Late Saalian and Eemian Interglacial at the Struga site (Garwolin Plain, central Poland)

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ABSTRACT. The paper reports pollen analyses of 47 samples from palaeolake sediments at WH-15 Struga near Puznówka on the Garwolin Plain in central Poland. The pollen succession covers Late Saalian (MIS-6) and fully developed Eemian (MIS-5e) successions. The Late Saalian section is well developed (more than 2 m thick) and contains sub-zones reflecting the alternating dominance of steppe-tundra and boreal forest communities. The analysed Eemian succession is an uncommon succession described as a variant with early appearance and culmination of *Tilia*. In these terms, the successions of WH-15 Struga resemble those of sites of the Eemian interglacial known from the vicinity of Warsaw: Błonie, Warszawa-Żoliborz and Warszawa-Wola. The WH-15 Struga site is one of several recently discovered fossil sites of Eemian lakes on the Garwolin Plain, constituting the southern fragment of the extensive Eemian lakeland in the Polish Lowland.

KEYWORDS: Pleistocene, Eemian interglacial, MIS-5e, Late Saalian glacial, MIS-6, Garwolin Plain, central Poland

INTRODUCTION

The vast majority of sites with limnic sediments of the Eemian interglacial in Poland occur along a latitudinal belt in the central and eastern parts of the country, between the maximum range of the last phase of the Weichselian glaciation (MIS-2) and the maximum range of the Saalian glaciation (MIS-6) (Bruj & Roman 2007). Sites with limnic sediments occur sporadically outside that belt. They are primarily lakes of post-glacial origin related to melting of blocks of dead ice.

The Garwolin Plain is an area where no palynological investigations have been conducted previously. The study area is in the southern zone of the occurrence of sites with sediments of the Eemian interglacial, constituting only a part of this large lakeland (Żarski 2017, Żarski et al. 2017a, b). During cartographic work performed for updating of the Garwolin sheet of the *Detailed Geological Map of Poland* (*1:50 000 Scale*) (Żarski 2017), numerous sites were identified containing biogenic sediments age-correlated with the Eemian interglacial (Żarski 2017), as indicated by pollen analysis of random samples from several profiles, including the WH-15 Struga profile (Dąbrowska et al. 2017). South of the Garwolin Plain, in a belt of land adjacent to the Vistula River valley, only single sites with sediments of the Eemian interglacial have been documented, including sites in Kletnia Stara near Dęblin (Żarski 1989), Wola Okrzejska near Okrzeja (Żarski et al. 2005), and Kontrowers near Żelechów (Kupryjanowicz et al. 2003).

In 2016, a preliminary geological and geomorphological reconnaissance at WH-15 Struga revealed a thick series of organogenic sediments underlying fluvioglacial sediments. The palynology of 22 random samples of gyttja

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and peat supported the Eemian age of the studied series (Pidek 2016).

The Eemian lakeland in central Poland has been studied by Żarski et al. (2005), Bruj and Roman (2007), Roman (2016) and others in the last decades. Our detailed palynological investigation of the newly discovered Eemian sediments of the WH-15 Struga profile on the Garwolin Plain is offered as a contribution to our knowledge of changes in the palaeoenvironment of that area, including its palaeoclimate.

STUDY AREA AND LITHOLOGY

The WH-15 Struga site is about 1 km north of Puznówka village in the valley of the river of the same name (Struga), at ca 138.5 m a.s.l. (Fig. 1). The valley is a transformed post-glacial channel. In Puznówka village it changes direction from latitudinal to meridional. The valley is incised about a dozen metres. On both sides of the valley floor, river terraces from the period of the Weichselian glaciation are developed. Above them are kame terraces built of silty and fine-grained sands. The terraces are directly adjacent to a plateau built of boulder clay. The WH-15 core was taken in the valley floor and reached 20 m. The limnic sediment series was drilled at depths in the 2.5–14 m range. The 14–7.4 m depth range contains fine-grained sands and glaciolacustrine muds of the Saalian glaciation deposited in a periodic through-flow waterbody. Boulder clays of the Saalian glaciation occur at 17.4–20 m depth.

The limnic series begins with non-calcareous grey gyttja 2.1 m thick, transitioning to calcareous olive green and dark green gyttja 1.5 m thick. The formations accumulated in a lake at the end of the Saalian glaciation. At ca 10.5 m depth a boundary is observed on the lithology core between the late glacial and Eemian interglacial. Calcareous gyttja continues from 10.5 m to 3.95 m depth. Admixtures of multi-grained sands occur at depths of 9.70–9.50 m and 5.30–4.80 m. The sequence of Eemian limnic sediments ends with peat 1.45 m thick (3.95–2.50 m). Formations of the Eemian interglacial are covered by fluvial sands with gravel of the Weichselian glaciation (2.50–0.3 m) underlying Holocene humic sands.
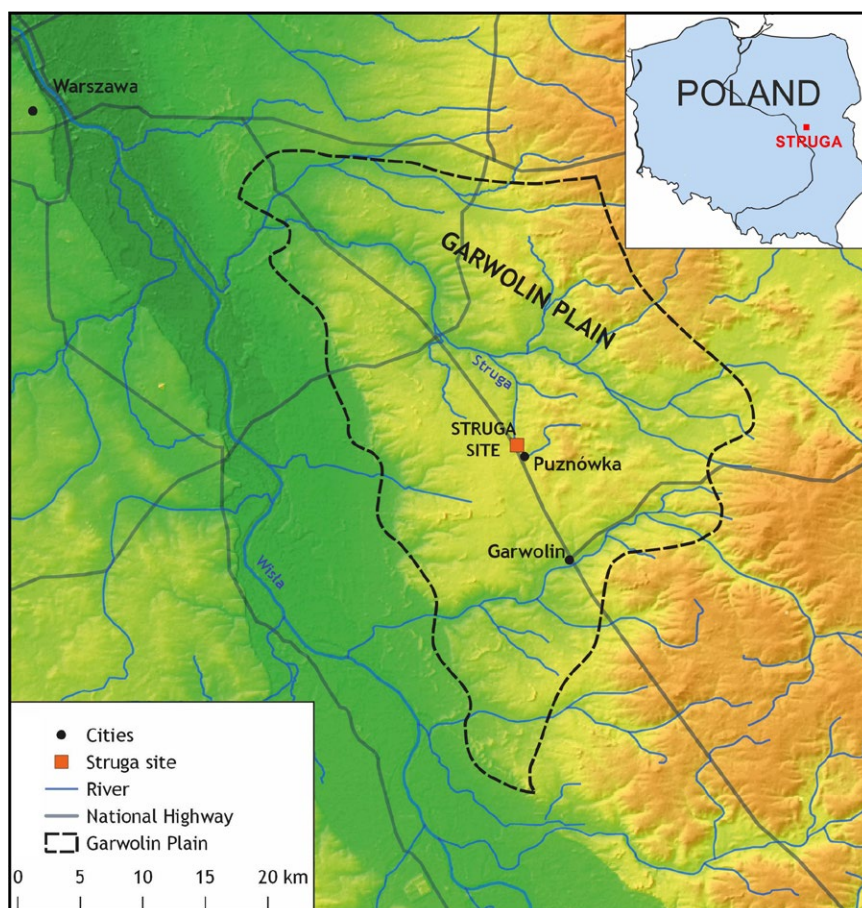

Fig. 1. Location of the study site (A. Bober)

STUDY MATERIAL AND METHODS

Material for palynological research was collected from the WH-15 Struga core. The organogenic series is 8.8 m thick (11.5–2.7 m depth). We used 47 samples from the series for palynological analysis.

Laboratory processing of the samples for pollen analysis followed the standard procedure (Berglund & Ralska-Jasiewiczowa 1986). After decalcification in 10% HCl and boiling in 3.5% KOH, the mineral fraction was removed by flotation. The samples were then macerated by Erdtman acetolysis. Pollen spectra were calculated from at least two slides until 700–1000 pollen grains had been analysed. In the late glacial section the very low frequency of sporomorphs made it sometimes necessary to make counts from four slides to reach a minimum 300 pollen grains. The total amount of pollen of trees and shrubs (AP) and dwarf shrubs and herbaceous terrestrial plants (NAP) was taken as 100%. The percentage shares of pollen of aquatic plants, spores, redeposited sporomorphs and colonies of algae of the genera *Pediastrum* and *Botryococcus* were calculated versus the adopted standard (total AP and NAP) but with the given taxon added before calculating its share.

The results of palynological analyses are presented in Table 1 and in a pollen diagram (Fig. 2) plotted using POLPAL software (Nalepka & Walanus 2003) divided into Local Pollen Assemblage Zones (L PAZ), which were assigned to Regional Pollen Assemblage Zones (R PAZ according to Mamakowa 1989).

STUDY RESULTS

Table 1 and the pollen diagram of the WH-15 Struga profile (Fig. 2) show that the organogenic series covers local pollen assemblage zones from St-1 to St-8 L PAZ. Zone St-1 L PAZ is characterized by low frequency and poor preservation of sporomorphs. Herbaceous plants (NAP) and *Pinus sylvestris* t. reach their highest shares. NAP are dominated by Cyperaceae, *Artemisia* and Chenopodiaceae. The pollen spectra show dominance of steppe-tundra assemblages. The high *Pinus sylvestris* t. pollen values are probably related to long-range transport. Some of the birch pollen grains (*Betula*) showed features of *Betula nana* t. pollen, suggesting the occurrence of shrub tundra assemblages on the landscape. The open character of the landscape is also suggested by *Juniperus* and *Ephedra* as well as *Hippophaë* and *Selaginella selaginoides*. Such a pollen spectrum composition suggests that the lake began to develop in the glacial environment before the Eemian interglacial. The occurrence of *Ceratophyllum* hair-like leaves in the upper part of St-1 L PAZ testifies to the presence of *Ceratophyllum* species in the water.

Further samples from the St-2 L PAZ and St-3 L PAZ show expansion of *Betula* and *Pinus sylvestris* t. and the decline of NAP, reflecting the development of boreal forests, initially birch and then pine-birch. Together, the continuous presence of *Ulmus* pollen and appearance of *Quercus* pollen point to the beginning of the development of riverine forests as a result of progressive warming. Together with elm, the oak *Quercus robur*, a tree preferring wet habitats more than *Quercus sessilis* does, was probably part of the composition of the developing riparian forests. Granoszewski (2003) made such a suggestion in interpreting the pollen diagram of the Horoszki Duże site.

Very high shares of *Quercus* pollen (probably two species of oak) in the St-4 L PAZ suggest the expansion of oak in different habitats. With pine it could develop mixed pine-oak communities, with elm it could develop riparian forests, and with hazel, ash and lime it could form mixed deciduous communities. The high content of *Quercus* pollen is accompanied by indicators of warm and humid climate (e.g. *Hedera helix* and *Buxus*), the continuous curve of *Humulus*, and continuous curves of the shares of *Fraxinus*, *Corylus* and *Alnus*. Riparian and mixed deciduous communities may also have included *Acer*. Its pollen grains occur in this zone. *Ceratophyllum* sp. and *Nuphar* sp. were present in the lake at that time, while the surrounding reedswamp vegetation was composed of *Typha latifolia* and *Phragmites australis*. *Equisetum* spores and pollen of several herbs typical of wetter communities (*Thalictrum*, *Mentha* t.) confirm their presence close to the lake shores.

In the samples from the St-5 L PAZ the share of *Corylus* rises considerably and reaches its culmination (81.5%). Its sharp increase is accompanied by a very rapid decrease of the *Betula* pollen curve. Those high values strongly suggest the dominance of hazel in different habitats. Granoszewski (2003) suggests that probably it was only an admixture in oak forests with lime, ash and maple, but also developed patches of warm hazel thickets following the type of modern *Peucedano cervariae – Coryletum* thickets (Matuszkiewicz 2000). Increasing values of *Alnus* pollen suggest the expansion of alder forest to humid areas, where it could form alder-ash riparian forests, and also alder carrs in poorer habitats and closed-drainage depressions. A decrease in the share of oak in the zone and an increase

Table 1. Characteristics of the local pollen assemblage zones (LPAZs) in the WH-15 Struga profile near Puznówka

L PAZ number	L PAZ name	Sample section	Description
St-8	*Pinus*	270–410 cm	*Pinus* and *Betula* values continue to increase, up to 85.5% and 20.5% respectively. *Alnus* values fall to 1%. *Picea* decreases sharply and then continues at ca 1–2%. Very significant decrease of curves of *Ulmus*, *Quercus*, *Corylus*, *Carpinus*, *Abies* and *Tilia*. NAP increases again: *Artemisia* to 2.5%, Poaceae to 3.5%, Cyperaceae to 2.5%. Continuous curve also characterizes Chenopodiaceae.
St-7	*Picea-Abies-Alnus*	420–490 cm	Increase of *Pinus* to 30% and *Betula* to 6.5% in upper part of zone. Continuous and sharply increasing pollen curve for *Abies*, with maximum of 18%. *Picea* culminates next (maximum of 30%), with *Alnus* values still high: up to 23% in lower part of zone and 11% in upper part. *Carpinus*, *Corylus*, *Quercus*, *Ulmus* and *Tilia* values fall significantly. Pollen of thermophilous taxa absent.
St-6	*Carpinus-Corylus-Alnus*	520–670 cm	Predominance of *Carpinus* through the whole zone, with maximum of 59% in upper part of zone. *Tilia* values still high (up to 8.5%) in older part of zone, falling to 1.8% in upper samples. *Alnus* 11–16.5%. *Taxus* pollen frequent. Large share of *Quercus* (8%) in the beginning, decreasing in upper part; similar trend for *Corylus*. Continuous curve of *Picea* shows low values. *Pinus*, *Betula* and NAP show the lowest values of the profile.
St-5	*Corylus-Quercus-Tilia*	700–770 cm	Sharp increase and culmination of *Corylus* to 81.5%. Simultaneous decrease in *Quercus* to 4.9%. *Alnus* values increase in upper part of zone to 28%, with simultaneous increase of *Tilia* to 10% and *Carpinus* to 7.5%. Regular presence of *Taxus* pollen grains.
St-4	*Quercus-Fraxinus-Ulmus*	800–870 cm	Sharp increase in *Quercus* pollen to maximum of 59% in uppermost sample of zone. Simultaneous increase in *Ulmus*, reaching maximum of 5% in upper part of zone. Significant fall of Pinus to 18% and *Betula* to 4%. Continuous low curve of *Corylus* increases rapidly to 9–14% in upper part of zone. Low percentages of *Alnus* pollen. Occurrence of *Tilia* pollen and sporadic pollen grains of *Carpinus*, *Hedera helix*, *Acer* and *Humulus*.
St-3	*Pinus-Betula-Ulmus*	880–940 cm	Constant predominance of *Pinus* and *Betula* and increase of *Ulmus* to 2.5% and *Quercus* to 4.9%. NAP values still declining.
St-2	*Pinus-Betula*	970–1040 cm	Increase of *Pinus* and *Betula* to 58–59%, with simultaneous decrease of NAP in upper part of zone to Cyperaceae 0.8%, *Artemisia* 1.0%, Poaceae 2.4%. Continuous curves of *Ulmus*, *Quercus* begins. Sporadic pollen of *Picea*. Pre-Quaternary taxa absent.
St-1	Cyperaceae-Poaceae-*Artemisia*	1080–1150 cm	Low frequency and rather poor presevation of sporomorphs. High NAP values, mainly Cyperaceae (up to 58.5%), *Artemisia* (up to 3.5%). Maximum of *Salix* (3.5%). Continuous curve of *Juniperus*. Presence of *Hippophaë* and *Ephedra fragilis* t. as well as pre-Quaternary rebedded pollen. Probably also pollen grains of thermophilous taxa such as *Carpinus*, *Corylus* and *Quercus* are rebedded. Numerous pollen grains indeterminable due to destruction.

in the share of lime, as well as the beginning of the continuous curve of *Carpinus*, suggests the transformation of mixed deciduous assemblages dominated by lime and hornbeam. Pollen grains of *Taxus*, associated with warm climate with oceanic features, also occur. Its appearance, together with high shares of alder and the presence of *Hedera helix*, *Ilex* and *Buxus*, strongly suggests humidification of the climate. *Taxus* could enter more humid assemblages such as alder forest, especially since it is a shade-tolerant tree (Zarzycki et al. 2002) and can occur as a tree of the lower layer, for example under tree crowns of alder forest. At the same time, NAP reaches minimum values in this zone. This suggests that all the available habitats were occupied by forest communities of various types.

The St-6 L PAZ is dominated by *Carpinus*. Its culmination (>59%) is accompanied by a sharp decrease in *Corylus* and a considerable decrease in *Tilia* and *Quercus*. Such changes suggest the development of mixed deciduous forests dominated by hornbeam, with a slight admixture of other trees. This community may have resembled modern Tilio-Carpinetum. *Acer* also appeared in these forests, either *Acer platanoides* or *Acer pseudoplatanus* or both. Riparian assemblages were not subject to such radical metamorphoses as mixed deciduous ones were. Ash-elm riparian and alder-ash forests still developed, as well as alder carrs. Yew and maple may have been part of the tree composition of different kinds of more humid forests. The low share of *Picea abies* pollen suggests a slight admixture of spruce, probably in alder forests. In the upper part of the zone, single *Abies* pollen grains also suggest the beginning of the expansion of fir, probably in the same assemblages as spruce. Research on modern pollen

Fig. 2. Percentage pollen diagram of organogenic deposits of the WH-15 Struga profile (pollen analysis by A. Bober & I.A. Pidek)
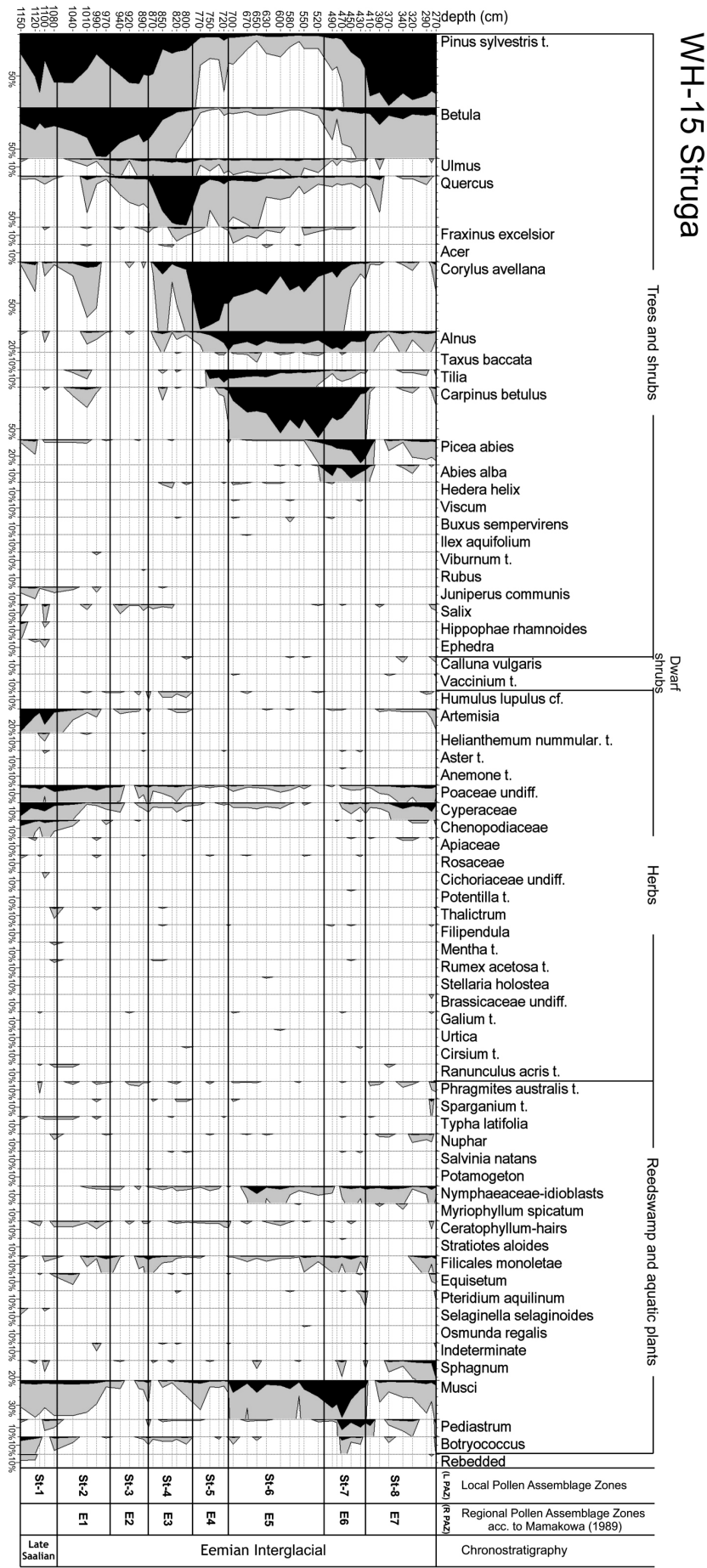
deposition indicates that heavy fir pollen is not spread long-distance in high amounts (Pidek et al. 2013). From this it can be inferred that in the dense tree stands of the climatic optimum of the interglacial, even sporadic *Abies* pollen grains suggest the presence of single fir trees in the tree communities (Pidek et al. 2013). Single pollen grains of plants indicating warm climate with gentle winters occur throughout the St-6 L PAZ: *Viscum*, *Ilex*, *Hedera helix* and *Buxus*. Sporadic pollen of *Nuphar* and reed-swamp plants (*Phragmites australis* t., *Sparganium* t.) may mean that the lake was big and rather deep at that time.

In the St-7 L PAZ the shares of all thermophilic taxa: *Carpinus betulus*, *Tilia*, *Quercus*, *Fraxinus excelsior*, *Ulmus*, *Corylus avellana*, *Acer*, *Hedera helix*, *Buxus sempervirens*, and *Ilex* pollen all decline. The shares of *Picea*, *Abies* and *Pinus sylvestris* t. pollen increase significantly. The shares of *Alnus* are somewhat higher than in the St-6 L PAZ. *Salix* pollen grains begin to appear sporadically. In the upper part of the zone, pollen of herbaceous plants, particularly Cyperaceae and Poaceae, is more frequent. In humid habitats there were fir and spruce assemblages, probably natural succession stages overgrowing alder forests. In poorer sandy habitats, pine forests returned. Two sub-zones can be distinguished in the pollen zone: lower, with culmination of *Abies*; and upper, with culmination of *Picea*. Such changes probably occurred as a result of climate cooling. In the middle part the zone, *Viscum* pollen occurs together with the fir culmination. This semi-parasite of different deciduous trees does not develop when the coldest-month mean temperature falls below −1.5°C (Iversen 1944). The upper sample of the zone shows a very significant decrease in fir and alder, a rapid increase in spruce and pine, a slight increase in birch, and the absence of indicators of warmer climate, suggesting a period of considerable cooling in which boreal trees (pine, spruce, birch) found conditions favouring their development. Spruce could then grow in habitats previously occupied by alder forests and fir assemblages. The increase in Musci spores may be partly related to the rich moss layer in these wet forests. The lake was probably more eutrophic, as evidenced by the presence of microsporangium tissue of *Salvinia natans*, a water fern overgrowing the surface of eutrophic waterbodies (Święta-Musznicka et al. 2011). The increasing

values of *Pediastrum* colonies, among which *Pediastrum simplex* var. *clathratum* occurs, have same ecological significance. Komárek & Jankovská (2001) relate this species with eutrophic reservoirs with neutral to alkaline water.

In the St-8 L PAZ, *Pinus sylvestris* t. pollen is largely predominant. The composition of the pollen spectrum reflects broad expansion of boreal pine forests with a slight admixture of birch, spruce and alder in humid habitats. Towards the top of the zone is seen a gradual increase of open areas overgrown with herbaceous plants. The sporadic pollen grains of thermophilic trees (*Tilia*, *Quercus*, *Carpinus*) probably were redeposited from older periods. The two uppermost samples with a still-high share of *Pinus sylvestris* t. are characterized by an increase in the amount of herbaceous plant pollen, suggesting further expansion of open areas on the landscape.

DISCUSSION

The presented vegetation succession is typical of the end phase of the Saalian (Warthe) glacial and Eemian interglacial. The zones of the interglacial seem complete; that is, they contain regional pollen zones from E1 to E7 (Mamakowa 1989). Our determination of the age of the analysed sediments is based on diagnostic features for the Eemian succession provided by Mamakowa (1989) and by Janczyk-Kopikowa (1974). Also used were correlations with the Eemian succession reconstructed based on high-resolution studies from eastern Poland (Granoszewski 2003, Kupryjanowicz 2008).

The St-1 L PAZ corresponds with the zone called LG MPG *Cyperaceae-Artemisia-Betula nana* R PAZ (Mamakowa 1989). Due to the relatively long distances between the palynological samples in the lower section of the WH-15 Struga profile, it is difficult to unambiguously determine the occurrence of a zone there that can be correlated with another late glacial zone (i.e. *Hippophaë-Betula* or NAP-*Hippophaë-Juniperus*), characterizing the late glacial section of the diagram from Warszawa-Wawrzyszew (Krupiński & Morawski 1993). The last diagram represents another late glacial succession variant (Mamakowa 1989). It was considered typical of the central Poland pattern of vegetation development at the decline

of the Saalian ice sheet (Granoszewski et al. 2012), and was compared by the mentioned authors to the late glacial part of the pollen succession of Dziewule (Bińka & Nitychoruk 2001), in which *Hippophaë* taxa do not play a major role. The occurrence of the NAP-*Picea-Pinus* zone, characteristic of profiles from eastern Poland, with a substantial share of spruce (Mamakowa 1989), is also rather improbable. Higher percentages of spruce pollen correspond somewhat with late glacial pollen zones with *Picea obovata*, typical for south-western Belarus and western Russia at the decline of the Pripiatskovo (=Saalian/Warthe) glaciation (Granoszewski et al. 2012). The thick series of sediments of the late glacial of the Saalian glaciation is representative not only for WH-15 Struga but also for the neighbouring Niesadna and Michałówka sites, analysed as part of the work on the Garwolin sheet of the *Detailed Geological Map of Poland* (*1:50 000 Scale*) (Pidek 2016). Further studies of the late glacial series from the Garwolin Plain should produce palaeoenvironmental conclusions regarding the presence or absence of small-scale climate oscillations during this period. According to Turner (2000), however, no such oscillations of the scale of the Younger Dryas preceding the Holocene should be expected.

A broad overview of Eemian pollen successions across temperate areas west and north of the European Plain (Zagwijn 1996, Turner 2000) points to their remarkable consistency,

probably the result of the opening of a seaway from the English Channel to the White Sea through the North Sea and Baltic Sea. These brought a mild, warm oceanic climate from the beginning of the interglacial and promoted rapid succession of the vegetation. Published data from the partially varved cores of Bispingen (Müller 1974), Quakenbrück (Hahne et al. 1994) and Gross Todtshorn (Caspers 1997) made it possible to determine the duration of the whole Eemian interglacial (10 000 to 11 000 years), and Caspers et al. (2002) were able to infer extreme sea level changes and their timing on the North Sea coast. They noted a much faster sea level rise at the beginning of the Eemian interglacial than at the beginning of the Holocene.

The whole Eemian interglacial pollen succession, divided in Poland into seven R PAZs according to Mamakowa (1989), correlates well with the Belarussian division of the same succession by Savchenko and Rylova (2001, cited in Granoszewski et al. 2012). In the latter division, R PAZs are labelled mr (=Muravian interglacial) and numbered from 1 to 9. The number of regional pollen assemblage zones is higher in Belarus than in Poland, due to the distinction of mr4 (*Corylus-Quercus-Tilia*) and mr5 (*Tilia-Corylus-Carpinus*) as separate zones, which have been treated as one zone (E4 R PAZ) in the Polish zonation. Similarly, zones mr 7 and mr 8 correspond to one zone (E6 R PAZ) in the Polish scheme (Tab. 2). The Polish zonation into

Table 2. Correlation of the L PAZs of the WH-15 Struga with R PAZs for Poland (acc. to Mamakowa 1989), Northern Germany (acc. to Turner 2002) and Belarus (acc. to Granoszeski et al. 2012)

Local Pollen Assemblage Zones WH-15 Struga	Regional Pollen Assemblage Zones for Poland acc. Mamakowa (1989)	Regional Pollen Assemblage Zones for Belarus acc. Savchenko, Rylova (2001)	Regional Pollen Assemblage Zone for Northern Germany acc. Turner (2002)	Stage
St-8 *Pinus* 2.70–4.10 m	E7 *Pinus*	mr9 *Pinus*	E6 *Pinus-Picea-Abies*	EEMIAN
St-7 *Picea-Abies-Alnus* 4.20–4.90 m	E6 *Picea-Abies-Alnus*	mr8 *Picea-Pinus*		
		mr7 *Carpinus-Picea*	E5 *Carpinus-Picea*	
St-6 *Carpinus-Corylus-Alnus* 5.20–6.70 m	E5 *Carpinus-Corylus-Alnus*	mr6 *Carpinus-Tilia*		
St-5 *Corylus-Quercus-Tilia* 7.00–7.70 m	E4 *Corylus-Quercus-Tilia*	mr5 *Tilia-Corylus-Carpinus*	E4 *Corylus-Taxus-Tilia*	
		mr4 *Corylus-Quercus-Tilia*		
St-4 *Quercus-Fraxinus-Ulmus* 8.00–8.70 m	E3 *Quercus-Fraxinus-Ulmus*	mr3 *Quercus-Pinus-Corylus*	E3 *Pinus-Quercetum mixtum*	
St-3 *Pinus-Betula-Ulmus* 8.80–9.40 m	E2 *Pinus-Betula-Ulmus*	mr2 *Pinus-Betula-Quercus*		
St-2 *Pinus-Betula* 9.70–10.40 m	E1 *Pinus-Betula*	mr1 *Pinus-Betula-Picea*	E2 *Pinus-Betula*	
St-1 Cyperaceae-Poaceae-*Artemisia* 10.80–11.50 m	Cyperaceae-*Artemisia-Betula nana*	pt-3-f- NAP-*Pinus-Picea obovata*	E1 *Betula-Hippophae-Juniperus*-NAP	LATE SAALIAN

regional PAZs correlates well with the one proposed by Turner (2000) (Tab. 2).

The St-2 and St-3 L PAZs from WH-15 Struga, which represent the protocratic period of the Eemian interglacial, correspond with the regional E1-E2 R PAZ according to Mamakowa (1989) and mr1–mr2 of the Belarussian palynostratigraphic scheme (Granoszewski et al. 2012). The early expansion of elm and oak starting from the St-2 and St-3 L PAZs reflects the influence of oceanic climate.

The pollen spectra of the St-4–St-7 L PAZs particularly show features characteristic of optimum phases of the Eemian succession E3-E6 R PAZ. In the E3 R PAZ, correlated with the St-4 L PAZ, the occurrence of rich mixed deciduous forest is observed, reflected in the pollen diagram in high shares of pollen of *Quercus* (max. 59%), *Ulmus* and *Fraxinus*, as well as the occurrence of *Hedera*. Granoszewski et al. (2012) point to a significant difference between the Polish and Belarussian pollen diagrams in that part of the succession: the absence of *Abies* and *Taxus* in the latter.

The St-5 L PAZ of *Corylus-Quercus-Tilia* is particularly interesting, correlated with the E4 R PAZ with very high culmination of hazel (81.5%) and the almost simultaneous culmination of *Tilia* (10%). The maximum values of lime should be assessed as very high because it is an entomophilous tree not producing high amounts of pollen. Values of ca 10% are considered high for the Polish Eemian sites in this zone, while at the Belarussian sites they reach as much as 55.8% (Granoszewski et al. 2012). Such a pattern of maximum values of the pollen curves of hazel and lime suggests the occurrence of the "early lime" variant within phase E4 in the palynological diagram from WH-15 Struga, similar to sites from the Warsaw vicinity: Warszawa-Błonie in Janczyk-Kopikowa (1974), and Warszawa-Żoliborz and Warszawa-Wola in Raniecka-Bobrowska (1954). As at WH-15 Struga, at many Eemian sites the presence of *Taxus* is recorded in this zone, suggesting the influence of humid oceanic climate (Kupryjanowicz et al. 2017), which situates the WH-15 Struga site in the transitional zone between oceanic and continental climate types further to the east. It should be stressed that *Taxus* is a very important component of Western European pollen diagrams, seen in the names of the pollen zones: for example, *Corylus-Taxus-Tilia* in northern Germany (Turner 2002) and *Corylus-Quercus-Taxus* at Grande Pile in France (de Beaulieu & Reille 1992).

In the E5 R PAZ, correlated with the St-6 L PAZ, the abundant occurrence of pollen of *Carpinus* (more than 59%) and still-high shares of *Tilia* confirm that hornbeam together with lime formed the primary component of the tree stands. Much higher *Carpinus* values appeared in pollen diagrams from eastern Poland (Granoszewski 2003). In Belarus they reach as high as 80% (Granoszewski et al. 2012). A comparison of the pollen shares of *Taxus*, *Tilia* and *Carpinus*, which were among the most important components of Eemian forests during the thermal optimum, leads to some conclusions: high synchronicity of vegetation development, and a sharp decrease of the humidity gradient towards the eastern part of the North European Plains, promoting the spread of lime and hornbeam towards the East, while the occurrence of *Taxus* and *Abies* communities was confined to more western areas.

The pollen diagram from WH-15 Struga has very significant values of *Abies* pollen, preceding the *Picea* ones in the zone St-7 LPAZ. In the pollen diagram from WH-15 Struga, the maximum for *Abies* precedes the *Picea* maximum in the St-7 LPAZ. For Polish Eemian sites it is typical for the silver fir maxima to occur first. According to Granoszewski (2003), the mesotrophic habitats of lime-hornbeam communities are suitable for the spread of fir. Although silver fir is a tree of mountain and upland areas nowadays, in North European lowlands its communities were widespread in the last part of the Eemian climatic optimum. They reach 10% at the Dziewule site (Bińka & Nitychoruk 2001) and 2.5% at Horoszki-Duże. As with *Taxus*, *Abies* is totally absent from the Belarussian sites, while in northern Germany it is a component of the zone labelled *Pinus-Picea-Abies*. These details further support the suggestion of a strong W–E humidity gradient across Europe.

The hornbeam phase of the Eemian interglacial (E5 R PAZ) in many profiles from Poland contains hiatuses and different types of disturbance, linked by Kupryjanowicz (2008) with a substantial drop of the groundwater level, presumably caused by melting of the permafrost to a considerable depth during the optimum of the interglacial. Sites with hiatuses in the hornbeam phase are adjacent to sites without sedimentation breaks. Discussions of such issues based on Eemian profiles from

northern Podlasie region (Kupryjanowicz 2008, Kupryjanowicz et al. 2017) have not resolved which factors caused those palaeohydrological disturbances. Moreover, the disturbances do not occur in all profiles, further complicating the problem. Our present work reveals a long palynological record of the hornbeam phase of WH-15 Struga, with an evident beginning, culmination and end of the phase, and a gradual retreat of hornbeam due to climate cooling, accompanied by the appearance of fir and spruce in the assemblages. The hornbeam phase in the WH-15 Struga profile extends through sediments more than 2.5 m thick. To solve the problem of potential disturbances, a sediment core sampled with a Geoprobe should be analysed, and the palynological data from several Eemian profiles from cores investigated in separate studies should be correlated.

Further palaeobotanical study of the WH-15 Struga profile together with data from other newly discovered Eemian sites on the Garwolin Plain (Niesadna, Michałówka), which have preliminary pollen-based age determinations, will help resolve palaeoecological, palaeoclimatic, and palaeoenvironmental issues regarding the period from the Late Saalian glaciation to the Early Weichselian in central Poland. No significant climatic cooling has been recorded in the St-8 LPAZ from WH-15 Struga so far, but an analysis of the uppermost section of the profile (above 2.70 m) may alter the picture. Cooling in the E7 *Pinus* R PAZ is seen in the Horoszki Duże and Solniki pollen diagrams, and in the Belarussian ones (Granoszewski et al. 2012, Kupryjanowicz 2008). Pollen data from countries to the west of Poland suggest unstable conditions in the late Eemian. For example, annually laminated sediments from the Eifel region and northern Germany point to widespread dust dispersal in Central Europe, called the Late Eemian Aridity Pulse (Seelos & Sirocko 2007).

CONCLUSIONS

The WH-15 Struga site is among several new sites of the Eemian interglacial on the Garwolin Plain, which is the southern part of an extensive Eemian lakeland.

Local pollen assemblage zones (L PAZs) from WH-15 Struga cover the whole Eemian interglacial and part of the Saalian late glacial preceding the interglacial succession. They have been correlated with regional pollen assemblage zones (R PAZ) for the Eemian interglacial E1-E7 analysed by Mamakowa (1989) and related to the division of the Eemian pollen successions from neighbouring countries (Belarus, Germany).

The thick series of the late glacial of the Saalian glaciation is representative of the WH-15 Struga site and also the neighbouring Niesadna and Michałówka sites analysed for the work on the Garwolin sheet for the *Detailed Geological Map of Poland* (*1:50 000 Scale*). In our study of the WH-15 Struga pollen succession we found no evidence of significant climate oscillations on the scale of the Younger Dryas preceding the Holocene.

All the Eemian interglacial R PAZs are represented in the WH-15 Struga pollen diagram, but significant differences in the pollen spectra, such as the early presence of *Taxus* and high *Abies* values, distinguish the WH-15 Struga pollen succession from the Belarussian ones. These features point to more humid climatic conditions in central Poland and situate the WH-15 Struga pollen sequence between western Eemian sites with *Taxus* and *Abies* and Eastern European ones without these components in the pollen spectra.

Since the Eemian organogenic sediments are thick and the palynological material is well preserved, a detailed analysis of the entire series of limnic sediments may help solve some palaeoecological and palaeoclimatic problems related to the end of the optimum of the Eemian interglacial, including hypotheses regarding rapid drying in the hornbeam phase (Kupryjanowicz 2008), labelled E5 R PAZ in the regional pollen stratigraphy for the Eemian interglacial (Mamakowa 1989).

Further palaeobotanical and palaeoclimatic studies should help identify another climate oscillation suggested at the decline of the E5 (*Carpinus-Corylus-Alnus*) R PAZ and/or the decline of the interglacial in the E7 (*Pinus*) R PAZ.

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