Human-affected disturbances in vegetation cover and peatland development in the late Holocene recorded in shallow mountain peatlands (Central Sudetes, SW Poland)

BARTŁOMIEJ GLINA, MALGORZATA MALKIEWICZ, ŁUKASZ MENDYK, ADAM BOGACZ AND PRZEMYSŁAW WOŹNICKA

Peatland ecosystems can be altered naturally as a result of climate fluctuations (McGuire et al. 2009) or landscape geomorphology (Francis 1990), or artificially, e.g. via human activity (Maegowan & Doyle 1997; Glina et al. 2016a). A significant role in peatland vegetation formation is played by deforestation (Pellerin et al. 2008), which in most cases is anthropogenic in nature, i.e. performed by humans to obtain new areas for cultivation or grazing (Ellis et al. 2013). Moreover, human-induced drainage, peat cutting and vegetation burning have also caused harmful changes ( Leroyer et al. 2015). These factors may modify both the species composition (Mangan et al. 2012; Novák et al. 2014) and the peat properties, including the degree of decomposition and peat compaction ( Prévost et al. 1999; Målson et al. 2008; Laine et al. 2011). Furthermore, fire is a key environmental factor (e.g. Stocks et al. 2001; Haydukiewicz & Muszer 2008; Morris et al. 2014) that may greatly affect peatland ecosystems (e.g. Usup et al. 2004; Mangan et al. 2012; Zaccoone et al. 2014). Apart from human-induced fires (e.g. Hope et al. 2005), wildfires caused by climate shifts may also appear in natural ecosystems (e.g. Aukala et al. 2011; Gennaretti et al. 2013). Changes in natural ecosystems caused by the above-mentioned factors are well reflected in peat profiles. This is why peatlands are considered a remarkable and interesting archive for investigating past and present changes in the environment (Shotyk et al. 1998, 2002; Proctor et al. 2002). Peatland stratigraphy has been used since the last century to investigate human activity and past climate change (e.g. Blackford 2000; Karasiewicz et al. 2014; Jäger et al. 2015; Plöciennik et al. 2015). The most commonly used methods in palaeoecology are: macrofossil remains, pollen analysis and radiocarbon dating (e.g. Genever et al. 2003; Väiliranta et al. 2012; Lamentowicz et al. 2014). Plant macrofossil analysis together with measurement of the degree of peat decomposition can be used as an indicator of changing hydrological conditions (Blackford & Chambers 1993, 1995; Blackford 2000). To date, a multiproxy approach has been widely used to reconstruct mire succession, including the West and East Sudetes Mountains, both in Poland and Czechia (Speranza et al. 2000; Baranowska-Kącka 2003; Jankovská 2007; Dudová et al. 2012, 2014; Kozáková et al. 2015; Kajukało et al. 2016). Peatlands in the Central Sudetes have been poorly studied in terms of the local vegetation development inferred from macrofossil, pollen and radiocarbon analyses. In particular, shallow peatlands remain completely unexplored despite the fact that they may provide detailed palaeoenvironmental information on peatland history, especially about regional and local environmental changes throughout the last

DOI 10.1111/bor.12203 © 2016 Collegium Boreas. Published by John Wiley & Sons Ltd
millennium. In the Polish part of the Central Sudetes, the first palaeoenvironmental approaches providing information about the peatlands’ history were presented by Stark (1936), Kuszell (1988), Madeyska (1989, 2005), Muszer (1989) and Marek (1998). These studies were mainly based on pollen analysis and were either poorly supported by radiocarbon dating or without any radiocarbon ages.

In this study, the reconstruction of Holocene vegetation history in the Central Sudetes was performed based on a palaeoecological analysis of four peatland areas formed under different conditions. In most cases, the available literature presents a vegetation history based on the results obtained from a single thick peat core. However, the last millennium was a period when climatic variability and increasing anthropogenic impacts were very strong and led to significant spatial variability within and amongst ecosystems (Jones & Mann 2004; Yeloff & Mauquoy 2006; De Vleeschouwer et al. 2012). For this reason, a single core analysis is in some cases insufficient, especially in mountain areas, where altitude gradient and varied micro- and mesorelief additionally affect human activity and the conditions of peatland formation.

The main objective of this study is to reconstruct the environmental conditions of shallow peatland growth in the Central Sudetes during the late Holocene. We assess the impact of biotic and abiotic factors on developing peatland ecosystems in the upland zone. This is used to address the question as to whether human activities significantly affected vegetation development and the formation of shallow peatlands. Furthermore, knowledge of past changes might be useful in evaluating recent and future ecosystem changes and to avoid pitfalls in the present management of peatlands. The data from four peatlands, the records of which cover the middle Holocene period to the present, were compared with those of peatlands from other parts of the Sudetes Mountains, on both the Polish and Czech sides.

Study area

The Stolowe Mountains are situated in the central part of the Sudetes Mountain range (SW Poland) at the Poland–Czechia border (Fig. 1). This part of the Sudetes is mainly formed by upper Cretaceous sandstones, with the coexistence of fine-grained sandstones, siltstones (mudstones) and claystones (Wojewoda et al. 2011). The local altitude of this mountain range varies between 391 and 919 m a.s.l. (Waroszewski et al. 2015b). The highest summits exceed altitudes of 840 m a.s.l., e.g. Skalniak Plateau 840–850 m a.s.l., Szczeliniec Mały 895 m a.s.l. and Szczeliniec Wielki 919 m a.s.l. (Migoń et al. 2011). The mean annual air temperature decreases with altitude from 6.5 °C at the eastern border to 4 °C in the central and western parts. The coldest months are January–February (−3 to −4.5 °C) and the warmest is July (13.5 to 15 °C) (Otop & Miszuk 2011). The mean annual precipitation, in turn, increases with altitude from 750 to 920 mm, with the maximum in July (above 1150 mm). Snow cover persists for 70–95 days (depending on the altitude) and typically lasts until April. The growing period begins in the second or third week of April and amounts to 190 days (Gałązka et al. 2014). The peatlands cover an estimated area of 132 ha, equivalent to 2.5% of the Stolow Mountains surface (Śniekiewicz & Wójcik 2012). In this range of the Sudetes Mountains, peatlands mainly occur at an elevation of between 500 and 900 m a.s.l. (Kaszubkiewicz et al. 1996). The largest ombrogenous bogs and transitional peatlands are on the flat plateaus and in the valleys (Marek 1998). Small spring fens, supplied by seepage groundwater, occur on steep slopes (Kabala 2015). Alternating layers of peat consisting of different decomposed organic materials are characteristic of peat soils in the Central Sudetes (Kabala et al. 2011). It is worth noting that, in the 19th and 20th centuries, peatlands in the Central Sudetes suffered from artificial drainage undertaken to obtain new space for planting Norway spruce (Stark 1936; Jędrzyszczak & Miscocki 2001) that prevails presently in 83% of stands (Gałązka et al. 2014).

Material and methods

Sampling sites, sample collection and preparation

The peat cores were collected from four shallow peatlands located in the Stolowe Mountains (Fig. 1, Table 1). The investigated peatlands differ in terms of ecological type, elevation, type of water supply and bedrock. The sampling sites are located in areas with varying exposure to southwest winds, which dominate in the Stolowe Mountains. Core A (80 cm), was collected in spring fen peatland fed by groundwater (Glina et al. 2013). This peatland is located on the northern slope of the Skalniak ridge, on the leeward side of this topographical threshold. Core B (64 cm) was sampled in ombrogenous peatland – the Długie Mokrądło peat bog – situated on the Skalniak summit-plateau (Glina et al. 2016b). Another ombrogenous peatland, Ninkaća Łąka, located on a wide flat valley deep in the heart of the Stolowe Mountains (Glina et al. 2016b), was the sampling place of core C (79 cm). The last of the investigated peat cores – D (36 cm) – was collected in a very shallow transition bog located on the flat summit of the Rogowa Kopa hill. Study sites B and D are the sites most exposed to the south and southwest winds amongst the investigated peatlands, directly on or in front of the topographical barriers (Glina et al. 2016b). The peatlands...
have developed on three different bedrock types: sandstone-mudstone (fen peatland A), sandstone (peat bogs B and C) and mudstone (transitional bog D) (Fig. 2). Sampling was performed in June 2013 using a semi-cylindrical ‘Instorf’ peat sampler (50 cm long and 5 cm in diameter). Coring was conducted in the deepest parts of the peatlands. Core handling and sample preparation followed the protocol defined by Givelet et al. (2004).

**Physical and chemical analysis**

Ash content (loss-on-ignition) was measured after placing dried samples for 5 h in a muffle furnace at 550 °C (Bojko & Kabala 2015), and selected samples were tested at 900 °C to check the completeness of the ignition. Bulk density was determined on the basis of 5-cm³ subsamples, dried at 105 °C to constant weight. The dry weight (g) was divided by the fresh sample.
volume (cm³) (Chambers et al. 2011). The degree of peat decomposition was determined based on fibre content in peat samples. Fibres were separated from peat samples by sieving rubbed peat on a 0.15-mm mesh under running tap water (Lynn et al. 1974). Based on the percentage content of rubbed fibre, peat samples were individually classified as slightly decomposed (>40%), moderately decomposed (16.6–40%) or strongly decomposed (<16.6%). For pH measurement, suspensions were prepared using dry rubbed peat and 1 M potassium chloride at the ratio 1:5 (Kabala et al. 2016). Total organic carbon (TOC) and total nitrogen (TN) were determined using a VarioMax elemental analyser (no carbonates were present, thus

<table>
<thead>
<tr>
<th>Core</th>
<th>Coordinates WGS 84 (N/E)</th>
<th>Elevation (m a.s.l.)</th>
<th>Site</th>
<th>Slope (°)</th>
<th>Vegetation</th>
<th>Sampling depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>50°28′05.6″/16°20′21.8″</td>
<td>767</td>
<td>Karlów</td>
<td>4</td>
<td>Mixed forest</td>
<td>0–80</td>
</tr>
<tr>
<td>B</td>
<td>50°28′25.1″/16°43.8″</td>
<td>842</td>
<td>Długie Mokrado</td>
<td>2.5</td>
<td>Coniferous forest</td>
<td>0–62</td>
</tr>
<tr>
<td>C</td>
<td>50°27′56.7″/16°23′42.1″</td>
<td>716</td>
<td>Niknąca Łaka</td>
<td>0</td>
<td>Coniferous forest</td>
<td>0–80</td>
</tr>
<tr>
<td>D</td>
<td>50°27′00.0″/16°20′12.7″</td>
<td>753</td>
<td>Rogowa Kopa</td>
<td>1</td>
<td>Sedge reed</td>
<td>0–36</td>
</tr>
</tbody>
</table>

Table 1. Basic data on the sampling sites.

Fig. 2. Stratigraphy of the peat cores. M = mursh; Hi = fibric peat; He = hemic peat; Ha = sapric peat; C = bedrock.
the total carbon equalized the total organic carbon). Each peat sample was analysed in duplicate.

Palaeobotanical analysis and age dating

Plant macrofossils were analysed in 5-cm-long samples. The samples were boiled with 5% KOH and sieved (mesh diameter 125 μm). Macrofossils were scanned using a binocular microscope (×10–50), and identified using an extensive reference collection of type material following Polish standard PN-85G-2500. Volume percentages of each peat component standardized to 50 cm³ were derived and macrofossil diagrams were created using C2 software (Juggins 2007).

For pollen analysis, samples were taken every 2–4 cm from the peat cores. The samples of peat were acetylated according to the standard methods of Fegri & Iversen (1989). Pollen types were identified using a microscope (×20, ×40) based on 800–1000 sporomorphs in each morph, and classified to the arboreal group, including trees and shrubs (AP), or non-arboreal group of herbs (NAP, except wetlands and aquatic plants). POLPAL palynological software was used to draw the pollen diagrams (Nalepka & Walanus 2003). In the diagram biostratigraphical units (L PAZ – local pollen assemblage zones) were distinguished with a characteristic content of sporomorphs in individual profile sections, thus illustrating the process of changes occurring in the vegetation cover (Berglund & Ralska-Jasiewiczowa 1986).

Based on distinct changes in pollen diagrams and macro charcoals, 11 samples were selected for radiocarbon dating. 14C dating using a liquid scintillation counting procedure was performed in the Laboratory of Absolute Dating in Skala (Poland). 14C measurements were carried out with a 3-photomultiplier spectrometer, the HIDEX 300SL (Krapić & Walanus 2011). Radiocarbon ages were calibrated with OxCal v4.2.3 (Bronk Ramsey 2013) using the IntCal13 calibration atmospheric curve (Reimer et al. 2013). In the main text, the presented age of each sample refers to the centre of an interpolated calibrated age BP, with a 95.4% probability. Hereafter, ages are presented as AD or BC years. Detailed information on the age of samples is reported in Table 2.

Results

Ash content, bulk density and peat chemistry

Ash content in peat layers was mostly below 20 g kg⁻¹ (Table 3). The smallest ash amounts were determined in core C, with some exceptions in layers 20–30 cm and between 60 and 79 cm (229–478 g kg⁻¹). In cores A, B and D, the highest ash content was recorded in the basal layers (Table 3). Bulk density was relatively constant throughout the cores (110–190 mg cm⁻³), except for the basal samples, in which density values were higher (230–350 mg cm⁻³). The lowest pH (2.8–3.3) was in core C, whereas the highest pH (5.2–5.7) was recorded in core A. The recorded pH values clearly correspond to the peat differentiation in terms of ecological types of peatlands (raised bogs – lower pH; fens – higher peat pH). In fen core A, the TOC/TN ratios were the lowest (the narrowest) of all the investigated cores, in particular in the top layer, and increased with the depth of the core (14.4–21.4). In contrast to core A, the TOC/TN ratios decreased in the bottom part of cores B, C and D (Table 3).

Peat decomposition

Peat samples from the fen peatland (core A) consisted mainly of a well-decomposed sapric organic material. Similarly, peat core D consisted of strongly decomposed peat, and a medium decomposed organic material occurred only in the surface part of this core. A higher percentage of fibre was recorded in peat cores B and C, mainly consisting of moderately to slightly decomposed peat material. Strongly decomposed peat (sapric) was found only in the deepest part of the cores at the transition to the underlying mineral material.

Chronology

The radiocarbon dating of the peat samples indicates a mid- to late Holocene age of the peatlands (Table 2). Bottom peat in bog B located on the Skalniak summit plateau was dated at 3301 BC and the beginning of peat accumulation in fen A was dated to 1370 BC. Peatlands C and D were significantly younger; the inception of these peatlands occurred during the youngest Holocene. The organic layer at the bottom of core C was dated at AD 1114, and in core D was slightly younger – AD 1137 (Table 2). Significant differences between two neighbouring dates, as observed in core B, indicate a hiatus in peat sedimentation. Moreover, the determined radiocarbon ages in each peat layer indicate a rather low rate of shallow peat accumulation in the Central Sudetes.

Macrophossils

In the upper part of core A (to 50 cm), the dominance of Carex sp. and Equisetum sp. was observed. The deepest layer (under 50 cm) was dominated by Alnus wood and bark (Fig. 3). The content of Sphagnum sp. macrofossils was clearly higher in peat bog cores B and C than in the other cores (Fig. 3). It is worth mentioning that peat core B also contained a significant amount of Eriophorum sp. and Polytrichum sp. remains, characteristic for Ombro-Sphagnion peat. The uppermost part (0–10 cm) of the thin peat core on
Rogowa Kopa (core D) was made up mainly of *Sphagnum* sp. remains, whereas an increase in the *Carex* sp. and *Poacea* sp. content was observed in the sub-surface part (10–36 cm) of the core. It is worth noting that the presence of Ericaceae sp. was recorded in this part of the core (Fig. 3).

**Pollen analysis**

Pollen analysis was carried out on 56 samples from core A (15 samples), core B (16 samples), core C (17 samples) and core D (eight samples) (Figs 4–7). Dedicated local pollen assemblage zones (L PAZ) were correlated mainly with the youngest chronostratigraphical unit of the Holocene, i.e. the ‘Subatlantic’ period (Mangerud et al. 1974). Pollen records indicate that the vicinity of the study areas was covered mainly by forest communities. The dominant taxon was *Picea*, which created a spruce forest, occasionally enriched with *Fagus*, *Betula* and *Sorbus*. Significant amounts of *Abies*, *Fagus*, *Carpinus* and *Quercus* pollen, observed in the older parts of the diagrams, indicate the presence of *Fagus–Abies* forests. At this time, coniferous forests dominated by *Picea* also constituted an important component of local stands. The spring fen peatland (core A) located on the southern slope of

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**Table 2.** Results of the radiocarbon dating.

<table>
<thead>
<tr>
<th>Core</th>
<th>Peatland type</th>
<th>Depth (cm)</th>
<th>Laboratory no.</th>
<th>Dated material</th>
<th>Uncalibrated 14C age (a BP)</th>
<th>Calibrated 14C age (cal. BC/AD) 95.4% probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fen</td>
<td>16–18</td>
<td>MKL–2115</td>
<td>Peat</td>
<td>240±60</td>
<td>cal. AD 1481–1698</td>
</tr>
<tr>
<td>B</td>
<td>Peat bog</td>
<td>26–28</td>
<td>MKL–2126</td>
<td>Peat</td>
<td>90±50</td>
<td>cal. AD 1677–1940</td>
</tr>
<tr>
<td>C</td>
<td>Peat bog</td>
<td>16–18</td>
<td>MKL–2123</td>
<td>Charcoals</td>
<td>40±50</td>
<td>cal. AD 1800–1940</td>
</tr>
<tr>
<td>D</td>
<td>Transition bog</td>
<td>15–17</td>
<td>MKL–2122</td>
<td>Charcoals</td>
<td>800±90</td>
<td>cal. AD 995–1279</td>
</tr>
</tbody>
</table>

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**Table 3.** Geochemical data. TOC = total organic carbon; TN = total nitrogen.

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<tr>
<th>Core</th>
<th>Depth (cm)</th>
<th>Bulk density (mg cm⁻³)</th>
<th>Ash (g kg⁻¹)</th>
<th>pH in KCl</th>
<th>TOC (g kg⁻¹)</th>
<th>TN (g kg⁻¹)</th>
<th>TOC/TN</th>
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<td>A</td>
<td>0–10</td>
<td>162</td>
<td>169</td>
<td>5.7</td>
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<td>120</td>
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Skalniak Plateau from 1370 BC to AD 1300 was overgrown by alder forest (L PAZ: K1) dominated by *Alnus* (Fig. 4). In core A a predominance of woody plants (AP) was observed, with *Picea* and *Alnus* in particular. Amongst the herbaceous plants (NAP) the most frequent ones were Cyperaceae and Poaceae (Fig. 4). The large amount of *Abies* pollen (>10%) in the lower part of diagram A (<40 cm) indicates the presence of a fir forest in the immediate neighborhood of the peatland. Pollen diagrams B and C were divided into four and seven phases, respectively (Figs 5, 6). The vast dominance of the arboreal species testifies to the dense afforestation in the nearest vicinity of the mires. Broadleaf and mixed forests predominated (LPAZ: N Ł1, N Ł2, N Ł3 and DM1, DM 2) during the first period of mire formation. Forest stands consisted mainly of *Fagus*, *Carpinus*, *Quercus*, *Tilia*, *Abies* and *Picea* (Figs 5, 6), conditioned by altitude and soil fertility (similarly to the reconstruction made for the Karkonosze Mts by Malkiewicz et al. 2016). *Corylus* were commonly present in the understorey layer (Figs 4–7). In the Middle Ages (AD 1114–1326), the forests in the surroundings of peatland C were dominated by *Fagus* on uplands and *Alnus* in valleys/depressions. In the case of peatland D (Fig. 7), a transitional nature of the peat-forming vegetation can be assumed. Here, we observed a similar species composition (L PAZ: Ł1 and Ł2) of the forest stands to those recorded in peat core A. However in this case, there was no such significant domination of *Alnus* over the other tree species (*Fraxinus*, *Tilia*, *Ulmus*). In the uppermost 16 cm of the pollen diagram, a steady decline in herbaceous vegetation (NAP) and subsequent rise in arboreal plants (AP) was observed, particularly wind-pollinated trees *Betula* and *Pinus*. In contrast to the pollen diagrams of cores B and C (peat bogs), pollen spectra obtained for core D indicated the vast dominance of non-arboreal plants over arboreal plants. The presence of the light-demanding *Betula* and *Poacea* indicate the open forest stands on the Rogowa Kopa in the Middle Ages (AD 1137–1530). A decrease in the proportion of deciduous trees and shrubs contribution and an increase in coniferous species was observed in the upper parts of the pollen diagrams (L PAZ: N Ł4, N Ł5, N Ł6, N Ł7; DM3 and DM4; Ł3 and Ł4; Figs 5–7). Furthermore, a decline in fir-beech forest and an increase in spruce forests in all diagrams are clearly visible. The presence of Poaceae, Apiaceae, Asteraceae, Brassicaceae and Caryophyllaceae families indicates the presence of open landscapes. The pollen diagrams reflect continuous human presence in the close and far proximity of the study area. This was confirmed by the pollen of secondary anthropogenic indicators, such as *Artemisia*, Chenopodiaceae, *Urtica, Plantago medalmajor* and *Rumex acetosella*. The constant occurrence of *Cerealia* undiff. and *Secale* pollen (primary anthropogenic indicators) in cores B, C and D indicates the presence of arable lands in close proximity to or even inside the mountain range (Figs 5–7). Furthermore, the arable production...
was accompanied by grazed grasslands, as indicated by *Rumex acetosa*, *Rumex acetosella* and *Plantago lanceolata*. The pollen of these synanthropic plants was present continuously throughout the diagrams B, C and D. However in core A (fen), relatively high amounts of anthropogenic indicators were observed only in the top 20 cm (AD 1590) of the pollen diagram (Fig. 4). In the top 26 cm of diagram B (Fig. 5) and throughout pollen diagram C (Fig. 6), asynchronous decline of *Sphagnum* spores was observed.

**Charcoal concentrations**

Either single or grouped burned wood particles were found in layer 60–62 cm in both cores B and C, and in two layers, 15–17 cm and 34–36 cm, in core D (Table 2, Fig. 2). The highest concentration of charcoal particles was in the bottom layer of core B. The latest fires on the investigated peatland areas may have taken place in the early modern ages (charcoals dated at AD 1530 – core D). Other charcoals found in the lower parts of cores B, C and D were dated, respectively, at AD 1141, AD 1326 and AD 1137 (High Middle Ages). No macro charcoals were found in the peat core from study site A.

**Discussion**

**Age of the Central Sudetes peatlands**

The oldest peatlands in the Sudetes Mountains started to form in the Boreal (9000–7500 BC) and Atlantic (7500–5000 BC) chronozones (Marek 1998; Baranowska-Kaźka 2003; Madeyska 2005). In comparison to these data, the shallow peatlands in the Central Sudetes (Stołowe Mountains) are quite young, as the peat formation initially started there from 3301 BC to 1370 BC. The peatlands of similar, Subboreal age are quite common in the other parts of the Sudetes, both in Poland (Kuszell 1988; Muszer 1989) and Czechia (Dudová et al. 2012; Kozáková et al. 2015). Much younger mountain peatlands (850 BC – AD 1241) were described by Novák et al. (2010), Kajukalo et al. (2016), Rybníček & Rybníčková (2004) and Treml et al. (2008).

The formation of the youngest of the peatlands in the Stołowe Mountains (peat bog C and transition bog D) may be related to the paludification of the impermeable mineral bedrock. This phenomenon could be connected to human-induced paludification, caused by artificial deforestation analogous to
bogs in Great Britain (Tallis 1998) or on the summit of the Keprnik Mountains (Treml et al. 2008). It has been widely reported that paludification is an important process leading to the development of rainwater-fed bogs (e.g. Charman 2002). The ages of the peat bog (study site C) and shallow transition bog (study site D) are younger than those of the peatlands located in the Mumlawski Wierch (East Sudetes), where Waroszewski et al. (2013) estimated the age of the blanket bog at AD 500. The discussed results of the radiocarbon ages from the Czech and Polish sides of the Sudetes show spatial differentiation in the origin of the peatlands. Moreover, the radiocarbon age indicates that peat accumulation was very low in the Stołowe Mountains (Central Sudetes). The late Holocene peat sediments in the Sudetes (Marek 1998; Baranowska-Kącka 2003; Madeyska 2005; Novák et al. 2010; Dudová et al. 2012; Kozáková et al. 2015) or Alps (Shotyk et al. 2002; Potoń et al. 2013; Jäger et al. 2015) are commonly one or even two metres thick. In comparison to these findings, the peatlands described here are very thin, which is the result of variable sedimentation conditions (climate shifts, fires, drainage) causing peat compaction and mineralization.

Palaeoecological records of peat formation and vegetation

From 3300 BC to AD 1500, the forest stands in the Stołowe Mountains were dominated by Fagus, Abies and Carpinus, as confirmed by pollen analysis (Figs 4–7). These prevailing stands were associated with Pinus and Picea, which probably occurred in the upper, less fertile (sandstones), colder and more moist part of the mountain range. The widespread presence of Abies–Fagus forests has also been confirmed in peat cores from other Central Sudetes mires, such as the Great Batorowskie bog (Marek 1998), Olszyny peat bogs (Muszer 1989) and Żeleńiec (Baranowska-Kącka 2003; Madeyska 2005). Abies and Fagus pollen are not transported over long distances (Huntley & Birks 1983), so this indicates the presence of fir–beech forests in the direct surrounding of the peatlands under study. At this time (1370 BC – AD 1326), Alnus prevailed in broadleaf stands on wetlands at springs and along watercourses, as on the northern slope of Skalniak (site A). The dominance of alder was confirmed by raised nitrogen content, low (narrow) TOC/TN ratio and numerous Alnus wood pieces in the peat core (Table 3, Fig. 3). Both palaeobotanical and geochemical analyses have shown evidence of water-table fluctuation.
during the formation of the studied shallow mires. In the case of study sites C and B (peat bogs), this is demonstrated by an asynchronous decline of Sphagnum spores in the pollen spectra (AD 1808 – Fig. 5; AD 1870 – Fig. 6), variable peat decomposition and TOC/TN ratios (Table 3). Similar changes were described by Bruins et al. (2014) and Pawłowski et al. (2015). Periodical disappearance of Sphagnum spores could be a response to climate cooling in the Little Ice Age (AD 1300–1850), as described by Kajukalo et al. (2016) in the East Sudetes, and by Barber et al. (2003) in England and Ireland. In addition, the transition of mixed beech–fir forest into spruce monocultures in pollen diagrams, just after AD 1300 (core C, Fig. 6), may confirm the climate cooling (Madeyska 2005).

The macrofossils of Polytrichum sp. present in the lower part (~45 cm) of core B confirmed a drier phase in peat formation, by analogy to findings of Laitinen et al. (2008). The presence of monocotyledons and Ericaceae in the pollen diagrams also indicates drier periods with drier bog surfaces (Stoneman 1993). Besides hydrological conditions, changes in vegetation may indicate the effect of local forest clear-cutting (Kozáková et al. 2015) or fires (Zaccone et al. 2014). The decline of Quercus, Fagus, Carpinus and Ulmus, with concomitant increases in photophilous species (Populus, Betula and Corylus), observed in the pollen spectra confirmed this. In the literature, a decrease in Quercus and increase in Betula and Cyperaceae are indicators of post-fire succession (e.g. Jamrichová et al. 2012). Furthermore, the increase in herbaceous plants such as Poacea, Calluna and other flowering plants from the Ericaceae family is visible in the pollen spectra. Open post-fire areas on acid soils are particularly attractive for encroaching vegetation from the Ericaceae family, especially Calluna vulgaris (Odgaard 1994). The fires are confirmed by the presence of macroscopic charcoal particles in peat cores under investigation that indicates possible large-scale fire events in the Central Sudetes during the late Holocene, especially in the Middle Ages. The hiatus in peat formation identified by radiocarbon dating in core B (3301 BC – AD 1141) may reflect a fire that destroyed the upper layer of the contemporary peat bog. Waroszewski et al. (2015a) noted the charcoal age in the Podzols in the eastern part of the Stolowe Mountains at AD 1100, which confirms that fires were responsible for the hiatus in core B and may also confirm that large-scale fires greatly impacted the vegetation in the late Holocene across the entire Stolowe Mountains, and probably all other ranges of the Sudetes Mountains. Previously cited works have confirmed examples of local or large-scale fires in the Eastern Sudetes (Rybníček & Rybníčková 2004; Treml et al. 2008; Novák et al. 2010) and Western Sudetes (Kajukalo et al. 2016) as well. Moreover, frequent fires in this time period have been reported in the Králický Sněžník Mountains between AD 830 and 1110 (Novák et al. 2010). In addition, Dudová et al. (2014) reported late Holocene fires in the Hercynian Mountains. We can assume that either climate shifts or human activity can depress the water table, causing peatland vegetation to desiccate, thereby enhancing susceptibility to burning (Benscoter & Vitt 2008). Probably due to regular fires and unfavourable climate conditions on the orographic barrier, the forest vegetation on the Skalniak summit plateau was permanently in an initial stage of forest succession. Similar ratios of tree/herb pollen testify (according to Dudová et al. 2012) for forest openings at higher altitudes caused by fires. By contrast, the lack of trees and shrubs may cause the reduction of evapotranspiration and groundwater table rise. This phenomenon probably initiated the re-paludification process at site B (peat bog). Fires leading to the paludification and the formation of peat bogs have been recorded in the Southern Sudetes (Rybníček & Rybníčková 2004; Treml et al. 2008).

**Human impact on plant succession in the Central Sudetes**

The upland zones of the Sudetes were mostly not colonized until the High Middle Ages (Madeyska 2005; Klášť 2012). In particular, an increase in Secale pollen was observed at the beginning of the ‘Subatlantic’ chronozone (Wasylków et al. 1985). Phases associated with the settlement are distinctly visible in the described pollen diagrams. Primary anthropogenic indicators Cerealia sp. and Secale cereale (Court-Picon et al. 2005), and secondary anthropogenic indicators Plantago lanceolata, Rumex acetosa and Urtica (Court-Picon et al. 2005) were weak, but continuously present in the pollen diagram (Figs 5–7). However, in peat core A (fen) the primary anthropogenic indicators were only recorded in the top 20 cm (Fig. 4). The specific location (northern slope) and vegetation (dense alder forest) of this site protected these areas against wind transport. Moreover, the possibility of detecting non-intensive human impact in pollen diagrams from forested landscapes becomes extremely limited (Růš 2000; Sköld et al. 2010). In forested landscapes the pollen signal of herbs is strongly eclipsed by arboreal pollen, which are great pollen producers (Hellman et al. 2009). This could explain why the occurrence of anthropogenic pollen indicators is mostly very rare in pollen diagrams from the Stolowe Mountains. The weak signal of the primary anthropogenic indicators present throughout diagrams B, C and D is the result of southwestern wind transport from the area of the Klodzka Basin or the Czech Basin. In these places, agricultural traces have been detected since the Bronze Age (Baranowska-Kačka 2003; Dudová et al. 2012), Iron Age (Dudová et al. 2014) and Late Iron...
Late Holocene human disturbances in vegetation and peatland development, SW Poland

Age (Kuszell 1988; Kozáková et al. 2015). Based on this, we can assume that human activity in the vicinity of the Stolowe Mountains probably started at the beginning of the Middle Ages, in the same time period as in the Western Sudetes–Karkonosze Mts (Malkiewicz et al. 2016) and Izera Mountains (Kajukalo et al. 2016). In the heart of the Stolowe Mountains, agricultural practices started no earlier than the 16th–17th centuries, as confirmed by pollen of Plantago lanceolata, P. major/medium and Rumex acetosa in the strata dated to AD 1481–1698 in fen A (Fig. 4). The presence of secondary anthropogenic indicators reflects pastures, meadows and ruderal sites in the close vicinity to this peatland (site A), as it is protected from the external pollen inflow by the topographical barrier of Skalniak ridge. Pollen signals of grazing or ruderal sites dating to the Early Middle Ages were also well preserved in the peat cores from the Eastern and Western Sudetes (Speranza et al. 2000; Kozáková et al. 2015). The gradual disappearance of Abies and Fagus pollen since the High Middle Ages relates to forest clear-cutting (deforestation) to obtain new areas for cultivation or grazing (Madeyska 2005; Kozáková et al. 2015). In addition, iron and glass smelting had a significant influence on forest composition in the Central Sudetes (Marek 1998), as beech wood was preferred by smelters (Staffa 2005). The decline of native beech–fir forests has also been reported in all other ranges of the Sudetes (Baranowska-Kącka 2003; Dudová et al. 2012; Kajukalo et al. 2016; Malkiewicz et al. 2016). The recorded disappearance of Sphagnum sp. spores and the increase in the proportion of Picea in the upper 26–20 cm of pollen diagrams B and C should be associated with intensive drainage and the introduction of Norway spruce (Galka et al. 2014). In the 19th and early 20th centuries, mires in the Stolowe Mountains were artificially drained to obtain new space for Norway spruce cultivation (Stark 1936). In this period, the amount of Norway spruce in the Sudetes forests increased from 30 to 96% (Jędryszczak & Miscicki 2001). Deterioration of hydrological conditions was especially harmful for peat bogs (sites B and C). Sphagnum sp. moss communities, sensitive to the fluctuating water table (Goetz & Price 2016), in dry conditions were unable to develop spores; this is why only macrofossils (stems, roots) were observed in peat cores B and C (Fig. 3).

Conclusions

Palaeoecological research of four peat cores showed relative diversity in plant communities covering the Stolowe Mountains, especially in the late Holocene. The reported results reflect human impact on vegetation development and peat accumulation from the Middle Ages to the present. The human-induced or wildfires observed in the late Holocene were an integral component of peatland ecosystems in the Central Sudetes. The historical records of fires in the Stolowe Mountains and in other parts of the Sudetes testify to the fact that during the late Holocene large-scale fires were quite frequent in this mountain range. Furthermore, the logging of trees and intensive agricultural activity in the High Middle Ages greatly influenced the vegetation composition. Moreover, palaeoecological analysis (sphagnum spores decline) and radiocarbon dating (AD 1870) confirmed the drainage in the 19th century, which firmly affected the peatland vegetation. This was the last severe human impact on vegetation composition and peat sedentation in the Central Sudetes. The variable sedimentation conditions throughout the late Holocene significantly influenced the thickness of the studied peatlands. This study indicates the importance of future research on peatland records in this region, in particular obtaining high-resolution charcoal chronologies.

Acknowledgements. – The research was co-financed by the European Union as part of the European Social Fund ‘Grant Plus’ program. We are grateful to Dr Tadeusz Stepka for participating in the laboratory work. Special thanks to Prof. Cezary Kabala and the anonymous reviewer for their comments and suggestions, which improved the manuscript.

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