Radiocarbon, Vol 56, Nr 1, 2014, p 109–125 DOI: 10.2458/56.16467

HIGH-RESOLUTION AGE-DEPTH MODEL OF A PEAT BOG IN POLAND AS AN IMPORTANT BASIS FOR PALEOENVIRONMENTAL STUDIES

B Fiałkiewicz-Kozieł[1,2] • P Kołaczek[1] • N Piotrowska[3] • A Michczyński[3] • E Łokas[4] •
P Wachniew[5] • M Woszczyk[6] • B Sensuła[3]

ABSTRACT. This article focuses on constructing a high-resolution age-depth model for the Puścizna Mała peat bog located in Orawa-Nowy Targ Basin (S Poland). The chronology was established on the basis of both ^{210}Pb and ^{14}C measurements, and further confirmed by pollen diagrams and the peat bulk composition (density, ash content, and measurements of C, N, S). The ^{137}Cs profile revealed significant downward migration of this radionuclide and was not suitable for geochronological interpretation. The peat profile in southern Poland records almost 2000 yr of paleoecological and geochemical changes. Major historical events linked to anthropogenic and climatic changes are recorded in the investigated proxies, which confirm the reliability of the age-depth model. Specifically, the Roman period, Migration period, Medieval times, as well as the Industrial Revolution are reflected in the palynology and bulk composition of the peat. However, dating results obtained for the core segment between 22–45 cm are problematic when confronted with other analyses. The highest peat accumulation rate of 2 mm yr^{-1} (AD 1300–1400 according to the age-depth model) is not compatible with the section of the highest peat decomposition revealed by lithological description. Moreover, the onset of a drastic decline of forests reflected in the palynological data and dated to AD 1280–1340 (40 cm) is difficult to explain in the light of historical data. Therefore, the lithology, bulk density, and pollen were used to validate the obtained age-depth model. External forcing factors on the peat formation process may be indicated, including agricultural activity, water-level fluctuations, and natural climatic factors, which paradoxically caused doubling of the obtained peat accumulation rate.

INTRODUCTION

Accurate and precise chronologies of peat sequences over centennial/millennial timescales can be obtained using well-known ^{14}C and ^{210}Pb methods. These methods refer specifically to ombrotrophic bogs, which are dependent on precipitation for all their water and nutrients (Shotyk 1996). Other radionuclides, including cesium (^{137}Cs), are also useful, although their reliability as geochronometric tools is still under debate (Oldfield et al. 1995; Le Roux and Marshall 2011).

Reliable chronologies supplemented by paleoecological, physical, and chemical features of peat deposits provide records of past changes in water levels, air temperatures, peatland chemistry, and the composition of local and regional vegetation over both short- and long-term timescales (e.g. Kilian et al. 1995; Mauquoy et al. 2002; Borgmark and Schoning 2006; Piotrowska et al. 2011). The bulk composition of peat (bulk density, ash value, carbon content, sulfur, and nitrogen) can provide sensitive markers of climatic and anthropogenic influences (e.g. Malmer and Holm 1984; Moore et al. 2004; Chambers et al. 2011). Changes in bulk density are caused by changes in plant composition as well as by fluctuations in water level and the rate of allochtonous and autochthonous mineral influx. Drier conditions induce the process of oxidation, decomposition, and mineralization of organic remains and cause an increase in bulk density. The contents of sulfur (S) and nitrogen (N) reflect acidic precipitation and provide information on human-induced acidification (Moore et al. 2004; Limpens et al. 2008).

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1. Department of Biogeography and Paleoecology, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Dzięgielowa 27, 61-680 Poznań, Poland.
2. Corresponding author. Email: basiaf1234@poczta.fm.
3. Department of Radioisotopes, Institute of Physics – Centre for Science and Education, Silesian University of Technology, GADAM Centre of Excellence, Krzywoustego 2, 44-100 Gliwice, Poland.
4. H. Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, 31-342 Kraków, Poland.
5. AGH – University of Science and Technology, Mickiewicza 30, 30-059 Kraków, Poland.
6. Department of Quaternary Geology & Paleogeography, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Dzięgielowa 27, 61-680 Poznań, Poland.

Up to now, attempts to date peat bogs from the Carpathians were made in Slovakia (i.e. Rybníček and Rybníčková 1985; Jankovská 1988; Wacnik 1995; Hájková et al. 2012; Dudová et al. 2013), Romania (i.e. Rösch and Fischer 2000; Tantau et al. 2006), and Poland (e.g. Margielewski et al. 2010, 2011; Michczyński et al. 2013). The Orawsko-Nowotarskie peatlands were studied by Obidowicz (1990) and Holynska et al. (1998) using absolute chronologies. The location of the studied bog between the Polish lowlands and the highest mountain range in the Western Carpathians (the Tatras) makes this peatland a promising archive for a broad spectrum of paleoecological changes in the Carpathian foreland over the last 2 millennia. The investigated peatland provides an important basis for a comprehensive reconstruction of the environmental and human history in the Orawa-Nowy Targ Basin from the Roman period to the present. The age-depth model, based on 45 dating results, was obtained by a combination of different dating methods (^{14}C and ^{210}Pb), and is currently one of the highest resolution models in Poland and eastern Europe. The model allows to compare the events recorded in peat archives with archaeological and/or historical episodes of human activity and environmental or climate changes.

MATERIAL AND METHODS

Sampling Site and Coring

The Puścizna Mała (PM) bog is located in the Orawa-Nowy Targ Basin (southern Poland), in the Carpathian foreland (Figure 1). In this region, precipitation exceeds evaporation between May and October and is an important factor contributing to the development of bogs in this region (Kowanetz 1998). The vegetation in this bog consists mainly of *Andromeda polifolia*, *Ledum palustre*, *Oxycoccus palustris*, *Vaccinium uliginosum*, and *Sphagnum* mosses, taxa characteristic of poor, acidic mires. More detailed information about the contemporary flora, climate, and geology can be found in Łajczak (2006) and Kołaczek et al. (2010).

A monolith (PM0) was taken from the dome of the PM in June 2006, after preparing an outcrop. The complete and undisturbed core (130 × 20 × 20 cm) was previously outlined in the outcrop using a stainless steel knife, then covered by a box, cut, and carefully removed. The monolith was sectioned into 1-cm slices using a stainless steel knife.

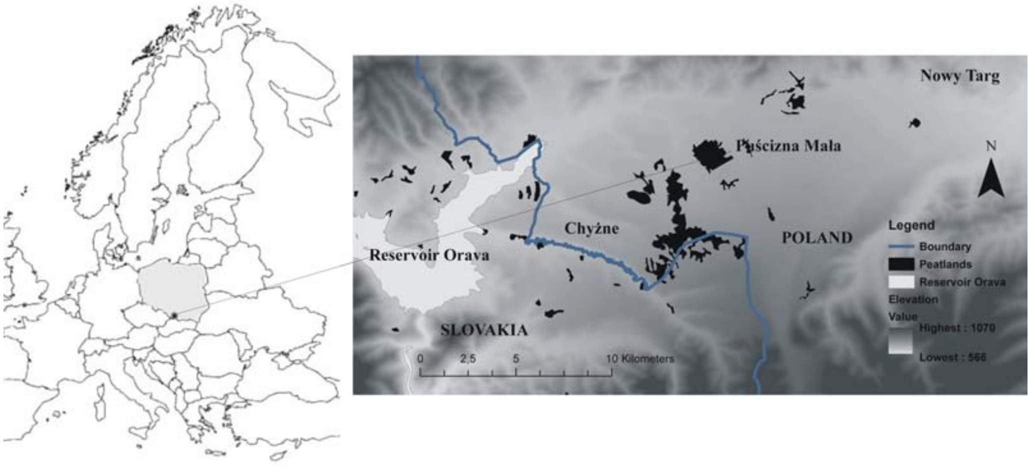

Figure 1 Location of the investigated peatland (49°2′76″N, 19°4′72″E)

Lithostratigraphical analysis of the peat core revealed the presence of *Sphagnum* peat (Kołaczek et al. 2010), with several sections exhibiting different levels of decomposition. Undecomposed or very poorly decomposed peat was identified in the uppermost section of the profile (1–23 cm), very weakly decomposed peat was observed between 99 and 114 cm, and weakly or very weakly decomposed peat was found in the depths 50–91 cm. Four sections had moderately decomposed peat (23–32, 46–50, 91–99, and 114–130 cm), whereas the section between 32 and 46 cm contained highly decomposed peat (Kołaczek et al. 2010).

Radionuclide Measurements (^{210}Pb, ^{137}Cs, ^{14}C)

Twenty measurements of ^{210}Pb activity were made using 1 g of dry peat material that was redried at 105°C, burned at 460°C (we burned samples in lower temperature because of the danger of Po volatilization at higher temperature) for 24 hr, and subsequently digested in concentrated HNO_3 and H_2O_2 for 24 hr. Polonium was deposited on silver disks from 0.5M HCl (after Holynska et al. 1998).

The activity of total ^{210}Pb was determined indirectly by measuring its decay product, ^{210}Po, using alpha spectrometry. ^{210}Po was chemically extracted from the material. To determine the efficiency of the extraction, the material was spiked with a known activity of ^{208}Po, which emits alpha particles with a different energy (E = 5.116 MeV) than ^{210}Po (E = 5.305 MeV). Alpha activity was measured with a spectrometer (Alpha Analyst Canberra-Packard, S570) with a surface-barrier Si semiconductor detector. The sensitive area of the detector was 450 mm^2. The typical measurement time was approximately 25 hr. Analyses of ^{137}Cs were conducted using high-resolution gamma-spectrometry with a HPGe detector. The activities were determined via the emission peak at 662 keV.

Twenty-six bulk peat samples from Puścizna Mała (six of which were previously reported by Kołaczek et al. 2010) were selected for ^{14}C dating and 50 g of wet peat was subjected to AAA pretreatment according to Piotrowska et al. (2011). Measurements were performed at the GADAM Centre, Gliwice, using liquid scintillation counting for 13 samples, which were converted to benzene. The remaining 13 samples were combusted to CO_2 and ^{14}C dated using the gas proportional counting technique (Pazdur et al. 2003). ^{14}C dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009) for prebomb dates and the NH1 postbomb curve (Hua and Barbetti 2004) for the modern dates. The ranges of calibrated ^{14}C ages of dated samples, which are presented in Table 2, were calculated using the OxCal v 4.1 calibration program (Bronk Ramsey 2009).

Bulk Composition

The bulk density (BD) was determined by drying 5-cm^3 subsamples at 105°C for 24 hr. The dry weight (g) was divided by the fresh sample volume (cm^3) using the procedure described by Chambers et al. (2011).

Prior to the chemical analyses, the peat samples were air-dried and milled in an agate mortar. The ash content (AC) was calculated as AC = 100% - LOI550 (loss on ignition at 550°C) for 4 hr (Heiri et al. 2001).

Total nitrogen (N), carbon (C), and sulfur (S) values were determined on duplicates analyzed with a Vario Max CNS elemental analyzer (Elementar Analyzensysteme GmbH, Germany). Sulfadiazine, CP1 (Agromat Compost), and SQC001S (metals in sewage sludge) were reference materials to control the quality of the measurements. Due to the absence of carbonates, total carbon was presumed to equal total organic carbon (C). The C/N ratio was calculated on a mass basis.

RESULTS

^{210}Pb and ^{137}Cs Activity

Unsupported ^{210}Pb activities were determined for each layer by subtracting the supported activities from the total ^{210}Pb activities (Table 1). The ^{210}Pb activities decreased with depth in a relatively regular manner. The resulting unsupported ^{210}Pb activities changed from 19 to 372 Bq kg^{-1}. The cumulative surface activities of ^{210}Pb shown in Figure 2 were calculated by integrating surface activities from the bottom of the profile to the middle of each layer assuming homogeneous distribution of ^{210}Pb in the layers. The ages correspond to the accumulation of peat at the upper boundaries of the layers. The top 19 cm of the Puścizna Mała core accumulated in 147 ± 16 yr, corresponding to the core-averaged accumulation rates of 1.3 ± 0.1 mm yr^{-1} (Figure 2).

Table 1 Calculated ages of the peat layers and the corresponding dry mass and linear accumulation rates. ^{210}Pb ages were obtained after applying the CRS (constant rate of supply) calculation model to the peat (Appleby 2001).

Depth (cm)	Age (yr)	Dry mass accumulation rate (g cm^{-2} yr^{-1})	Linear accumulation rate (cm yr^{-1})
0–3	2006 ± 0.1	0.06 ± 0.03	0.89 ± 0.06
3–4	2001 ± 0.2	0.04 ± 0.02	0.54 ± 0.06
4–5	1998 ± 0.4	0.04 ± 0.02	0.42 ± 0.06
5–6	1993 ± 0.6	0.03 ± 0.01	0.36 ± 0.08
6–7	1988 ± 0.9	0.04 ± 0.03	0.34 ± 0.12
7–8	1984 ± 1.1	0.03 ± 0.01	0.32 ± 0.11
8–9	1979 ± 1.3	0.02 ± 0.01	0.29 ± 0.10
9–10	1974 ± 1.5	0.02 ± 0.01	0.27 ± 0.10
10–11	1967 ± 1.7	0.02 ± 0.01	0.25 ± 0.09
11–12	1960 ± 1.9	0.02 ± 0.01	0.25 ± 0.14
12–13	1955 ± 2.2	0.05 ± 0.03	0.23 ± 0.11
13–14	1948 ± 2.6	0.01 ± 0.01	0.21 ± 0.08
14–15	1938 ± 2.7	0.02 ± 0.01	0.21 ± 0.13
15–16	1931 ± 3.0	0.02 ± 0.01	0.20 ± 0.10
16–17	1922 ± 3.5	0.02 ± 0.01	0.17 ± 0.05
17–18	1901 ± 5.0	0.01 ± 0.01	0.13 ± 0.04
18–19	1868 ± 9.0	0.01 ± 0.01	0.12 ± 0.07
19–20	1837 ± 16	0.01 ± 0.01	—

More than half of the total cesium surface activity is retained in the upper 3 layers (0–6 cm); below this level, ^{137}Cs activities showed little variation to the bottom of the profile (33 cm). The surface activities of ^{137}Cs calculated for particular layers in this peat bog varied from 13 to 2614 ± 102 Bq m^{-2} (Figure 3). A previous study performed on a nearby peat bog (Matisoff et al. 2011) revealed that Chernobyl fallout was greater than the average global fallout from the 1960s.

Initial Age-Depth Model

An initial age-depth model was constructed using the Bacon software (Blaauw and Christen 2011) (Figure 4). This program simulates the accumulation of deposits through small, random increments and also considers the limitations on the accumulation rate and its variability. In the calculations performed for Puścizna Mała, the results of the ^{14}C dating were combined with the ages derived from ^{210}Pb dating to produce a continuous age-depth model for the whole core. The age-depth model was calculated for 25 sections of 1 cm thickness. The priors for accumulation rate were set as a

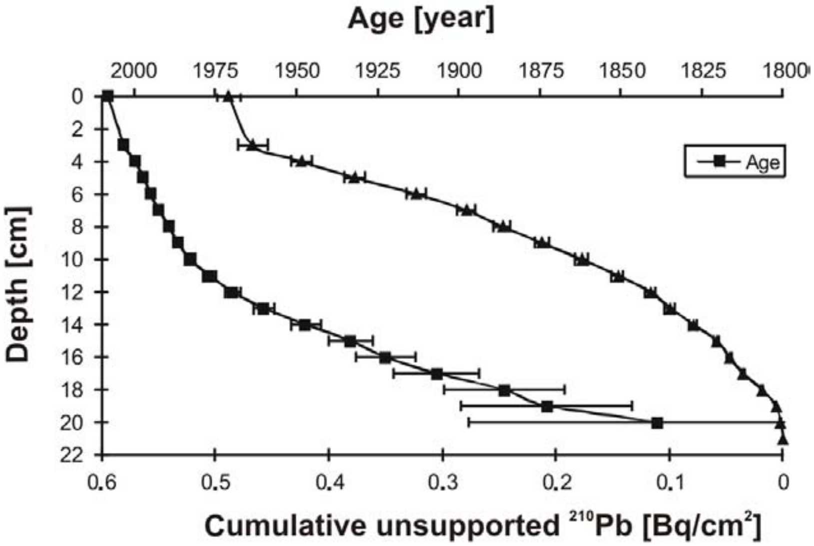

Figure 2 Cumulative unsupported activity of ^{210}Pb, calculated by integrating the surface activities of the successive layers and age versus depth in the Puścizna Mała profile. The ^{210}Pb ages were obtained after applying the CRS (constant rate of supply) calculation model to the peat (Appleby 2001).

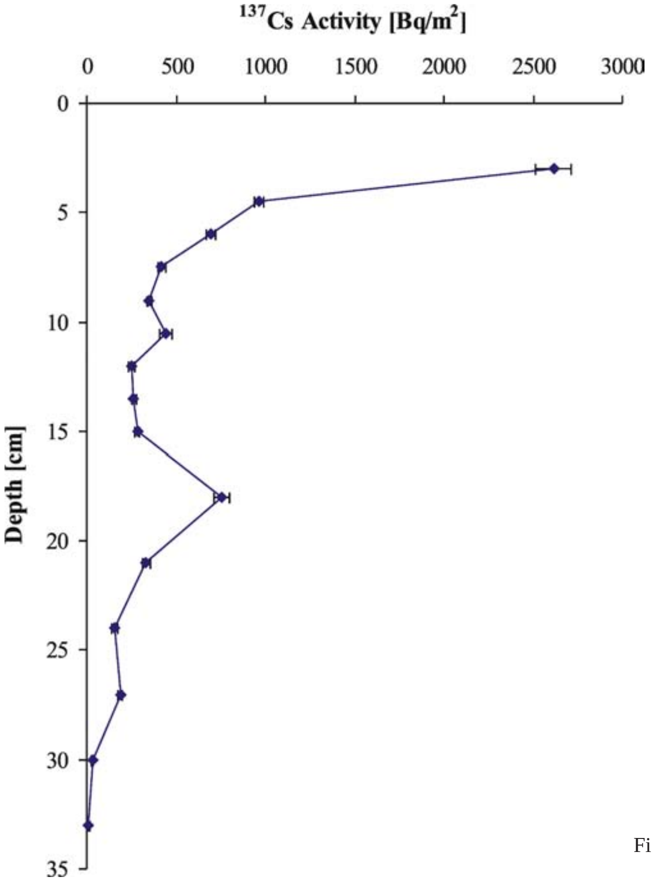

Figure 3 ^{137}Cs activity in Puścizna Mała profile gamma distribution with a mean of 10 yr cm^{-1}, shape 2. The accumulation variability was set with a beta distribution with strength of 4 and a mean of 0.7. (These parameters allow for a large range of posterior memory values, according to the manual for Bacon_2.2 [Blaauw and Christen 2012]). Because the deepest of the dated samples was obtained from the depth 123–124 cm, the age model was extrapolated to cover the full range of analyzed proxies, i.e. down to 130 cm.

Table 2 Radiocarbon dating results for Puścizna Mała profile.

Lab nr	Age ^{14}C (BP)/ F^{14}C	Uncertainty (1σ)	Depth (cm)	Calibrated age ranges AD			
				68.2%		95.4%	
Gd-19017	1.304	0.010	6–7	1979	1983	1958	1985
Gd-19019	1.464	0.010	11–12	1968	1973	1963	1976
Gd-19011	1.0302	0.0080	15–16	1954	1958	1952	1960
GdS-441	1.0068	0.0056	18–19	1891	1960	1697	1961
Gd-19013	110	50	21–22	1688	1927	1674	1943
GdS-442	463	48	24–25	1412	1466	1324	1620
GdS-443	519	45	27–28	1330	1441	1310	1451
GdS-444	762	48	30–31	1224	1280	1169	1377
GdS-446	743	48	33–34	1226	1288	1186	1387
GdS-447	644	48	39–40	1287	1391	1279	1403
Gd-12945	480	50	42–43	1405	1456	1316	1616
Gd-12917	830	50	45–46	1168	1260	1046	1279
Gd-12925	650	45	48–49	1286	1390	1277	1401
Gd-12949	730	50	51–52	1226	1296	1208	1391
GdS-464	877	52	57–58	1048	1220	1036	1255
Gd-19020	950	55	63–64	1025	1155	995	1210
GdS-465	1081	56	69–70	896	1017	781	1036
GdS-466	1059	52	75–76	900	1023	832	1151
Gd-19021	1240	70	81–82	688	867	657	962
GdS-467	1251	52	87–88	681	856	666	886
GdS-468	1143	53	93–94	784	975	772	1016
GdS-470	1471	56	99–100	551	642	434	660
Gd-12955	1420	75	105–106	555	670	434	771
GdS-469	1493	48	111–112	539	634	434	649
Gd-19022	1750	70	117–118	216	391	87	429
Gd-19024	1680	80	123–124	246	504	140	546

The age-depth model (Figure 4) for the Puścizna Mała core, based on ^{210}Pb and ^{14}C data, covers the period from about AD 300 to the present. The average peat accumulation rate is 0.48 mm yr^{-1}; however, the shape of the model is rather complex, and three periods of significantly different shape can be distinguished. The first (bottom) period ranges from 45–130 cm (about AD 300–1200), with a relatively constant accumulation rate of ~0.6 mm yr^{-1}, and the average 95.4% probability range for the modeled ages is ~140 yr. The shape of the model for the most recent period (0–22 cm) is arc-shaped, reflecting the changes in compaction and bulk density (see Figure 6). The average accumulation rate for this interval is ~1.1 mm yr^{-1}, and the average 95.4% probability range for the modeled ages is ~40 yr, although it is only a few years for the period covered by precise ^{210}Pb results.

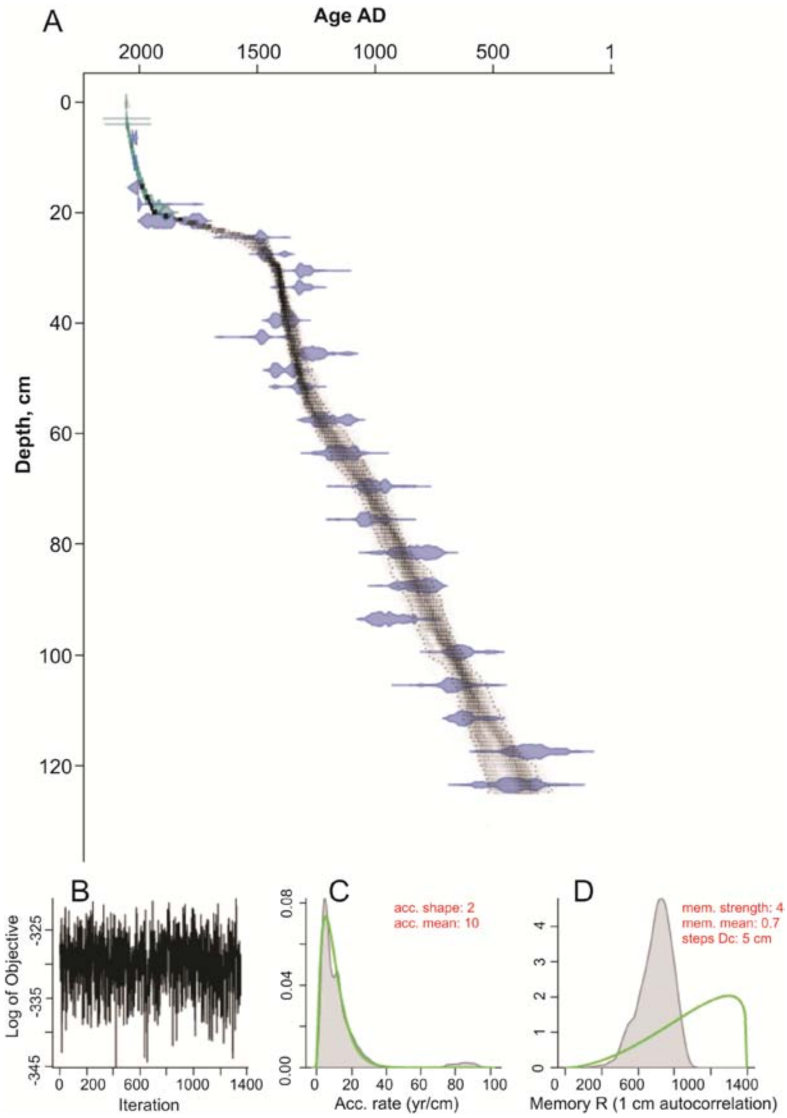

Figure 4 Age-depth model obtained with use of Bacon software: (A) modeled age versus depth plot, gray shaded area represents 95.4% probability range, while the "cloudy" shapes show the probability ranges of calibrated ages for individual samples; (B) MCMC diagnostic plot, no observed trend indicates stable solution. (C) and (D) prior (line) and posterior (gray shape) distributions of accumulation rate (C) and memory R (D), confirming the reasonable choice of the parameters.

The transitional part of the core section from 22 to 45 cm, containing a highly decomposed peat layer (Figure 6), is partially affected by inversions of age. However, none of the dates was considered an outlier, as there is a finite probability that all of them agree with the chosen assumptions. At present, we did not introduce to the analysis any hiatus in the core. On the other hand, Bacon output for this section is characterized by very narrow age ranges (95.4% probability interval is ~50 yr), resulting from the prior information about constant sedimentation rate and the attempt to meet the agreement of all dates with assumed continuous peat accumulation. This precision may be illusory and suggests that careful analysis of the obtained age estimates should be undertaken. The reliability of the obtained model is discussed in the following section in the light of agreement or discrepancy between modeled ages and proxy data.

Bulk Composition of Peat

The bulk physical and chemical features of the Puścizna Mała profile were divided into three parts: 130 to 45 cm (cal AD 300–1280), 45 to 22 cm (cal AD 1280–1800), and 22 to 0 cm (cal AD 1800–2000) (Figure 5), with the highest fluctuations observed in the top layers. Ages in this section are those modeled from Bacon.

The lowest section of the peat had only minor vertical variability in bulk composition. The bulk density varied between 0.08–0.14. Three pronounced maxima were observed at the levels 126–130, 99–105, and 57–69 cm. The ash content was less than 2% except for the two lowermost layers (126–130 cm). The sulfur content varied between 0.08–0.15%, with the highest values detected at 126–130 and 72 cm. Carbon was between 45 and 51%, and the nitrogen content ranged from 0.6 to 1.5%. Both of these fluctuated similarly. The C/N ratio fluctuated considerably, varying over a broad range from 34 to 72. Between cal AD 300 and 1150, the C/N ratio values in the core increased.

The 45–22 cm depth section was the most problematic; however, the most dramatic changes were observed in the top of this part with maximum values of ash content, bulk density, and nitrogen. Beginning in the 15th century, the C/N ratio diminished from 60 to a minimum of 30 by the mid-17th century, indicating an increase of peat humification.

In the uppermost layer (22–0 cm), ash content and bulk density revealed pronounced maxima at the 12–13 cm level. Sulfur showed a slightly different pattern of increasing during the 19th century (15–18 cm). The negative shift of C/N ratios was followed by an increasing trend until the 1960s, when the C/N ratio dropped rapidly to <40 in the surface layer, contrary to nitrogen and carbon (Figure 5).

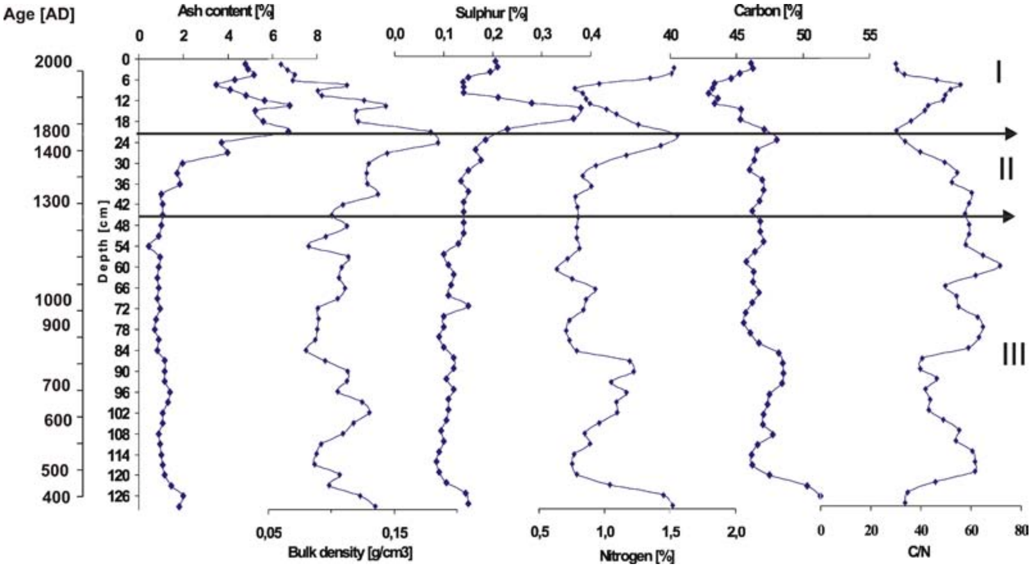

Figure 5 Bulk composition of the Puścizna Mała profile versus depth and Bacon model

Revised Age-Depth Model

After comparing the results of bulk composition and palynology with the Bacon model, it was assumed that the middle part of the peat profile was considerably disturbed, probably by humans during peat extraction. This disturbance may include one or more “hiatus” events and also reversals of peat layers. Because we have no knowledge what kinds of disturbances occurred, we can assume only that the whole section at 45–30 cm depth is older than layers located above it, and younger than the layers located below this section. We estimated that the upper boundary of this part is located at a depth of 22 cm (comparing with ^{210}Pb dating, maximum value of bulk density and lithostratigraphy; see Figures 5 and 6) and assumed that the lower boundary may be assigned to a depth of 45 cm. Therefore, the whole profile was divided into three parts: the upper part (0–22 cm), the middle part (22–45 cm), and the bottom part (below 45 cm). The revised age-depth model was constructed using OxCal v 4.1 software (Bronk Ramsey 2009) and the IntCal09 calibration curve (Reimer et al. 2009). For the lower (older) part of the peat profile, an age-depth relation is constructed using the OxCal *P_Sequence* command (Bronk Ramsey 2008) with the *k* parameter, which describes a magnitude of random variation from a constant sedimentation rate, set to 0.5 (1/cm). The sequence of 14 ^{14}C dates included in this part is limited from the top by the *Boundary* command corresponding to 45 cm depth (the lowest level of assumed disturbance of the peat profile), and from the bottom by a *Boundary* command assigned to 130 cm depth (in order to cover by the model the full range of analyzed proxies). Also, for the upper (younger) part of the peat profile an age-depth relation is constructed using the OxCal *P_Sequence* command with the *k* parameter equal to 0.5 (cm^{-1}). This part includes 18 ages derived from ^{210}Pb dating and two ^{14}C dates. The sequence of these dates is

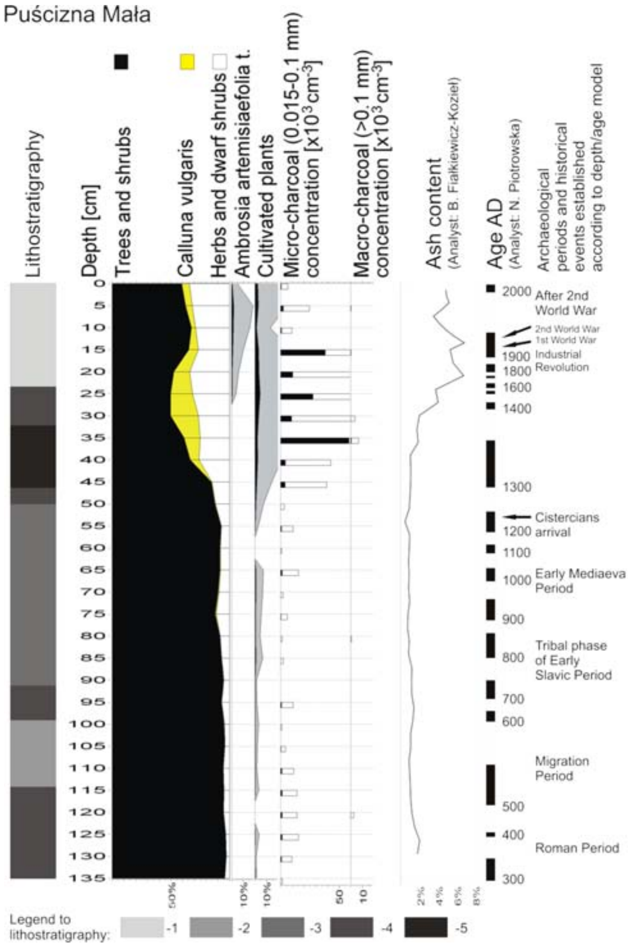

Figure 6 Human impact in the light of palynological analysis following Kołaczek et al. (2010). Age was assessed on the basis of Bacon model. Lithostratigraphy: (1) not decomposed; (2) very weakly decomposed peat; (3) weakly or very weakly decomposed peat; (4) moderately decomposed peat; (5) highly decomposed peat.

limited from the top by the *Boundary* command assigned to depth = 0 cm, and from the bottom by the *Boundary* command corresponding to the uppermost level of disturbed peat core (22 cm depth). An unordered group of dates assigned to the disturbed part of the peat profile is placed between these two sequences and defined by the OxCal *Phase* command. All three parts of the model are included in the OxCal *Sequence* command. Because of a low individual agreement index, four ^{14}C dates (Gd-19017, Gd-19011, GdS-441, and Gd-12945) were excluded from this model. Three of these dates came from the part of the peat profile that was precisely dated by ^{210}Pb dating; therefore, we decided do not include them in the model (see Appendix 1, online Supplementary file).

DISCUSSION

Distribution of ^{210}Pb and ^{137}Cs

The atmospheric flux of ^{210}Pb to the Puścizna Mała core, derived using the CRS model, is 152 ± 5 (Bq m^{-2} yr^{-1}) and is within the range of estimates derived from other peat deposits (reviewed by Turetsky et al. 2004). This value is also comparable to the measured and modeled (Piliposian and Appleby 2003) atmospheric fluxes of ^{210}Pb over the central European longitudes.

The upper layer, comprised of living material (0–3 cm), retained most of the ^{137}Cs, and the deeper layers, formed by peat at different stages of humification, contained relatively little ^{137}Cs. The occurrence of ^{137}Cs at the bottom of the core (33 cm) clearly indicates downward movement of cesium by leaching. It should be noted that most of ^{137}Cs activity in this profile was found in living moss plants, formed after the Chernobyl fallout. The concentration of ^{137}Cs in the upper segments of the peat bog profiles is due to the chemical similarity between cesium and potassium (Gerdol et al. 1994), which facilitates the upward transport of ^{137}Cs through the roots and aboveground parts of plants growing in the peat bog. The transfer of ^{137}Cs from peat to plants varies depending on the species, physical and chemical interactions, and localization of study site. Vascular plants tend to accumulate Cs (Rosén et al. 2009). A similar phenomenon is described by Gaca et al. (2006) in an ombrotrophic peatland located 15 km east of the study site. The mechanisms and intensity of mobility of cesium remain unclear. The translocation and radionuclide availability for plants in organic soils have been shown to be different than those in mineral soils (i.e. Shand et al. 1994). Therefore, knowledge of the radionuclide mobility and distribution in bog profiles could be a good platform for developing theoretical transport models and could be used to reconstruct the fallout history.

Age-Depth Model of Puścizna Mała Profile Compared to Human Impact

The Bottom Part (130–45 cm; cal AD 300–1280)

The main information about human impact in this area and the bog development comes from historical data and palynological analysis made by Kołaczek et al. (2010), here combined with the Bacon model (Figure 4). The obtained results correspond to historical data, which confirmed the reliability of the age-depth model.

Human impacts on the Puścizna Mała profile (Figure 6) were reflected by a small number of *Cerealia* pollen grains before AD 500 (up to 120 cm) and by a slight increase in the bulk composition (see Figure 5). The minimal number of published paleoecological human indicators in this area is most likely due to the relatively low agricultural activity of the Púchov culture (an archaeological culture named after the Púchov-Skalka site in Slovakia). Their probable ancestors were the Celt Cotini tribe and their successors, the Przeworska culture.

Between AD 480 and 510 (106–104 cm), a decrease in agricultural activity is observed. This event is a manifestation of a broader tendency recorded in the pollen profiles across central Europe (e.g. Ralska-Jasiewiczowa et al. 2003; Noryśkiewicz 2004; Dreßler et al. 2006; Zolitschka et al. 2006) and coincides with the Migration period, during which great shifts took place in both culture and politics, and the roots of modern Europe were formed (Collins 1999; Geary 2002). Traces of agriculture (regular record of Cereal-type pollen) reappeared at the beginning of 6th century and lasted until the beginning of the 12th century (100–55 cm; Kołaczek et al. 2010). The 12th century marks the onset of Cistercian economic activity in the Orawa-Nowy Targ Basin (Jost 2004).

The Middle Part (45–22 cm; cal AD 1280–1800)

Dramatic discrepancies are observed within the middle part of the analyzed profile. The subsequent drastic decline of forests reflected in the palynological data, and dated to cal AD 1280–1340 (45 cm) according to the Bacon model, is difficult to explain in the light of historical data. The establishment of settlements near the Puścizna Mała bog was dated to the 16th century (Trajdos 1993). Before that time, such drastic deforestations in the bog vicinity were rather impossible due to the fact that the Orawsko-Nowotarskie peatlands and forests were treated as a natural barrier to prevent invading the territory of Poland from the south (Łajczak 2006, 2007).

This phenomenon of decrease in arboreal pollen grains might be explained by fires on the Orawsko-Nowotarskie peatlands accidentally or intentionally induced by shepherds, who used bogs as pastures probably since the beginning of Medieval settlement in the 13th century until the 20th century (Łajczak 2006). The described decrease coincides with an increase in charcoal particles 15–100 µm diameter (Kołaczek et al. 2010), which could confirm the hypothesis about fires. On the other hand, the enhanced concentration of charcoal particles in peat can also be explained by long-distance transport of carbon particles. This supposition seems to be supported by the infrequent occurrence and even lack of particles >100 µm, considered to be indicators of local fires (see Tonney and Anderson 2006). Furthermore, the ash content is <15%, which is regarded to be a minimum frequency indicative of local fires (Holynska et al. 1998). The mineralogical analysis of other profiles of Puścizna Mała (Fiałkiewicz-Kozieł et al. 2011) has indicated that higher ash content correlates with higher amounts of aluminosilicates and iron oxides, which are linked to industrial activity and suggest a younger age for the layer.

In the 45–27 cm section (AD 1300–1400 according to the Bacon age-depth model), the highest peat accumulation rate of 2 mm yr^{-1} was found. Interestingly, within the same level, Kołaczek et al. (2010) found the highest degree of peat decomposition (see also Figure 6). The higher peat decomposition correlates with higher bulk density and decreases in C/N ratio to 30–50, indicating enhanced degradation of plant litter as well as allogenic mineral matter input to peat bogs (Chagué-Goff and Fyfe 1996; López-Buendia et al. 2007). The paradox of doubled organic matter content and increased peat accumulation rates in experimentally drained peatlands was described by Turetsky et al. (2011). However, they also indicate the dramatic loss of carbon after a wild fire, estimated at the equivalent of more than 450 yr of peat accumulation, which significantly changed the age of their peat layers. In the studied case, no such dramatic gap is observed in age-depth model. This fact also excludes hypotheses about fire on the studied peatland.

Possible causes of changes in the Puścizna Mała bog could be anthropogenic land-use changes, water-level fluctuations, or natural climatic factors. The large increase in the bulk density and substantial drop in the C/N ratio between the 15th and 18th centuries might be attributed to Little Ice Age climate deterioration, which is recorded in peat profiles throughout Poland (De Vleeschouwer et al. 2009; Lamentowicz et al. 2009).

The expansion of *Calluna* progressed simultaneously with the rapid deforestation (at the beginning of the 14th century according to our initial age-depth model; Kołaczek et al. 2010), contrary to results detected in the Stążki mire (N Poland), where the similar optimum of *Calluna* was dated at about the 19th century (Lamentowicz et al. 2009). Moreover, the concomitant increase in *C. vulgaris* and the occurrence of maize (*Zea mays*) pollen in the Puścizna Mała profile (40 cm; Kołaczek et al. 2010) suggest that the age of this layer (40 cm) is younger than suggested by the ^{14}C data. The Europeans imported maize from the Americas in the early 16th century, but it appeared in Poland only in the 17th century for the first time (Gąsiorowski 2006). These arguments suggest a high probability that the acceleration of mass deforestations reflected in pollen data from the Puścizna Mała bog have modern origins (19th–20th century). Moreover, such a deep occurrence of maize could have been a result of mechanic disturbances on the bog surface, as well.

Another inconsistency between the palynological data and age-depth model in the PM0 profile is the overly early appearance of *Ambrosia artemisiaefolia*-type pollen dated to about cal AD 1450. This type of pollen is produced by American representatives of the *Ambrosia* genus (mostly *Ambrosia artemisiifolia*) introduced to Europe in the middle of the 19th century (Chłopek and Tokarska-Guzik 2006). The increase in the rate of its expansion was detected after World War I in southern and central Europe (Csontos et al. 2010) and probably since that time it could have been reflected in the pollen influx. Nonetheless, the discrepancy between the appearance of *Ambrosia* pollen and the results of age-depth modeling may be explained alternatively by the possibility of postdepositional pollen migration deep down into the loose structure of the acrotelm. This phenomenon has rarely been considered in the interpretations of pollen records; however, Clymo and Mackay (1987) found that up to 25% of sporomorphs can be inwashed 3 cm or more into the peat. The 3-cm-long migration distance seems to be too low to disturb the reconstruction of *Ambrosia* significantly and, thus, to explain the observed discrepancy. Taking these arguments into consideration, further research, preferably with the use of several dating techniques and chronological proxies, is necessary to understand the pollen signal of *Ambrosia* in Europe.

The Upper Part (22–0 cm; cal AD 1800–2006)

At the beginning of the 20th century, the Puścizna Mała peat bog was in a good condition, confirming Lubicz-Niezabitowski (1922) and relatively high peat accumulation rate during the 20th century might be an effect of the acrotelm regeneration. The anthropogenic impact on the peat bog in the recent past is indicated by the sulfur content. Sulfur in ombrogenic peat originates mainly from atmospheric deposition linked to acid precipitation (Chagué-Goff and Fyfe 1996; Mandernack et al. 2000; Moore et al. 2004). Moreover, some authors have reported that the sulfur content in living *Sphagnum* moss is proportional to the load of airborne sulfur (Novák et al. 2005). However, its postdepositional mobility in peat slightly decreases the reliability of the reconstructions of past sulfur deposition (Novák et al. 2005). Nevertheless, in the PM0 profile, the distinct enrichment in sulfur in the 19th century deposits (Figure 5) is in overall agreement with published historical S-concentration curves (Novák et al. 2005) and thus may indicate the anthropogenic emission of S compounds to the atmosphere. Interestingly, ash content correlates with the total content of sulfur, which suggests the predominance of the inorganic fraction of sulfur and a link to anthropogenic activity.

Revised Age-Depth Model

Taking into account the described discrepancies in the middle part of the Puścizna Mała profile, the updated age-depth model is presented in Figure 7. The overall agreement index of the model is rather low (A = 56%), but in our opinion it is enough for accepting this model as reliable, because this value is the result of a low agreement index of only one sample (GdS-468, individual agreement index = 26%). Moreover, the experience of the authors suggest that for complex OxCal models constructed with a use of *P_Sequence* command, the threshold value of the overall index recommended for a typical models (A = 60%) may be overestimated (Michczyński 2011).

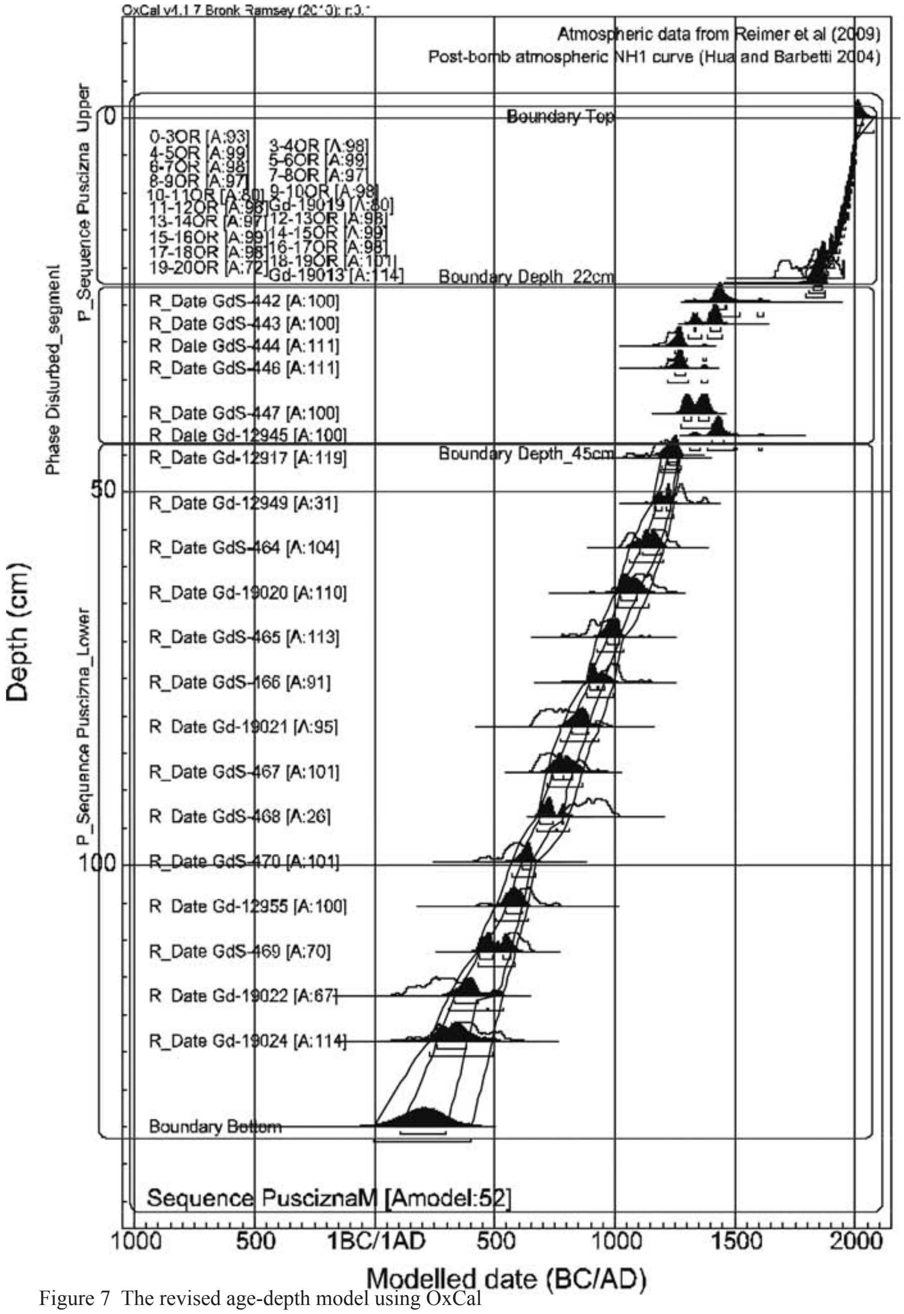

Figure 7 The revised age-depth model using OxCal

One can see the boundary between the upper part of the profile and the disturbed part of the profile, located at the depth 22 cm, is dated to AD 1825–1865 (68.2% confidence interval, rounded to 5 yr). The age of the boundary between the disturbed part and the lower part of the peat profile is estimated to AD 1225–1265 (68.2% confidence interval, rounded to 5 yr). This shows a disturbance in the peat between the 13th and 19th centuries. As an example to support this argument consider that the youngest sample from the disturbed part (GdS-442) is dated to AD 1410–1465 (68.2% confidence interval, rounded to 5 yr). It clearly suggests that some levels of the peat profile had to be removed from the peat bog as a result of human activity. Therefore, this event (or series of events) probably took place between the 18th and 19th century. Unfortunately, we cannot construct an age-depth relation for that time period because of these disturbances.

The two applied age-depth modeling approaches, although based on the same data set of ^{14}C results, differ in their construction assumptions. The Bacon software models the accumulation rate, which *a priori* is considered to have a beta distribution. The bog record is assumed to be complete, with no gaps nor hiatuses. On the contrary, in the OxCal software it was possible to introduce the assumptions about possible disturbances of peat layers between 22 and 45 cm. This modification allowed to statistically support the conclusions for possible causes of the discrepancies introduced by humans, who extracted the peat layers formed between the 13th and 19th century.

CONCLUSIONS

The peat profile in southern Poland records almost 2000 yr of paleoecological and geochemical changes. Up to the 12th century, major historical events linked to anthropogenic and climatic changes are recorded and confirm the reliability of the age/depth model. Specifically, the Roman, Migration, and Medieval periods are reflected in the pollen and bulk composition of the peat. However, the core segment between 22–45 cm (13th–18th century) was affected by complex disturbances. A doubled peat accumulation rate was detected, which is in contrast with higher peat decomposition and higher bulk density; thus, the described section is not compatible with a Bacon model of continuous deposition. This may indicate the possible influence of humans, decomposition of peat, and mixing the peat material. In the light of the limitations mentioned above, a more appropriate age-depth model is proposed, which takes better account of the disturbance that may have occurred during the history of peatland development.

It is postulated that the bulk composition of peat can be used as an anthropogenic tracer as well as to validate the obtained age-depth model. Adapting age models to fit proxies with other information, or, wiggle-matching, can be dangerous because one might fall into the trap of circular reasoning; however, we encourage scientists to discuss obtained models in more detail, because, as is the case discussed, in spite of a very high-resolution model, we can find dramatic discrepancies between proxies and dating.

ACKNOWLEDGMENTS

We would like to thank two anonymous reviewers for all valuable comments, which improved our manuscript. We also would like to thank Dr hab Bernard Palowski for supervising, Prof Anna Pazdur and Prof Kazimierz Różański for providing the laboratories, Paulina Wach and Władysław Lipian for technical work, and Dr Monika Karpińska-Kołaczek for non-pollen palynomorph analysis. Prof Krystyna Milecka and Dr Francois De Vleeschouwer are acknowledged for valuable comments on an early version of manuscript. English editing was partly made by American Journal Experts. The research was funded by the Polish Ministry of Science and Higher Education (grant N304 275134 and 2011/01/D/ST10/02579).

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