard from around 1900 CE showing the life of the inhabitants of Tuchola Pinewoods and their integration with the forest (from the collection of the Muzeum Pomorza, www.muzeumpomorza.pl) and wood run-off down the Wda River.

Supplementary Figure 3 | A postcard from around 1900 CE showing the life of the inhabitants of Tuchola Pinewoods and their integration with the forest (from the collection of the Muzeum Pomorza, www.muzeumpomorza.pl) as well as the life of the inhabitants of pine monocultures.

Supplementary Table 1 | Parameters (fall speed, PPE, and PPE error) of pollen used to prepare REVEALS reconstruction.

Supplementary Files | Absolute chronologies derived from 14C and 210Pb dates from the Martwe peat profile (MAR-1).

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