Studia Quaternaria, vol. 30, no. 1 (2013): 29–40. DOI: 10.2478/squa-2013-0003

LIGHTNING-CAUSED AND HUMAN-INDUCED FOREST FIRES AS EVIDENCED BY *PTERIDIUM* SPORES IN SELECTED QUATERNARY RECORDS FROM POLAND

Krzysztof Bińka[1], Jerzy Nitychoruk[2]

[1] *Bińka, K., Warsaw University, Institute of Geology, Department of Paleontology, Al. Żwirki i Wigury 93, 02-089, Warszawa, Poland, email: k.binka@uw.edu.pl*

[2] *Warsaw University, Institute of Geology, Department of Climate Geology, email: j.nitychoruk@uw.edu.pl*

Abstract

The occurrence of *Pteridium* spores – the common fire-adapted plant – was observed in Poland's Pleistocene (three interglacials and numerous interstadials) and Holocene pollen sequences. Until the onset of the middle Holocene, bracken was recorded relatively rarely. This marks climatic conditions with sporadic wildfires, followed by quick removal of the clones (or maintenance of the clones in a suppressed state) in the subsequent, post fire successional stages. In each interglacial we can also identify short periods (most often synchronous) of somewhat higher frequency of *Pteridium*, indicating a possible increase in natural fires as an effect of stormy conditions. These short periods are placed mainly within phases dominated by coniferous woodlands. The very high content of bracken found from a reanalysis of the long Saalian sequence at Ossówka as three regular culminations just above three non-tree phases, eastern Poland is the unique exception. To explain this we found the close modern analogue of the above phenomenon in the Alaskan region, at the boundary between the tundra and the boreal zone where in a very narrow forest zone, especially with the continental signature, lightning-initiated fires are very frequent (the edge effect). Pleistocene records of bracken during forest periods might indicate that thunderstorms and lightning strikes were responsible for its higher content. This is not to exclude the possibility that interglacial fires were set by Palaeolithic humans. However, it is more likely that the wildfires were utilized and to some extent controlled, especially at Ossówka, where the palaeolake existed for a long time after the interglacial; and this surely attracted the attention of game and humans. Our investigations show that rare, more abundant *Pteridium* in the Pleistocene sequences can be traced throughout the corresponding periods even at distant sites. This might be indirect evidence of a climatic pattern that promote stormy conditions and fires at that time. In the Holocene, different factors seem to be responsible for the long-term dynamics in *Pteridium* clones. Both in Poland and in adjacent areas bracken peaked in the middle Holocene from 8000 to 5000 BP, when this territory was occupied by deciduous woodlands. There is agreement that this is due to burning of forests by the hunter-gatherer societies of the Late Mesolithic. However, in spite of increased clearings in the subsequent phases bracken substantially decreased in abundance. This means first of all that fires rather than clearings were responsible for the rise in *Pteridium* spores in the Holocene pollen sequences.

Key words: bracken spores, fires, Quaternary, Poland

INTRODUCTION

Pteridium aquilinum is a common plant growing on every continent except in Arctic/Antarctic regions. For many reasons – first of all economic – it is an important plant, often invasive and difficult to eradicate; and because of this the literature concerning every aspect of its modern existence is voluminous. In Europe, it occurs both in open-canopied woods as well as in open habitats (mostly in western, maritime regions) such as heaths, grasslands and moors (Marrs, Watt 2006 and references).

Winter frosts are the critical factor controlling the absence of bracken in northern European treeless areas (Marrs, Watt 2006). Hence in northern Finland in the transitional zone of birch forest, sizable patches become smaller and scattered and they have no sporulation (Oinonen 1967). In Poland, clones of bracken are noted commonly in forested areas with higher light intensity, especially at the forest edges, in open woodlands and canopy gaps where they are very vigorous plants. Ephemeral, short-lived stands in open areas after clear-cutting where *Pteridium* is limited by drought, are also described (Markowski 1971). The *Pteridium* spores noted in Quaternary sequences seem to be a good indicator of fire. Oinonen (1967) pointed out that germination of spores is possible exclusively in the presence of ash.

There are records for bracken spores in Poland from temperate periods during the Quaternary. In some sequences however *Pteridium* is noted more frequently or even very abundantly – e.g. in the Holocene – whereas in the Pleistocene units it is recorded sporadically or its spores form low curves. In exceptional cases only deposits yielded more abundant spores than in the Holocene cores from the investigated area.

Views about the cause of the Holocene maxima of bracken are only partly coincident. It is evident that in earlier periods humans intensively destroyed woodlands, which influenced the abundance and distribution of this light demanding plant. As several authors have pointed out, disturbances such as burnings or clearings formed new habitats for bracken, which resulted in a higher frequency of spores (Dolling 1999, Pakeman *et al.* 2000, Mars, Watt 2006). However, which of the two factors is responsible for this, is less clear. Furthermore, some workers see climate as an additional contribution to its Holocene abundance. In older intervals, when human impact on vegetation is hard to identify in pollen spectra, bracken has not attracted attention of researchers, because spores are rather barely represented. In this case the main causes of the bracken occurrence seem to have been natural forest regeneration cycles and a fire regime that has been climatically induced.

The impetus for this study was the unusual cyclic occurrence of three very regular, high culminations of bracken in the sequence at Ossówka (Podlasie region, eastern Poland), yielding pollen flora from the Holsteinian/Early Saalian age (Fig. 1). This very long, monotonous core of lake marl accumulated over several thousand years is the key profile for the Middle Pleistocene in Central Europe. Its post-interglacial period was reexamined. This high percentage of bracken is unusual, because it is noted three times, just after tree-less phases. This is atypical both for its modern distribution, where *Pteridium* near the northern forest limit is a rare plant and shows poor or no sporulation, and for its very fragmentary fossil record in such an initial forest. This gave rise to close scrutiny of the available pollen sequences of different ages for mapping the occurrence of bracken. This might also allow a broader spectrum of problems to be covered with respect not only to fire regimes but also indirect factors, which it generates – e.g. storm systems – confined to some stages of interglacial succession. Let us – from a palynological perspective – look into the Pleistocene and the Holocene occurrence of *Pteridium* in the studied area.

MATERIALS AND METHODS

The starting point for the analysis was the well-known Holsteinian/Saalian sequence at Ossówka (Krupiński 1995), with a number of boreal interstadial events and tree less stadials. The newly analyzed profile was taken from a deeper, central part of the palaeolake (Nitychoruk *et al.* 2006) and sampled with a higher resolution. The 22 m long core (24 m – 2 m) consists of lake marl rich in diatoms at most levels analyzed. Only at the top (4.5 m – 2 m) the deposits pass into a non-calcareous silt. The core was sampled for pollen analysis at 10 cm intervals and after that, we used standard palynological preparation methods with hydrofluoric acid, Erdtman's acetolysis and *Lycopodium* spores (Stockmarr 1971). Because of frequency variations, counts range from 300 to 1000 pollen grains in each sample.

Pollen diagrams of Poland and to a lesser extent of adjacent areas were used as supplementary material to the examination. In many ways they represent a source of data, which has a different value. We tried to pick out deep-water lacustrine sequences (Fig. 2), because succession in peat bogs is often disturbed and sporomorphs are badly preserved. Also in peat deposits, because of the proximity to the source area, bracken is often overrepresented in the spectra (Greisman, Gaillard 2009). This may deform the pattern of floristic change inferred from the pollen count.

Undoubtedly, long Holocene sequences with short sampling intervals – especially these from the project IGCP 158b – are positive examples. Pleistocene records with reliable pollen data and sufficient sampling, are rather rare. Usually pollen diagrams are fragmentary, showing only a part of succession. In a large number of sequences bracken spores are not noted – probably because of editorial requirements (diagrams have to fit on a page). We have at our disposal mainly pollen diagrams representing the 'true' interglacials: the oldest one – the Ferdynandovian (Cromerian III and IV) – two extensive pollen diagrams, with interglacial flora and the complex of adjacent stadials/interstadials, the Mazovian (Holsteinian) interglacial (about 340 000 – 325 000 yrs BP) – a number of sites, sometimes with the long Saalian succession; and the Eemian – numerous diagrams.

Fortunately, a large part of the analyzed sequences is located in a relatively small area in central and eastern Poland, where after successive glaciations, palaeo-lakelands were formed. This allows more reliable comparisons between pollen successions of different ages, which were situated in the same geographical region with relatively similar climate conditions and habitat tolerance for bracken. This fact is important, because e.g. in the UK *Pteridium* favors equally often open areas after forest clearings (pastures, heaths) (Pakeman *et al.* 2000), whereas in Poland it is a very rare visitor in such places. Hence, the reasons for bracken peaks in sequences from such areas might have been different.

The possibility of mapping *Pteridium* at sites dispersed in time and space depends on the high resolution of pollen diagrams, in which, unfortunately, spores of bracken are often omitted and not included in the list of identified types. In the Pleistocene record only the high total sum (about 1000 pollen counted) permits a reconstruction of more subtle trends in bracken occurrence. Also spores of bracken seem to be easy identified. From a side view and when the pollen slide is too thin, which can lead to a rupture of the exine along leasures and some spores can be overlooked during counts. Thus, correct identification needs some proficiency.

RESULTS

The Pleistocene

The Ferdynandovian Interglacial

In this interglacial (e.g. at Zdany, Pidek 2003, Fig. 2) bracken spores was found rarely. However, higher values of *Pteridium* occurred in a few samples before each of the two characteristically warm temperate phases for this succession (about 3% with a maximum up to 5–7%). Their culmination coincides with expansion of the initial pine-birch forest (with an admixture of oak before the second optimum).

Holsteinian Interglacial and the Early Saalian

In many Holsteinian sequences a bracken is noted sporadically throughout the interglacial (e.g. at Nowiny Żu-

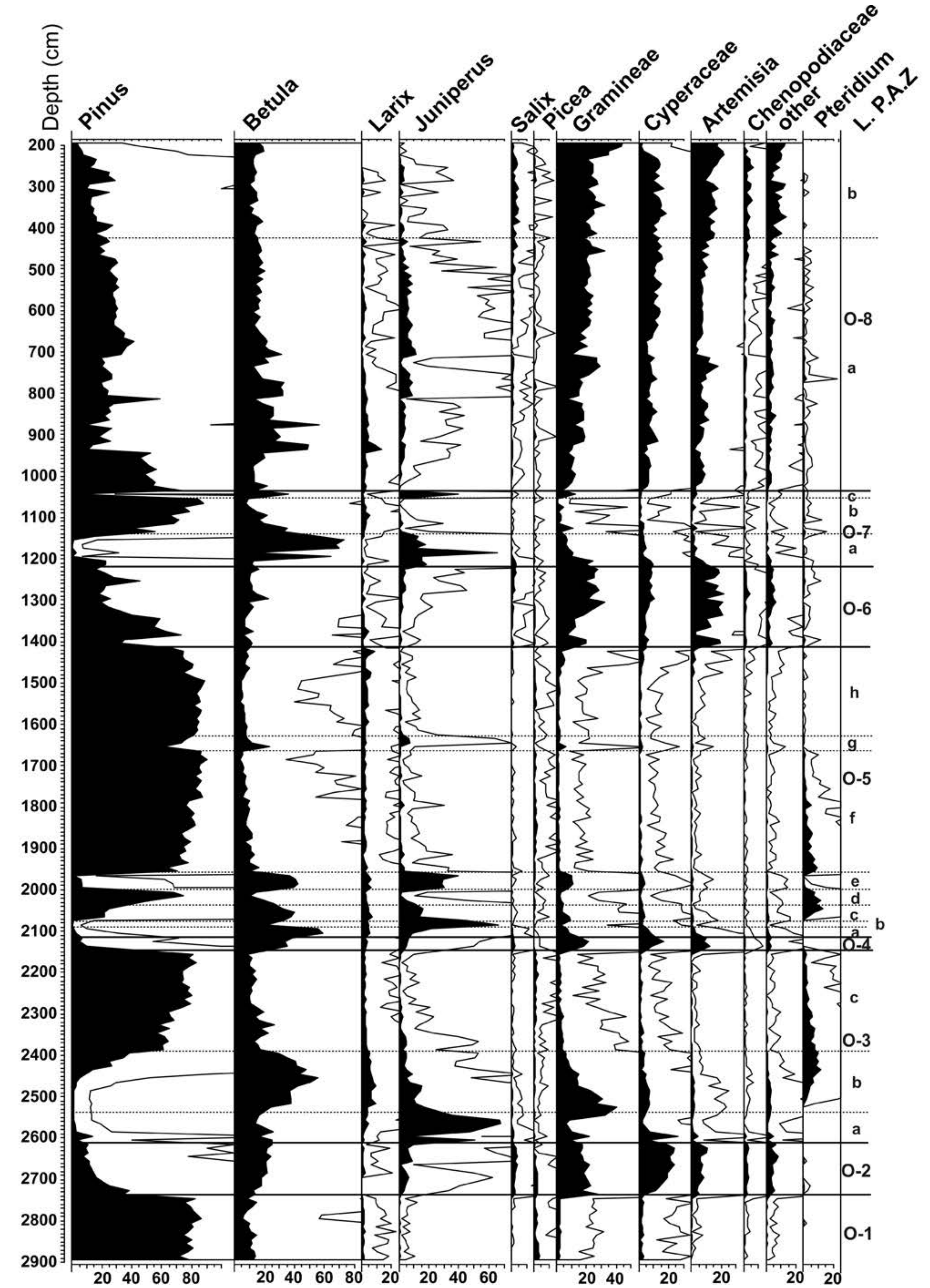

Fig. 1. Simplified pollen diagram of the Ossówka core.

Fig. 2. Sites in Poland mentioned in the text.

kowskie – Hrynowiecka-Czmielewska 2010; at Brus – Pidek 2003). At some sites higher values of *Pteridium* (2–7 spores/1000 or more) were found during the transitional pine zone between yew and hornbeam-fir phase (at Raków 1 and 2, Malice 3 and 2 – Nita 2009; at Woskrzenice – Bińka and Nitychoruk 1995; at Kaliłów, about 2% – Bińka and Nitychoruk 1996; at Ossówka and Komarno – Krupiński 1995) and at the end of the temperate phase (at Białe Ługi 3 and 2, at Wielki Bór 2 – Nita 2009).

Of particular interest is the occurrence of three impressive culminations of bracken in the Early Saalian with the percentages decidedly higher than in the Holocene sequences. They show almost the same pattern – the starting point in the birch zone, the amplitude, the culmination and the gradual decrease. The bracken expansion is best expressed in the long pollen sequence at Ossówka (Fig. 1) where three cycles were found against two maxima in the core, which was analyzed earlier (Krupiński 1995). The amount attained maximum values of ca 13%. From the nearby sites at Wilczyn, at a distance of about 5 km from Ossówka (Bińka *et al.* 1997) as well as at Kaliłów at a distance of 10 km (Bińka and Nitychoruk 1996) very high percentages of bracken were also reported. However, the character of pollen spectra in the corresponding intervals suggests that they might have been produced in an intermittent fashion. Abundant bracken appears soon after short period of tree-less vegetation dominated by grasses, sagebrushes, sedges and a very characteristic peak in juniper (O-2). The last species marks already some climatic amelioration. The further increase in temperature causes the expansion of a gradually more closed birch forest with larch and juniper (O-3 b). At that point spores of bracken begin to rise pronouncedly and culminate just below the boundary with the pine zone (O-3 c). Throughout this phase its curve gradually decreases. This scheme is almost exactly repeated after the successive cooling (O-4) with the difference being that the gradual decline of bracken in the pine zone was abruptly interrupted by a cold birch-juniper period (O-5 e). This cycle repeats again.

In the successive Saalian zones bracken occurred sparsely just as at other sites of corresponding age e.g. Wielki Bór 1, 2 (Nita 2009) and Brus (Pidek 2003).

Eemian Interglacial and the Early Vistulian

In the Eemian Interglacial, if this information is given, spores of bracken are noted rarely, but regularly (about 1–2 spores/1000), e.g. at Imbramowice (Mamakowa 1989) and at many other sites. In several pollen diagrams however, apart from this pattern, a somewhat higher frequency is observed e.g. in the *Picea* pollen zone at Nidzica 12–19, maximum 27/1000 spores were noted (Bińka *et al.* 2011; Fig. 4), and at Dziewule (Bińka and Nitychoruk 2001, 2003) – about 7–14/1000 spores. Also in other records in this zone we can see a little higher percentage of bracken spores, which forms the curve –a several spores were probably found in each sample – at Solniki (Kupryjanowicz 2008), Horoszki (Granoszewski 2003), Studzieniec (Krupiński 2005) and Czaple (3–5 spores/1000; Bińka and Nitychoruk 2011). The abundance of *Pteridium* was also reported from the *Picea* zone from adjacent areas e.g. at Hollerup (Björck 2000).

The *Quercus* pollen zone is the second interval within the Eemian where *Pteridium* spores show higher values. In some sequences an increased frequency of bracken is recognizable: at Czaple (throughout the oak zone, at 8 spores per sample) as well as at Solniki – at the beginning of the oak zone.

In the Early Vistulian only in the late Brörup *sensu stricto* and in the late Amersfoort were a slightly higher amount of bracken spores sometimes reported (e.g. at Czaple).

The Holocene

In the Holocene bracken commonly occurred in a variety of forest habitats and is noted more often in the pollen sequences than in the Pleistocene. In Poland, the increasing frequency of spores exceeding 1% has been reported since ca 8000 BP and it gradually declined at about 4500 years ago, with the highest content between 7000–5000 BP inferred from isopollen maps (Madeja *et al.* 2004). Only non-significant regional differences were observed. The simplified pollen diagrams from Błędowo (Bińka *et al.* 1991) (Fig. 3), central Poland, and from many other sites e.g. Lake Suszek (Miotk-Szpiganowicz 1992), Lake Steklin (Noryśkiewicz 1982), Lake Woryty (Pawlikowski *et al.* 1982) and Lake Łukcze (Bałaga 1982), where the higher curve of bracken started as early as 8000 BP, show this pattern. At Błędowo in the mid-Holocene, bracken reached the maximum of 1% to 3% (even to 6% in one sample). In the sequences outside Poland, e.g. in Finland, which were sampled with higher resolution, we can also see the same scheme (Ojala, Alenius 2005, Heikkilä, Seppä 2003).

DISCUSSION

There are a few features of bracken, which are important for palynological investigation. In the life cycle of bracken two features are essential – the vegetative reproduction of *Pteridium* by rhizomes forming constantly expanding patches, and the expansion into new territories by spores dispersed by wind, where new clones are established. Admittedly, the germination of spores in a laboratory under various growth parameters is high (Marrs and Watt 2006), but Oinonen (1967) pointed out that under natural conditions this process is possible almost exclusively in the presence of charred biomass or ash allowing germination. For such relationships, see Page (1986) and Oberdorfer (1990). This means that germination of spores in the presence of ash allows the founding of new populations and their further vegetative expansion, and as an effect the higher production and distribution of spores. This close link between spores of bracken and fire is especially important for palynological consideration.

Recent observations of bracken have shown that it, once established, remains unchanged under the closed tree canopy for several years (Dolling 1999). Oinonen (1967) observed long-lived clones, which were relatively static during a 20 years investigation. This status quo can be disturbed by changes in the light conditions, for example bracken invades new grounds rapidly on clear-cut areas, however, fronds expand only where rhizomes are present; otherwise the expansion is slow (Dolling 1999). Similarly, natural disturbances such as fires or gaps cause an increase in fronds density. In areas with more humid climate e.g. in England, *Pteridium* forms permanent patches outside the woodland habitat, which are hard to eradicate and to control. This is regarded as an intermediate stage towards woodland (Marrs *et al.* 2000). In Poland, bracken can persist only a short period in open spaces and is removed quickly in successional stages.

From a palynological point of view, it is noticeable that the shade from a dense frond canopy and thick leaf-litter layer may be important barriers to the establishment of young trees. Dolling (1996) noted in Sweden a high mortality of pine in the bracken clones, both when seeding experiments were conducted and when seedlings were planted. The mortality of *Picea abies* in turn was very low. Marrs and Hicks (1986), Marrs (1987a,b), Marrs *et al.* (2000) observed in their studies in England that seedlings of both *Betula* and *Pinus sylvestris* persisted under a bracken canopy, but did so more willingly when frond densities were lower.

The Pleistocene pollen diagrams show that like today this plant did not occur in the non-tree pollen phases, both with the cold steppe and the tundra signatures. Its spores are sometimes found in intervals with open vegetation but with the presence of reworked pollen derived from interglacial sediments. Also transport via wind from the south to open areas is not excluded, because spores are noted in modern pollen rain (Lacey, McCartney 1994). Within interglacial sequences spores are rather sparsely reported (about 1–2 spores/1000 in some samples), and sometimes the continuous curves (about 1% or more) are rarely formed. Also the high frequency of spores is a rare phenomenon and limited only to the Holocene and a few Pleistocene sites. Thus, in the interglacial forest *Pteridium* is noted rather rarely. New clones were generated due to local wildfires and quickly after these natural clearings were shaded out in the subsequent successional tree stages. As a result, patches of bracken considerably decreased or were eliminated if the new disturbances such as natural fires, wind throws, and gaps during the forest regeneration cycle did not taken place. These conclusions are partly consistent with that drawn by Mc Vean (1958, also Marrs, Watt 2006) for the early Holocene. According to his

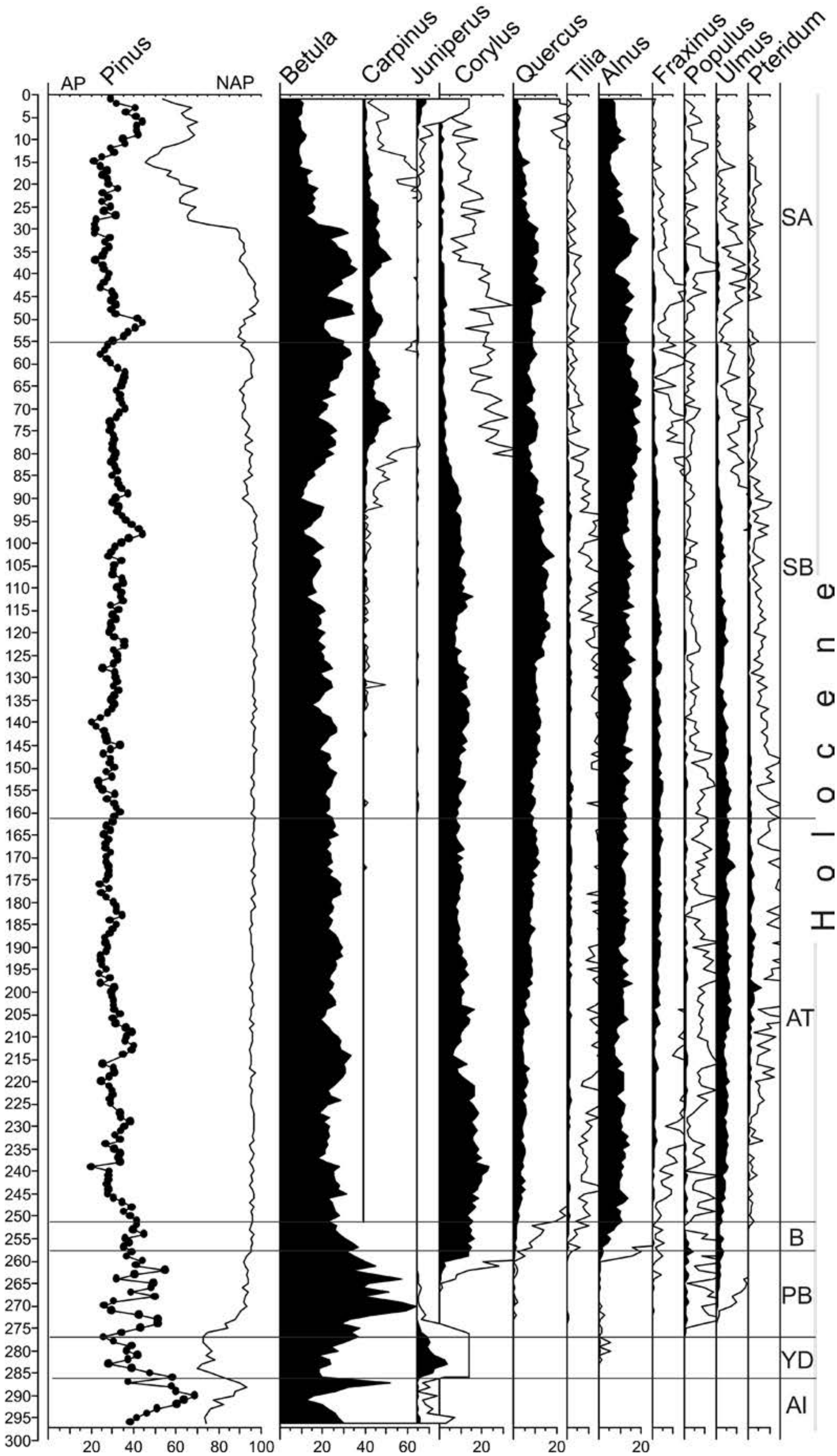

Fig. 3. Simplified pollen diagram from Lake Błędowo (Holocene) after Bińka *et al.* (1991), modified.

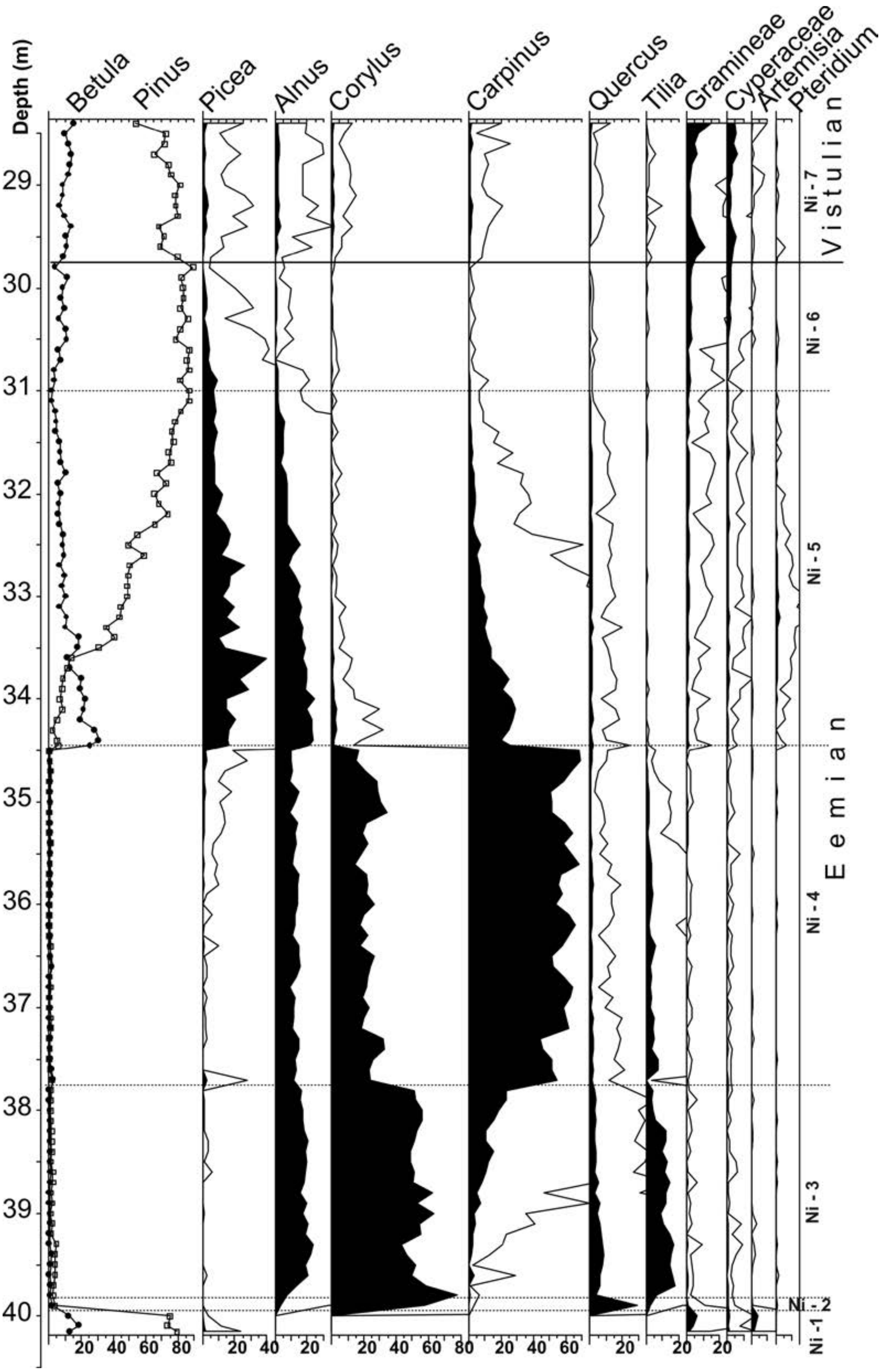

Fig. 4. Simplified pollen diagram from Nidzica site (Eemian) after Bińka *et al.* (2011), modified.

opinion, despite the suitable habitat and climate for bracken, climax woodlands were unfavorable for the establishment of *Pteridium* in any way and it was excluded by competition. Thus, this plant can persist only when natural gaps following disturbances are formed. Natural fires were, in our opinion, the key process allowing the persistence of bracken as a subordinate component in the primeval forest.

Against this, the intervals of higher content of bracken spores are intriguing, especially these at Ossówka, because of their cyclicity, their magnitude and their position in successional stages. Two factors influenced the dynamics of bracken at Ossówka: fires which triggered the initiation of young individuals and their vegetative invasion in the birch zone (the increase of spores in the spectra), and diminishing of competition from the pine forest, which gradually suppressed the expansion of patches and finally eliminated them from communities (the continuous decline of the bracken curve). The experiments mentioned above (Marrs, Hicks 1986; Marrs 1987a, b; Marrs *et al.* 2000; Dolling 1996) show that the elimination of bracken, although difficult, is possible.

Increased fire disturbances may have contributed to higher *Pteridium* abundances, though it is difficult to assess the cause of this fire-regime shift. The analysis of the distribution of lightning-ignited fires in Finland, in areas with modern vegetation similar to that at Ossówka in pollen zones O-3 and O-5, showed that despite strike density that was twice as high in the northern areas than in southern ones, natural fires were registered less often in northern Finland, because of more 'wet' fuel (Larjavaara *et al.* 2005). What is more, in the forest of northern Finland, which serves as an analogue of the birch zone at Ossówka, the frequency and size of the bracken patches clearly decreased and they showed poor sporulation (Oinonnen 1967). This is not the only difference. Oinonen (1967) observed that sporulation was rather rare even in warmer regions of Finland. Hence, it is not excluded that new clones could have been initiated from spores transported by wind from more southern areas. Thus climatic conditions in the birch zone at Ossówka would be different to those in northern Finland. At this site, the only forcing mechanism seems to have been extreme strikes and the presence of larch, a genus underestimated in the pollen rain as a potential source of fuel. Extreme strikes and intense forest fires, limited to temporal and territorial scope were noted, e.g. in northern Finland during the season 1924–1927 (Larjavaara *et al.* 2005). They caused a six times greater increase in wildfires than in later periods. This time span is too short to explain the long lasting presence of bracken at Ossówka.

A close analogue to the hypothesized scenario at Ossówka would be the distribution of lightning strikes at interior Alaska in the boundary between the boreal zone and the tundra (Dissing, Verbyla 2003), where wildfires affect the large forested areas (Wendler *et al.* 2010). Here the highest lightning strike densities fall within a 10–25 km zone of boreal forest close to the open vegetation in this area. Decidedly lower lightning frequencies are observed in the tundra or in the transitional zone of shrub vegetation. However, also in this case most of the strikes have taken place in the narrow tree-less zone adjacent to the boreal forest. It is interesting that with the progression from a maritime to a continental climate the number of strikes is markedly higher in the forested areas and low and stable in the tundra zone. The range of mean temperatures for Alaska interior including boreal forest, the area investigated by Dissing and Verbyla (2003), varies from about –14°C in the coldest month to about 13°C in the warmest one in maritime regions (e.g. at Bethel), and from –20°C to –24°C and about 16°C respectively in the western areas with a more continental climate (Shulski, Wendler 2007).

On the basis of our pollen and spore evidence, especially *Larix*, we thus hypothesize that climatic conditions at Ossówka were continental with extreme seasonal variation and dry summers. Besides promoting the availability of dry fuels this situation may have contributed to more lightning, inducing more fires during the initial stages of the two Saalian interstadials (pollen zones O-3 and O-5).

Some similarity to these extreme events can be seen in the high level of charcoals reported from the Late Glacial. In the Netherlands charcoals or even charred pine trunks, commonly found at the top of Allerød soils (Usselo layer), are linked with the access to the large masses of dry, dead wood from the Allerød age, which resulted from Younger Dryas cooling (Hammen and Geel 2008) and natural fires. In Poland, abundant charcoals were found in the same position, e.g. in Wolin Island. At this site, however, the activity of the Late Paleolithic man might have contributed to such an increase in the charcoal influx (Latałowa and Borówka 2006). In North America similar charcoal peaks in the sequences at the onset of the Younger Dryas are associated with a hypothesized comet impact and as a consequence of the extinction of the Pleistocene megafauna (Firestone *et al.* 2007). Close inspection of many sites by Marlon *et al.* (2009) showed that throughout the Late Glacial an increase in fire activity is commonly registered in North America but large-scale fire events rather coincided with the rapid climate change, with the exception of the Allerød/Younger Dryas boundary.

We think, that climatic pattern (maitime?) during the abrupt climate change and/or the migration rate of *Pteridium* are the reasons, that wildfire events at the scale observed at Ossówka based on bracken are not registered in Poland during the transition from tree-less phases to boreal forest in the last 500,000 years. In Poland, such transitional vegetation in this time span is noted in the pollen diagrams at least 27 times, based predominantly on the long pollen sequences.

A subsequent more abundant occurrence of *Pteridium* spores is noted in the Holsteinian intra-interglacial cooling, well defined in the sequence at Kaliłów (Bińka and Nitychoruk 1996). However, a higher curve (about 2% in each sample) appeared in the late yew pollen zone, influenced by the maritime climate and continued throughout the whole length of the pine zone, markings the shift towards a more continental climate (Bińka and Nitychoruk 1996). In the last case the dry biomass of the forest floor in the summer would not have been the potential reason for natural fires because spores occurred continuously both in the more 'wet' and the more 'dry' zones. Obviously then, the extreme strikes rather than the coniferous forest were likely to be the main force which influenced the fire regime in this case.

In the Holsteinian the scarce appearance of bracken spores in the *Picea* zone (before the yew phase) is significant, because this means that wild fires do not show a clear preference for such a forest. In the Eemian in turn, an increased frequency of bracken in the spruce zone (e.g. at Nidzica, Fig. 4) is especially interesting because in this interval the vegetative spread of patches of bracken seems to be more difficult. Oinonen (1967) noted, that dense tree stands, particularly spruce are able to weaken and shatter the bracken stands and gradually perhaps to eradicate it completely from the site. In this interval a decrease in summer and winter temperatures as well as an increase in precipitation is hypothesized (Zagwijn 1996; Kühl, Litt 2003). Because natural fires are the product of a few driving forces – fuel moisture in the late spring/summer, lightning density or the type of forest (deciduous and coniferous), therefore the last two forces seem to have been the only features favoring fires in the Eemian *Picea* zone. Also in this case it is worth stressing that despite the high mortality of *Pinus* in patches of bracken (Dolling 1996), the expansion of *Pteridium* was finally suppressed by the pine forest in the sequence from Nidzica. Spruce in turn, seedlings of which can persist under the bracken canopy and later shatter the patches, shows a curve decline during bracken culmination. This depression and sudden peak in *Picea* versus the gradual and quiescent rise in *Pinus* speaks for the view that it was the fires, which caused the result rather the spruce forest. The higher magnitude of lightning strikes in the *Picea* zone, being an effect of weather favoring thunderstorms, seems to have been more broadly distributed geographically, as we can infer from Andersen‘s pollen sequence from Denmark (Björck *et al.* 2000) with similar bracken dynamics to those at Nidzica.

The Eemian oak pollen zone is another interval with a little higher frequency of bracken spores. High summer temperatures and the oak forest accompanied by *Pinus* are surely supporting factors in fire development. In the same vegetation scenario in the oldest interglacial (Ferdynandovian), a similar proportion of bracken spores is noted before the first temperate climatic optimum (Pidek 2003) with the forest resembling Eemian oak-pine vegetation. In the same position within interglacial succession and similar vegetation of pine-oak-larch forest (Krupiński *et al.* 1987) found a very high curve, approximately 10% of bracken. The age of this temperate interval is however problematic.

Judging from the broader geographical range of some bracken phases in the Pleistocene, a natural ignition due to lightning rather than human activity seems to be responsible for fires. The case of post interglacial fire events at Ossówka could be exceptional. The large, deep lakes at this time are rarely noted. They must have been places where numerous animals came from the vicinity looking for food and water.

This, combined with fires, must have attracted Palaeolithic man. It is worth mentioning that at the classical site at Hoxne there is definite evidence that people were present close to the interglacial lake (West and Mc Burney 1954).

There is no doubt, that in light of the Pleistocene records, the mid-Holocene maxima of bracken were due to human activity (burning). This conclusion is based on several grounds:

1 – the maximum spread of bracken, having taken place when the climate became wetter in the so called Atlantic period, an interval of rather fireproof conditions,

2 – the dominance of the deciduous forest at this time which are also fireproof,

3 – the higher frequency of *Pteridium*, which is rare in the Pleistocene interglacial sequences in the studied area, except from some sites analyzed in this work,

4 – the shape of the curves of *Pteridium*, which shows sudden peaks in the Holocene (Madeja *et al.* 2004) against relatively smooth curves in the Pleistocene, e.g. at Ossówka or at Nidzica.

In Poland, the middle Holocene peaks of bracken are commonly related to the Late Mesolithic and the Early Neolithic economy, in which fire was a useful tool for deforestation (Latałowa 1992; Ralska-Jasiewiczowa and van Geel 1998; Madeja *et al.* 2004). From the post Neolithic onwards the continuous increase in herbs, which suggests the presence of open-canopied woodlands or open spaces as a result of forest clearing and clearance for cultivation, generally did not produce an increase in bracken spores. This implies the use of clearing methods other than fire. Where burning was involved the final effect had to result in a greater area occupied by bracken as compared to when only manual clearings were practiced because, apart from re-vegetation from underground rhizomes, new clones were established from germinating spores. This means that even an increasingly open forest since the Neolithic (a continuous increase in light demanding pollen types – Bińka *et al.* 1991), which should have encourage vegetative expansion of this fern, did not restrain the bracken decline when the suitable habitats, rich in ash, decreased. Another possible reason for the decrease in bracken spores might have been cattle grazing in the forest, which in Poland has been common practice as a supplementary activity to farmland grazing even after the Second World War. Thus, trampling impacts and bracken fronds eaten by cattle could have been a means of controlling this plant in the past (Marrs, Watt 2006).

In some areas of Western Europe the above scenario might have been different. Not only this, the scale of the disturbance by hunter-gatherers of the Late Mesolithic in this area to the climax woodlands was, in contrast to Poland, low as it is evidenced by *Pteridium* (Huntley, Birks 1983). In England where bracken, forming dense, long lasting patches, occurs abundantly in many open communities such as grasslands or heaths (Marrs, Watt 2006), the high amount of spores in palynological records from the Neolithic (Huntley and Birks 1983) can be both a result of forest clearing (burning) and/or invasion into newly cleared ground after deforestation. In such open areas the production of spores in non-shaded conditions is high (Dring 1965) and the dispersal range of bracken spores is wider than in woodlands. For these reasons there can be an abundance of airborne spores deposited finally into the lakes.

It is clear, that the distance from the late glacial refugia in southern Europe (Huntley, Birks 1983), the type of burning activity, the terrain morphology or a different pattern of settlement phases are the real reasons, the time span of bracken maxima in sequences from Europe must be more differentiated. For example, in the southern Alps a higher content of *Pteridium* is found around 6000 BP; however it peaks at a later time (Tinner *et al.* 1999; 2000). At a nearby site Lago di Annone (Wick, Möhl 2006) spores were more abundant since 7000 cal BP and in the southern Pre-alps (Lago di Fimon) bracken culminates like in Poland (Valsecchi *et al.* 2008).

In the Holocene, bracken spores were sometimes accompanied by charcoals. In Germany, according to Kalisa *et al.* (2003) just after the Atlantic period, pronounced peaks of charcoal were noted despite the establishment of fireproof deciduous forest at that time. The observation of Tinner *et al.* (1999, 2000) as well as other reports (Bos, Urz 2003) prove that the presence of *Pteridium* and charcoal may show a positive correlation, a phenomenon observed by Odgaard (1992) in the case of *Calluna*, where a higher abundance of pollen largely depends on fire, but where the heathland is formed only. Because the transport and deposition of charcoal particles is a more complex process (Condera *et al.* 2009) such a coincidence of charcoal and bracken spores has not always been documented. In southern Sweden, the fire regime in the Holocene which was identified using a charcoal method (Greisman and Gaillard 2009; Olsson *et al.* 2010), is partly coincident with the one in Poland based on bracken. However, in Sweden *Pteridium* is almost absent in phases of high fire activity with the exception of one sample with an unusual frequency of spores, suggesting the location of plants just near a peat bog.

It is interesting that some workers reconstructing the Holocene fire regime see climate as a primary force. According to Olsson *et al.* (2010) peaks of charcoal recorded on sites in southern Sweden were controlled by the climate (warmer and drier phases) of the early/middle Holocene rather than by human induction. Others, e.g. Huntley and Birks (1983) as well as Tinner *et al.* (1999, 2000), consider the combined effects of human activity and climate as the triggering factors for Holocene fires, based on bracken occurrences.

In Poland records for bracken from the Pleistocene and Holocene clearly show that during the latter forest fires may be strongly considered due to burning by humans. In more western areas other forestry practices and the expansion of bracken into open grounds would be partly responsible for bracken culmination (Pakeman 2000; Huntley, Birks 1983), which is, in our opinion an effect of different climatic-floristic conditions.

FINAL CONCLUSION

Analysis of the Quaternary occurrence of *Pteridium* spores in lacustrine sequences seems to point to a different scenario to explain the expansion and decline of this plant in the forested areas of the Pleistocene and the Holocene. Generally, the sporadic appearance of bracken spores throughout the interglacial – interstadial sequences under the temperate and boreal climates as well as in the Early Holocene is typical for most sites in Poland. In the Pleistocene the periods of a higher (or high) proportion of *Pteridium* spores in the interglacial/interstadial phases – sometimes with a broader geographical range – are rather limited to intervals with a higher content of conifers. Fires were initiated by natural ignition due to lightning strikes during thunderstorms under a specific climate, probably with a continental signature, with seasonal variations and dry summers. If this triggering mecha-n ism, which generates new patches, was to disappear, the bracken stage, being a transitional successional stage would finally be eliminated from vegetation. In the mid-Holocene in turn, the culmination of bracken shows that it peaked in conjunction with woodland clearance by burning and not in conjunction with favorable climatic conditions. Therefore, human activity was the main force behind the higher occurrence of *Pteridium* at that time.

Acknowledgment

This research was funded by Ministry of Science and Higher Education grant No. N 307 508438 in 2010–2013.

REFERENCES:

Bałaga K. 1982. Vegetational history of the lake Łukcze environment (Lublin Polesie, E. Poland) during the Late-Glacial and Holocene. Acta Palaeobot. 22/1, 7–22.

Bińka K., Cieśla A., Łącka B., Madeyska T., Marciniak B., Szeroczyńska K., Więckowski K. 1991. The Development of Błędowo Lake (Central Poland) – a palaeoecological study. Stud. Geol. Pol . 100, 1–83.

Bińka K., Nitychoruk J. 2001. Late Saalian climate changes in Europe in the light of pollen analysis and the problem of two-step deglaciation at the oxygen isotope stage 6/5e transition. Boreas 30, 307–316.

Bińka K., Nitychoruk J. 2003. The Late Saalian, Eemian and Early Vistulian pollen sequence at Dziewule, eastern Poland. Geol Quart 47/2, 155–168.

Bińka K., Lindner L., Nitychoruk J. 1997. Geologic-floristic setting of the Mazovian Interglacial sites in Wilczyn and Lipnica in southern Podlasie (eastern Poland) and their palaeogeographic connections. Geol. Quart. 41/3, 381–394.

Bińka K., Nitychoruk J. 1996. Geological and palaeobotanical setting of interglacial sediments at the Kaliłów site in southern Podlasie. Geol. Quart. 40/2, 269–282.

Bińka K., Nitychoruk J. 1995. Mazovian (Holsteinian) lake sediments at Woskrzenice near Biała Podlaska. Geol. Quart. 39/1, 109–120.

Bińka K., Nitychoruk J., Dzierżek J. 2011. Climate stability during the Eemian – new pollen evidence from the Nidzica site, northern Poland. Boreas 40/2, 342–350.

Bińka K., Nitychoruk, J. 2011. Cyclicity in the Eemian climate? A case study of the Eemian site 3 at Czaple, Eastern Poland. Rev. Palynol. Palaeobot. 164/1–2, 39–44.

Björck S., Noe-Nygaar N., Wolin J., Houmark-Nielsen M., Jürgen Hansen H., Snowball I. 2000. Eemian Lake development, hydrology and climate: a multistratigraphic study of the Hollerup site in Denmark. Quat. Sci. Rev. 19, 509–536.

Bos J.A.A., Urz R. 2003. Late Glacial and early Holocene environment in the middle Lahn river valley (Hessen, central-west Germany) and the local impact of early mesolithic people–pollen and macrofossil evidence. Veget. Hist. Arch. 12, 19–36.

Condera M., Tinner W., Neff Ch., Meurer M., Dickens F.A., Krebs P. 2009. Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. Quat. Sci. Rev. 28, 555–576.

Dissing D., Verbyla D.L. 2003. Spatial patterns of lightning strikes in interior Alaska and their relations to elevation and vegetation. Can. J. For. Res. 33/5, 770–782.

Dolling A., 1996. Interference of bracken (*Pteridium aquilinum* L. Kuhn) with Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) seedling establishment. Forest. Ecol. Management 88, 227–235.

Dolling A. 1999. The vegetative spread of *Pteridium aquilinum* in a hemiboreal forest – invasion or revegetation? Forest. Ecol. Management 124/2–3, 177–184.

Firestone R.B., West A., Kennett J.P., Becker L., Bunch T.E., Revay Z.S., Schultz P.H., Belgya T., Kennett D.J., Erlandson J.M., Dickenson O.J., Goodyear A.C., Harris R.S., Howard G.A., Kloostermanm J.B., Lechler P., Mayewski P.A., Montgomery J., Poreda R., Darrah T., Que Hee S.S., Smith A.R., Stich A., Topping W., Wittke J.H., Wolbach W.S. 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. PNAS 104, 16016–16021.

Granoszewski W. 2003. Late Pleistocene vegetation history and climatic changes at Horoszki Duże, eastern Poland: a palaeobotanical study. Acta Paleobot. suppl. 4, 1 –95.

Greisman A., Gaillard M.J. 2009. The role of climate variability and fire in early and mid-Holocene forest dynamics of southern Sweden. J. Quat. Sci. 24, 593–611.

van der Hammen T., van Geel B. 2008. Geo(Im)pulse. Charcoal in soils of the Allerød–Younger Dryas transition were the result of natural fires and not necessarily the effect of an extra-terrestrial impact. Netherl. J. Geosci. — Geol. en Mijnbouw 87/4, 359 – 361.

Heikkilä M., Seppä H. 2003. A 11,000 yr palaeotemperature reconstruction from the southern boreal zone in Finland. Quat. Sci. Rev. 22, 541–554.

Huntley B., Birks H.J.B. 1983. An Atlas of Past and Present Pollen Maps for Europe: 0–13000 Years Ago. Cambridge University Press, Cambridge, UK.

Hrynowiecka-Czmielewska A. 2010. History of vegetation and climate of the Mazovian (Holsteinian) interglacial and the Liviecian (Saalian) glaciation on the basis of pollen analysis of palaeolake sediments from Nowiny Żukowskie, SE Poland. Acta Palaeobot. 50/1, 17–54.

Kalisa A.J., Merkt J., Wunderlich J. 2003. Environmental changes during the Holocene climatic optimum in central Europe – human impact and natural causes. Quat. Sci. Rev. 22, 33–79.

Krupiński K.M. 1995. Pollen stratigraphy and succession of vegetation during the Mazovian interglacial based on studies of sediments from Podlasie. Acta Geograph. Lodz. 70, 1–200.

Krupiński K.M., Marks L., Szynkiewicz A. 1987. Three New Sites of the Middle Pleistocene Fossil Floras from the Bełchatów Mine, Central Poland. Bull Polish Acad. Sci. Earth Sci. 35/4, 359–377.

Krupiński K.M. 2005. Badania paleobotaniczne młodoplejstoceńskich osadów jeziornych Wysoczyzny Płockiej. Pr. Państw. Inst. Geol. 184, 1–58 (in Polish with English summary).

Kupryjanowicz M. 2008. Vegetation and climate of the Eemian and the early Vistulian lakeland in northern Podlasie. Acta Palaeobot. 48/1, 1–130.

Kühl N., Litt T. 2003. Quantitative time series reconstruction of Eemian temperature at three European sites using pollen data. Veget. Hist. Archaeobot.12, 205–214.

Lacey, M.E., McCartney, H.A., 1994. Measurement of airborne concentrations of spores of bracken (*Pteridium aquilinum*). Grana 33, 91–93.

Latałowa M. 1994. The Mesolithic economy and the beginning of agriculture in the Polish coastal zone in the light of palynological data. Pol. Bot. Stud. Guidebook Series 11, 135–153 (in Polish with English summary).

Latałowa M. 1992. Man and vegetation in the pollen diagrams from Wolin Island (NW Poland). Acta Palaeobot. 32/1, 123–249.

Latałowa M., Borówka M.K. 2006. The Allerød/Younger Dryas transition in Wolin Island, northwest Poland, as reflected by pollen, macrofossils, and chemical content of an organic layer separating two aeolian series. Veget. Hist. Archaeobot. 15, 321–331.

Larjavaara M., Kuuluvainen T., Rita, H. 2005. Spatial distribution of lightning-ignited forest fires in Finland. Forest Ecol. Management 208, 177–188.

McVean D.N. 1958. Island vegetation of some west Highland freshwater lochs. Transactions of the Botanical Society of Edinburgh 37, 200–208.

Madeja J., Bałaga K., Harmata K., Nalepka D. 2004. Pteridium aguilinum (L.) Kuhn -Bracken. In: Ralska-Jasiewiczowa M, Latałowa M, Wasylikowa K, Tobolski K, Madeyska E, Wright HE, Turner Ch (eds) Late Glacial and Holocene history of vegetation in Poland based on isopollen maps. W. Szafer Institute of Botany Academy of Science, Kraków, pp 444.

Mamakowa K. 1989. Late Middle Polish Glaciation, Eemian and Early Vistulian vegetation at Imbramowice near Wrocław and the pollen stratigraphy of this part of the Pleistocene in Poland. Acta Palaeobot. 29/1, 11–179.

Markowski J. 1971. Regeneration of acidophilous forest communities on clearings of the island Wolin and south-eastern Uznam. PTPN, Wydział Matematyczno-Przyrodniczy, Prace Kom. Biol. 35/1, 1–29 (in Polish with English summary).

Marlon J.R., Bartlein P.J., Walsh M.K., Harrison S.P., Brown K.J., Edwards M.E., Higuera P.E., Power M.J., Anderson R.S., Briles C., Brunelle A., Carcaillet C., Danielsk M., Hu F.S., Lavoie M., Long C., Minckley T., Richard P.J.H., Scott A.C., Shafer D.S., Tinner W., Umbanhowar C.E., Jr, Whitlock C. 2009. Wildfire responses to abrupt climate change in North America. PNAS 106/8, 2519–2524.

Marrs R.H. 1987a. Studies on the conservation of lowland Calluna heaths. I. Control of birch and bracken and its effects on heath vegetation. J. Applied. Ecol. 24, 163–175.

Marrs R.H. 1987b. Studies on the conservation of lowland Calluna heaths. II. Regeneration of Calluna, and its relation to bracken. J. Applied. Ecol. 24, 177–189.

Marrs, R.H., Hicks, M.J., 1986. Study of vegetation change at Lakenheath Warren: a reexamination of A. S. Watt‘s theories of bracken dynamics in relation to succession and vegetation management. J. Applied. Ecol. 23, 1029–1040.

Marrs R.H., Watt A.S. 2006. Biological Flora of the British Isles: *Pteridium aquilinum* (L.) Kuhn. J. Ecol. 94, 1272–1321.

Marrs R.H., Le Duc M.G., Mitchell R.J., Goddard D., Paterson S., Pakeman R.J., 2000. The Ecology of Bracken: Its Role in Succession and Implications for Control. Annals of Bot. 85, 3–15 (Suppl B).

Miotk-Szpiganowicz G. 1992. The history of the vegetation of Bory Tucholoskie and the role of man in the light of palynological investigations. Acta Palaeobot. 32, 39–122.

Nita M. 2009. Stratygrafia pyłkowa i historia roślinności interglacjału mazowieckiego i starszej części zlodowacenia liwca w zachodniej i środkowej części Wyżyn. Prace Naukowe Uniwersytetu Śląskiego (in Polish with English summary).

Nitychoruk J., Bińka K., Ruppert H., Schneider J. 2006. Holsteinian Interglacial = Marine Isotope Stage 11? Quat. Sci. Rev. 25/21–22, 2678–2681.

Noryśkiewicz B. 1982. Lake Steklin a reference site for the Dobrzyń-Chełmno Lake District, N. Poland, Report on palaeoecological studies for the IGCP – Project No.158 B, Acta Palaeobot XXII/1, 65–83.

Oberdorfer E. 1990. Pflanzensoziologische Exkursionflora. Verlag Euglen Ulmer-Stuttgart.

Odgaard B.V. 1992. The fire history of Danish heathland areas as reflected by pollen and charred particles in lake sediments. The Holocene 2/3, 218–226.

Oinonen E. 1967. Sporal regeneration of bracken (*Pteridium aquilinum* (L.) Kuhn.) in Finland in the light of the dimensions and the age of its clones. Acta For. Fenn. 83/1, 1–96.

Ojala A.E.K., Alenius T. 2005. 10 000 years of interannual sedimentation recorded in the Lake Nautajärvi (Finland) clastic–organic varves. Palaeogeography, Palaeoclimat., Palaeoecol. 219/3–4, 285–302.

Olsson F., Gaillard M-J., Lemdahl G., Greisman A., Lanos P., Marguerie D., Marcoux N., Skoglund P., Wäglind J. 2010. A continuous record of fire covering the last 10,500 calendar years from southern Sweden — The role of climate and human activities. Palaeogeography, Palaeoclimat. Palaeoecol. 291, 128–141.

Page C.N., 1986. The strategies of bracken as a permanent ecological opportunist. In Smith R.T., Taylor J.A., (eds.). Bracken: ecology, land use and control technology. Leeds, pp 173–181.

Pakeman R.J., Le G., Duc M., Marrs R.H. 2000. Bracken Distribution in Great Britain: Strategies for its Control and the Sustain-

able Management of Marginal Land. Annals of Bot. 85, 37–46 (Suppl B).
Pawlikowski M., Ralska-Jasiewiczowa M., Schönborn W., Stupnicka E., Szeroczyńska K. 1982. Woryty near Gietrzwałd, Olsztyn Lake District, NE Poland – vegetational history and lake development during the last 12000 years. Acta Palaeobot. 22/1, 85–116.
Pidek I.A. 2003. Mesopleistocene vegetation history in the northern foreland of the Lublin Upland based on palaeobotanical studies in the profiles from Zdany and Brus sites. Wydawnictwo Uniw. M. Curie-Skłodowskiej.
Ralska-Jasiewiczowa M., Goslar T., Madeyska T., Starkel L. 1998. Lake Gościąż, Central Poland. A monographic study. W. Szafer Institute of Botany, Polish Academy of Sciences, pp 340.
Shulski M., Wendler G. 2007. Climate of Alaska. University of Alaska Press. Stockmarr J. 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13, 615–621.
Tinner W., Hubschmid P., Wehrli M., Ammann B., Conedera M. 1999. Long-term forest-fire ecology and dynamics in southern Switzerland. J. Ecol. 87, 273–89.
Tinner W., Conedera M., Gobet E., Hubschmid P., Wehrli M., Ammann B. 2000. A palaeoecological attempt to classify fire sensitivity of trees in the southern Alps. The Holocene 10/5, 565–574.
Valsecchi V., Finsinger W., Tinner W., Ammann B. 2008. Testing the influence of climate, human impact and fire on the Holocene population expansion of *Fagus sylvatica* in the southern Prealps (Italy). The Holocene 18/4, 603–614.
Wendler G., Conner J., Moore B., Shulski M., Stuefer M. 2010. Climatology of Alaskan wildfires with special emphasis on the extreme year of 2004. Theor. Appl. Climatol. 104/3–4, 459–472.
West R.G., Mc Burney C.M.B. 1954. The Quaternary deposits at Hoxne, Suffolk, and their archaeology. Proc. Prehist. Soc. 20.
Wick L, Möhl A., 2006. The mid-Holocene extinction of silver fir (Abies alba) in the Southern Alps: a consequence of forest fires? Palaeobotanical records and forest simulations. Veget. Hist. Archaeobot. 15, 435–444.
Zagwijn W.H. 1996. An analysis of Eemian climate in western and central Europe. Quat. Sci. Rev. 15, 451–469.