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Postglacial vegetation changes of the Wigry National Park on the background of cold climatic oscillations

PhD dissertation

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I. SUMMARY

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Intermittent cold glacials and warm interglacials occurred regularly during the Quaternary period. Each glacial-interglacial cycle was characterised by changes of climate and vegetation (Iversen, 1958). In general, the pattern of environmental changes during each cycle was very similar. Glaciation (the cryocratic stage of the cycle with the lowest temperatures) was followed by the oldest part of the interglacial, when temperatures gradually increased and subsequently soils and pioneering birch and pine forests were formed (the protocratic stage). The middle part of the cycle was the warmest climatic optimum of the cycle (the mezocratic stage). The sequence of occurrence of dominant thermophilic trees during the climatic optimum was characteristic of each cycle. Further, gradual climate cooling took place, accompanied by decreasing soil fertility and impoverishment of vegetation (telocratic stage), progressing until the beginning of the next glacial (cryocratic stage of the next glacial-interglacial cycle).

During the Holocene, which lasted ca. 11550 years, as in all previous interglacials, the pattern of environmental changes was consistent with the above-described one. However, the palaeoecological reconstructions employing increasingly higher-resolution chronostratigraphy carried out in recent decades revealed that the typical interglacial climate changes during the Holocene coincided with quite regular sudden and short (ca. 150-50 years) cooling periods. They form a series of climatic events repeated at every ca. 1470±500 years. These events (Bond cycles) have been investigated in detail in ice cores from Greenland and marine sediments from the North Atlantic. They also affected other parts of the world, which is reflected in the record of vegetational changes in some parts of Europe and fluctuations in water levels in the Central European lakes - a detailed literature review on this issue is provided in articles 2 and 3. These records show that palaeoecologists have still not reached a consensus on the global nature of cold mid-Holocene climatic events and the intensity of their effect on the environment in different regions of the world. Therefore, further palaeoecological studies aimed at clarifying these phenomena are necessary.

Particularly valuable information regarding the impact of sudden climatic events on vegetation are obtained from studies in regions where plants are most sensitive to all

environmental changes, including climate. One of these is north-eastern Poland, located in the transition zone between oceanic and continental climates. Many plant species have their limit of distribution here, which also means the limit of their ecological tolerance. Considering this fact, even minor and short-term climate changes may improve or deteriorate the condition of specimens representing these species and change pollen production, while prolonged cold periods may lead to significant changes in the composition of vegetation due to changes in the size of populations of some species, and may even shift the limits of their distribution range.

The main objective of the palaeoecological research carried out in Wigry National Park, located in north-eastern Poland, was to determine potential records of short mid-Holocene climate oscillations in this region and the impact of these oscillations on the postglacial development of vegetation. Three detailed aims of the study were formulated under the primary aim, and they also corresponded with stages of research: (1) to reconstruct the main stages of vegetational changes in the analysed region; (2) to identify possible disturbances in the interglacial vegetational succession and their climatic reasons through their chronostratigraphic correlation with short-term climate oscillations; (3) to explain whether changes were transient and had no significant impact on the vegetational succession during Holocene, which primarily depended on the main trend in the interglacial climatic pattern, or whether these changes had a significant impact on the succession pattern of Holocene vegetation, initiating or modifying its subsequent stages.

Deposits from three lakes were analysed: Suchar Wielki, Suchar II and Ślepe. The research mainly relied on pollen analysis, which allowed for the reconstruction of changes in terrestrial vegetation around the investigated lakes and in the them. The age of the analysed deposits was determined using radiocarbon dating and palynostratigraphic correlation of obtained pollen profiles with well-dated profiles from Wigry and Szurpiły lakes. Findings from additional palaeoecological analyses, such as cladoceran and diatom analysis conducted by specialists in this discipline, were also used for the interpretation of the obtained pollen data.

Data from the preliminary pollen analysis of sediments from all the investigated lakes are presented in **article no. 1**. They were used for the reconstruction of major stages of vegetational succession in the region of Wigry National Park in the late glacial of the last glaciation (Suchar Wielki) and during the Holocene (all the investigated lakes). The obtained pollen record was used to identify 10 regional pollen zones (R PAZ) characterising these stages. The study revealed that vegetational succession at that time was strongly shaped by the trend in glacial and interglacial climate changes, but some short-term changes in vegetation, potentially caused by cold climate oscillations, were also documented. One of such changes was a sudden short-term expansion of birch in the younger part of the Preboreal period, possibly in response to climate cooling called Preboreal oscillation (PBO; 8th Bond event). The second was a temporary spread of spruce which was marked in the Subboreal period and could be associated with one of the cold climate oscillations of that period.

The reconstruction of the main stages of Holocene vegetational succession in the vicinity of the investigated lakes and identification of Holocene phases characterised by the probable effects of sudden climate cooling on the vegetation of Wigry National Park was followed by a more detailed investigation of changes in vegetation in two of these periods. **Article no. 2** presents a detailed reconstruction of changes in vegetation around and in Suchar Wielki lake during the Preboreal period (ca. 1160-9800 cal. years BP). Pollen analysis for that time documented as many as four short-term (ca. 50-150 years) cold climatic events. The first three were dated at ca. 11300-11150, 11100-11000 and 10900-10850 cal. years BP, and were separated by relatively short (ca. 50-100 years) warmer periods, which documents the significant climate instability of the older part of the Preboreal period. The last registered cooling took place in the younger part of the Preboreal period ca. 10300-10200 cal. years BP, and was preceded by a ca. 300-year-long gradual climate cooling. A series of three cold events recorded in the older part of the Preboreal was correlated with a Bond cycle, when the lowest temperature was dated at 11100 cal. years BP, and cooling registered in the younger part of this period with the Bond cycle was dated at 10300 cal. years BP.

The three early-Preboreal cold events corresponding with event 11.1 ka were reflected in the pollen record as lower pollen concentrations for both three species forming forests at that time, pine and birch, indicating a significantly limited florescence, and pollen production by these trees. During the oldest of these cold events the response of birch to cooling was less pronounced that of pine, which, in diagrams with pollen percentage, was manifested by the decreased share of *Pinus* pollen and peak value for *Betula* pollen. On the other hand, during both younger cold events, the response of pine and birch, reflected in limited pollen production due to climate deterioration, was very similar, which may suggest that the temperature drop was less marked at that time than during the oldest cooling. The composition of birch and pine forests probably did not change in any of the early-Preboreal cold events, which only caused changes in the intensity of pollen production by trees forming forests.

Late-Preboreal cooling correlated with event 10.3 ka in the area of Wigry National Park was associated with reduced climate humidity. During this cold event a short-term spread of birch range in the studied area probably took place. This is supported by the fact that pollen concentration for this taxon increased, as well as its percentage share.

The comparison of obtained palynological and palaeoecological records for different parts of Europe has led to the conclusion that changes in flora and fauna described for the Preboreal periods probably occurred in response to a sequence of cold events that had different effects on the natural environment, and thus the response was different across the European continent.

Article no. 3 presents a detailed reconstruction of changes in vegetation cover around and in Suchar Wielki and Suchar II lakes during the Atlantic period (ca. 9200-5750 cal. years BP). The reconstructed changes in vegetation pointed to five cold events during that time, dated at ca. 9050-8950, 8700-7800, 7600-7250, 7100-6600 and 6050-5900 cal. years BP. The most important was the second cold event, chronostratigraphically corresponding with oscillation 8.2 ka (5th Bond cycle).

It was demonstrated in this paper that cooling correlated with event 8.2 ka, and in the investigated area it could have lasted even ca. 900 years. During that period a temporary remodelling of forests probably took place, associated with changes in the share of individual forest-forming tree species. It was documented that hazel was the most sensitive to climatic oscillations considering all trees and shrubs forming forest community in the investigated area. In the pollen record this was reflected in a significant drop in hazel pollen concentrations, which, among other things, corresponded with a reduced percentage share of hazel, and could also result from the limited area of hazel during cold event 8.2 ka.

Other Atlantic coolings probably lasted for only several to several dozen seasons, with longer and colder winters, and affected only the intensity of pollen production by plants, particularly thermophilic ones. This suggests that all these climate changes had a much weaker effect on the local environment than the cooling at 8.2 ka. Nevertheless, the results of palynological studies confirmed the occurrence of a series of cold events that were also reported for other regions of Europe.

In conclusion, the high-resolution reconstruction of the postglacial vegetation development in the Wigry National Park area and the parallel changes in the aquatic environment of the studied lakes have provided new and important information on the effects of short-term, cold, mid-Holocene climate oscillations on the pattern of vegetational succession during the Holocene. The response of vegetation in Wigry National Park to climate cooling, i.e. Bond cycles, was documented. Thus, new data on the global nature of these climate oscillations has been provided. It has been shown that only coolings dated at ca.

10.3 ka and 8.2 ka could have caused a temporary remodelling of vegetation in the investigated area, while other cold events caused only periodic reduction in pollen production by trees and shrubs. This clearly shows that the cold events had no significant effect on the pattern of vegetational succession. Nevertheless, the reported cold events are important for the chronostratigraphic correlation of various records of environmental changes that took place in Europe. In addition, the obtained results helped identify climate changes of variable impact on the natural environment, indicating the complexity of correlations between climate and vegetation, and emphasizing the role of differences in the response of individual tree species, e.g. birch and hazel, during particular stages of the Holocene.

II. STRESZCZENIE

Postglacjalne zmiany roślinności Wigierskiego Parku Narodowego na tle chłodnych oscylacji klimatycznych

Magdalena Fiłoc

W czwartorzędzie regularnie przeplatały się z sobą okresy zimne zwane glacjałami i okresy ciepłe zwane interglacjałami. Każda jednostka złożona z glacjału i następującego po nim interglacjału określana jest jako cykl klimatyczno-roślinny (Iversen, 1958). Przebieg zmian środowiska zachodzących w czasie każdego takiego cyklu był generalnie bardzo podobny. Po zlodowaceniu (stadium kriokratyczne cyklu z przypadającą tu kulminacją zimna), w najstarszej części interglacjału następowała stopniowa poprawa warunków termicznych, pociągająca za sobą rozwój gleb i pionierskich lasów brzozowo-sosnowych (stadium protokratyczne). W środkowej części cyklu dochodziło do kulminacji ocieplenia, czyli optimum klimatycznego cyklu (stadium mezokratyczne). Kolejność pojawiania się drzew termofilnych dominujących podczas optimum klimatycznego była cechą charakterystyczną każdego cyklu. Potem następowało stopniowe ochładzanie się klimatu, któremu towarzyszyło ubożenie gleb i roślinności (stadium telokratyczne), postępujące aż do początku kolejnego glacjału (stadium kriokratyczne następnego cyklu klimatyczno-roślinnego).

W trwającym od ok. 11550 lat holocenie, tak jak we wszystkich wcześniejszych interglacjałach, zmiany środowiska przebiegały według opisanego powyżej schematu. Jednak w ostatnich dekadach, dzięki rekonstrukcjom paleoekologicznym o coraz wyższej rozdzielczości chronostratygraficznej, okazało się, że na typowy dla interglacjału trend zmian klimatu holocenu nałożyły się pojawiające się dość regularnie nagłe, krótkotrwałe (ok. 150-50 lat) ochłodzenia. Tworzą one serię epizodów klimatycznych powtarzających się z cyklicznością co ok. 1470±500 lat. Epizody te (tzw. cykle Bonda) zostały szczegółowo rozpoznane w rdzeniach lodowych z Grenlandii i w osadach morskich z północnego Atlantyku. Objęły także inne rejony świata, co zarejestrowano między innymi w zapisie zmian roślinności niektórych częściach Europy i wahań poziomu wód w środkowoeuropejskich jeziorach – szczegółowy przegląd literatury odnoszącej się do tej problematyki przedstawiono w artykułach nr 2 i 3. Wynika z niego, że ciągle jeszcze nie ma wśród paleoekologów zgodności co do globalnego charakteru chłodnych śródholoceńskich

epizodów klimatycznych, a także co do siły ich oddziaływania na środowisko w różnych rejonach świata. Dlatego kolejne badania paleoekologiczne nastawione na wyjaśnienie tych zjawisk są niezbędne.

Do badań nad wpływem nagłych zdarzeń klimatycznych na roślinność szczególnie cenne są rejony, na których rośliny są najbardziej wrażliwe na wszelkie zmiany środowiska, w tym klimatu. Takim rejonem jest m.in. północno-wschodnia Polska położona w strefie przejściowej pomiędzy klimatem oceanicznym i kontynentalnym. Wiele gatunków roślin ma tutaj granice swojego zasięgu, co oznacza, że występują one na progu swojej tolerancji ekologicznej. W tej sytuacji nawet niewielkie i krótkotrwałe zmiany klimatu mogą skutkować poprawą lub pogorszeniem kondycji przedstawicieli tych gatunków i zmianami w intensywności ich pylenia, a dłużej trwające okresy chłodu mogą prowadzić do istotnych zmian w składzie roślinności, wynikających ze zmian liczebności populacji niektórych gatunków, a nawet z przesuwania się granic ich zasięgu.

Głównym celem badań paleoekologicznych podjętych na terenie położonego w północno-wschodniej Polsce Wigierskiego Parku Narodowego było ustalenie, czy uwidoczniły się w tym rejonie krótkotrwałe, śródholoceńskie oscylacje klimatu i czy miały one wpływ na postglacjalny rozwój roślinności. W ramach tak ujętego celu głównego sformułowano kilka celów szczegółowych, które wyznaczały jednocześnie kolejne etapy prowadzonych badań: (1) rekonstrukcja głównych etapów przemian szaty roślinnej badanego regionu; (2) wskazanie ewentualnych zaburzeń w interglacjalnej sukcesji roślinności i rozpoznanie ich klimatycznych przyczyn poprzez chronostratygraficzne skorelowanie tych zmian z krótkotrwałymi wahnieniami klimatu; (3) ustalenie czy były to zmiany przejściowe, nie wpływające w istotniejszy sposób na przebieg holoceńskiej sukcesji roślinności, która zależała przede wszystkim od głównego trendu w interglacjalnym rozwoju klimatu, czy też zmiany te wywarły znaczący wpływ na przebieg holoceńskiej sukcesji roślinności, inicjując lub modyfikując jej kolejne etapy.

Badaniom poddano osady trzech jezior: Suchar Wielki, Suchar II i Ślepe. Główną metodą badawczą była analiza pyłkowa, która umożliwiła odtworzenie zmian roślinności zarówno w otoczeniu badanych jezior jak i w nich samych. Wiek badanych osadów określono metodą radiowęglową oraz poprzez korelację palinostratygraficzną uzyskanych profili pyłkowych z dobrze datowanymi tą metodą profilami z jezior Wigry i Szurpiły. Przy interpretacji uzyskanych danych pyłkowych wykorzystano także rezultaty dodatkowych analiz paleoekologicznych, takich jak analiza wioślarkowa i okrzemkowa, które zostały wykonane przez specjalistów w danej dziedzinie.

Dane uzyskane w wyniku wstępnej analizy pyłkowej osadów wszystkich badanych jezior przedstawiono **w artykule nr 1**. Pozwoliły one na odtworzenie głównych etapów rozwoju roślinności regionu Wigierskiego Parku Narodowego w późnym glacjale ostatniego zlodowacenia (Suchar Wielki) i w czasie holocenu (wszystkie badane jeziora). Uzyskany zapis palinologiczny pozwolił na wyróżnienie dziesięciu regionalnych poziomów pyłkowych (R PAZ) charakteryzujących te etapy. Udowodniono, że sukcesja roślinności w tym czasie zależała przede wszystkim od głównego trendu w glacjalnym i interglacjalnym rozwoju klimatu, ale udokumentowano także pewne krótkotrwałe zmiany roślinności, które mogły być spowodowane przez chłodne oscylacje klimatyczne. Jedną z takich zmian była nagła krótkotrwała ekspansja brzozy w młodszej części okresu preborealnego, która mogła być reakcją na ochłodzenie klimatu zwane oscylacją preborealną (PBO; 8 cykl Bonda). Drugą było przejściowe rozprzestrzenienie się świerka, które zaznaczyło się w okresie suborealnym i mogło być związane z jedną z zimnych oscylacji klimatycznych tego okresu.

Po odtworzeniu głównych etapów holoceńskiego rozwoju roślinności w sąsiedztwie badanych zbiorników i wytypowaniu okresów holocenu, w których prawdopodobny był wpływ nagłych ochłodzeń klimatu na roślinność Wigierskiego Parku Narodowego, przystąpiono do bardziej dokładnego rozpoznania zmian roślinności w dwóch z tych okresów. **W artykule nr 2** przedstawiono szczegółową rekonstrukcję zmian szaty roślinnej w okolicy jeziora Suchar Wielki oraz w samym zbiorniku wodnym w okresie preborealnym (ok. 1160-9800 lat kal. BP). Analiza pyłkowa udokumentowała występowanie w tym czasie aż czterech krótkotrwałych (po ok. 50-150 lat) chłodnych epizodów klimatycznych. Pierwsze trzy z nich zostały wydatowane na ok. 11300-11150, 11100-11000 i 10900-10850 lat kal. BP i były oddzielone od siebie stosunkowo krótkimi (po ok. 50-100 lat) okresami charakteryzującymi się poprawą warunków termicznych, co dokumentuje dużą niestabilność klimatu w starszej części okresu preborealnego. Ostatnie z zarejestrowanych ochłodzeń miało miejsce w młodszej połowie okresu preborealnego, ok. 10300-10200 lat kal. BP i było poprzedzone trwającym przez ok. 300 lat stopniowym ochładzaniem się klimatu. Serię trzech chłodnych epizodów odnotowanych w starszej części okresu preborealnego skorelowano z cyklem Bonda, w którym maksimum chłodu datowane jest na 11100 lat kal. BP, a ochłodzenie zarejestrowane z młodszej części tego okresu z cyklem Bonda datowanym na 10300 lat kal. BP.

Trzy wczesnopreborealne, chłodne epizody odpowiadające wydarzeniu 11,1 ka odzwierciedliły się w zapisie pyłkowym poprzez spadki koncentracji pyłku obydwu drzew budujących ówczesne drzewostany, zarówno sosny jak i brzozy, wskazujące na znaczne ograniczenie kwitnienia i pylenia tych drzew. Podczas najstarszego z tych ochłodzeń reakcja brzozy na spadek temperatury była wyraźnie słabsza niż sosny, co w procentowym zapisie pyłkowym zamanifestowało się spadkiem udziału pyłku *Pinus* i kulminacją pyłku *Betula*. Natomiast w czasie obydwu młodszych ochłodzeń odpowiedzi sosny i brzozy w postaci ograniczonego pylenia na pogorszenie się klimatu były bardzo podobne, co może sugerować, że spadek temperatury był wtedy mniej wyraźny niż podczas najstarszego ochłodzenia. W żadnym z wczesnopreborealnych ochłodzeń najprawdopodobniej nie doszło do zmiany składu panujących wtedy lasów brzozowo-sosnowych. Powodowały one jedynie zmiany w intensywności pylenia budujących je drzew.

Późnopreborealne ochłodzenie korelowane z wydarzeniem 10,3 ka powiązane było na terenie Wigierskiego Parku Narodowego z obniżeniem wilgotności klimatu. W czasie tego ochłodzenia mogło dojść do krótkotrwałego rozszerzenia się areału brzozy na badanym terenie. Świadczy o tym wyraźny wzrost koncentracji pyłku tego taksonu i wynikający z tego wzrost jego udziału procentowego.

Zestawienie uzyskanych danych palinologicznych z danymi paleoekologicznymi pochodzącymi z różnych części Europy doprowadziło do wniosku, że zmiany flory i fauny opisywane w okresie preborealnym w Europie mogły być odpowiedzią na ciąg następujących po sobie ochłodzeń, z których każde oddziaływało na środowisko przyrodnicze z różną siłą, przez co odpowiedź na nie była inna w różnych częściach naszego kontynentu.

W artykule nr 3 opracowano rekonstrukcję zmian szaty roślinnej w okolicy jezior Suchar Wielki i Suchar II oraz w samych zbiornikach wodnych w okresie atlantyckim (ok. 9200-5750 lat kal. BP). Odtworzone zmiany szaty roślinnej wskazały na wystąpienie w tym czasie pięciu chłodnych epizodów, datowanych na ok. 9050-8950, 8700-7800, 7600-7250, 7100-6600 i 6050-5900 lat kal. BP. Najbardziej znaczące było drugie z tych ochłodzeń, chrostratygraficznie odpowiadające tzw. oscylacji 8,2 ka (5 cykl Bonda).

W pracy wykazano, że ochłodzenie korelowane z wydarzeniem 8,2 ka, na badanym terenie mogło trwać nawet ok. 900 lat. W tym okresie mogło dojść do tymczasowej przebudowy ówcześnie panujących lasów, poprzez zmianę udziału poszczególnych drzew wchodzących w ich skład. Udokumentowano, że spośród wszystkich drzew i krzewów tworzących zbiorowiska leśne na badanym terenie, najbardziej wrażliwa na wahania klimatu była w tym czasie leszczyna. W zapisie pyłkowym, zostało to zarejestrowane jako znaczny spadek koncentracji jej pyłku, co m.in. przekładało się na spadek udziału procentowego tego krzewu i mogło być też wynikiem ograniczenia areału leszczyny podczas ochłodzenia 8,2 ka

Pozostałe atlantyckie ochłodzenia prawdopodobnie obejmowały tylko po kilka-kilkadziesiąt sezonów z dłuższymi i chłodniejszymi zimami i wpływały jedynie na intensywność pylenia roślin, w szczególności termofilnych. Sugeruje to, że wszystkie te zmiany klimatu miały znacznie mniejszy wpływ na środowisko badanego terenu niż ochłodzenie 8,2 ka. Nie mniej jednak, wyniki badań palinologicznych, potwierdziły występowanie serii ochłodzeń, które zostały też zaobserwowane w innych częściach Europy.

Podsumowując, wysokiej rozdzielczości rekonstrukcja postglacjalnego rozwoju roślinności rejonu Wigierskiego Parku Narodowego oraz przebiegających równolegle z nim zmian w środowisku wodnym badanych jezior, dostarczyła nowych i ważnych informacji na temat wpływu krótkotrwałych, chłodnych, śródholoceńskich oscylacji klimatu na przebieg holoceńskiej sukcesji roślinności. Udokumentowano reakcję roślinności Wigierskiego Parku Narodowego na ochłodzenia klimatu mi. cykle Bonda. Tym samym dostarczono nowych danych o globalnym charakterze tych oscylacji klimatycznych. Wykazano, że jedynie ochłodzenia datowane na ok. 10,3 ka i 8,2 ka mogły spowodować tymczasową przebudowę szaty roślinnej na badanym terenie. Natomiast, na pozostałe ochłodzenia klimatu drzewa i krzewy reagowały jedynie okresowym spadkiem intensywności pylenia. Jednoznacznie pokazuje to, że nie przyczyniły się one w istotny sposób do zmian w przebiegu sukcesji roślinności. Nie mniej jednak, mają one ważne znaczenie dla korelacji chronostratygraficznej różnych zapisów zmian środowiska, jakie miały miejsce w Europie. Ponadto, uzyskane wyniki pozwoliły na wskazanie zmian klimatu o różnej sile oddziaływania na środowisko przyrodnicze, wykazując złożoność zależności klimat/roślinność oraz podkreślając znaczenie dynamiki odpowiedzi poszczególnych drzew m.in. brzozy i leszczyny w różnych okresach holocenu.

III. ARTICLES INCLUDED IN THE PhD DISSERTATION

1.

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LATE GLACIAL AND HOLOCENE VEGETATION CHANGES IN THE WIGRY NATIONAL PARK, NE POLAND – NEW POLLEN DATA FROM THREE SMALL DYSTROPHIC LAKES

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Abstract

The main phases of the Late Glacial and Holocene development of vegetation in the Wigry National Park were reconstructed based on the pollen analysis of sediments from three small dystrophic lakes (Lake Suchar Wielki, Lake Suchar II and Lake Ślepe). At the current stage of research, the age of the studied deposits was determined by AMS radiocarbon dating of few samples only. This meant that the chronology of the investigated profiles had to be estimated also indirectly using their palynological correlation with a radiometrically well-dated profile from Lake Wigry. The obtained pollen data confirmed the picture of the postglacial vegetation changes of the Wigry National Park, which was based on earlier studies of Lake Wigry. Furthermore, it documented the existence, mainly in the Preboreal and Atlantic chronozones, of temporary changes in vegetation, which might be a reaction to a short-lived cold fluctuations of climate.

Key words: postglacial succession of vegetation, palaeoecological reconstruction, climate changes, Late Glacial, Holocene, pollen analysis, Wigry National Park, NE Poland

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INTRODUCTION

The degree of knowledge on postglacial vegetation development in the Suwałki region, as for the entire north-eastern Poland, is still not satisfactory (Ralska-Jasiewiczowa *et al.*, 2004, Kupryjanowicz 2008). The palaeobotanical research in this area started in the first half of the 20th century (Osinki I and II, Krzywe, Suchar Dembowskich, Zakąty – Ołtuszewski 1937), and then continued in the second half of this century (Krusznik – Stasiak 1971), however, from the point of view of contemporary standards of palaeoecological researches, all of these studies are only of historical value. Solely the results of recent palaeobotanical studies conducted in the last decade, which have been supported by many additional palaeoecological analyzes, can be used to carry out the modern palaeoecological reconstructions (Lake Wigry – Kupryjanowicz 2007, Kupryjanowicz and Jurochnik 2009, Rutkowski and Krzysztofiak 2009; Lake Hańcza – Lauterbach *et al.*, 2010; Lake Szurpiły – Tylmann *et al.*, 2011; Lake Linówek – Gałka and Tobolski 2013). Even these, however, do not provide a complete picture of the changes. The profile from Lake Wigry – the largest water body in the Wigry National Park, while it allowed to reconstruct the main stages of postglacial succession of vegetation in the region (Kupryjanowicz 2007), yet for the Late Glacial and Early Holocene provided a very low resolution of the record of environmental changes (every 200–300 years). In the profile from Lake Szurpiły, the biogenic sedimentation was interrupted at the beginning of the Atlantic period by the accumulation of a thick (about 1 m) layer of sand not containing pollen (Tylmann *et al.*, 2011). In the profile from Lake Hańcza there is a sedimentation hiatus, covering almost whole the middle Holocene (Lauterbach *et al.*, 2010). Therefore, further studies are needed to complement the existing deficiencies.

From few years the Department of Botany at the University of Bialystok has been conducting an interdisciplinary palaeoecological research of several dystrophic lakes located within the Wigry National Park (Drzymulska and Kupryjanowicz 2012, Drzymulska 2012, Drzymulska *et al.*, 2013a, b, c, Fiłoc 2013a, b, Fiłoc and Kupryjanowicz 2013a, b). The study includes a lot of aspects of the history of the examined lakes. A part of the project is a pollen analysis of sediments from three water bodies – Lake Ślepe, Lake Suchar Wielki and Lake Suchar II. Its main purpose is to reconstruct the vegetation changes both around and within studied water bodies under the influence of the climate changes that have been taking place over the last ca. 12 thousand years. In this paper we presented the preliminary results of these studies, which made it possible to reconstruct the main stages of vegetation development in the Wigry National Park during the Late Glacial of Vistulian and the Holocene. These data were confronted with the prior knowledge of the post glacial vegetation development in the Suwałki region.

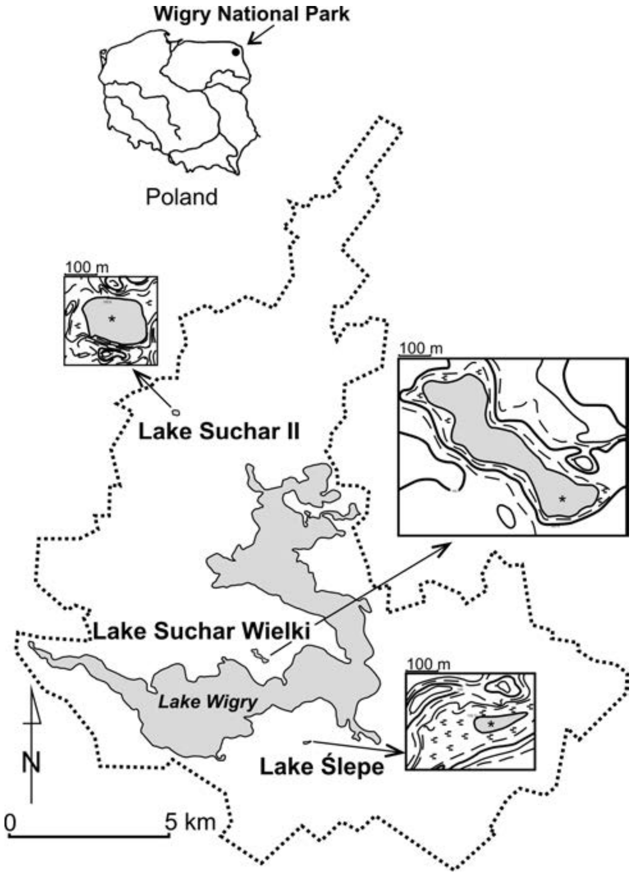

Fig. 1. Location of studied lakes. * – places of the corings.

STUDY AREA

Lake Ślepe (LS), Lake Suchar II (LSII), and Lake Suchar Wielki (LSW) are located in the Wigry National Park (WNP), north-eastern Poland (Fig. 1). The two physical-geographical mesoregions, the East Suwałki Lakeland and the Augustów Upland, occur in this part of Poland, and both are included in the Lithuanian Lakeland (Kondracki 1994). The terrain of this area was shaped during the Pomeranian phase of the main stadial of the Vistula Glaciation (Marks 2002). The climate of this area is temperate transitional with a tendency toward continental. This area is characterized by the most severe climatic conditions across the lowland parts of the country (Krzysztofiak and Olszewski 1999). Not far from the Wigry National Park there are the range limits of many plant species, mainly trees (e.g. *Picea abies*, *Taxus baccata*, *Acer pseudoplatanus*, *Quercus sessilis*, *Fagus sylvatica*), shrubs (e.g. *Salix lapponum*) and dwarf shrubs (e.g. *Rubus chamaemorus*) (Szafer and Zarzycki 1977). These all plants occur here on the border of their ecological tolerance.

METHODS

Fieldworks

The drilling in deep spots of all the lakes was carried out using the Więckowski's probe with a length of 110 cm and a diameter of 5 cm. Cores of bottom sediments with the thickness of 9.60 m (Lake Suchar Wielki), 5.95 m (Lake Suchar II) and 5.18 m (Lake Ślepe) were collected. It was necessary to supplement the collected profiles with top layers of highly liquefied sediments that could not be collected with a Więckowski's probe. The missing sediments from Lake Suchar Wielki – 0.50 m and from Lake Ślepe – 0.23 m were collected using the Kajak probe. The sediments from Lake Suchar II were not collected yet.

Table 1

Radiocarbon dating of the analyzed sediments.

Core	Depth [m]	Dated material	Age ^{14}C (yrs BP)	Calibrated age (cal.yrs BP)	
				range 68.2%	range 95.4%
SW	10.42	plant remains	3,170±25	3,443–3,404	3,449–3,359
SW	13.82	sediment	7,820±35	8,629–8,560	8,704–8,521
SW	15.02	plant remains	8,560±50	9,550–9,495	9,627–9,470
SW	15.74	sediment	9,640±45	11,172–10,827	11,189–10,785
SII	12.17	sediment	10,120±30	11,916–11,626	11,987–11,508

SW – Lake Suchar Wielki, SII – Lake Suchar II

Table 2

Lithology of analyzed profiles. Depths are counted from the water surface

Depth [m]	Sediment description
Lake Suchar Wielki	
7.57–16.74	dy
16.74–16.77	sand with shells
16.77–16.80	fine-detritus gyttja
16.80–16.86	sand with shells
16.86–16.94	calcareous gyttja
16.94–17.06	clay with sand
Lake Suchar II	
6.50–12.20	dy
12.20–12.32	silt
12.32–12.42	peat-like sediment
12.42–12.51	sand with shells and gravel
12.51–12.55	silt
12.55–12.60	sand with shells and gravel
Lake Ślepe	
0.75–5.73	dy
5.73–5.80	silt
5.80–6.23	sand with shells and gravel
6.23–6.40	gravel

Age of sediments

The age of the 4 samples of sediments from Lake Suchar Wielki and 1 sample of sediments from Lake Suchar II was determined by AMS radiocarbon method (Tab. 1). OxCal 4.2.3 online software (Bronk Ramsey 2009) was used to calibrate the radiocarbon age of the samples. Due to a very small number of radiocarbon age determinations in the studied profiles, the chronology of events recorded in these profiles has been determined also indirectly, based on a similarity between pollen spectra with the radiometrically well-dated profile from the nearby Lake Wigry (Kupryjanowicz 2007). The age of the sediments determined thus was compared with AMS radiocarbon dating (Fig. 2).

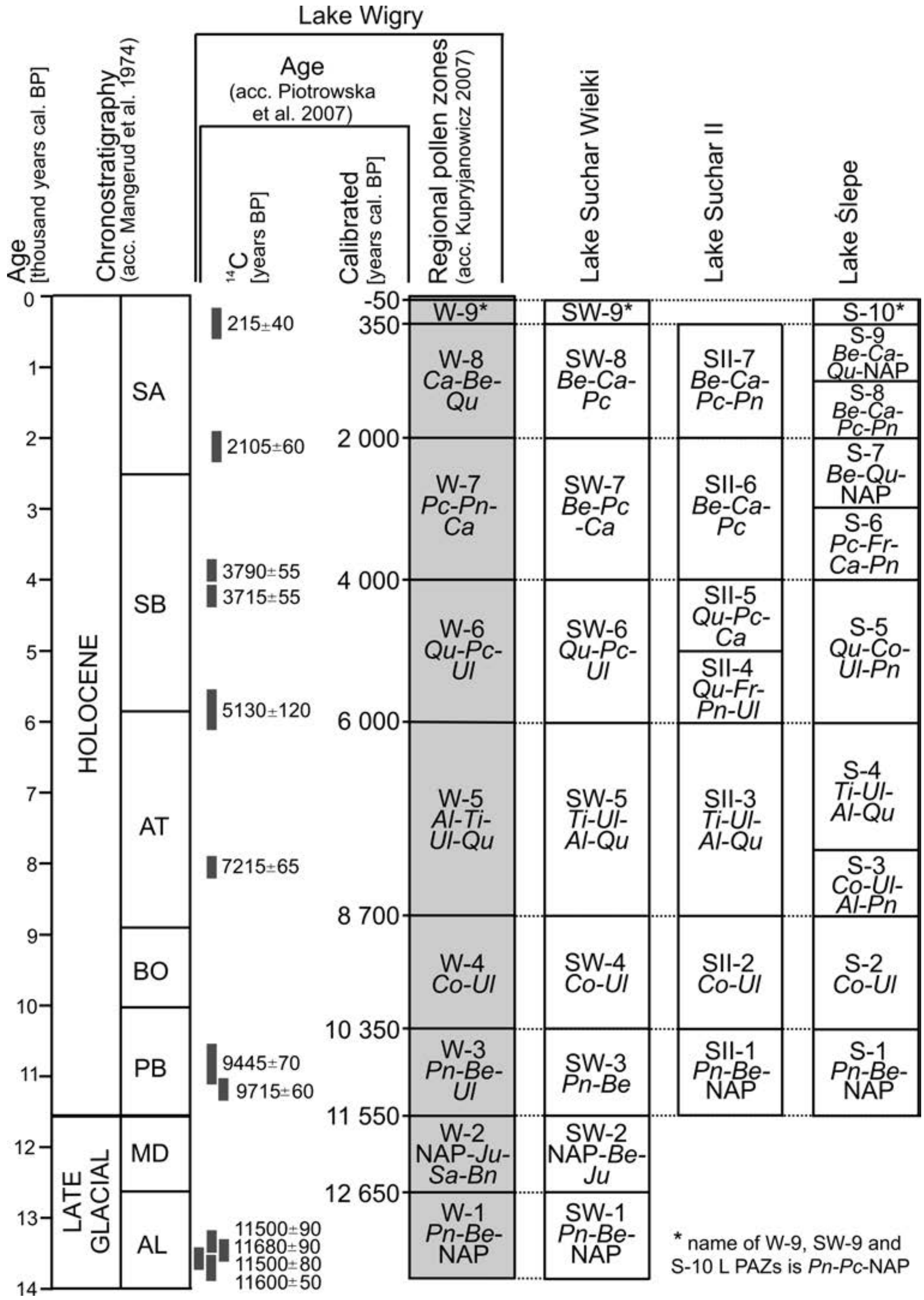

Fig. 2. Correlation of the pollen record from studied lakes and from Lake Wigry.

Pollen analysis

Samples for pollen analysis were taken every 2 cm. The samples were subject to maceration applying the method of Erdtman's acetolysis (Faegri and Iversen 1975). The preparation of the samples and their microscopic analysis were carried out in accordance with the standard procedure (Berglund and Ralska-Jasiewiczowa 1986).

In each sample, at least 500 sporomorphs were counted. Pollen and spores were identified using several keys (e.g. Moor *et al.*, 1991; Beug 2004). The percentage value of each pollen taxon has been calculated in relation to the total sum of trees and shrubs pollen (AP) and herbaceous plants pollen (NAP), excluding pollen of local plants, limnophytes and telmatophytes. The results are presented as percentage pollen diagrams prepared with POLPAL 2004 ver. 2011 software (Walanus and Nalepka 1999; Nalepka and Walanus 2003). The diagrams were divided into local pollen assemblage zones (L PAZ) (Figs 3–5) with the use of CONISS (POLPAL) application results.

RESULTS

The analyzed cores had been shortly described during the field works, and then completed after cleaning them in the laboratory (Tab. 2).

Table 3

Characterization of the local pollen assemblage zones (L PAZ) distinguished in the analyzed profiles

Symbol and name	Depth [m]	Description of pollen spectra
Lake Suchar Wielki		
SW-1 *Pinus-Betula*-NAP	16.90–16.45	Domination of *Pinus sylvestris* t. (53–86%); high values of *Betula alba* t. (6–33%), rise of NAP proportion to 12%; maximum of *Salix* (2%); still presence of *Juniperus communis*.
SW-2 NAP-*Betula*-*Juniperus*	16.45–15.95	Maximum of NAP (27%) represented mainly by *Artemisia* (8–16%), and *Juniperus communis* (8%); increase of *Betula alba* t. to ca. 45%; depression of *Pinus sylvestris* t. (22%); low-percentage culmination of *Picea abies* t. (3%) in the top.
SW-3 *Pinus-Betula*	15.95–14.65	Domination of *Pinus sylvestris* t. (36–64%) and *Betula alba* t. (29–58%); start of continuous curves of *Ulmus* and *Corylus avellana* and their gradual increase to 4% and 5%, respectively; rather high NAP proportion (3–6%) and *Salix* (to 1%).
SW-4 *Corylus-Ulmus*	14.65–14.25	Maximum of *Corylus avellana* (22%); relatively high proportion of *Ulmus* (ca. 6%); rise of *Alnus* to ca. 6%; start of continuous curves of *Tilia cordata* t., *Quercus* and *Fraxinus excelsior*.
SW-5 *Tilia-Ulmus-Alnus-Quercus*	14.25–11.55	Maximum of *Tilia cordata* t. (5%), *Ulmus* (9%), *Alnus* (22%) and *Fraxinus excelsior* (4%); systematic increase of *Quercus* to 8%; *Corylus avellana* slightly lower than previous zone; still presence of *Picea abies* t.
SW-6 *Quercus-Picea-Ulmus*	11.55–10.55	Maximum of *Quercus* (13%); relatively high values of *Fraxinus excelsior* (ca. 3%) and *Corylus avellana*; gradual rise of *Picea abies* t. to 3%; start of *Carpinus betulus* continuous curve; decrease of *Alnus* to 16%, *Tilia cordata* t. to 1% and *Ulmus* to 2%.
SW-7 *Betula-Picea-Carpinus*	10.55–9.45	Significant rise of *Betula alba* t. (to 38%); slight increase of *Carpinus betulus* (to 3%); relatively high proportion of *Corylus avellana* (6–12%), *Quercus* (4–8%) and *Tilia cordata* t. (1–2%); rise of NAP to 4%.
SW-8 *Betula-Carpinus-Picea*	9.45–8.25	High percentage of *Betula alba* t. (28–39%); relatively high values of *Carpinus betulus* with two peaks (5% and 6%) as well as *Quercus* (4–8%); *Corylus avellana* lower than previous zone (ca. 3%); still presence of *Picea abies* t. (1–4%); decrease of *Alnus* to 8%; very low proportion of *Ulmus*, *Tilia cordata* t. and *Fraxinus excelsior*; NAP slightly lower than previous zone.
SW-9 *Pinus-Picea*-NAP	8.25–7.57	High values of *Pinus sylvestris* t. (35–48%) and NAP (4–18%), including cultivated plants as Cerealia t., *Fagopyrum* and *Cannabis sativa* cf., as well as few human indicators as *Rumex acetosella* t., *Plantago lanceolata*, *Artemisia*, Poaceae and Chenopodiaceae; relatively high proportion of *Picea abies* t. (2–5%); decline of all other trees and shrubs.
Lake Suchar II		
SII-1 *Pinus-Betula*-NAP	12.60–11.85	Domination of *Pinus sylvestris* t. (44–80%), and next of *Betula alba* t. (to 77%); high proportion of NAP (6–11%); start of continuous curves of *Ulmus*, *Corylus avellana* and *Alnus* in the top part of the zone; presence of *Corylus avellana*, *Alnus*, *Ulmus*, *Quercus* and *Tilia cordata* t. in the bottom part – probably in secondary bed.
SII-2 *Corylus-Ulmus*	11.85–11.35	Maximum of *Corylus avellana* (25%); relatively high proportion of *Ulmus* (ca. 6%); rise of *Alnus* from 2% to 5%; start of continuous curves of *Tilia cordata* t., *Quercus*, *Fraxinus excelsior* and *Picea abies* t.
SII-3 *Tilia-Ulmus-Alnus-Quercus*	11.35–9.35	Culminations of *Tilia cordata* t. (2–5%), *Ulmus* (5–11%) and *Alnus* (to 24%); systematic rise of *Quercus* (1–7%) and *Fraxinus excelsior* (1–5%); values of *Corylus avellana* slightly low than previous zone (10–22%).
SII-4 *Quercus-Fraxinus-Pinus-Ulmus*	9.35–8.75	Maximum of *Quercus* (10%); relatively high values of *Fraxinus excelsior* (2–4%); increase of *Pinus sylvestris* t. to ca. 37%; small rise of *Picea abies* t.; still fairly high values of *Corylus avellana* (10–15%); fall of *Tilia cordata* t. (to 2%) and *Ulmus* (to 3%).
SII-5 *Quercus-Picea-Carpinus*	8.75–7.85	Rise of *Picea abies* t. to ca. 5%; relatively high proportion of *Quercus* (ca. 9%) and *Corylus avellana* (6–14%); start of *Carpinus betulus* continuous curve; slight increase of *Betula alba* t. (to 27%); decrease of *Tilia cordata* t. (to 1%), *Ulmus* (to 1%) and *Fraxinus excelsior* (to 1%).
SII-6 *Betula-Carpinus-Picea*	7.85–7.35	Increase of *Betula alba* t. to 35%, *Carpinus betulus* to 4% and NAP to 6%; relatively high values of *Picea abies* t. (to 4%), *Quercus* (to 8%) and *Pinus sylvestris* t. (to 31%); proportion of *Corylus avellana* much lower than previous zone (5–6%); fall of *Alnus*, *Ulmus*, *Tilia cordata* t. and *Fraxinus excelsior*.
SII-7 *Betula-Carpinus-Picea-Pinus*	7.35–6.65	Maximum of *Carpinus betulus* (5%); increase of *Pinus sylvestris* t. to ca. 43%; relatively high values of *Picea abies* t. (4%), *Betula alba* t. (33%), *Quercus* (7%) and NAP (7%); low-percentage culmination of *Salix*; decline of all other trees and shrubs.
Lake Ślepe		
S-1 *Pinus-Betula*-NAP	5.60–5.35	At first peak of *Betula alba* t. (45%), and then *Pinus sylvestris* t. (53%); relatively high NAP values (4–8%); rising values of *Ulmus* and *Corylus avellana*; presence of *Salix*, *Alnus* and *Quercus*.
S-2 *Corylus-Ulmus*	5.35–5.05	Maximum of *Corylus avellana* (27%); high percentages of *Betula alba* t. (35%); relatively high proportion of *Ulmus* (ca. 8%); depression of *Pinus sylvestris* t. (22–30%); rise of *Alnus* to 6% and *Quercus* to 2%; start *Tilia cordata* t. continuous pollen curve.
S-3 *Corylus-Ulmus-Alnus-Pinus*	5.05–4.65	Two peaks of *Pinus sylvestris* t. (45% and 40%); depression of *Corylus avellana* (15–21%) and *Ulmus* (5%); *Betula alba* t. lower than previous zone (18–25%); increase of *Alnus* to 20%, *Tilia cordata* t. to 3% and *Quercus* to 2%.
S-4 *Tilia-Ulmus-Alnus-Quercus*	4.65–3.55	Maximum of *Tilia cordata* t. (7%), *Ulmus* (9%), *Alnus* (30%) and *Salix* (3%); increase of *Quercus* to 8% and *Fraxinus excelsior* to 4%; *Pinus sylvestris* t. lower than previous zone (14–29%); *Betula alba* t. oscillating around 13–30%, and *Corylus avellana* around 10–19%.
S-5 *Quercus-Corylus-Ulmus-Pinus*	3.55–3.15	Maximum of *Quercus* (14%); two peaks of *Corylus avellana* (21% and 18%) and *Pinus sylvestris* t. (28% and 33%); still quite high values of *Ulmus* (2-6%); continuous occurrence of *Picea abies* t. and *Carpinus betulus*; depressions of *Tilia cordata* t. (1%) and *Fraxinus excelsior* (1%).

Table 3 continued

Symbol and name	Depth [m]	Description of pollen spectra
Lake Ślepe		
S-6 *Picea-Fraxinus-Carpinus-Pinus*	3.15–2.65	Culminations of *Picea abies* t. (4%), *Carpinus betulus* (3%), *Fraxinus excelsior* (4%) and *Pinus sylvestris* t. (37%); depression of *Quercus* (6%); fall of *Corylus avellana* to 6%, *Ulmus* to 1% and *Tilia cordata* t. to 1%.
S-7 *Betula-Quercus*-NAP	2.65–2.25	Rise of *Betula alba* t. to 33%; small peak of *Quercus* (10%); NAP culmination (3–6%); depressions of *Pinus sylvestris* t. (ca. 26%), *Picea abies* t. (ca. 1%) and *Carpinus betulus* (2%); decrease of *Corylus avellana* to 3%.
S-8 *Betula-Carpinus-Picea-Pinus*	2.25–1.45	Very high proportion of *Betula alba* t. (26–34%); relatively high values of *Carpinus betulus* (3–5%); culmination of *Pinus sylvestris* t. (29–42%) and *Picea abies* t. (1–3%); decline of *Alnus*, *Corylus avellana*, *Ulmus*, *Tilia cordata* t. and *Fraxinus excelsior*; NAP lower than previous zone.
S-9 *Betula-Carpinus-Quercus*-NAP	1.45–0.95	Culminations of *Betula alba* t. (34–41%), *Carpinus betulus* (2–7%), *Quercus* (3–9%) and *Alnus* (10–17%); meaning increase of NAP (4–20%), including cultivated plants as Cerealia t., *Fagopyrum* and *Cannabis sativa* cf., as well as few human indicators as *Rumex acetosella* t., *Plantago lanceolata*, *Artemisia*, Poaceae and Chenopodiaceae; depression of *Pinus sylvestris* t. (19-30%); still presence of Salix; very low proportion of all other trees and shrubs.
S-10 *Pinus-Picea*-NAP	0.95–0.75	Very high values of NAP (9–18%); rise of *Pinus sylvestris* t. to 49% and *Picea abies* t. to 3%; decline of *Betula alba* t. to 20%, *Carpinus betulus* to 1%, *Quercus* to 2% and *Alnus* to 7%; very low percentages of all other trees and shrubs.

In the simplified pollen diagrams, 9 local pollen assemblage zones were distinguished for Lake Suchar Wielki (Fig. 3), 7 for Lake Suchar II (Fig. 4) and 10 for Lake Ślepe (Fig. 5). Their short characteristics are showed in Table 3.

DISCUSSION – RECONSTRUCTION OF VEGETATION CHANGES

Late Glacial

Allerød interstadial (ca. 13350–12650 cal. years BP according to Ralska-Jasiewiczowa *et al.*, 1999 and Litt *et al.*, 2001) is represented only in pollen profile from Lake Suchar Wielki (SW-1 *Pinus-Betula*-NAP L PAZ – Fig. 3). The palynological record shows the dominance of the forest with a strong predominance of pine (*Pinus sylvestris* t. pollen) and the presence of open communities with grasses and other herbs (*Artemisia*, Chenopodiaceae Apiaceae, *Thalictrum*, Cichoriaceae) as well as shrub communities of juniper (*Juniperus communis*), dwarf birch (*Betula nana* t. pollen) and shrubby willows (pollen of *Salix pentandra* t., *Salix* cf. *herbacea*).

Younger Dryas stadial (ca. 12650–11550 cal. years BP according to Ralska-Jasiewiczowa *et al.*, 1999 and Litt *et al.*, 2001) like the previous period, is represented only in the pollen profile from Lake Suchar Wielki (SW-2 NAP-*Betula-Juniperus* L PAZ – Fig. 3). The palynological record shows a significant increase in the acreage of open communities (maximum of herbaceous plants in the pollen record), responding to the climate cooling. The maximum spread of mugwort (*Artemisia*), goosefoot (Chenopodiaceae), and juniper (*Juniperus*) suggests not only the drop in temperature, but also a significant reduction in moisture (Ralska-Jasiewiczowa *et al.*, 1998). The vegetation was of a mosaic nature with patches of shrubby tundra formed mainly by dwarf birch (*Betula nana* t. pollen) and shrubby willows (pollen of *Salix pentandra* t. and *Salix* undiff.) in wet places and patches of juniper (*Juniperus communis*) and steppe grasslands in dry habitats.

The pollen of pine (*Pinus sylvestris t.*) and of woody birch (*Betula alba t.*), which dominates the pollen spectra, could have come from a long distant transport, although one cannot rule out the presence of small clusters of trees among herbaceous and shrubby vegetation. The continuous pollen curve of *Picea abies* t. in the upper part of the SW-2 pollen zone may suggest that in the meantime spruce was present in the Wigry region – as its quite heavy pollen grains are not transported over long distances. Pollen data from north-eastern Poland (Gałka *et al.*, 2013) and Lithuania (Stančikaitė *et al.,* 2002) confirm that spruce was present at that time in northeastern part of Central Europe. Such an early presence of spruce in this area was most likely associated with the spread of Siberian spruce (*Picea obovata*) from its glacial refugia located in western Russia (Huntley and Birks 1983; Terhürne-Berson 2005; Latałowa and van der Knapp 2006).

Holocene

Preboreal chronozone (ca. 11550–10350 cal. years BP according to Mangerud *et al.*, 1974 and Walanus and Nalepka 2010) contained the initial stage of Holocene forest development. It is represented in all analyzed profiles (SW-3 *Pinus-Betula* L PAZ – Fig. 3, SII-1 *Pinus-Betula*-NAP L PAZ – Fig. 4, S-1 *Pinus-Betula*-NAP L PAZ – Fig. 5). The climate warming at the transition between the Late Glacial and the Holocene, have limited the area of open plant communities. This is particularly visible in the decline of *Juniperus com munis* and herbaceous plants pollen and the significant increase in the percentage of pollen of *Pinus sylvestris* t. and *Betula alba* t. pollen. The vegetation that dominated the Wigry region all that time were forest with a predominance of pine and a large share of birch. In the second part of the Preboreal period, from about 11000 cal. years BP, first trees and shrubs with a more demanding climatic conditions, such as elm (*Ulmus*) and hazel (*Corylus avellana*), could have reached this area. This is documented by the beginning of the continuous curves of pollen of both taxa.

The most developed pollen record of this period is registered in the profile from Lake Suchar Wielki, in which it is represented by the SW-3 *Pinus-Betula* pollen zone. There is a significant probability that the middle part of this zone,

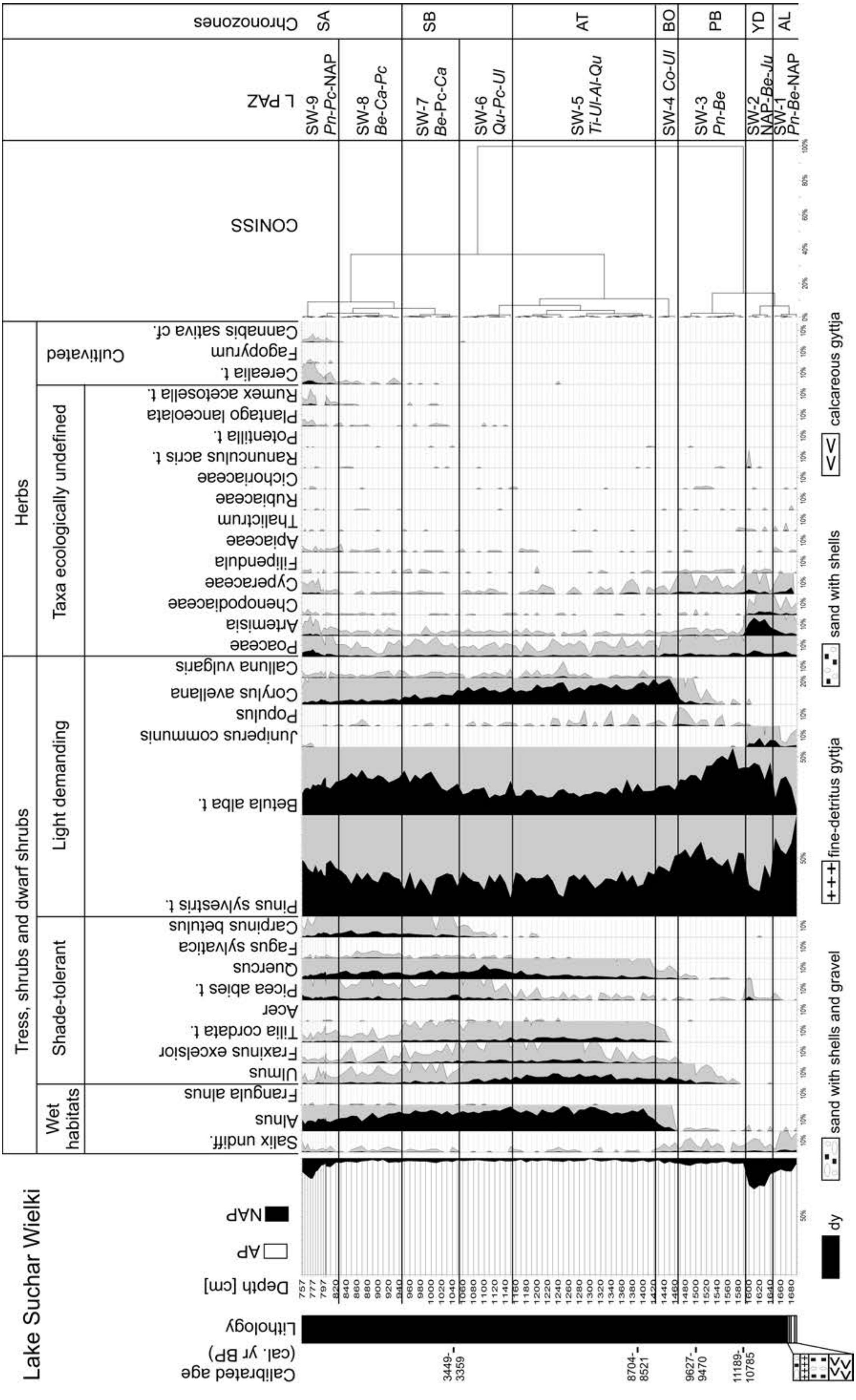

Fig. 3. Simplified percentage pollen diagram (only curves of selected taxa) from the profile Lake Suchar Wielki. Chronozones (acc. Mangerud *et al.*, 1974): AL – Allerød, YD – Younger Dryas, PB – Preboreal, BO – Boreal, AT – Atlantic, SB – Subboreal, SA – Subatlantic.

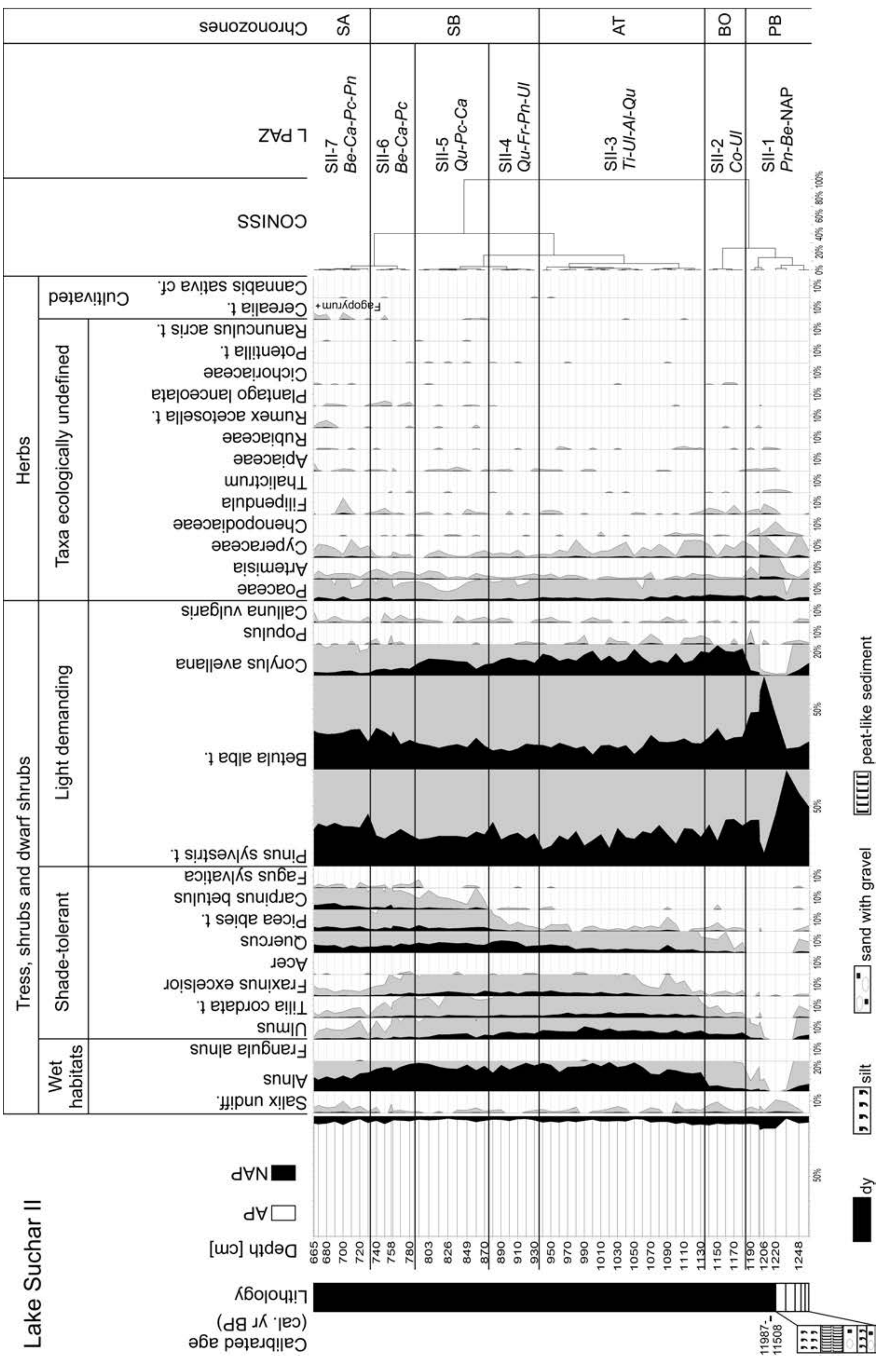

Fig. 4. Simplified percentage pollen diagram (only curves of selected taxa) from the profile Lake Suchar II. Explanations as in Fig. 3.

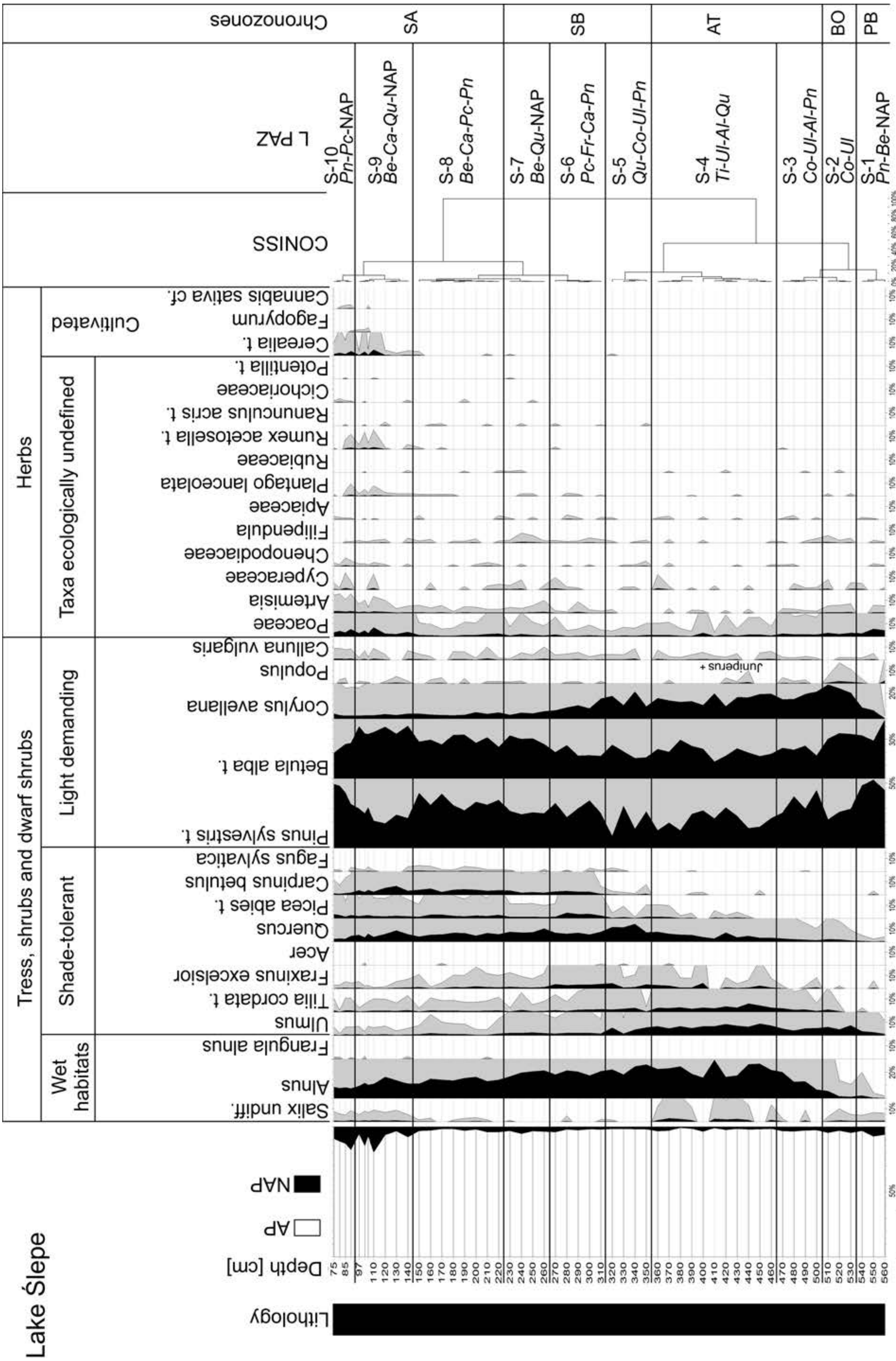

Fig. 5. Simplified percentage pollen diagram (only curves of selected taxa) from the profile Lake Ślepe. Explanations as in Fig. 3.

showing the significant spread of birch (ca. 60% peak of *Betula alba* t. pollen at the depth of 15.70 m) related to the reduction of the importance of pine, may reflect the cool climate oscillation attributable to ca. 11100 cal. years BP. These assumptions are confirmed by radiocarbon date 11189–10785 cal. years BP. Also the peaks of *Betula alba* t. in the profiles of Lake Suchar II (SII-1 L PAZ, depth of 12.06 m, dated at ca. 11987–11508 cal. years BP – Fig. 4) and Lake Ślepe (S-1 L PAZ, depth of 5.60 m – Fig. 5), correspond to this first Preboreal cold oscillation.

Quite a high proportion of pollen of mesophilic taxa, mainly *Corylus avellana*, *Ulmus* and *Alnus*, in the bottom section of the Lake Suchar II profile (lower part of the SII-1 L PAZ) representing the older part of the Preboreal period is probably due to a contamination of the core with younger sediments which were "drawn back" during drilling.

Boreal chronozone (ca. 10350–8700 cal. years BP according to Mangerud *et al.*, 1974 and Walanus and Nalepka 2010) is represented in all studied profiles (SW-4 *Corylus-Ulmus* L PAZ – Fig. 3, SII-2 *Corylus-Ulmus* L PAZ – Fig. 4 and S-2 *Corylus-Ulmus* L PAZ – Fig. 5). The most characteristic feature of the vegetation changes that falls for this part of Holocene is the expansion of hazel respectively documented by an increase in the value of its pollen by over 10%. Hazel arrived in the studied area much sooner, as early as the second part of the Preboreal chronozone, but only in about 10350 cal. years BP did it come to its rapid growth (Huntley and Birks 1983; Miotk-Szpiganowicz *et al.*, 2004). Hazel played a significant role in forest communities, where it is probably formed an undergrowth. The development of hazel contributed to a significant reduction in the role of birch and pine trees, for which the increased shading of the forest floor significantly hindered the renewal process. Wetland habitat gradually began to be overtaken by alder (increase of *Alnus* pollen). The role of elm steadily grew. Along with the willows, it created riparian forest in the river valleys. At the end of the Boreal chronozone, the first mesophilic deciduous forest with elm (*Ulmus*), lime (*Tilia cordata* t. pollen), oak (*Quercus*) and ash (*Fraxinus excelsior*) – began to form in the most fertile habitats.

The radiocarbon date from Lake Suchar Wielki, ca. 9627–9470 cal. years BP is likely to have been rejuvenated.

Atlantic chronozone (ca. 8950–5750 cal. years BP according to Mangerud *et al.*, 1974 and Walanus and Nalepka 2010) is represented in all the studied profiles (SW-5 *Tilia-Ulmus-Alnus-Quercus* L PAZ – Fig. 3, SII-3 *Tilia-Ulmus-Alnus-Quercus* L PAZ – Fig. 4, S-3 *Corylus-Ulmus-Alnus-Pinus* and S-4 *Tilia-UlmusAlnus-Quercus* L PAZ – Fig. 5). This is confirmed by radiocarbon data ca. 8704–8521 cal. years BP obtained from the depths 13.81–13.82 m from Lake Suchar Wielki. Already at the beginning of this period, there was an expansion of alder. It was probably associated with the spread of *Alnus glutinosa*, which formed alder forest in wet peaty shores of lakes common in the studied area (Szczepanek *et al.*, 2004). Thermophilous trees such as lime, elm and ash, reached at the time the optimum of their Holocene development. In the shady woods the development of hazel was limited due to the less abundant flowering (slight decrease in *Corylus avellana* pollen). The importance of oak and ash was steadily growing. The increase in the percentage of *Picea abies t.* pollen by over 0.5% may indicate the presence of single trees of in spruce in the local forest stands (Harmata 1987). However, in palaeoecological reconstructions different pollen values are accepted as evidence for the presence of spruce. Björkmar (1996) assumes that a value around 1% indicates a local presence of this tree, while Bortenschlager (1970), Markgraf (1980) and Huntley and Birks (1983) suggest that it reflects only by pollen values higher than 5%.

Subboreal (ca. 5750–2650 cal. years BP according to Mangerud *et al.*, 1974 and Walanus and Nalepka 2010) chronozone in the pollen record of the studied profiles is clearly divided into two parts. The older part (ca. 6000–4000 cal. years BP) is represented in all the studied profiles (SW-6 L *Quercus-Picea-Ulmus* L PAZ – Fig. 3, SII-4 *Quercus-Fraxinus-Pinus-Ulmus* and SII-5 *Quercus-Picea-Carpinus* L PAZ – Fig. 4, S-5 *Quercus-Corylus-Ulmus-Pinus* L PAZ – Fig. 5). At this time there was a significant increase in the role of oak in the forest communities of the Wigry region – it reached the maximum of its Holocene spread, which is documented by an increase of *Quercus* pollen to 10%. The acreage of ash increased as well. The importance of lime and elm decreased, compared to the Atlantic chronozone. Spruce became an increasingly important component of forest. Alder expanded its area significantly in the wetland habitats.

The younger part of the Subboreal chronozone (ca. 4000–2000 cal. years BP) is represented in all studied profiles (SW-7 *Betula-Picea-Carpinus* L PAZ – Fig. 3, SII-6 *Betula-Carpinus-Picea* L PAZ – Fig. 4, S-6 *Picea-Fraxinus-Carpinus-Pinus* and S-7 *Betula-Quercus*-NAP L PAZ – Fig. 5). The beginning of this period in the Suwałki region is marked by one of the most important change of the forest in the entire Holocene, which was the expansion of spruce. According to results of palynological research of Lake Wigry, this tree reached in this time the maximum of its Holocene spread in the region (Kupryjanowicz 2007). Its percentage values in the profile from Lake Wigry (about 14%) are much higher, than the values listed for *Picea abies* t. at the same time in other sites from the north-eastern Poland (Obidowicz *et al.*, 2004). This is most likely due to the north-eastern direction of migration of spruce in the areas in this part of the country and the climatic conditions of the region, encouraging the development of spruce. In sections of studied profiles, representing the younger part of the Subboreal period, the proportion of *Picea abies t. pollen* is much lower than in the profile from Lake Wigry – in the profile from Lake Suchar II spruce reaches a maximum of 5% (SII-6 L PAZ), and in the profiles from Lake Suchar Wielki (SW-7 L PAZ) and Lake Ślepe (Ś-6 L PAZ) only 4%. This results most likely from the fact that the phase of the maximum spread of spruce lasted a relatively short time (the studies in Lake Wigry shows that was only about 100 years – Kupryjanowicz 2007) and it is possible that the studied profiles do not contain a full-blown pollen record. In Lake Suchar Wielki the spread of spruce was dated at about 3449–3359 cal. years BP.

Starting from ca. 4000 cal. years BP, could have been there a local presence of hornbeam (Carpinus betulus) in the area of the lakes studied, which is indicated by the beginning of a continuous curve of this tree pollen in all profiles containing the record of the younger part of Subboreal chronozone. The values of *Carpinus betulus* pollen in the sediments of the studied lakes at this time are still much lower than in other localities in the north-eastern Poland (Kupryjanowicz 2004, Ralska-Jasiewiczowa *et al.*, 2004). This is probably due to the quite harsh continental climate of the Wigry region, which was not, and is still not, conducive to the development of hornbeam.

Subatlantic chronozone (from ca. 2650 cal. years BP to the present day according to Mangerud *et al.*, 1974 and Walanus and Nalepka 2010) due to the development of vegetation can be divided into two parts. Its older part (ca. 2000–350 cal. years BP) is represented in all profiles (SW-8 *Betula*-*Carpinus*-*Picea* L PAZ – Fig. 3, SII-7 *Betula*-*Carpinus*-*Picea*-*Pinus* L PAZ – Fig. 4, S-8 *Betula*-*Carpinus*-*Picea*-*Pinus* and S-9 *Betula*-*Carpinus*-*Quercus*-NAP L PAZ – Fig. 5). At this time, when the climate became warmer and wetter, hornbeam and birch increased in importance. There was a slight decrease in the role of spruce compared to the younger part of the Subboreal chronozone. This change, at least in part, may have been caused by anthropogenic factors – as indicated by the presence of many palynological human indicators.

The younger part of the Subatlantic chronozone (from ca. 350 to ca. 50 cal. years BP) was registered only in the profile of Lake Suchar Wielki (SW-9 *Pinus*-*Picea*-NAP L PAZ) and the profile of Lake Ślepe (S-10 *Pinus*-*Picea*-NAP L PAZ). The pollen data indicate a nearly complete degradation of the majority of trees with higher thermal requirements, such as lime, elm and ash, and the spread of pine. The increased pollen percentages of herbaceous plants, mainly cultivated and related to human activity, when compared to the earlier period, reflect the highest reduction throughout the Holocene of surfaces covered by forest communities and an enlargement of the area of fields, meadows and human settlements. However, the herbaceous plant pollen share is several times lower than in the positions in other parts of Poland, suggesting that anthropogenic impact had never been as strong here as in the central or western Poland (Latałowa 1992, Makohonienko 2000).

Only the profiles from Lake Suchar Wielki (SW-9 *Pinus*-*Picea*-NAP L PAZ – Fig. 3) and Lake Ślepe (S-10 *Pinus*-*Picea*-NAP L PAZ – Fig. 5) registered the youngest part of the Subatlantic chronozone (ca. 2000–2007 AD), which in the Wigry region was characterized by a weakening of anthropogenic impact and the development of pine forest (Kupryjanowicz 2007). The profile from Lake Suchar II contains no record corresponding to this period, which is due to the fact that with the used equipment it was not possible to retrieve the upper, most hydrated layers of sediments.

SUMMARY AND CONCLUSIONS

The main phases of the vegetation development in the Wigry National Park during the Late Glacial of the last glaciation and the Holocene were reconstructed.

– Late Glacial is represented only in the sediments of Lake Suchar Wielki. The record of Allerød interstadial shows the dominance of forest with pine and birch and the presence of open communities. During the Younger Dryas stadial the vegetation took the character of a mosaic with patches of shrubby tundra and cold steppe communities.

– The beginning of the Holocene was the time of pine and birch forest development. It had been disturbed in the older part of Preboreal chronozone by a temporary change in vegetation, expressed by an short-lived expansion of birch, which was accompanied by a decrease in the pine importance. It was most likely a reaction to a short-term climate cooling. Due to the lack of precise dating of this phenomenon in the studied pollen profiles, its correlation with Preboreal cold oscillation or Bond's event is purely hypothetical at this moment. This problem requires more extensive discussion at a later stage of the studies.

– The Boreal chronozone was characterized by an expansion of hazel, which reached its Holocene maximum and a gradual overtaking of wetland habitats by alder.

– The Atlantic chronozone was the time of the maximum Holocene development of thermophilous trees such as lime, elm and ash.

– The Subboreal chronozone was the period of the growth of oak combined with an increase of ash in the area and an appearance of hornbeam. Its younger parts were the time of the development of spruce. The expansion of spruce registered in pollen diagram from Wigry expressed by a rapid increase in the share of *Picea abies t.* pollen to 10–15% in just 100 years is dated on ca. 3972 cal. years BP. Such drastic changes in the composition of forests were due to different causes. Pollen records of investigated lakes in which the share of *Picea abies* t. pollen rapid rose to 5% and was lower than from Lake Wigry. It indicates that the presence of spruce could be intensified by cold and humid climate was attributable to that part of the Holocene – one of cold climate fluctuations.

– The Subatlantic chronozone was the time of an increased importance of hornbeam and birch, and in its younger part there was a degradation of the majority of trees with larger thermal requirements linked to the spread of pine. Judging by a significant increase in the share of herbaceous plants, which were the so called human indicators, it can be assumed that the causes of these changes were associated with anthropogenic impact.

The pollen record of vegetation changes registered in the profiles of the studied lakes is very similar to that from other sites of the north-eastern Poland (lakes: Wigry, Hańcza, Szurpiły, Linówek) – both in terms of the nature of the recorded changes and their dating. However, on the present stage of research, may be notice that a sudden climate fluctuations known as Bond's events most likely appear in the studied region very clearly, and the large thickness of sediments will allow to precise study of some of them. The discrepancies in the dating of some significant changes in vegetation (e.g. the emergence of spruce) also will require further research, especially those related to a more precise determination of the age of the studied sediments.

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Response of terrestrial and lake environments in NE Poland to Preboreal cold oscillations (PBO)

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ABSTRACT

The multi-proxy data (pollen, diatoms, Cladocera, ^{14}C) from the sediments of Lake Suchar Wielki representing the period ca. 11,600–9800 cal. BP have allowed the reconstruction of the influence of Preboreal cold oscillations on terrestrial and aquatic environments in NE Poland. The reconstructed changes in plant, cladoceran and diatom communities indicated an occurrence of four short-lasting negative climate events during the Preboreal period. The first three of them occurred in the early Preboreal (ca. 11,300–11,150, 11,100–11,000 and 10,900–10,850 cal. BP) and they were separated by short, warmer intervals. The obtained palynological data indicated that these events did not result in the transformations of the pine-birch forests strongly dominant in that period, but were only manifested by changes in the pollen production by the trees forming woodstands. In the lake during these coolings, cold-water Cladocera species developed, and the abundance of aquatic organisms decreased. Water level in the lake during two older early-Preboreal cold events increased significantly, and remained low during the last event. In the late Preboreal a fourth cooling took place. The cold peak was relatively short (ca. 10,300–10,200 cal. BP), but was preceded by a ca. 300-year-long period when conditions for plants were unfavourable. The drop in temperature was accompanied by a decrease in the humidity of the climate and a decrease in the water level in the lake. Again, the abundance of cold-water species increased. The acreage covered by pine decreased, and a temporary spreading of birch occurred. This last cold event in the Preboreal was followed by a relatively stable warm phase at the end of this chronozone. The recorded climate changes in NE Poland during the Preboreal correspond fairly well with those reported for other regions of Europe and the whole Northern Hemisphere.

1. Introduction

The temporary cooling at the beginning of the Holocene was first described by van Geel and Kolstrup as early as 1978. However, it was not until data from the Greenland ice core (GRIP) were available that a reconstruction of a more complete picture of this cooling, called the Preboreal oscillation (PBO), was possible, as well as the dating of this event to ca. 11,400–11,250 cal. BP (Kapsner et al., 1995; Björck et al., 1996; van der Plicht et al., 2004). The probable causes of the PBO were changes in the activity of the sun (Bond et al., 2001; Fleitmann et al., 2003; Hu et al., 2003; Gupta et al., 2005; Wang et al., 2005; Viau et al., 2006) and the influx of meltwater from Lake Agassiz (e.g. Fisher et al., 2002; Teller et al., 2002) and from Scandinavian ice sheets (Björck et al., 1997; Husum and Hald, 2002; Aharon, 2003; Nesje et al., 2004) to the North Atlantic, which resulted in disturbances of thermohaline circulation (e.g. Paul and Schulz, 2002; Renssen et al., 2002, 2006; Schulz et al., 2007). The PBO can also be linked to the drop in the atmospheric concentration of methane and greenhouse gases (Brook et al., 2000), as well as with stronger winds and weak rainfall in the Atlantic Ocean region (Hughen et al., 1996). This all suggests the global nature of this event.

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The PBO is reflected in many terrestrial pollen records from North-Western Europe, Iceland and Greenland, in which it was dated similarly as in the Greenland ice core to ca. 11,300–11,150 cal. BP (Björck et al., 1996, 1997). At that time the Early Holocene expansion of birch forests was interrupted in Western Europe by a temporary spread of open grassland vegetation. This period is named the Rammelbeek Phase, and it is one of the best-described climate changes in our continent (e.g. van der Plicht et al., 2004; Bohncke and Hoek, 2007; Bos et al., 2007). Beyond palynological data, numerous other palaeoecological records from the Northern Hemisphere also indicate climate fluctuations at the beginning of the Preboreal period. The chironomid data from Lake Sils and Lake Silvaplana in the Central Alps present a temperature drop of 2 °C, dated to 11,450–11,350 cal. BP (Ilyashuk et al., 2009). In the chironomid record from Lake Brazi in the Romanian Carpathian Mountains, a decline in temperature by ca. 0.7 °C was noted between 11,480 and 11,390 cal. BP (Tóth et al., 2012). In Lake Lykkjuvøtn on the Faroe Islands the Preboreal cold event was dated to ca.11,200–11,120 cal. BP (Jessen et al., 2008), in Lake Torfadalsvatn in Iceland to ca. 11,200 cal. BP, and in Lake N14 in Greenland to ca. 11,075–11,000 cal. BP (Andresen et al., 2007). The occurrence of the cold oscillation at the beginning of the Preboreal is confirmed by records of water level rises in European lakes dated to ca. 11,250–11,050 cal. BP (e.g. Magny, 2001, 2004).

In north-eastern Poland, as a record of the PBO, the maximal spread of *Betula* registered at several sites studied by pollen analysis is described (e.g. Lake Miłkowskie – Wacnik, 2009; the Biebrza Upper Basin – Klerk et al., 2006; paleolake in Budzewo – Kołaczek et al., 2013). Also a short-term decrease in the $\delta^{18}O$ Ostracoda record from Lake Hańcza between ca. 11,400 and 11,200 cal. BP is correlated with this cooling of the climate (Lauterbach et al., 2011).

A comparison of data on the PBO from the Netherlands (van Geel et al., 1981; Björck et al., 1997; van der Plicht et al., 2004; Bos et al., 2007), Switzerland (Ilyashuk et al., 2009), Germany (Bos, 2001), Poland (Ralska-Jasiewiczowa et al., 2003; Klerk et al., 2006; Wacnik, 2009; Laterbach et al., 2011; Kulesza et al., 2012; Kołaczek et al., 2013) and Lithuania (Stančikaitė et al., 2008, 2009) indicates that the cooling was not synchronized in Europe.

Sudden warming took place after the PBO, reaching 4 ± 1.5 °C. It is dated to 11,270 cal. BP in a GISP2 Greenland ice core (Kobashi et al., 2008). In north-western Europe rapid improvement of the climatic conditions was dated to ca. 11,125 cal. BP (Bos et al., 2007; Magny et al., 2007). This favoured the expansion of *Corylus avellana* (Giesecke et al., 2011). A reconstruction of water temperature based on the Mg/Ca concentration in planktonic foraminifers from the Andfjorden record, north Norway, shows an increase in temperature ca. 11,000 cal. BP by ca. 1 °C (Aagaard-Sørensen et al., 2011).

The next cold period took place in southern Greenland between 11,000 and 10,800 cal. BP. Two returns to more arid and colder conditions appeared in ca. 10,975–10,900 and 10,860–10,800 cal. BP, which were registered in Lake N14, and three cold episodes, appearing between 11,100 and 10,800 cal. BP were recorded in Lake Lykkjuvøtnon on the Faroe Islands (Andresen et al., 2007). During this period the water flow from Lake Agassiz to the North Atlantic continued; it began ca. 11,335 cal. BP and lasted until 10,750 cal. BP (Nesje et al., 2004).

The subsequent Preboreal cold period occurred after ca. 10,700 cal. BP. It was probably associated with a long-lasting influx of melt water from Lake Agassiz to the North Atlantic between 10,500 and 10,200 cal. BP (Nesje et al., 2004), or with three shorter influxes in 10,600, 10,400 and 10,300 cal. BP (Teller, 2001; Teller et al., 2002). Similarly dated (at ca. 10,600, 10,450 and 10,300 cal. BP) three cold events also occurred in the records from the Faroe Islands (Jessen et al., 2008). Three short-lasting changes in vegetation were registered in ca. 10,700, 10,500 and 10,300 cal. BP also in a profile from Lake Flåfattjønna, which could be a reflection of those climate oscillations in Norway (Paus, 2010). In the Alps, temperature drops of 0.8 °C (Heiri and Lotter, 2003) or even 1 °C (Larocque-Tobler et al., 2010) occurred in ca. 10,700–10,500 and 10,700–10,300 cal. BP, respectively. In the record from Lake N14 in Greenland, cooling in ca. 10,600 cal. BP was marked (Andresen et al., 2007). The short-term cooling in the eastern Carpathian Mountains was described between 10,350 and 10,100 cal. BP (Feurdean et al., 2008), and in the southern Carpathians a temperature drop of 1 °C occurred between 10,350 and 10,190 cal. BP (Tóth et al., 2012). The cooling also took place in Russia ca. 10,200–10,000 cal. BP, which was expressed by a marked reduction in vegetation cover (Subetto et al., 2002). All of these events were recorded at similar times in the whole of Europe, from the west to the east (Fig. 2). The reconstruction of water temperature from the Andfjorden record, north Norway, shows an increase in temperature after ca.10,000 cal. BP by ca. 1 °C (Aagaard-Sørensen et al., 2011).

Despite the large amount of data on coolings during the Preboreal period, the issue is still not well recognized, and requires new paleoecological data that will allow for better interpretation. In this article we present our research on Preboreal climate fluctuations registered in the multi-proxy record from a small dystrophic lake in NE Poland, located in the transitional zone between oceanic and continental climates (Woś, 1995). Due to this specific location, this region is an interesting area for palaeoecological study. We discuss the implications of Preboreal climate oscillations for the terrestrial and aquatic environmental changes in this part of Europe. This will result in a better understanding of the complexity of these changes and their connection with similar changes registered in records from other regions of Europe.

2. The study area

Lake Suchar Wielki (8.9 ha, 9.6 m max. depth, 54°01′41″ N, 23°03′21″ E) is located in Wigry National Park (WNP), few kilometres to the west of Lake Wigry, the biggest lake in this park. In the physical-geographical division it is assigned to the mesoregion of the East Suwałki Lake District, which is part of the Lithuanian Lake District. The climate of this area is temperate transitional with a tendency toward continentality, and it is characterized by the lowest temperatures in the lowland part of the country and the greatest number of days with average temperatures below 1 °C (Kondracki, 1994). The relief of the area was modelled by the Vistula (Weichselian) Glaciation (Ber, 2000). A number of kames, eskers, and frontal moraine heights occur in the northern and middle parts of WNP, while the southern part of the park comprises an extensive sandur with a strongly transformed primary glacial relief (Ber, 2009).

The forests of WNP constitute the northern part of the Augustów Primeval Forest, which covers almost 1150 km^2 and is one of the largest forest complexes in Poland. The severe climate of north-eastern Poland results in the occurrence of forest communities of a boreal character (Sokołowski, 1999). Numerous northern species forming these communities occur here at the limit of their ecological tolerance (Szafer and Zarzycki, 1977).

3. Methods

3.1. Coring

Drilling in a deep spot of Lake Suchar Wielki (Fig. 1) was carried out using Więckowski's probe with a length of 110 cm and a diameter of 5 cm. A core of bottom sediments with a thickness of 9.60 m was collected in winter 2009 from the ice surface of the lake.

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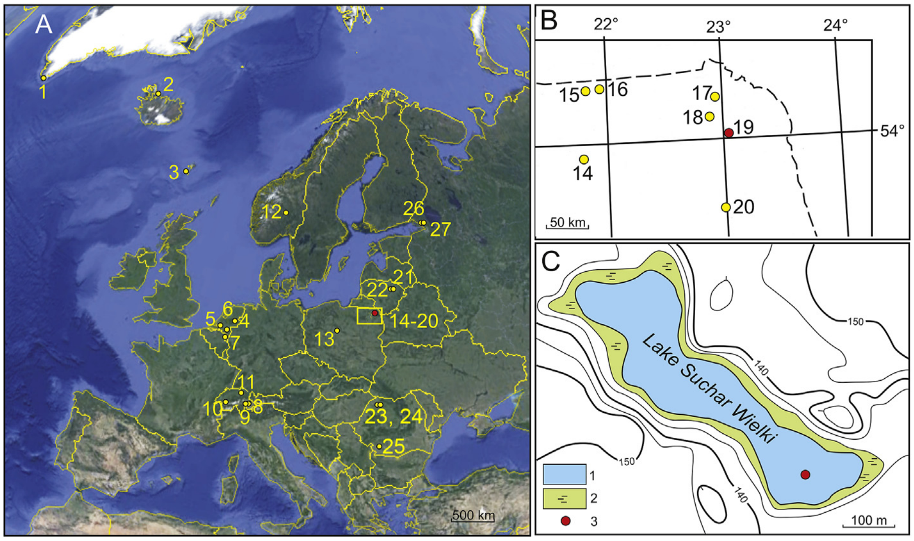

Fig. 1. A – Greenland and European sites with the record of Preboreal cold oscillations (PBO) cited in the text on Google map: 1 – Lake N14, Greenland (Andresen et al., 2007); 2 – Lake Torfadalsvatn, Iceland (Andresen et al., 2007); 3 – Lake Lykkjuvøtn, Faroe Island (Jessen et al., 2008); 4 – Borchet, Netherlands (Bos et al., 2007); 5 – Kreekrak, Netherlands (Bos et al., 2007); 6 – Haelen, Netherlands (Bos et al., 2007); 7 – Kingbeekdal, Netherlands (Bohncke and Hoek, 2007); 8 – Lake Sils, Switzerland (Ilyashuk et al., 2009); 9 – Lake Silvaplana, Switzerland (Ilyashuk et al., 2009); 10 – Lake Hinterburgsee, Switzerland (Heiri and Lotter, 2003); 11 – Lake Egelsee, Switzerland (Heiri and Lotter, 2003; Larocque-Tobler et al., 2010); 12 – Lake Flaåfattjønna, Norway (Paus, 2010); 13 – Lake Gościąż, Poland (Pazdur et al., 1995; Ralska-Jasiewiczowa et al., 1998, 2003); 21 – Lake Petrasiunai, Lithuania (Stančikaitė et al., 2009); 22 – Juuodonys peat-bog, Lithuania (Stančikaitė et al., 2009); 23 – Lake Preluca Tiganului, Romania (Feurdean et al., 2008); 24 – Lake Steregoiu, Romania (Feurdean et al., 2008); 25 – Lake Brazi, Romania (Tóth et al., 2012); 26 – Lake Medvedevskoye, Russia (Subetto et al., 2002); 27 – Lake Pastorskoye, Russia (Subetto et al., 2002). **B** – location of Lake Suchar Wielki and other records in north-eastern Poland: 14 – Lake Miłowskie, Poland (Wacnik, 2009); 15 – Budzewo, Poland (Kołaczek et al., 2013); 16 – Rapa, Poland (Kołaczek et al., 2013); 17 – Lake Hańcza, Poland (Lauterbach et al., 2011); 18 – Linówek, Poland (Gałka et al., 2014); 19 – Lake Suchar Wielki (in this paper); 20 – Biebrza Upper Basin, Poland (Klerk et al., 2006). **C** – hypsometry of the Lake Suchar Wielki area: 1 – open water, 2 – floating matt, 3 – place of coring made for palaeoecological investigation in Lake Suchar Wielki.

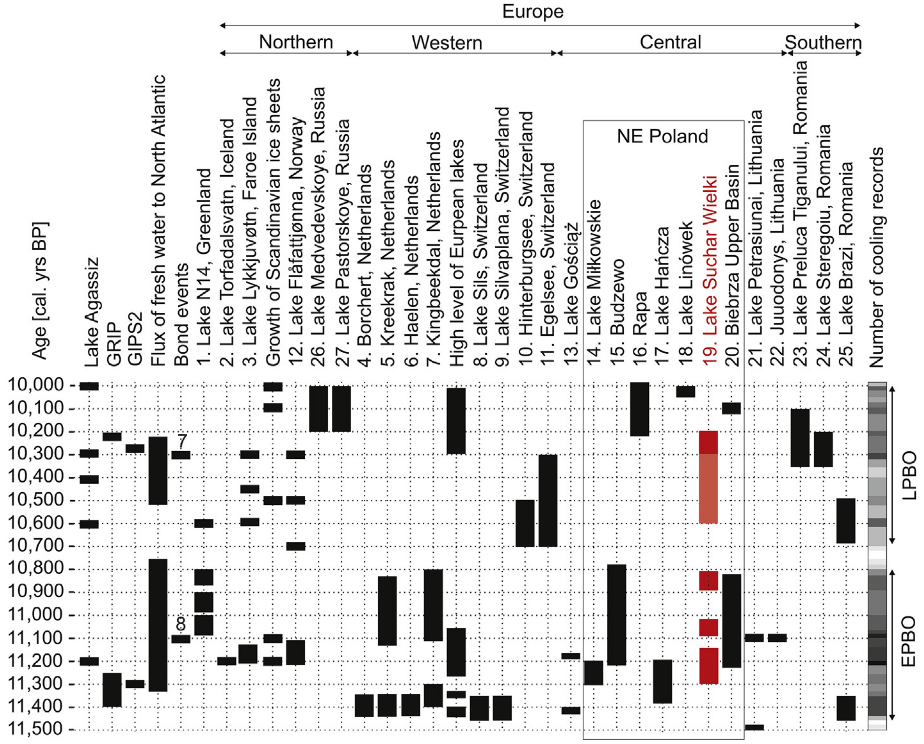

Fig. 2. Dating of the Preboreal cold oscillations (PBO) at different sites from the Northern Hemisphere: outbursts of Lake Agassiz according to Teller et al. (2002), Greenland Ice Core Project (GRIP) – Grönvold et al. (1995) and Björck et al. (1996, 2001), Greenland Ice Sheet Project (GISP2) – Zielinski et al. (1997), freshwater fluxes to the North Atlantic – Nesje et al. (2004), Bond cold events – Bond et al. (1997, 2001), phases of Scandinavian ice sheet development – Matthews and Dresser (2008); Nesje (2009), periods of high level water in mid-European lakes – Magny (2001, 2004) and Magny et al. (2007); for references for the other sites see Fig. 1.; darker shade of gray means more positions with the registered coolings. (EPBO – the early preboreal oscillations; LPBO – the late preboreal oscillations).

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The lithology of the analyzed core was briefly described during the fieldwork, and then a description was completed after cleaning of the core in the laboratory.

3.2. Dating

The age of sediments from the Lake Suchar Wielki profile was determined by the AMS radiocarbon method in the Gliwice Radiocarbon Laboratory (Table 1). OxCal 4.2.3 online software (Bronk Ramsey, 2013) was used to calibrate the radiocarbon age of the samples. Due to the small number of radiocarbon datings in the studied profile, the chronology of this profile was also determined indirectly, based on the similarity between the high resolution pollen data record registered in the Lake Suchar Wielki profile, and in the precisely radiometrically dated profile from nearby Lake Szurpiły (Kinder et al., 2013). The similarity of both these profiles permits their correlation (for details see article by Drzymulska et al., 2014), and then the transfer of some absolute dates from the Lake Szurpiły profile to the profile from Lake Suchar Wielki (Table 2).

procedure (Berglund and Ralska-Jasiewiczowa, 1986). In order to establish the absolute sporomorphs concentration in the sediments, *Lycopodium* indicator tablets (20,848 spores) were added to each sample (Stockmarr, 1971). Samples were counted every 1–4 cm. More than 500 terrestrial pollen grains were counted from each sample. We counted grains of terrestrial plants and all accompanying pollen grains and spores for aquatic and mire plants, and some non-pollen palynomorphs (NPPs). Pollen and spores were identified using several keys (e.g. Moor et al., 1991; Beug, 2004). The percentage values were calculated on the basis of the total sum including trees and shrubs (AP) and herbs (NAP), and excluding aquatic and mire plants and other microfossils. The results are presented as a percentage pollen diagram and a diagram of pollen concentration prepared with POLPAL software (Nalepka and Walanus, 2003). The diagrams was subdivided into local pollen assemblage subzones both by visual inspection of changes in pollen concentration, and by using stratigraphically constrained cluster analysis for percentage pollen values (CONISS) (Grimm, 1987).

Table 1
Radiocarbon dating of sediments from the Lake Suchar Wielki. Depths are counted from the water surface.

Depth [cm]	Dated material	Laboratory number	Age ^{14}C (BP)	Calibrated age (cal. BP)	
				Range 68.2%	Range 95.4%
1042	Plant remains	GdA-2963	3170 ± 25	3443–3368	3449–3359
1382	Sediment	GdA-2962	7820 ± 35	8629–8560	8704–8521
1502	Plant remains	GdA-2964	8560 ± 50	9550–9496	9625–9470
1574	Sediment	GdA-2965	9640 ± 45	11,172–10,827	11,189–10,785

Table 2
Main palaeocological events registered by the pollen record both in the Lake Suchar Wielki profile and in the well dated profile from Lake Szurpiły (data from Lake Szurpiły after Kinder et al., 2013). Depths for Lake Suchar Wielki are counted from the water surface, and for Lake Szurpiły from the top of sediments.

Depth [cm]		Characteristics of the pollen record	Calibrated age (cal. BP)
Szurpiły	Suchar Wielki		
89	782	The decrease in pollen curve *Carpinus betulus* below 2%, following shortly after its maximum	303–272
261	900	The first increase *Carpnius betulus* to about 5%	1388–1345
657	1210	Maximum *Tilia cordata*	6333–6256
1033	1645	The fall NAP and rise *Pinus sylvestris* t., indicating the start Younger Dryas	13,000

The ^{14}C dates, both those obtained during our research and those transferred by us from Lake Szurpiły, were used for the construction of an age-depth model for the whole analysed profile (Drzymulska et al., 2014). The model was built in the Depth/Age program (Walanus and Nalepka, 2015).

3.3. Loss on ignition

LOI was estimated following the methods described by Bengtsson and Enell (1986). In the studied section of the core 16 samples were analyzed. The samples were dried at 105 °C for 12 h and thereafter ignited at 550 °C for 12 h. LOI represents an estimation of organic matter content (%) from the loss on ignition method.

3.4. Pollen analysis

Samples for pollen analysis were subject to maceration, applying the method of Erdtman's acetolysis (Faegri and Iversen, 1975). The preparation of the samples and their microscopic analysis were carried out in accordance with the standard

3.5. Cladocera analysis

Preparation of sediment samples for Cladocera analysis followed standard methods described by Szeroczyńska and Sarmaja-Korjonen (2007). However, due to the lack of carbonates, no HCl treatment was used. Sediment sub-samples (1 cm^3 volume of wet sediments) were heated in 10% KOH for 25 min, washed and sieved through a 33-μm mesh with distilled water, and topped-up to a volume of 10 ml in a scaled test tube. In addition, due to the large amount of adhered organic particles, ultrasonic treatment was applied to increase the quality of cladoceran remains (Nowak et al., 2008). Before counting, the remains were dyed with glycerol-safranine. Samples were then analyzed and identified under a compound microscope (100–400 × magnification). The identification followed the key of Szeroczyńska and Sarmaja-Korjonen (2007). The remains were identified down to the lowest possible taxonomic level, although in some samples the unequivocal identification of species *Alona rectangula* and *Alona guttata*, as well as *Bosmina (E.) longispina* and *Bosmina (E.) coregoni*, was problematic. The former remains were grouped together and drawn as ‘small *Alona*’, and the latter were presented jointly as *Eubosmina*. For

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community analysis a minimum of 200 cladoceran individuals were enumerated for each level (Kurek et al., 2010). The number of the most abundant body part (carapaces, headshields, postabdomens, ephippia) was used as a representation of the number of individuals of each taxa. The counts were plotted as percentage diagrams.

As indices and ratios used in the characterization of Cladocera community structure the total abundance, planktonic to littoral ratio (p/l), species richness (n) and dominance index (D) were used. All indices were calculated with the application of PAST software (Hammer et al., 2001).

Cladocera assemblage zones (CAZ) were established based mainly on changes within dominant taxa, the diversity measures, and the p/l ratio, supported by cluster analysis with the CONNIS method (Grimm, 1987). In subzones (CASZ) delimitation we focused on the presence/absence of temperature-related, rare (<2%) species (Nevalainen et al., 2013). All Cladocera diagrams were prepared in Tilia software (Grimm, 1987).

3.6. *Diatom analysis*

Diatoms were prepared for counting by using the standard techniques of Battarbee (1986). Sediment samples were treated with 10% HCl to remove the calcareous matter, washed with distilled water, and treated with 30% H_2O_2 in a water bath to remove organic matter. After several washings with distilled water a known amount of microspheres in solution (concentration 8.02×10^6 microspheres/cm^3) was added to the diatom suspensions to enable estimation of diatom concentrations (Battarbee and Kneen, 1982). A few drops of diatom suspension were dried on a cover-glass. Permanent microscope slides were mounted in Naphrax.

The results are presented as a percentage diatom diagram prepared with Tilia software (Grimm, 1991–2011). We considered indicator parameters such as habitat category, dominant taxa (with frequency over 2%) and preference for pH and trophy.

4. Results and interpretations

4.1. *Lithology and age of sediments*

Lithology of the whole profile from Lake Suchar Wielki is showed in Fig. 3 (for details see Drzymulska et al., 2014).

The studied section of the Lake Suchar Wielki profile contains sapropel. Results of LOI measurements indicate high and rather stable content of the organic material in this sediment, between 67 and 72% (Fig. 5). Only in the lowest analyzed sample, value of the organic matter is slightly lower, about 63%.

The age-depth model shows that the sedimentation rate in analysed section of the Lake Suchar Wielki profile is quite uniform (Fig. 3). It also made it possible to determine the approximate age of each sample analyzed by palaeoecological methods (Figs. 4 and 5). The chronostratigraphic resolution of analyzed samples oscillated between 15 and 45 years.

The beginning of a series of Preboreal climate coolings registered in the Lake Suchar Wielki profile was radiometrically dated at 9640 ± 45 ^{14}C BP. About 9600 ^{14}C BP, there was a radiocarbon *plateau* (Reimer et al., 2013) – about a 200-yr period, wherein the rate of ^{14}C disappearance in the organic remains was similar as a decline rate of the 14C concentration in the atmosphere. Thus, the obtained ^{14}C date identifies a calendar age with a big error of ca. 150 years (11,189–11,034 cal. BP). In the age-depth model of the Lake Suchar Wielki profile, we used the date of the lower boundary of this age range (11,189 cal. BP), assumpting that the beginning of the radiocarbon plateau was simultaneously the beginning of the climate cooling. The decrease of ^{14}C content in the atmosphere was not only the effect of a reduction in its production resulting from the changes in the Sun's magnetic field and the intensity of cosmic radiation. In addition, it also reflects the release of carbon from the Earth's natural sources, e.g. the oceans, wetland sediments, erosion of $CaCO_3$, volcanic eruptions, etc., where the concentration of ^{14}C is much lower than atmosphere. Some processes of the carbon release were influenced no climate, and vice versa – the climate

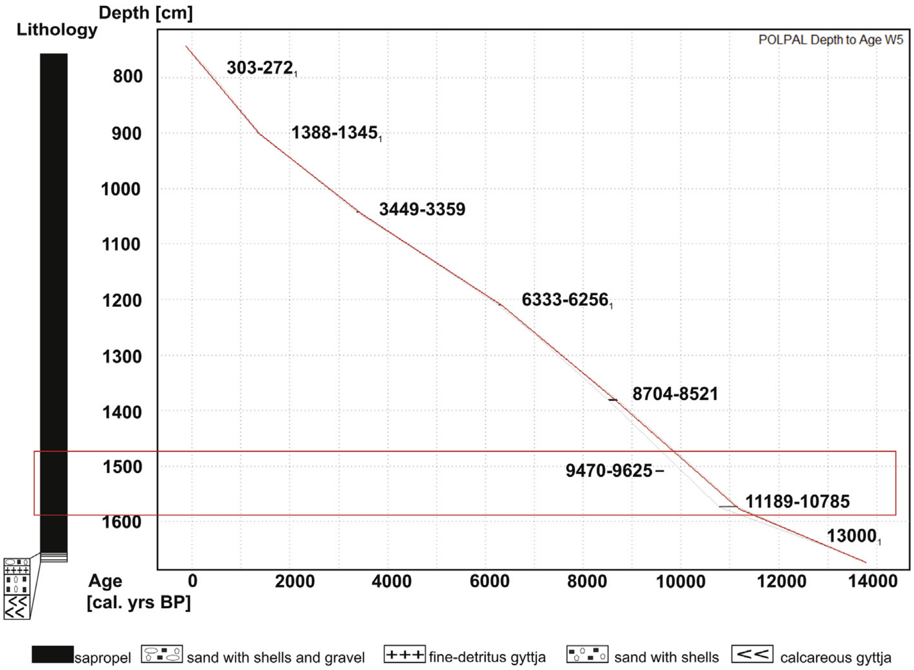

Fig. 3. Lithology of analyzed profile and age/depth model for the Lake Suchar Wielki profile: 1 – dates transferred from the well dated profile from Lake Szurpiły (see Table 2). Depths are counted from the water surface.

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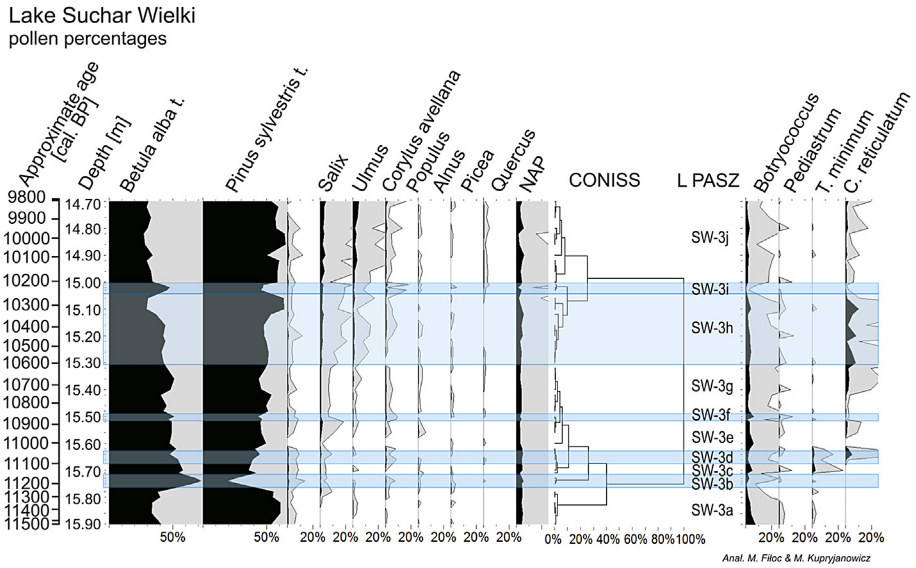

Fig. 4. Simplified pollen percentage diagram from the Preboreal part of the Lake Suchar Wielki profile (only selected pollen curves). Blue color indicates subzones reflecting the climate coolings. *T. minimum* – *Tetraedron minimum*, *C. reticulatum* – *Coelastrum reticulatum*. Depths are counted from the water surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

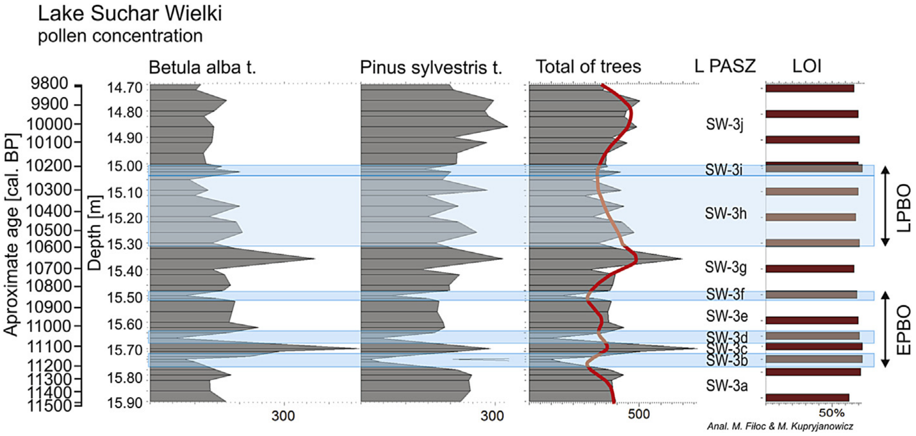

Fig. 5. Simplified pollen concentration diagram from the Preboreal part of the Lake Suchar Wielki profile (only selected pollen curves). Red line on the diagram with total concentration of trees pollen marks smoothened by 25%. Blue color indicates subzones reflecting the climate coolings. EPBO – the early Preboreal oscillations; LPBO – the late Preboreal oscillations. Depths are counted from the water surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was affected some of these processes. This effect is known to have occurred 10,000–11,000 years ago, during the Younger Dryas (Walanus and Goslar, 2009).

The radiocarbon date defining the youngest cold climate oscillation recorded in the Lake Suchar Wielki profile (8560 ± 50 ^{14}C BP = 9625-9550 cal. BP) suggests its mid-Boreal age. Nevertheless, we find this date to be rejuvenated, due to clear dominance during this episode, of *Pinus sylvestris* t. and *Betula alba* t. and the almost complete absence of *Corylus avellana* in the pollen record. The last has a maximum of spreading throughout Central Europe during the Boreal (Giesecke et al., 2011).

In the aforementioned situation, the upper date used in the age-depth model of the studied part of the Lake Suchar Wielki profile is the date of the sample taken from a core about 1 m above (7820 ± 35 ^{14}C BP = 8704–8529 cal. BP). Due to the constant sedimentation rate of sapropel sediment in other humic lakes situated nearby (e.g. Drzymulska et al., 2014), we put forward that the obtained resolution of ^{14}C dates (about 2000 years) is sufficient for a reliable age-depth model (cf. Walanus and Goslar, 2009). Moreover, the correctness of the modeled age is confirmed by the good agreement between the age of the youngest registered cold oscillation (ca. 10,200 cal BP) and the beginning of the next radiocarbon *plateau*, about 8900–9000 ^{14}C BP (Björck et al., 1997) attributable to ca. 10,200–10,000 cal. BP.

4.2. Local pollen zonation

All the local pollen assemblage zones (L PAZ) determined in the complete percentage pollen profile from Lake Suchar Wielki were described in detail in previous articles (Drzymulska et al., 2014; Fiłoc et al., 2014). The section of pollen profile presented in this paper belongs to SW-3 *Pinus-Betula* L PAZ. Ten local pollen assemblage subzones (L PASZ) were established for this zone; they are marked by the subsequent letters from a to j (Figs. 4 and 5; Table 3).

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Table 3
Characteristics of local pollen assemblage subzones (L PASZ) distinguished in the Preboreal part of the profile from Lake Suchar Wielki. Blue color indicates subzones reflecting the climate coolings. Depths are counted from the water surface.

Zone/sub-zone	Depth [m]	Approximate age [cal. BP]	Description
SW-3 Pinus-Betula	15.90 −14.70	11,590–9825	Domination of *Pinus sylvestris* t. (36–64%) and *Betula alba* t. (29–58%); start of continuous curves of *Ulmus* and *Corylus avellana* and their gradual increase to 4% and 5%, respectively; rather high proportion *Salix* (to 1.5%) and *Populus* (to 2%); share of NAP quite low (3–6%).
SW-3a *Pinus*	15.90 −15.78	11,590–11,296	Peak of both percentages (54–61%) and concentration of *Pinus sylvestris* t.; depression of *Betula alba* t. percentages (34–41%). Pollen tress concentration relatively high (430–300). Culmination of *Botryococcus* (7.5%).
SW-3b *Betula*	15.75 −15.73	11,193–11,164	High peak of *Betula alba* t. percentages (66–72%) and depression of *Pinus sylvestris* t. (19–28%). The lowest concentration of pollen tress in the whole analyzed part of the profile (100). Decline in share of *Botryococcus* (below 1%).
SW-3c *Pinus-Botryococcus-Pediastrum-Tetraedron*	15.71 −15.70	11,142–11,120	Fall of *Betula alba* t. below 57%; increase of *Pinus sylvestris* t. above 35%. Maximum of pollen tress concentration (above 750). Culmination of *Tetraedron minimum* (to 3%); the increase in the share of *Botryococcus* (5%).
SW-3d *Pinus-Populus*	15.66 −15.64	11,075–11,031	Further decline of *Betula alba* t. below 47%. Increase of *Pinus sylvestris* t. above 45%. Decrease of pollen tress concentration (to 110). Depression of *Botryococcus* and *Tetraedron minimum*; First peak of *Coelastrum reticulatum* (5%).
SW-3e *Pinus-Coelastrum*	15.62 −15.52	11,017–10,884	Proportions of *Betula alba* t. and *Pinus sylvestris* t. oscillating around 50%. Increase of pollen tress concentration (360–430). Increase in share of *Botryococcus* (5%); disappearance of *Tetraedron minimum*.
SW-3f *Pinus-Betula*	15.51 −15.50	10,870–10,855	Increase of *Betula alba* t. to 51% and decline of *Pinus sylvestris* t. to 44%. Sharp decrease in tress concentration (150). Percentages of *Coelastrum reticulatum* (to 1%) lower than previous subzone; peak of *Botryococcus* (6%).
SW-3g *Pinus*	15.48 −15.32	10,840–10,634	Decrease of *Betula alba* t. to ca. 41%, and rise of *Pinus sylvestris* t. to ca. 54%. High concentration tress with maximum (690). Re-appearance of *Tetraedron minimum*; the increase in the share of *Coelastrum reticulatum* (3%);
SW-3h *Ulmus-Corylus-Coelastrum*	15.30 −15.06	10,605–10,296	Share of *Betula alba* t. below 44% and *Pinus sylvestris* t. above 48%; increase of *Ulmus* and *Corylus avellana* to about 2%. Fall of pollen concentration (470–250). Culmination of *Coelastrum reticulatum* (to 10%).
SW-3i *Betula-Populus*	15.03 −15.01	10,252–10,222	Peaks of percentages and concentration of *Betula alba* t. (to 48%) and *Populus* (2%); depression of *Pinus sylvestris* t. (ca. 45%). Concentration of tress still low to 290. Deep depression of *Botryococcus* (below 1%) and *Coelastrum reticulatum* (below 0.5%).
SW-3j *Ulmus-Corylus*	15.00 −14.70	10,163–9825	*Ulmus* proportion higher than previous subzones (1–4%); increase of *Corylus avellana* to ca. 5%; continuous occurrence of *Quercus* (below 1%); values of *Pinus sylvestris* t. (oscillating around 55%); decline of *Betula alba* t. to ca. 27%. Pollen tress concentration high (310–470). Gradual rise of *Botryococcus* to ca. 3% and *Coelastrum reticulatum* to ca. 5%.

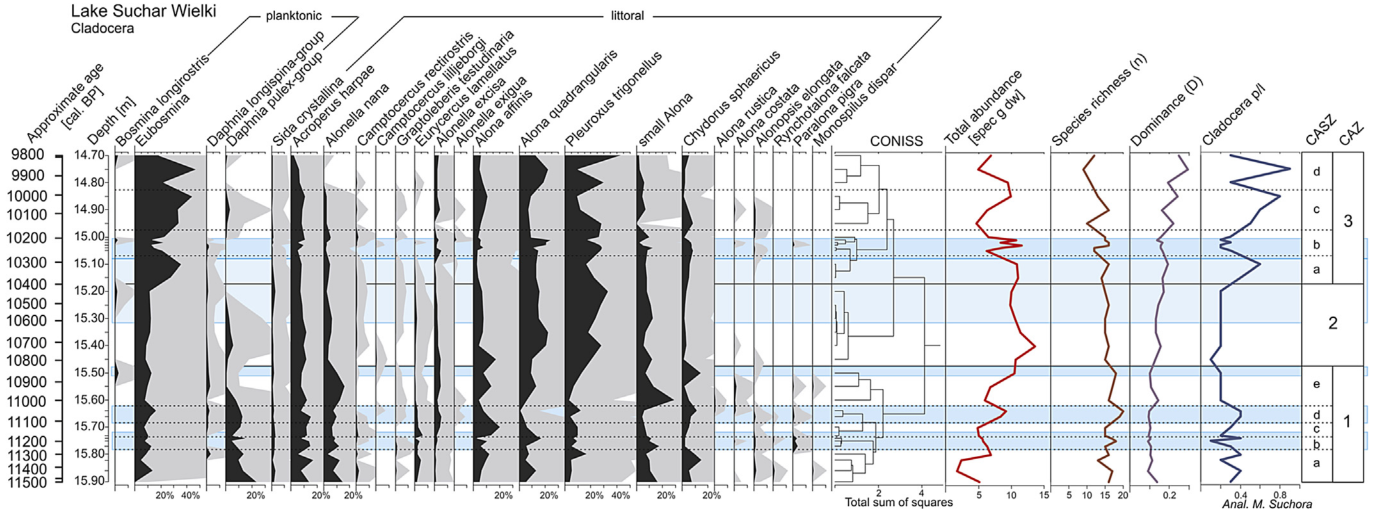

Fig. 6. Cladocera percentage diagram from the Preboreal part of the Lake Suchar Wielki profile. Blue color indicates subzones reflecting the climate coolings. Depths are counted from the water surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Cladocera assemblage zones

In the studied section of the core we identified 24 Cladocera taxa, belonging to four families: Bosminidae, Daphniidae, Chydoridae and Sididae. Within the entire section the dominance of littoral taxa (constituting 53–88% of the Cladocera population), as well as low species richness (9–20 taxa in single sample), were typical. Three Cladocera assemblage zones (CAZ) with subzones (CASZ) are distinguished in the diagram illustrating the used results (Fig. 6; Table 4).

Table 4
Characteristics of Cladocera assemblage zones (CAZ) and subzones (CASZ) distinguished in the Preboreal part of the profile from Lake Suchar Wielki. Blue color indicates subzones reflecting the climate coolings. Depths are counted from the water surface.

Zone/ subzone	Depth [m]	Approximate age [cal. BP]	Description
CAZ 1	15.90–15.50	11,590–10,855	Fluctuating total Cladocera abundance (1.7–9.1 × 104 spec./g dw), with generally increasing trend. Low dominance in the population structure. Domination of the littoral species – high abundance of *Acroperus harpae, Alonella nana, Chydorus sphaericus, Pleuroxus trigonellus, Alona affinis* and *Alona quadrangularis* as well as taxa of small *Alona*. Share of planktonic Cladocera from 13% to 31% (p/l ratio 0.2–0.4) – high share of Daphnidae (*Daphnia pulex*-group) and *Eubosmina*.
CASZ 1a	15.90–15.80	11,590–11,340	Increased number of Cladocera individuals. In planktonic group taxa of *Daphnia longispina*-group appear. Among littoral cladocerans, presence of *Alonopsis elongata, Monospilus dispar* and *Rynchotalona falcata*.
CASZ 1b	15.78–15.74	11,296–11,193	Drop of total Cladocera abundance. Disappearance of taxa from *Daphnia longispina*-group. Decline in relative abundance of *Pleuroxus trigonellus, Chydorus sphaericus* and *Alona afinis*. Co-existence of oligotrophic *Alonopsis elongata, Rynchotalona falcata, Paralona pigra*. Fluctuations in p/l ratio (0.1–0.4).
CASZ 1c	15.73–15.70	11,164–11,120	Reappearance of *Daphnia longispina*-group taxa. Maximum of *Alona affinis*. Decline of *Alonopsis elongata*, *Rynchotalona falcata* and *Paralona pigra.*
CASZ 1d	15.66–15.64	11,075–11,031	Increase of species richness and total Cladocera abundance. Rather high p/l ratio (0.2–0.3). Appearance of *Camptocercus lilljeborgi.* Culminations of *Alonopsis elongata, Rhynchotalona falcata* and *Paralona pigra.*
CASZ 1e	15.60–15.50	11,017–10,855	Clear decline of planktonic taxa, both Bosminidae and Daphnidae – p/l ratio 0.2. Decline of *Camptocercus lilljeborgi, Alonopsis elongata* and *Rynchotalona falcata.* Maxima of *Alonella nana* and small *Alona*. At the end of the sub-phase elevated species richness (due to appearance of *B. longirostris, C. lilljeborgi* and re-appearance of *A. elongata*) and peak of *Chydorus sphaericus.*
CAZ 2	15.45–15.20	10,825–10,472	Highest in whole profile number of individuals (98–136 × 103 spec./g dw). Increasing dominance due to high abundance of large-bodied littoral taxa – *Pleuroxus trigonellus* and *Alona quadrangularis.* Disappearance of oligotrophic taxa (*Rynchotalona falcata, Paralona pigra, Alonopsis elongata*). Low and very stable p/l ratio (0.1–0.2).
CAZ 3	15.15–14.70	10,428–9825	High proportion of planktonic species, namely *Eubosmina*. Fluctuations in the total number of cladocerans, with generally decreasing trend. Decrease of species richness and further increase of dominance (mainly due to expansion of *Eubosmina*).
CASZ 3a	15.15–15.10	10,428–10,355	Increase of planktonic taxa due to increase of *Eubosmina* taxa, whilst total decay of *Daphnia pulex*-group – peak of p/l ratio (0.4–0.6). High total abundance (109–110 × 10^4 spec./g dm).
CASZ 3b	15.05–15.00	10,296–10,222	Decline of planktonic species expressed by low p/l ratio (0.2–0.3). High changeability of Cladocera abundance (a decrease followed by an increase). Initially present *Alonopsis elongata,* then *Camptocersus lilljeborgi* and *Paralona pigra.*
CASZ 3c	14.98–14.85	10,193–10,046	Re-appearance of *Daphnia pulex*-group; increase of *Eubosmina*; rise of p/l ratio from 0.3 to 0.9; presence of *Alonopsis elongata*.
CASZ 3d	14.80–14.70	9957–9825	Final decline of *Alonopsis elongata*, as well as *Alona nana*, *Alonella exigua* and *Graptoleberis testudinaria*. Decline of species richness.

4.4. Diatom assemblage zones

In the studied section of the core we identified 136 taxa of diatoms (species and varieties). The diatom diagram was divided into 6 diatom assemblage zones (DAZ); three of them were divided into subzones (DASZ) (Fig. 7; Table 5).

4.5. Changes in the environment of the Lake Suchar Wielki region during the Preboreal

Ten stages of environmental changes in the region of Lake Suchar Wielki were recognized for the Preboreal period of the Holocene. They were distinguished mainly based on palynological

Table 5
Characteristics of diatom assemblage zones (DAZ) and subzones (DASZ) distinguished in the Preboreal part of the profile from Lake Suchar Wielki. Blue color indicates subzones reflecting the climate coolings. Depths are counted from the water surface.

Zone/ subzone	Depth [m]	Approximate age [cal. BP]	Description
DAZ 1	15.90–15.82	11,590–11,370	Decline in the share of planktonic diatoms, and increase of benthic diatoms (*Staurosira construens*, *Navicula radiosa*). Presence both of circumneutral and alkaliphilous taxa. Diatom valve concentration rise from 12.6 to $21.0 \times 10^6/\mathrm{cm}^3$.
DAZ 2	15.80–15.65	11,340–11,053	Domination of planktonic diatoms. Prevailing of oligotraphentic species; relatively high proportion of oligotraphentic, oligo-mesotraphentic, eutraphentic and meso-eutraphentic diatoms. Increase indicator p/l to 5.4. High diatom valve concentration: $75.9 \times 10^6/\mathrm{cm}^3$.
DASZ 2a	15.80–15.76	11,340–11,244	Firstly domination of planktonic (*Cyclotella comensis*, *Puncticulata radiosa*) and then benthic species (*Achnanthidium minutissima*, *Navicula vulpine*, *Sellaphora laevissima*). Increase participation of pH circumneutral taxa; decrease of alkaliphilous taxa. Domination of oligotraphentic taxa; decrease of meso-eutraphentic; relatively high proportion of mesotraphentic and eutraphentic. At the begging of subzone high proportion of indicator p/l – 5.0, next decreases until 1.5.
DASZ 2b	15.75–15.74	11,193–11,178	Increase of planktonic diatoms (*Cyclotella comensis*, *Puncticulata radiosa*). Participation of pH circumneutral taxa slightly decrease. Increase of oligotraphentic taxa. Rise of indicator p/l to 3.4.
DASZ 2c	15.73–15.71	11,164–11,142	Increase of benthic diatoms (*Achnanthidium minutissima*, *Navicula radiosa*); deep decline of planktonic diatoms. Increase participation of pH circumneutral taxa; fall of alkaliphilous taxa. Increase of meso-eutraphentic; decrease of oligotraphentic taxa. Decrease of indicator p/l to 2.9.
DASZ 2d	15.70–15.65	11,120–11,053	Re-increased share of planktonic diatoms (*Cyclotella comensis*, *Cyclotella planktonica*, *Puncticulata radiosa*). Decrease participation of pH circumneutral taxa; rise of alkaliphilous taxa. Increase share of oligotraphentic and eutraphentic taxa; drop of meso-eutraphentic. Re-increased share of indicator p/l from 0.9 until 5.4.
DAZ 3	15.64–15.42	11,031–10,766	Domination of benthic diatoms; low proportion of planktonic taxa. Still prevailing of pH circumneutral taxa; occurrence of no-numerous alkaliphilous taxa. High proportion of meso-eutraphentic, mesotraphentic diatoms and taxa with a broad range of tolerances (oligo- to eutraphentic). Decrease indicator p/l to 1. Diatom valve concentration lower than previous zone from 23.8 to $1.4 \times 10^6/\mathrm{cm}^3$.
DASZ 3a	15.64–15.58	11,031–10,972	Significant participation of planktonic taxa (*Cyclotella comensis*). High proportion of oligotraphentic diatoms. Low rate of p/l – 1.2.

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Table 5 (*continued*)

Zone/ subzone	Depth [m]	Approximate age [cal. BP]	Description
DASZ 3b	15.52 −15.42	10,884–10,766	Decline in participation of planktonic taxa, and then rise. Proportion of oligotraphentic diatoms decreases, and of oligo-mesotraphentic diatoms increases. The lowest values of p/l − 0.1.
DAZ 4	15.40 −15.20	10,722–10,472	Absolute domination of benthic diatoms (*Sellaphora laevissima, Achnanthidium minutissimum, Pinnularia gibba*). Absolute domination of circumneutral taxa; slightly higher than previous zone proportion of meso-eutraphentic and mesotraphentic diatoms and taxa with a broad range of tolerances (oligo- to eutraphenic). Still low indicator p/l. Very low diatom valve concentration 4.2 $\times$ 10^6/cm^3
DAZ 5	15.15 −14.90	10,848–10,090	Participation of planktonic species rise and then decline. Domination of circumneutral taxa; rise of alkaliphilous taxa. Prevailing of oligotraphentic species; high proportion of eutraphentic and mesotraphentic taxa. Fluctuations of indicator p/l. Increase in share of Diatoms/Chrysophyceae cysts. High and variable diatom valve concentration, from 4.8 until 31.9 $\times$ 10^6/cm^3.
DASZ 5a	15.15 −15.10	10,848–10,355	Domination of planktonic diatoms, mainly *Cyclotella comensis* and *Puncticulata radiosa*. Prevailing of pH circumneutral, and then alkaliphilous taxa. Firstly domination of oligotraphentic, and next eurtraphentic species. Indicator p/l increases from 6.3 until 31.9. First and the largest increase in share of Diatoms/Chrysopohyceae cysts (51.7).
DASZ 5b	15.06 −15.02	10,296–10,237	Decline of planktonic taxa; benthic species rise, mainly *Amphora copulata*, *Navicula radiosa*, *Neidium ampliatum*, *Pinnularia gibba* and *Sellaphora laevissima*. Domination of pH circumneutral; low proportion of alkaliphilous diatoms. Prevailing of mesotraphentic taxa; high values of meso-eutraphentic and oligo-eutraphentic taxa; deep depression in oligotraphentic taxa. Indicator p/l decreases to 1.0, a then slightly increases. Drop in share of Diatoms/Chrysopohyceae cysts until 1.0.
DASZ 5c	15.01 −15.00	10,222–10,207	Co-occurrence planktonic (*Cyclotella comensis* and *Puncticulata radiosa*) and benthic taxa (*Pinnularia viridis*). Prevailing of oligotraphentic taxa; high values of meso-eutraphentic and oligo-eutraphentic taxa. Indicator p/l higher (1.8) than previous subzone. Increase share of Diatoms/Chrysopohyceae cysts: 3.3.
DASZ 5d	14.95 −14.90	10,163–10,090	Values of particular taxa and their ecological groups similar as the subzone DASZ 5a. Indicator p/l increases to 27.1. High share of Diatoms/Chrysopohyceae cysts: 7.9–9.3.
DAZ 6	14.80 −14.70	9957–9825	Firstly domination of benthic (*Sellaphora laevissima*, *Pinnularia gibba*) and then planktonic species (*Cyclotella comensis*). Domination of pH circumneutral; increase of alkaliphilous diatoms. High share of mesotraphentic, meso-eutraphentic and diatoms and taxa with a broad range of tolerances (oligo- to eutraphentic). Indicator p/l temporarily decreases to 1.4. Share of Diatoms/Chrysopohyceae cysts lower than previous zone. Low diatom valve concentration 10.7 $\times$ 10^6/cm^3.

data reflecting terrestrial vegetation around the studied lake, and thus correspond with subsequent pollen subzones.

The main cause of reconstructed vegetation changes in the vicinity of the examined lake, and aquatic assemblages of algae, diatoms and cladocerans inhabiting this water body, were most likely climate oscillations. When interpreting the obtained pollen records in terms of changes in vegetation that could have resulted from cold climate oscillations during the Preboreal, we assumed that a minor and/or short-time deterioration in climate conditions does not have to have resulted in the decline of some species and changes in the composition of vegetation, but might only have reduced the level of flowering and pollen production. In palynological records from lake sediments this should be manifested by reduced concentrations of pollen, but only if the rate of sediment accumulation has not changed considerably, as was the case in the analysed sediment profile. This concerns both the total pollen concentration and concentrations of pollen produced by individual taxa, particularly those more sensitive to low temperatures.

4.5.1. Phase 1 – quite warm and humid (ca. 11,600–11,300 cal. BP)

L PASZ SW-3a; CASZ 1a; DAZ 1 and DASZ 2a – lower and middle part.

At the very beginning of the Holocene, pine and birch were the only trees growing in the vicinity of Lake Suchar Wielki, and pine-birch forests dominated in the vegetation cover of the region. This is shown by the high percentage values of *Pinus sylvestris* t. and *Betula alba* t. pollen (Fig. 4). The area of open herbaceous vegetation was relatively small (low values of non-arborescent pollen – NAP). A high concentration of *Pinus sylvestris* t. and *Betula alba* t. pollen in sediment (Fig. 5) documents favourable conditions for the intensive flowering of these trees and abundant production of their pollen. The first thermophilous tree which could have reached into the studied area at that time was elm. Its probable presence is indicated by the start of its continuous (though low-percentage) pollen curve.

The high total concentration of diatoms and cladocerans indicates favourable conditions for the development of fauna and flora inhabiting the studied lake. However, despite generally good

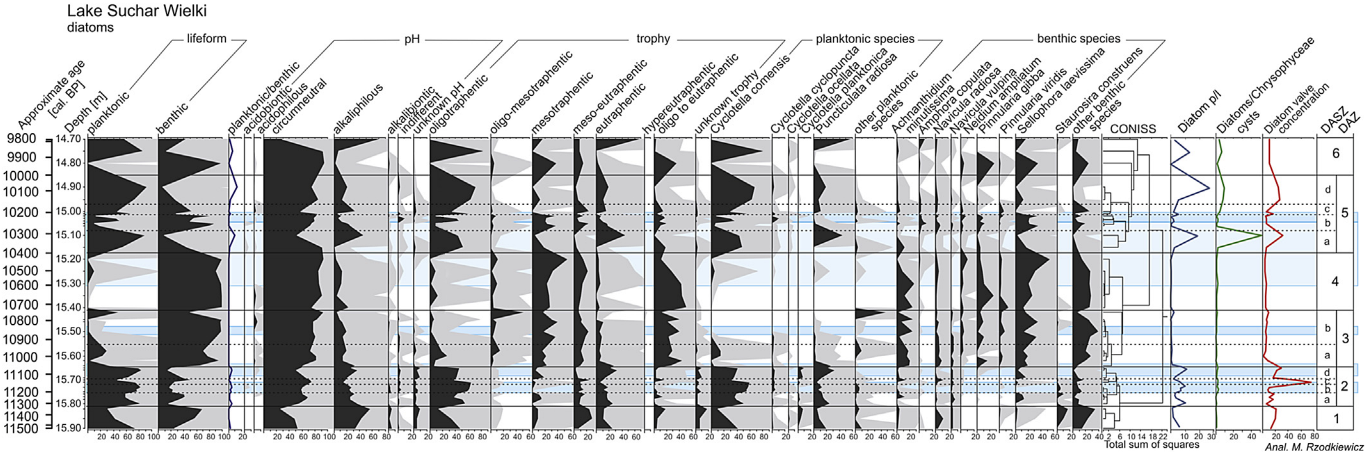

Fig. 7. Diatom percentage diagram from the Preboreal part of the Lake Suchar Wielki profile. Blue color indicates subzones reflecting the climate coolings. Depths are counted from the water surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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thermal conditions, the lake was oligotrophic (or oligo-mesotrophic), which can be concluded from the high proportion of oligotraphentic diatoms, as well as from the presence of cladocera taxa preferring low trophy (e.g. *Bosmina (E) longispina*, *Daphnia pulex*-group, *Alonopsis elongata, Rynchotalona falcata, Paralona pigra*). Many cladocerans present at that time in the lake in high numbers represented arctic species, with a tolerance to a wide spectrum of temperature and trophy levels (e.g. *Acroperus harpae, Alonella nana, Chydorus sphaericus, Alona quadrangularis, Eurycercus lamellatus*). They were already present in the lake (in low numbers) at the end of late glaciation; only *Alona affinis* appeared in the lake only at the beginning of the Preboreal (M. Suchora, unpublished data). Moreover, cold-preferring taxa such as *Alonopsis elongata* and, oligotrophic, *Rynchotalona falcata* were also previously present.

The dominance of littoral over planktonic species (p/l), both among cladocerans and diatoms, indicates that the lake in that period was relatively shallow. This could also indicate an intense development of littoral assemblages, which even in a deep, well-lit, clear-water lake could occupy most of the bottom surface.

4.5.2. Phase 2 – cooling (ca. 11,300–11,150 cal. BP)

L PASZ SW-3b; CASZ 1b; DASZ 2a – uppermost part, 2b, 2c.

The strong and rapid decrease in pollen concentration (Fig. 5) illustrates an instant cooling. The deterioration of the climate resulted mainly in a significant reduction in the flowering and pollen production of pine (a dramatic decline in the concentration of *Pinus sylvestris* t. pollen). The cooling probably restricted the florescence of birch less, as it is more resistant to low temperatures than pine. The very reduced supply of pine pollen to the sediment, and much less restriction in the supply of birch pollen is reflected in the palynological record as a rapid fall in the percentage values of *Pinus sylvestris* t. pollen, and a simultaneous strong increase in the percentage of *Betula alba* t. pollen (Fig. 4). This pattern should not, therefore, be interpreted as indicative of birch spreading.

The impact of cooling on the lake ecosystem was reflected by a decrease in the frequency of some green algae (*Botryococcus* – Fig. 4), and in the total concentration both of diatoms and cladocerans (Figs. 6 and 7). Some taxa of Cladocera (*Bosmina* (E) *longispina*, *Daphnia pulex*-group) can tolerate the changed conditions better than other (Alonso, 1996). However, in Cladocera taxonomic composition we observed the decline of taxa from the *Daphnia longispina*-group, and the lower abundance of *Pleuroxus trigonellus*, *Graptoleberis testudinaria* and *Chydorus sphaericus*, specific for waters with higher trophy. According to Fitzmaurice (1965), *Pleuroxus trigonellus* reaches its maximum development in late summer, early autumn and winter. A shorter warm season and the earlier than normal onset of cold temperatures could have a negative effect on this species. These signals, as well as a common increase in the share of oligotrophic and cold-preferring taxa – *Alonopsis elongata, Rynchotalona falcata* and the appearance of *Paralona pigra*, confirm the cooling and decreasing trophy of the lake (Duigan, 1992; Hessen and Walseng, 2008). As *Alonopsis elongata* is a common taxon in lakes from northern areas (Hessen and Walseng, 2008), its presence suggests a decrease in water temperature (Szeroczyńska and Zawisza, 2011). It is also associated with waters of low trophy and conductivity. Also diatom data show unstable physical and/or chemical conditions in the contemporary lake. Cooling could be indicated by *Cyclotella* sp., dominant at this time, and typical for clear, oligotrophic Arctic water bodies (e.g. Gregory-Eaves et al., 1999; Rühland and Smol, 2002; Rühland et al., 2008) and alpine-tundra lakes (Bigler and Hall, 2002), and *Staurosirella* sp. type, often present in ice cover on lakes (Smol, 1988; Lotter and Bigler, 2000), and tolerant to worse light conditions (Anderson, 2000) or indicative of high alkalinity (Battarbee, 1986).

At this time a slight increase in water level was observed, as suggested by the increased value of the p/l ratio for Cladocera and diatoms.

4.5.3. Phase 3 – warming (ca. 11,150–11,100 cal. BP)

L PASZ SW-3c; CASZ 1c; DASZ 2d – lowest part.

The rapid and very strong increase in the concentration of birch and pine pollen suggests an improvement in the thermal conditions (the concentration of pine pollen increased 14 times, and of birch 7 times – Fig. 5). There are also numerous other signals of climate amelioration.

The frequency of green algae (*Pediastrum, Botryococcus*, *Tetraedron*) rises (Fig. 4). The share of oligotrophic and cold-preferring taxa of cladocerans (*Alonopsis elongata, Rynchotalona falcata* and *Paralona pigra*) declines (Fig. 6). The highest diatom valve concentration indicates the mass spreading of diatoms, the greatest in the whole Preboreal.

4.5.4. Phase 4 – cooling and increase in humidity (ca. 11,100–11,000 cal. BP)

L PASZ SW-3d; CASZ 1d; DASZ 2d – middle and upper part and DASZ 3a – lowest part.

The second cold event was recorded as again a decrease in the concentration of pine and birch pollen (Fig. 5). Due to the fact that the decline in the concentration of both these trees is similar, their percentage values remain almost unchanged (Fig. 4).

In the lake at this time, decline in algae (Fig. 4) and diatom (Fig. 7) abundance took place, which was also caused by cooling. Increase in Cladocera (Fig. 6) abundance could result from an increased share of *Pleuroxus trigonellus*, a species feeding on detritus (Fryer, 1996). Increase in the share of oligotrophic and cold-preferring taxa of Cladocera – *Alonopsis elongata, Rynchotalona falcata* and *Paralona pigra* confirms a cooling and decrease in the trophy of the lake. *Graptoleberis testudinaria,* present during the previous cold event, also reappeared in the lake. The first occurrence of *Camptocercus lilljeborgi* was observed, a species typical of lakes of the Northern area (Hessen and Walseng, 2008), and reported for the time of a cold event 8.2 ka in Lake Ostrowite, N Poland (Szeroczyńska and Zawisza, 2011). *Camprocercus lilljeborgi*, cladocerans species characteristic of cold periods occurred for the first time (Fig. 6).

A slight increase in the population of planktonic cladocerans and a stable high share of planktonic diatoms (increased p/l ratio for Cladocera and diatoms) are indicative of the higher water level in the lake.

4.5.5. Phase 5 – warming and drying (ca. 11,000–10,880 cal. BP)

L PASZ SW-3e; CASZ 1e – lower and middle part; DASZ 3a – middle and upper part and DASZ 3b – lower part.

Both high percentage values of *Pinus sylvestris* t. and *Betula alba* t. pollen (above 50% each – Fig. 4) and their high concentration (Fig. 5) document an improvment of the thermal conditions.

Climate warming and the subsequent increase in the trophy of the studied lake are suggested by the decline of cold-tolerant oligotrophic cladocerans *Paralona pigra* and *Alonopsis elongata* (Fig. 6). *Cyclotella comensis,* a species of diatoms characteristic for water poor in nutrients, is no longer dominant after this phase (Fig. 7). The number of planktonic cladocerans (from Daphnidae and Bosminidae families) drops significantly, which is reflected in a significantly lower p/l ratio for cladocerans, and may suggest a reduction in the water level in the lake, and thus lower humidity during this period. These changes are confirmed by a strong reduction in the share of planktonic diatoms, as well as in the value of the p/l ratio for diatoms.

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4.5.6. Phase 6 – cooling, still dry (ca. 10,880–10,850 cal. BP)

L PASZ SW-3f; CASZ 1e – uppermost part; DASZ 3b – middle part.

The short-lasting (probably ca. 50 years) cooling after ca. 10,850 cal. BP is indicated by an important decrease in pollen concentration (Fig. 5). The forest stands did not change their composition, although the flowering of trees was significantly reduced.

In the composition of Cladocera and diatom assemblages, there are no clear signs of a worsening in thermal conditions. But yet, cold-preferring cladocerans of *Alonopsis elongata* and *Camptocercus lilljeborgi* species typical of the lake of Northern area (Hessen and Walseng, 2008), present during previous cold events, reappear (Fig. 6). A low diatom valve concentration and a high share of Chrysophyceae cysts is observed (Fig. 7), which can also be indicative of climate cooling. On the other hand, the high number of Cladocera species (17–18) and their abundance suggest the presence of favourable conditions for fauna development. A temporary decrease in the frequency of species from the *Daphnia pulex*-group, and the emergence of *Bosmina longirostris* (preferring higher trophy levels) indicate that these favourable conditions could have resulted from improved trophy. The population of *Pleuroxus trigonellus* clearly increased, and from that time this species was dominant among all Chydoridae. A slight increase in trophy level is also suggested by the analysis of diatoms (increased share of mesotrophic and mesoeutrophic species). The very low p/l ratio for diatoms and cladocerans indicates the persistence of low water levels, and thus low humidity during that period.

4.5.7. Phase 7 – warming, still dry (ca. 10,850–10,650 cal. BP)

L PASZ SW-3g; CAZ 2 – lower part; DASZ 3b – upper part and DASZ 4 – lower part.

After ca. 10,800 cal. BP, trees and shrubs with higher thermal requirements, like elm and hazel, could reach into the area more and more (pollen *Ulmus* up to 2%, and *Corylus avellana* up to 1% – Fig. 4). Warming probably progressed quite slowly. This is evidenced by the gradual increase in the share of these mesophilic taxa, and by the gradual decline in the share of birch in favour of pine. It is possible that one last colder period, but of a lower rank than previous coolings, occurred during this phase. Significant fluctuations in the concentration of pollen (Fig. 5) may indicate an unstable and changeable climate in this part of the Preboreal, but with a clear general trend, first to improving (from ca. 10,800 cal. BP), and then to a gradual deterioration (from ca. 10,600 cal. BP). In contrast to wide variations in concentration, only slight variations in the percentage of pine and birch pollen are noted.

In the lake, more eutrophic conditions prevailed at that time. This is indicated by the development of green algae of *Coelastrum reticulatum* (Fig. 4) and a high share of diatoms tolerant to oligotrophic-to-eutrophic waters (Fig. 7). Cladocerans – *Alonopsis elongata, Paralona pigra* – disappeared (Fig. 6), and the water level was still low (low values of p/l ratio).

4.5.8. Phase 8 – warm, initially dry, then an increase in humidity (ca. 10,650–10,300 cal. BP)

L PASZ SW-3h; CAZ 2 – upper part and CASZ 3a; DASZ 4 – upper part, DASZ 5a and DASZ 5b – lower part.

This phase was diversified in terms of climatic conditions, and its paleoecological record is relatively complicated and difficult to interpret. A gradual decrease in pollen concentration suggests a gradual deterioration in plant flowering conditions (Fig. 5). This, however, did not result from cooling, considering the persistent presence of mesophitic elm and hazel (Fig. 4). In the older subzone of this phase, before ca. 10,450 cal. BP, the causative factor could have been low climate humidity due to persistent low water levels in the analysed lake. This is reflected in the dominance of benthic species of cladocerans (Fig. 6) and diatoms (Fig. 7). A relatively high trophy level persisted in the shallow lake, explaining the development of mesotrophic and mesoeutrophic diatoms and the appearance of Cladocera *Bosmina longirostris*. Moreover, the disappearance of the *Daphnia pulex* group, and the presence of *Daphnia longispina* may also indicate increased trophy. The massive growth of *Tetraedron minimum* and *Coelastrum reticulatum* algae is also associated with increased trophy (Jankowská and Komárek, 2000).

A rapid increase in the share of planktonic species, both diatoms and cladocerans, and their p/l ratio at a depth of 15.15 m (Figs. 6 and 7) is indicative of increased water level in the analysed lake ca. 10,450 cal. BP, which resulted from increased humidity. At that time the cold episode suggested a significant increase in the share of cysts of Chrysophyceae.

A synchronised drop in the concentration and percentage values of *Betula alba* t. pollen and a simultaneous increase in the concentration and percentage value of *Pinus sylvestris* t. pollen document the spread of pine.

4.5.9. Phase 9 – cooling and drying (ca. 10,300–10,250/10,220 cal. BP)

L PASZ SW-3i; CASZ 3b; DASZ 5b – upper part and DASZ 5c – lower part.

The cold, dry climate caused a sudden, short-term spread of birch and a decrease in the share of pine. The simultaneous increase in the concentration and the percentage of birch (Fig. 5) documents the change in the composition of forests at the time and the temporary spread of birch. This was accompanied by a slight decrease in the share of pine and hazel, and the instantaneous reduction of share of poplar.

The impact of cooling on the aquatic ecosystem of Lake Suchar Wielki is related primarily to the decreased frequency of green algae (*Botryococcus* and *Coelastrum reticulatum* – Fig. 4), cysts of Chrysophyceae, and share of planktonic Cladocera and diatoms (Figs. 6 and 7). The record of diatoms and Cladocera indicates very abrupt changes at this time. In the Cladocera population, as during the previous coolings, *Alonopsis elongata* and *Paralona pigra* re-appeared (already noted at the end of the previous phase – sample 15.10 and both species decline in the decay of the phase). Also *Alona quadrangularis* reach a greater share. Moreover, the share of planktonic Cladocera decreased – *Bosmina* (*E.*) *coregoni, Bosmina* (*E.*) *longispina* and *Daphnia longispina*-group declined, and *Daphnia pulex* completely disappeared (Fig. 6). This might be associated with the decline in water level. Also, the presence of *Camptocercus lilljeborgi* was noted. Furthermore, analysis of diatoms showed unstable physical and/or chemical conditions in the contemporary lake (Fig. 7). The trophy level of the lake was also reduced, which in the diatom record is indicated by an increase in oligotraphenic species, preferring poor waters, and in the pollen record by the temporary disappearance of eutrophic algae *Coelastrum reticularum* (Fig. 4). In the diatom population, as during the earlier coolings, *Cyclotella comensis* dominated, a characteristic species for water poor in nutrients. A high share was found for benthonic taxa (*Sellaphora laevissima, Navicula radiosa, Pinnularia gibba, Amphora copulata*) generally present in poor waters (Hofmann, 2000). At the same time, there was also a decrease in the concentration of diatoms. This might also be associated with the decline in water level. Water level in the lake decreased significantly (fall of p/l ratio both for diatoms and cladocerans) Fig. 8.

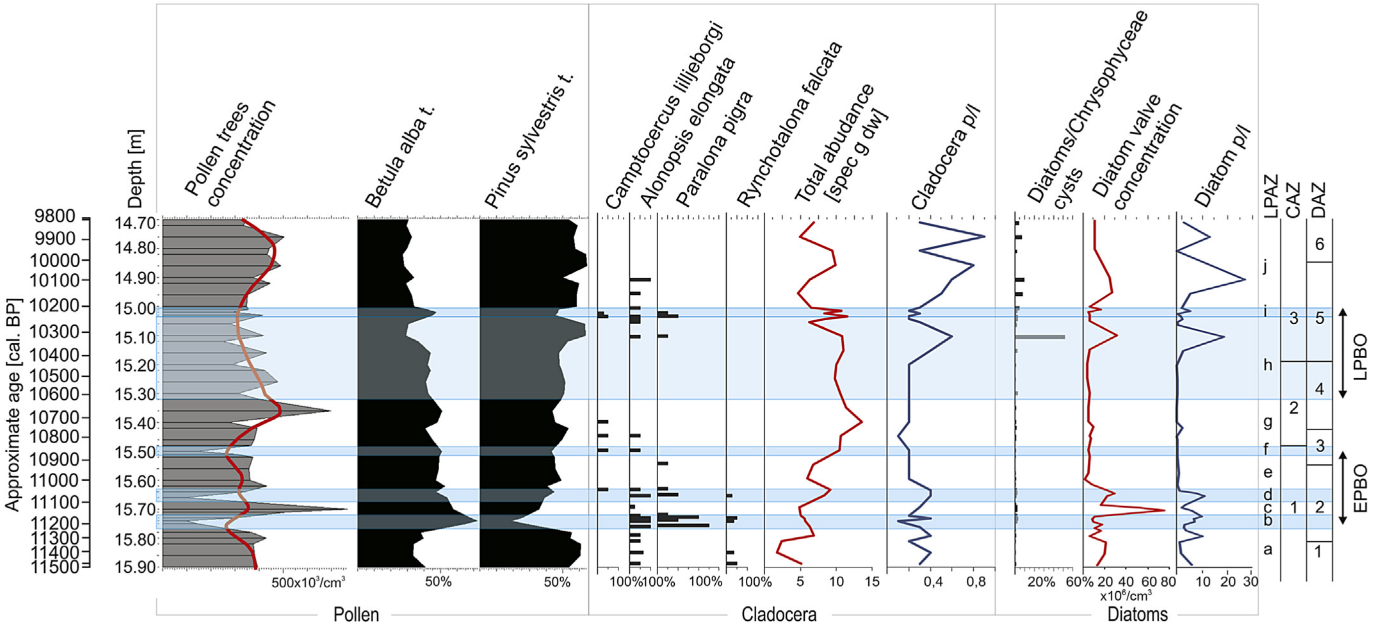

Fig. 8. Correlation of the pollen, Cladocera and diatom records of cold Preboreal oscillations registered in the profile from Lake Suchar Wielki. Blue color indicates subzones reflecting the climate coolings. EPBO – the early Preboreal oscillations; LPBO – the late Preboreal oscillations. Depths are counted from the water surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.5.10. Phase 10 – warming and significant increase in humidity (ca. 10,250/10,220–9850 cal. BP)

L PASZ SW-3j; CASZ 3c and CASZ 3d; DASZ 5c – upper part 5d and DAZ 6.

A return to warm conditions is visible in the continuation of forests with a predominance of pine, birch, and an increasing share of thermophilous plants such as hazel and elm. The concentration of pine and birch declined, but on the other hand the concentration of hazel increased. The improvement in the climate is so large that a continuous pollen curve for oak (*Quercus*) appears.

In the aquatic environment green algae had a higher share than at the previous level, which may indicate improved thermal conditions (Fig. 4). The share of mesoeutrophic and eutrophic diatom taxa and those characteristic for water with a broad spectrum of tolerance increased, but their concentration reduced. The number of *Cladocera* at that time fluctuated. Changes was in the structure of planktonic cladocerans – an increased number of *Bosmina (E.) coregoni*, and at the same time a decreased share of cladocerans from the family Daphnidae – may indicate pressure from predatory fish. From 14.85 onward in Cladocera species composition we observe a decrease in the total abundance, species richness and disappearance of oligotrophic taxa associated with previous coolings (*Alonopsis elongata, Paralona pigra*). The disappearance of other taxa associated with plants (*Alonella nana*, *Alonella exigua, Graptoleberis testudinaria*) may be indicative of a very poor and low-diversified habitat. Diatom communities are dominated by oligotrophic taxa. A strongly oscillating p/l ratio, both for cladocerans and diatoms, indicates significant changes in water levels.

5. Discussion

5.1. The course of cold oscillations during the Preboreal

At the very beginning of the Holocene, from ca. 11,550 to 11,300 cal. BP, forests with strongly prevailing pine dominated in the study area. This might have resulted from the rapid expansion of pine on outwash plains dominating in the vicinity of Lake Suchar Wielki (Ber, 2009) favourable to the development of pine forests due to the dry, sandy soil, and the improving thermal conditions. Outside the study region, in north-eastern Poland the warming at the beginning of the Holocene was associated with the expansion of tree birches (e.g. Klerk et al., 2006; Wacnik, 2009; Lauterbach et al., 2011). This situation indicates that the climate in the study area at the beginning of the Preboreal could have become more continental and/or drier in summer than in other parts of our country. On the Northern Hemisphere the very beginning of the Holocene was characterized by high summer insolation, but still cool or temperate climate (Renssen et al., 2009). Elm (*Ulmus*), as the first tree with greater climatic demands, approached in the Wigry region in NE Poland at that time (Kupryjanowicz, 2007). This is confirmed in the profile from Lake Suchar Wielki by the start of the continuous pollen curve of *Ulmus* ca. 11,350 cal. BP. The initial relatively warm part of the Preboreal registered in NE Poland may be correlated with the warm Friesland Phase occurring in north-western Europe around 11,530–11,500 cal. BP (van der Plicht et al., 2004; Bos et al., 2007). At that time, with an increase in temperature, the amount of precipitation also rose (Bos et al., 2007), which indicates humid climatic conditions.

After the warm beginning of the Holocene few cold episodes occurred in the study region during the following ca. 1.7 thousand years of the Preboreal period. The first three cold episodes occurred in the early Preboreal, between ca. 11,300 and 10,800 cal. BP, and were separated from each other by short warm intervals. In the palynological profile from Lake Suchar Wielki the first of these coolings was registered at ca. 11,300–11,150 cal. BP. The increase in the percentage values of birch, cold-preferring taxa of Cladocera (*Alonopsis elongata, Rynchotalona falcata, Paralona pigra*), and water level suggest colder and wetter conditions in the study area. Furthermore, birch seems to be more resistant to cooling. Although the concentration of pine and birch pollen significantly decreases, pine drops lower. Moreover, the similarly dated cold event was recognized at numerous sites in different parts of north-eastern Europe (e.g. Birks and Birks, 2008; Stančikaitė et al., 2009). It was also noted at several localities in NE Poland. In the profile from Lake

Miłkowskie it was dated to ca. 11,200 cal. BP (Wacnik, 2009), and in the core from Budzewo palaeolake at ca. 11,208–10,780 cal. BP (Kołaczek et al., 2013; Mirosław-Grabowska, 2013). In Lake Hańcza a record of the climate cooling, took place between ca. 11,400 and 11,200 cal. BP (Lauterbach et al., 2011). Also, in the Biebrza Upper Basin, a change in vegetation reflecting the cold early-Preboreal event was registered. It was dated to ca. 11,180–10,820 cal. BP, and it lasted for ca. 60–160 years (acc. Klerk et al., 2006). In addition to the increase in the percentages of *Betula,* this cold climate event was expressed there also by the rise of numerous taxa representing open plant communities. Based on this, Klerk et al. (2006) conclude that the climate at that time become both cooler, but also drier and/or more continental. Magny et al. (2007) suggest that mid-European latitudes underwent wetter conditions in response to the PBO. This has been documented by the higher lake water levels recorded in a large number of European lakes between 11,300 and 11,150 cal. BP. In Poland higher lake-level conditions have been reconstructed, for example in Lake Gościąż at ca. 11,180 cal. BP (Pazdur et al., 1995). This agrees with the data from Lake Suchar Wielki, where the increase in abundance of planktonic diatoms and cladocerans indicate the rise of water level during the first early-Preboreal cold event.

After the first Preboreal cooling, a short warm episode is registered in the profile from Lake Suchar Wielki at ca. 11,150–11,100 cal. BP as a significant increase in the concentration of pine and birch pollen. This short-lived warming was followed by the next abrupt climate cooling, starting from ca. 11,100 cal. BP, during which the concentration of birch and pine decreased again. In this time reappeared cold-water species of Cladocera and diatoms. Moreover, increased p/l ratio for cladocerans and diatoms document another increase in water level. Similar multiple Preboreal cool oscillations, defined as a sequence of fluctuations in water levels, were reported by Magny et al. (2007), who identified in west-central Europe three higher water levels, ca. 11,450–11,400, 11,350 and 11,300–11,150 cal. BP. On Faroe Islands, Iceland and Greenland cold events took place between 11,200 and 11,000 cal. BP (Andresen et al., 2007; Jessen et al., 2008). In the Netherlands ca. 11,127–10,830 cal. BP the colder period still lasted (Bohncke and Hoek, 2007), and similarly in NE Poland ca. 11,280–10,780 cal. BP (Kołaczek et al., 2013).

The improvment of climatic conditions in the vicinity of Lake Suchar Wielki during ca. 11,000–10,900 cal. BP is documented by the rise in the concentration of pine and birch pollen. This warming was related to the shallowing of the lake, as indicated by the decline in the share of planktonic diatoms and cladocerans. At the same time a decrease in water level was also recorded in SE Poland (Kulesza et al., 2012). Between 10,880 and 10,850 cal. BP, in the region of Lake Suchar Wielki, the next cold event took place, which is evidenced by the decrease in the concentration of pine and birch pollen in sediments. This last of the sequence of three coolings was milder. The water level was low at that time, which is also reported for other regions of Poland (e.g. Kulesza et al., 2012) and Europe (Kalis et al., 2003). No decrease in lake trophy was observed, but cold-water cladocerans re-appeared.

The early-Preboreal cold events occurring in Lake Suchar Wielki also occurred at a similar time in a few other sites in NE Poland (ca. 11,208–10,780 cal. BP – Kołaczek et al., 2013), in The Netherlands (ca. 11,127–10,830 cal. BP – Bohncke and Hoek, 2007), and beyond the European continent, in southern Greenland (ca. 11,075–10,800 cal. BP – Andresen et al., 2007) and on the Faroe Islands (ca. 11,000–10,800 cal. BP – Jessen et al., 2008).

The cold events at the beginning of the Preboreal was recognized a long time ago in European records, as a sequence of warm-cold-warm events (e.g. Behre, 1967, 1978). In north-western Europe such an event was defined by Björck et al. (1997) as Preboreal oscillation (PBO) and dated to ca. 11,300–11,150 cal. BP. In the Netherlands the early-Preboreal cooling was registered in several pollen profiles, and it was called the Rhammbeelk phase. It is dated, unlike in north-western Europe, to ca. 11,430–11,350 cal. BP (e.g. Bos et al., 2007) or 11,400–11,300 cal. BP (e.g. Bohncke and Hoek, 2007). Dating of the early-Preboreal cold events was also similar in some other parts of Europe, e.g. in Romania (11,480–11,390 cal. BP – Tóth et al., 2012), in Switzerland (11,450–11,350 cal. BP – Ilyashuk et al., 2009) and in central Poland (11,435–11,400 cal. BP – Ralska-Jasiewiczowa et al., 2003). However, in many European palynological records the cooling dated at the beginning of the Preboreal is absent or not recognized (e.g. Hoek and Bohncke, 2002; Bos et al., 2007). This may be due to the short duration of the cold pulse (only ca. 50–150 yrs), which in the standard resolution pollen analysis has not been registered. On the other hand, the differences in dating of the early-Preboreal cold events registered at various sites suggests that in this period occurred one cooling which could have taken a long time, even about 400 years. This cool period was probably diverse in terms of thermal conditions, and included two or more episodes of cold separated by a warmer period. The record of three early-Preboreal coolings in the studied lake and in southern Greenland (Andresen et al., 2007), and two in Lake Gościąż, Poland (Pazdur et al., 1995; Ralska-Jasiewiczowa et al., 2003), Kingbeekdal, Netherlands (Hoek and Bohncke, 2002), and Juodonys and Petrašiūnai, Lithuania (Stančikaitė et al., 2009), as well as three episodes of high water levels in European lakes (Magny, 2004; Magny et al., 2007) confirm this type of climate change in the early Preboreal (Fig. 2). The early-Preboreal coolings registered in terrestrial profiles from Europe probably overlap in time to the first cool event described in the North Atlantic cores (Bond et al., 1997) and in Greenland ice cores (Björck et al., 1998), at least partially.

After the last of the early-Preboreal cold oscillations, at ca. 10,850 cal. BP, warming was observed in the profile from Lake Suchar Wielki as a rapid increase in total pollen concentration, which was especially marked for pine and birch. It generally lasted up to ca. 10,300 cal. BP. However, it should be noted that the symptoms of climate worsening (probably only drying and/or rise of continentality, without a clear cooling) were recorded in terrestrial ecosystem from ca. 10,600 cal. BP.

In the profile from Lake Suchar Wielki, the record of the late-Preboreal cold oscillation resulting in the short-term changes of vegetation was dated to ca. 10,300–10,200 cal. BP. It probably coincided with a cooling registered in North Atlantic marine records at ca. 10,300 cal. BP (Bond et al., 1997), the Greenland Ice Core Project at ca.10,240 cal. BP (Grönvold et al., 1995; Björck et al., 2001), the Greenland Ice Core Project 2 at ca. 10,275 cal. BP (Zieliński et al., 1997), and a few terrestrial records from Europe (Fig. 2). The temperature dropped by 1 °C in the Carpathian Mountains at ca. 10,350–10,190 cal. BP (Tóth et al., 2012). Magny (2004) determines the increase in water level of a mid-European lake at 10,300–10,000 cal. BP. The pollen record from Lake Flåfattjønnain in southern Norway recorded three changes in vegetation, which could have been caused by cooling (Paus, 2010). They were dated to ca. 10,700, 10,500 and 10,300 cal. BP. Cooling in about 10,200–10,000 cal. BP has also been recognized in the Karelian Isthmus, north-western Russia, where it resulted in a reduction of the vegetation cover (Subetto et al., 2002). Similarly, other records show three shifts in a row, which were recorded at ca. 10,600, 10,450 and 10,300 cal. BP from the Faroe Islands (Jessen et al., 2008).

The trend, when the concentration of birch and pine started a gradual decline, began in the vicinity of Lake Suchar Wielki from around 10,600 cal. BP. At that time pine became dominant in forests. It is worth noting that from ca. 10,450 cal. BP changes were also noted in the lake. The analysis of diatoms and cladocerans indicate that between 10,450 and 10,300 cal. BP the water level increased in the studied lake. In nearby Romoty paleolake, higher water level between 10,500 and 10,350 cal. BP was also noted (Mirosław-Grabowska et al., 2015). The first signs of cooling at that time include the reappearance of *Alonopsis elongata* and increase in the share of Chrysophyceae cysts, and next, an increased percentage share of *Betula alba* t. ca. 10,300–10,200 cal. BP, together with its increased concentration, and decreased concentration of *Pinus sylvestris* t. Simultaneously, the water level in the lake declined, unlike in central-European lakes, where water level increased between 10,300 and 10,000 cal. BP (Magny, 2004). This chronologically uneven response of the terrestrial and lake environment marks three phases of cooling from ca. 10,600, 10,450 and 10,300 cal. BP, which may be associated with three subsequent climate changes that occurred at that time. These coolings were probably connected with the influxes of melt water from Lake Agassiz (see introduction and Fig. 2). Similar changes were observed, for example, on the Faroe Islands, where the recorded winter cooling centred at c. 10,600 cal. BP, a winter/summer cooling centred at c. 10,450 cal. BP and a winter/summer cooling centred at c. 10,300 cal yr BP (acc. Jessen et al., 2008). In Scandinavia, at least three late-Preboreal cold oscillations are recognized (Fig. 2). Moreover, ca. 10,300 cal. BP, there was another change in the activity of the Sun (e.g. Bond et al., 2001; Gupta et al., 2005).

In NE Poland the late-Preboreal cold oscillation was reflected in the record at the Rapa site, where it was dated to 10,250–9917 cal. BP (Kołaczek et al., 2013). A similar oscillation has been dated in the profile of Lake Linówek to ca. 10,050 cal. BP (Gałka et al., 2014).

5.2. Were the Preboreal cold oscillations really caused the spread of birch forests?

In all palynological reports the increased percentage share of *Betula* in pollen records defining cooling in the older phase of the Preboreal is interpreted as a temporary spreading of birch forests, which was a reaction to the colder and wetter climate (e.g. Wacnik, 2009; Kołaczek et al., 2013). Palynological data obtained by us from Lake Suchar Wielki indicate, however, that without analysing changes in the concentration of pollen in the sediment such an interpretation may be unjustified. In the Lake Suchar Wielki profile, during the first Preboreal cold event, a rapid increase in the percentage share of *Betula alba* t. pollen is observed. At the same time the total concentration of pollen, both of *Pinus sylvestris* t., and *Betula alba* t., strongly decreased (Figs. 5 and 8). Because no increased rate of sediment deposition potentially responsible for the decrease in pollen concentration was recorded for that period, and there was no input of the terrestrial material, this change could have only resulted from reduced pollen supply. This was most likely caused by a clear deterioration in the flowering and pollen production by all plants during cold events. Neither the scale of this cooling (decrease in annual mean temperature by ca. 1 °C – e.g. Lotter and Bigler, 2000; Larocque-Tobler et al., 2010), nor the short duration of this event (ca. 150 years – e.g. Björck et al., 1997; Wagner et al., 1999) indicate that any of the plant taxa reduced their cover significantly at that time. Because the drop in the pollen concentration for *Pinus sylvestris* t. was considerably greater than that for *Betula alba* t. we can assume that cold events more negatively affected pollen production by pine than birch, which is more resistant to low temperatures, particularly *Betula pubescens* (Browicz, 1979). Furthermore, research in central Norway also indicate that the pine is somewhat more demanding as regards temperature than birch (Paus, 2010), which is characterized by a wide tolerance as regards climate and soil. Therefore, in our opinion the peak in the percentage values of *Betula* pollen mainly results from statistical conversion with respect to considerably lower total pollen of other plants. However, it does not reflect the spread of birch in forests in the region of Lake Suchar Wielki. This may also concern pollen records from other European sites. Therefore, it would be necessary and important to analyse in detail not only changes in the percentage share of pollen produced by individual taxa, but also changes in its concentration during the Preboreal coolings, and influx for sediments characterised by a variable accumulation rate.

In Central and Eastern Europe the pattern of vegetation changes during the first Preboreal oscillation differs from that observed in Western Europe records. In the west, in The Netherlands, the share of birch decreased during the first PBO, and open grassland vegetation expanded (van der Plicht et al., 2004; Bohncke and Hoek, 2007; Bos et al., 2007). The climate during this cold event was cold and dry in this region (Bos et al., 2007). In the study area (NE Poland) cooling has been expressed as a decrease in the concentration of pine pollen and a smaller decline in the concentration of birch pollen. This has been reflected in the increase in the percentage share of birch. This was connected most likely not only with cooling but also with an increase in humidity, which can also intensify cooling, comparing it with the last cooling in the study area. It is worth noting, that the direct response to climate change is dependent on geographical locations and local conditions. This indicates that probably one climate change had larger consequences in some parts of Europe, where it caused a return to open grassland vegetation, typical for very cold periods, than in other parts Europe, like NE Poland, where mainly changes in the concentration of pine and birch pollen were observed, indicative of reduced flowering and/or pollen production.

The record of the cold event, which is visible in the pollen percentage diagram from the Lake Suchar Wielki profile ca. 10,300–10,200 cal. BP, is similar to that for the first early-Preboreal oscillation – there are a clear peak of *Betula alba* t. and an evident depression of *Pinus sylvestris* t. However, the record of changes in pollen concentration is completely different in this part of the profile than in the part corresponding to the previous cooling – the concentration of pine and hazel pollen decreases here, while that of birch rises, which corresponds very well with the changes in the percentage values of these taxa. Such a record illustrates that the reaction of vegetation to climate changes during the late-Preboreal cold event was different from that of the early-Preboreal oscillations. This results from the fact that water level declined significantly during ca. 10,300–10,200 cal. BP. Cold climate during this cold event, caused a reduction in the concentration of pine, but an increase in the concentration of birch. During the cold phase ca. 11,140 cal. BP, in the Biebrza Upper Basin percentage increases in the share of birch indicate cold, but also drier and/or more continental in character (Klerk et al., 2006). A similar event took place ca. 11,100 cal. BP during cooling in NE Lithuania, when an increased share of birch coincided with low water levels and low humidity (Stančikaitė et al., 2009). During cold event 8.2 ka, when pine concentration was also low in the dry phase, the concentration of birch did not decrease, but only slightly fluctuated (Paus, 2010).

The increased concentration of birch and humidity levels recorded during the cold event in the late-Preboreal cooling, and observations from other sites in Europe indicate that birch is more resistant to cold, regardless of simultaneous changes in humidity.

6. Conclusions

(1) Changes in aquatic and terrestrial environment registered by us document that the climate in NE Poland during the Preboreal was marked by four cold oscillations (Fig. 8). Three short-term negative climate events occurred in the early Preboreal ca. 11,300–11,150, 11,100–11,000 and

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10,900–10,850 cal. BP, and one in the late Preboreal ca. 10,300–10,200 cal. BP proceeded by gradual cooling ca. 10,600–10,300.

(2) In the early Preboreal short-term coolings were separated by equally short warmer intervals, that documents the significant instability of environmental conditions in NE Poland during that period. The oldest early-Preboreal cold oscillation resulted in a strong reduction in the flowering of both trees forming contemporary stands, but the response of birch to this cooling was significantly less pronounced than that of pine. During the two later early-Preboreal cold events birch and pine responded very similarly to the deteriorated climate conditions, which may indicate a less significant decrease in temperature than during the first coolings. None of early-Preboreal cold events resulted in the transformation of the structure of the pine-birch forests. They all were only manifested by changes in the intensity of pollen production by trees and changes in the lake.

(3) During the late Preboreal cold oscillation the drop in temperature was accompanied by a decrease in the humidity of the climate, which resulted in a decrease in the lake water level. Cold-preferring species of cladocerans began to develop. A decrease in the acreage of pine occurred and a temporary spreading of birch.

(4) Changes recorded in the environment of NE Poland during the Preboreal correspond fairly well with cold and warm events reported for other regions of Europe and the whole Northern Hemisphere. The dating of these episodes varies significantly across Europe. Further high-resolution palaeoclimatic reconstructions using different terrestrial and aquatic proxies are needed to advance our knowledge about the impact of climate on the nature of these changes.

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Environmental changes related to the 8.2-ka event and other climate fluctuations during the middle Holocene: Evidence from two dystrophic lakes in NE Poland

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Abstract

Multi-proxy palaeoecological data (pollen, diatom, Cladocera) about the environment during the middle-Holocene from Suchar II and Suchar Wielki, dystrophic lakes, in NE Poland are presented. Fluctuations in the pollen concentration, indicative of changes in pollen productivity and shifts in woodland composition, document the considerable instability of the climate in NE Poland between 9200 and 5750 cal. yr BP. The recognised colder events were dated to ca. 9050–8950, 8700–7800, 7600–7250, 7100–6600 and 6050–5900 cal. yr BP. All these coolings are expressed as decreases in the pollen concentration of thermophilous taxa such as *Corylus avellana, Ulmus, Quercus, Tilia cordata* t. and *Fraxinus exelsior*. The most pronounced was the second of these cold climatic anomalies, which lasted about nine centuries and can be equated with the 8.2-ka event. Significant cooling at that time is confirmed by the appearance of cold-water species of cladocerans and diatoms.

Keywords

Cladocera, climate changes, cold oscillations, diatoms, pollen, 8.2 ka

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Introduction

In classic palaeoecological studies, the middle part of the Holocene (ca. 9000–5800 cal. yr BP) has generally been regarded as a period with a relatively warm, humid and stable climate, and thereby with the optimal climatic conditions for the development of vegetation. However, new data have revealed that the climate during this part of the Holocene was unstable, with several short, abrupt climatic oscillations (e.g. Bond et al., 2001; Wanner et al., 2011). The best known climate cooling is an event around 8200 cal. yr BP (e.g. Allen et al., 2002; Alley et al., 1997; O'Brien et al., 1995). This oscillation, the so-called 8.2-ka event, was recognised in all the most important palaeoclimate records, that is, in the Greenland ice cores and North Atlantic deep sea cores (Alley et al., 1997; Bond et al., 1997; Klitgaard-Kristensen et al., 1998; O'Brien et al., 1995). It has been estimated that the temperature decreased during this period by 3.3 ± 1.1°C in Greenland (Kobashi et al., 2007), while in the European continent by 0.5–1.5°C (Seppä et al., 2007) to 2–3°C (Veski et al., 2004).

The possible reasons for cold climate events were the perturbations in the North Atlantic thermohaline circulation (THC), which resulted from two causes. The first of these was the variable solar activity (e.g. Allen et al., 2007; Bond et al., 2001; Fleitmann et al., 2003; Gupta et al., 2005; Hu et al., 2003; Viau et al., 2006; Wang et al., 2005), with a solar minimum output between 8400 and 7900 cal. yr BP (Muscheler et al., 2004). A reduction in solar irradiance weakened THC, and a consequence of this phenomenon was the disruption of the Atlantic Meridional Overturning Circulation (AMOC; Daley et al., 2011; Holmes et al., 2011; Hughes et al., 2006; Kleiven et al., 2008; Wiersma and Renssen, 2006). Similar perturbations of the AMOC occurred in the case of an influx of freshwater from glacial lakes Agassiz and Ojibway to the North Atlantic (Barber et al., 1999). The outburst drainage from glacial lakes was associated with a significant North Atlantic Deep Water (NADW) slowdown. This event took place between 8600/8450 and ca. 7800 cal. yr BP (Clark et al., 2001; Clarke et al., 2004), which means that the 8.2-ka cooling could have lasted for up to 650–800 years. The climate proxy records of this oscillation document that this event in different regions of the world lasted for 200–600 years (Rohling and Pälike, 2005). This is demonstrated in the many records from Europe, including oscillations in $\delta^{18}O$ values in lake sediments'

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profiles (Daley et al., 2011; Larocque-Tobler et al., 2010; Tibert et al., 2007; Veski et al., 2004), peat cores (Daley et al., 2009) and speleothems (Fohlmeister et al., 2012). Additionally, this climate anomaly was recorded as a higher water level in mid-European lakes (Magny, 2004).

The 8.2-ka oscillation has also been clearly reflected in the pollen record from many regions of Europe (Figure 1) as the decrease in the pollen percentage share and concentration of thermophilous trees and shrubs and the accompanying increase in pine and/or birch pollen.

In Poland, the 8.2-ka event was recorded in Lake Gościąż as a decrease in pollen and Cladocera concentration and composition (Starkel et al., 1998; Szeroczyńska and Zawisza, 2011), in Lake Słone as the appearance of cold-water Cladocera and ostracoda taxa (Kulesza et al., 2012) and in Lake Charzykowskie as the appearance of cold-water Cladocera (Mirosław-Grabowska and Zawisza, 2014). In NE Poland, data from Lake Linówek point to a decline in the share of thermophilic taxa pollen ca. 8450–8050 cal. yr BP (Gałka et al., 2014), while in Piotrowo-Ławniki paleolake a decrease in the C/N ratio and $\delta^{13}C$ and $\delta^{15}N$ in organic matter ca. 8740–8320 cal. yr BP (Kołaczek et al., 2015); in Romoty paleolake, a decrease in oxygen isotope ca. 8400 cal. yr BP (Mirosław-Grabowska et al., 2015) has been noted. Moreover, in Lake Purwin the water level increased between 8600 and 7300 cal. yr BP (Gałka and Apolinarska, 2014).

Apart from the 8.2-ka event, other smaller climate oscillations between 9200 and 5800 cal. yr BP were recorded in Greenland ice cores. They were correlated to minima in solar activity that occurred ca. 9200, 8400, 7500–7000, 6900–6800, 6150 and 5900 cal. yr BP (Bond et al., 1997, 2001). This applies to the record of oxygen isotope in a stalagmite from Oman indicating episodes of reduced rainfall at 9000, 8300, 7400 and 6300 cal. yr BP (Neff et al., 2001). Furthermore, the oxygen isotope series from the Dongge Cave, China, showed minima of summer and winter monsoons around 8200, 7300, 6200 and 5900 cal. yr BP (Wang et al., 2005; Wang and Quansheng, 2013).

In the European continent, many different records suggest the occurrence of several cold periods during the climatic optimum of the Holocene (Figure 1a and e). For example, reconstruction on the basis of chironomid analysis from the Alps indicates a temperature decrease between 8200 and 7700 cal. yr BP and two others at ca. 7000 and 6250 cal. yr BP (Heiri and Lotter, 2003). At this time, three to four glacier advances occurred in Scandinavia (Nesje, 2009) and the Austrian and Swiss Alps (Hormes et al., 2001; Joerin et al., 2006). The level of the mid-European lakes has increased tree times that coincided with an increase in annual precipitation and a decrease in summer temperature (Magny, 2004). Furthermore, there were phases of higher flood frequency or frequent rainy seasons (Starkel, 2002; Starkel et al., 2006). Several vegetation changes related to coolings were recorded in profiles from Ireland (Ghilardi and O'Conell, 2013), Austria (Kofler et al., 2005) and Romania (Feurdean, 2005; Grindean et al., 2015).

In this article, we discuss the implications of climatic oscillations in the north-eastern part of Central Europe for the vegetation and lake environments of this region. We focus on a period between 9200 and 5800 cal. yr BP. Our research is conducted on two small dystrophic lakes in NE Poland. This area is located in the transition zone between oceanic and continental climates (Woś, 1995). Therefore, thermophilous species occur here at their ecological tolerance limit, so their abundance, regeneration and pollen production are constrained by climate. A major assumption in our study is that short-term climate change may result in significant changes in pollen production. In our studies, pollen analysis was supplemented by analyses of cladocerans and diatoms, which are of special importance because of their quick response to the changes in climate conditions, especially temperature.

The study area

Lakes Suchar II and Suchar Wielki are located in NE Poland (Figure 1a–d) in Wigry National Park (WNP). Lake Suchar II (2.6 ha, 9.5 m max. depth, 54°05′14″N, 23°01′03″E) lies in the northwest part of the park, while Lake Suchar Wielki (8.9 ha, 9.6 m max. depth, 54°01′41″N, 23°03′21″E) lies to the west of Lake Wigry, the biggest lake of WNP.

The study area is assigned to the East Suwałki Lake District, which is part of the Lithuania Lake District. The climate of this area is temperate transitional with a tendency towards continentality, and it is characterised by the lowest temperatures in the lowland part of the country (Kondracki, 1994).

The forests of WNP constitute the northern part of the Augustów Primeval Forest, which covers almost 1150 km^2 and is one of the largest forest complexes in Poland. The severe climate of NE Poland results in the occurrence of forest communities of a boreal character (Sokołowski, 1999).

Methods

Corings

Drillings in deep spots of lakes Suchar II (Figure 1c) and Suchar Wielki (Figure 1d) were carried out using Więckowski's probe with a length of 110 cm and a diameter of 5 cm. The total length of cores was 6.10 m in Lake Suchar II and 9.06 m in Lake Suchar Wielki. The lithology of the analysed cores was briefly described during the fieldwork, and then a description was completed after cleaning the core in the laboratory.

Dating

The selected samples of sediments from both studied lakes were dated in the Gliwice Radiocarbon Laboratory (GdA) and Skała Radiocarbon Laboratory (MKL). OxCal 4.2.3 online software (Bronk Ramsey, 2013) was used to calibrate the radiocarbon age of the samples.

The chronology of the studied profiles was also determined indirectly, based on the similarity between the obtained pollen records and pollen records in well-dated profiles from nearby Lake Szurpiły (Kinder et al., 2013 and Kupryjanowicz's unpublished pollen data) and Lake Wigry (Kupryjanowicz, 2007). The similarity of all these profiles permits their correlation (for details, see the article by Drzymulska et al., 2014) and then the transfer of some absolute dates from Szurpiły and Wigry profiles to the profiles from Suchar Wielki and Suchar II.

Pollen analysis

Samples for pollen analysis were taken at every 2 cm. They were prepared using Erdtman's acetolysis (Faegri and Iversen, 1975). To establish the absolute sporomorphs' concentration in sediments, one *Lycopodium* indicator tablet (20,848 spores) was added to each sample (Stockmarr, 1971). More than 500 pollen grains of terrestrial plants and all accompanying pollen grains and spores of aquatic and mire plants were counted. Pollen and spores were identified using keys of Moor et al. (1991) and Beug (2004). The obtained results were presented as percentage and concentration diagrams (Berglund and Ralska-Jasiewiczowa, 1986). The percentage values were calculated on the basis of the total sum including trees and shrubs (AP) and herbs (NAP) and excluding aquatic and mire plants' pollen, spores and other microfossils. The diagrams were drawn using POLPAL software (Nalepka and Walanus, 2003; Walanus and Nalepka, 2011).

Cladocera analysis

We analysed 51 samples from Suchar Wielki and 74 samples from Suchar II, with resolution of 2–10 cm. Samples (1 cm^3 volume of

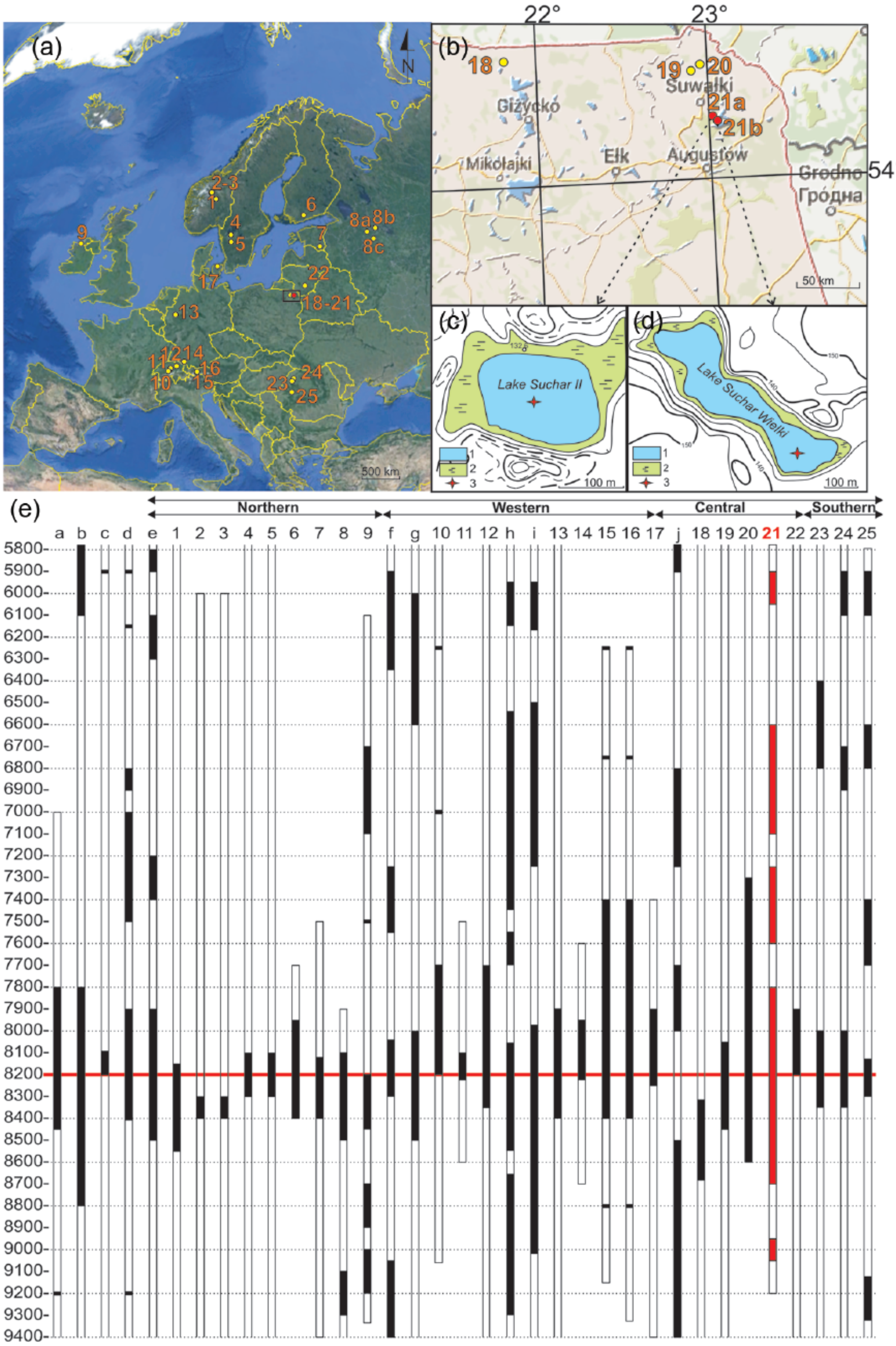

Figure 1. (a) European sites with the record of Atlantic cold oscillations: 1: Lake Flaåfattjønna, Norway (Paus, 2010); 2: Lake Topptjønna, Norway (Paus et al., 2011); 3: Lake Ristjønna, Norway (Paus et al., 2011); 4: Lake Igelsjön, Sweden (Seppä et al., 2005); 5: Lake Flarken, Sweden (Seppä et al., 2005); 6: Lake Arapisto, Finland (Sarmaja-Korjonen and Seppä, 2007); 7: Lake Rõuge, Estonia (Veski et al., 2004); 8a: Mire Staroselsky Moch, Russia (Novenko and Olchev, 2015); 8b: Lake Galich, Russia (Novenko and Olchev, 2015); 8c: Mire Klukva, Russia (Novenko and Olchev, 2015); 9: Cooney Lough, Lake NCY1, Ireland (Ghilardi and O'Conell, 2013); 10: Lake Sägistalsee, Switzerland (Heiri and Lotter, 2003); 11: Lake Soppensee, Switzerland (Tinner and Lotter, 2001); 12: Bog Egelsee, Switzerland (Wehrli et al., 2007); 13: Bunker Cave, Germany (Fohlmeister et al., 2012); 14: Lake Schleinsee, Germany (Tinner and Lotter, 2001); 15: Bog Krummgampen, Austria (Kofler et al., 2005); 16: Bog Brunnboden, Austria (Kofler et al., 2005); 17: Lake Højby Sø, Denmark (Hede et al., 2010; Rasmussen et al., 2008); 22: Lake Braunis, Lithuania (Gryguc et al., 2013); 23: Lake Preluca Tiganului, Romania (Feurdean, 2005; Feurdean et al., 2008); 24: Lake Steregoiu, Romania (Feurdean et al., 2005, 2008); 25: Bog Ic Ponor, Romania (Grindean et al. 2015). (b) Location of the records in NE Poland: 18: Mire Piotrowo-Ławniki (Kołaczek et al., 2015); 19: Lake Linówek (Gałka et al., 2014); 20: Lake Purwin (Gałka and Apolinarska, 2014); 21a: Lake Suchar Wielki (in this article), 21b: Lake Suchar II (in this article).
(c) Hypsometry of the Lake Suchar Wielki area: 1: open water, 2: floating matt, 3: place of coring made for palaeoecological investigation.
(d) Hypsometry of the Lake Suchar II area: 1: open water, 2: floating matt, 3: place of coring made for palaeoecological investigation. (e) Dating of the mid-Holocene cold oscillations at different sites from the Northern Hemisphere: a – outbursts of Lake Agassiz (acc. Nesje et al., 2004; Teller et al., 2002); b – Greenland Ice Core Project (GRIP), sea salt and terrestrial dusts (O'Brien et al., 1995), Greenland Ice Sheet Project (GISP2); c – Bond cold events (Bond et al., 1997); d – minima of solar activity recorded as peaks of 10Be (Bond et al., 2001); e – phases of Scandinavian glacier advances (Nesje, 2009); f – periods of high water level in mid-European lakes (Magny, 2004); g – phases of higher flood frequency (Starkel, 2002); h – phases of Swiss Alps glacier advances (Joerin et al., 2006); i – phases of central Swiss and Austrian Alps glacier advances (Hormes et al., 2001); j – phases of more frequent rainy seasons (Starkel et al., 2006); for references for the other sites, see Figure 1a.

wet sediments) were prepared according to a standard procedure (Frey, 1986). They were heated in 10% KOH for 25 min, washed and sieved through a 33-µm mesh with distilled water and then topped-up to a volume of 10 mL in a scaled test tube. Because of the lack of carbonates, no HCl treatment was used.

Before counting, the remains were dyed with glycerolsafranine and analysed under a compound microscope (100−400× magnification). A single microscopic slide was prepared using 0.1 mL volume of homogenised solution. In each sample, at least 200 individuals were counted (two to four microscopic slides). The identification followed the keys of Flössner (2000) and Szeroczyńska and Sarmaja-Korjonen (2007). In some samples from Suchar II, the unequivocal identification of species *Alona rectangula* and *Alona guttata* as well as *Bosmina* (*E.*) *longispina* and *Bosmina* (*E.*) *coregoni* was problematic. The former remains were grouped together as 'small *Alona*', and the latter were presented jointly as *Eubosmina*. The counts were plotted as concentration diagrams (number of individuals per cm^3 of wet sediments).

For Lake Suchar Wielki, the proportion of Cladocera ephippia was calculated to characterise reproductive patterns (Sarmaja-Korjonen, 2004). All diagrams were prepared with Tilia software (Grimm, 1991–2011).

Diatom analysis

Diatoms were prepared for counting using the standard techniques of Battarbee (1986). Sediment samples were treated with 10% HCl, washed with distilled water and treated with 30% H_2O_2 in a water bath. After several washings with distilled water, a known amount of microspheres in solution (concentration 8.02 × 10^6 microspheres/cm^3) was added to the diatom suspensions to enable estimation of diatom concentrations (Battarbee and Kneen, 1982). A few drops of diatom suspension were dried on a coverglass. Permanent microscope slides were mounted in Naphrax.

The results are presented as a percentage diatom diagram using C2 software (Juggins, 2007). Reconstruction of pH (DI-pH) was performed using Ernie software (version 1.0; Juggins, 2001) and a combined pH dataset from different regions of Europe (e.g. Birks et al., 2004; Cameron et al., 1999; Catalan et al., 1993; Larsen, 2000). A total of samples made up the combined pH dataset. Reconstruction of pH was performed using weighted averaging partial least squares (WA–PLS) regression and correlation. The pH calibration model had a root mean square error of prediction (RMSEP) of 0.46 pH units and a coefficient of determination (r^2) of 0.76.

Reconstruction of TP was performed using the locally weighted averaging (LWWA) regression and correlation. The TP calibration model had an RMSEP of 0.30 and a coefficient of determination (r^2) of 0.70. Reconstruction of pH and TP was based on diatom taxa which were present at more than 1% abundance in a particular sample.

Results and interpretations

Lithology and age of sediments

The lithology of the studied profiles covering the period analysed in this article (ca. 9200–5750 cal. yr BP – depth of 11.50–9.28 m in the profile from Lake Suchar II and 14.20–11.80 m in the profile from Lake Suchar Wielki) is represented by only one sediment unit, which is sapropel (for details, see Drzymulska et al., 2014).

The dates of Figure 2 for Suchar Wielki profile were presented in the article by Fiłoc et al. (2016). The radiocarbon dates from Suchar II profile (all from sediment) are as follows:

- 691–697 cm – 1170 ± 80 14C yr BP (MKL-2071), that is, 1180–983 cal. yr BP (range 68.2%) and 1268–939 (range 95.4%)
- 851–855 cm – 4120 ± 100 14C yr BP (MKL-2072), that is, 4820–4527 cal. yr BP (range 68.2%) and 4865–4410 cal. yr BP (range 95.4%)
- 1217 cm – 10,120 ± 30 14C yr BP (GdA-2372), that is, 11,916–11,626 cal. yr BP (range 68.2%) and 11,987–11,508 cal. yr BP (range 95.4%)

Two dates were interpolated to the Suchar II profile from Lake Wigry profile (Kupryjanowicz, 2007) and one date from Lake Szurpiły profile (Kinder et al., 2013 and Kupryjanowicz's unpublished pollen data) based on similarity of pollen record in both these profiles:

- 1185–1190 cm – 10,562–10,214 cal. yr BP (8612–8264 cal. yr BC in the Wigry profile; the first increase in *Corylus avellana* to about 5%)
- 1140–1150 cm – 9192–8804 cal. yr BP (7242–6854 cal. yr BC in the Wigry profile; the maximum share of *C. avellana* ca. 25%)
- 803–807 cm – 3824–3700 cal. yr BP. (depth of 497–505 cm in the Szurpiły profile; pick of *C. avellana* ca. 15%)

The model was built in the depth–age program (Walanus and Nalepka, 2015). The depth–age model for Lakes Suchar Wielki and Suchar II is shown in Figure 2.

Special pollen zones

The changes in the concentration of thermophilous pollen taxa were the basis for the distinction of 11 special pollen zones (SPZs) in a studied part of the profiles from Lakes Suchar Wielki and Suchar II (Figure 3). Because the changes in the concentration of pollen for individual taxa did not correlate with distinct changes in their percentage pollen values, it was impossible to distinguish classical pollen assemblage zones or subzones.

The characteristics of SPZs are very similar in both investigated profiles, and thus they were described together (Table 1). The rate of sediment deposition in the both analysed lakes was relatively steady (Figure 2), so fluctuation in pollen supply to the sediment is the main reason responsible for the observed changes in the concentration of pollen. These changes were most likely caused by different intensities of flowering and pollen production in response to climatic changes (e.g. Fiłoc et al., 2016).

Generally, SPZs with odd numbers (1, 3, 5, 7, 9 and 11 SPZs) are characterised by an increased concentration of thermophilous taxa pollen, representing periods with slightly more favourable climatic conditions promoting florescence and pollen production by plants. In contrast to that, in zones with even numbers (2, 4, 6, 8 and 10 SPZs), the concentration of thermophilous taxa pollen decreases, which illustrates lower pollen production because of worsening climate.

Changes in Cladocera and diatom assemblages

The diagrams presenting the results of the Cladocera and diatom analyses do not contain classical assemblage zones (Figures 4–6). The changes in these organisms were described with reference to stages based on the changes in pollen concentration (Table 2).

In both lakes, littoral Cladocera dominated over planktonic forms. However, considerable fluctuations of planktonic/littoral (p/l) ratio were noted (Figure 4). Moreover, the common pattern was the dominance of plant-associated taxa over sediment-associated.

Mid-Holocene environmental changes

Stage 1 – warm, ca. 9200–9050 cal. yr BP. The pollen record indicates that the area around both investigated lakes was

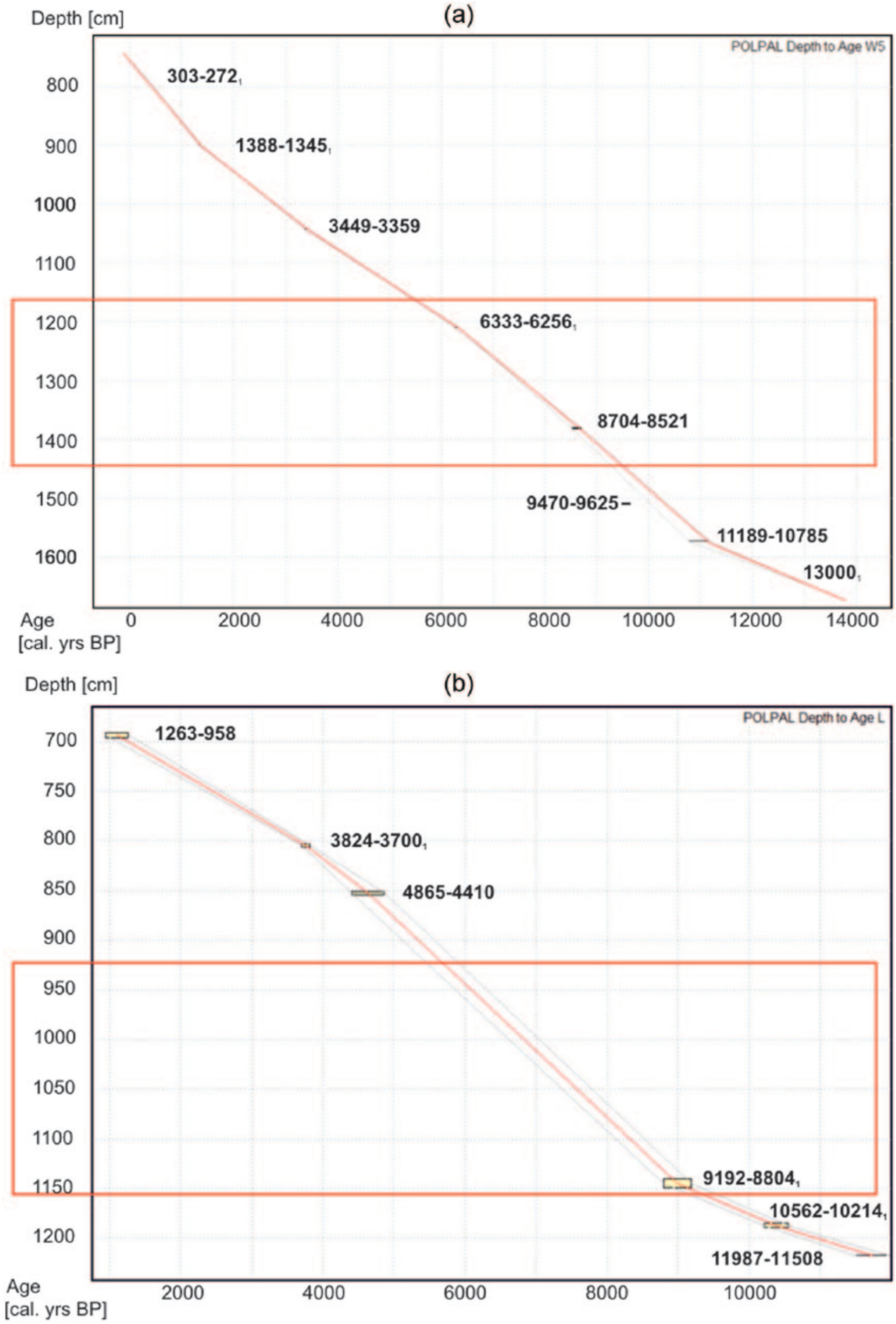

Figure 2. Age–depth model for (a) Suchar Wielki profile and (b) Suchar II profile. Date with the number one on the bottom transferred from the well-dated profiles from Lake Szurpiły and Lake Wigry. Depths are counted from the water surface.

mostly covered by pine-birch forests (ca. 36% of *Pinus sylvestris* t. pollen and ca. 22% of *Betula alba* t. pollen – Figure 3). More fertile habitats were occupied by mesophilous mixed deciduous forests with *Ulmus, Tilia* and *Quercus*. Hazel, forming underwood, was common in both types of these forests (ca. 23% of *Corylus avellana* pollen). The area covered by alder was small (5–14% of *Alnus* pollen). The conditions for the growth of mesophilous species (hazel, elm, oak, ash and lime) were favourable, which is reflected by the high concentrations of these taxa pollen.

Cladocera and diatom assemblages found in sediments from Lake Suchar Wielki point to its oligoeutrophic character (Figures 4 and 5). In contrast, Lake Suchar II had a more mesoeutrophic character (Figure 4, Table 2).

Stage 2 – cooling, ca. 9050–8950 cal. yr BP. The strong decrease in pollen concentration of all taxa, including thermophilous taxa (Figure 3), illustrates an instant deterioration of conditions for florescence and pollen production by all plants. Because negative changes affected cold-tolerant trees (pine and birch) less, the decline in the concentration of their pollen was less marked compared with thermophilous trees. In the pollen record, this is reflected as the increase in percentage values of their pollen, which is the effect of statistical calculations, and does not reflect their actual spread at that time. In addition, the spread of alder was inhibited suggesting probably a relatively dry climate.

The changes in diatom assemblages indicate a decrease in pH value in Lake Suchar Wielki, accompanied by a decline in its trophic status (Figure 5). *Karayevia oblongella*, characteristic

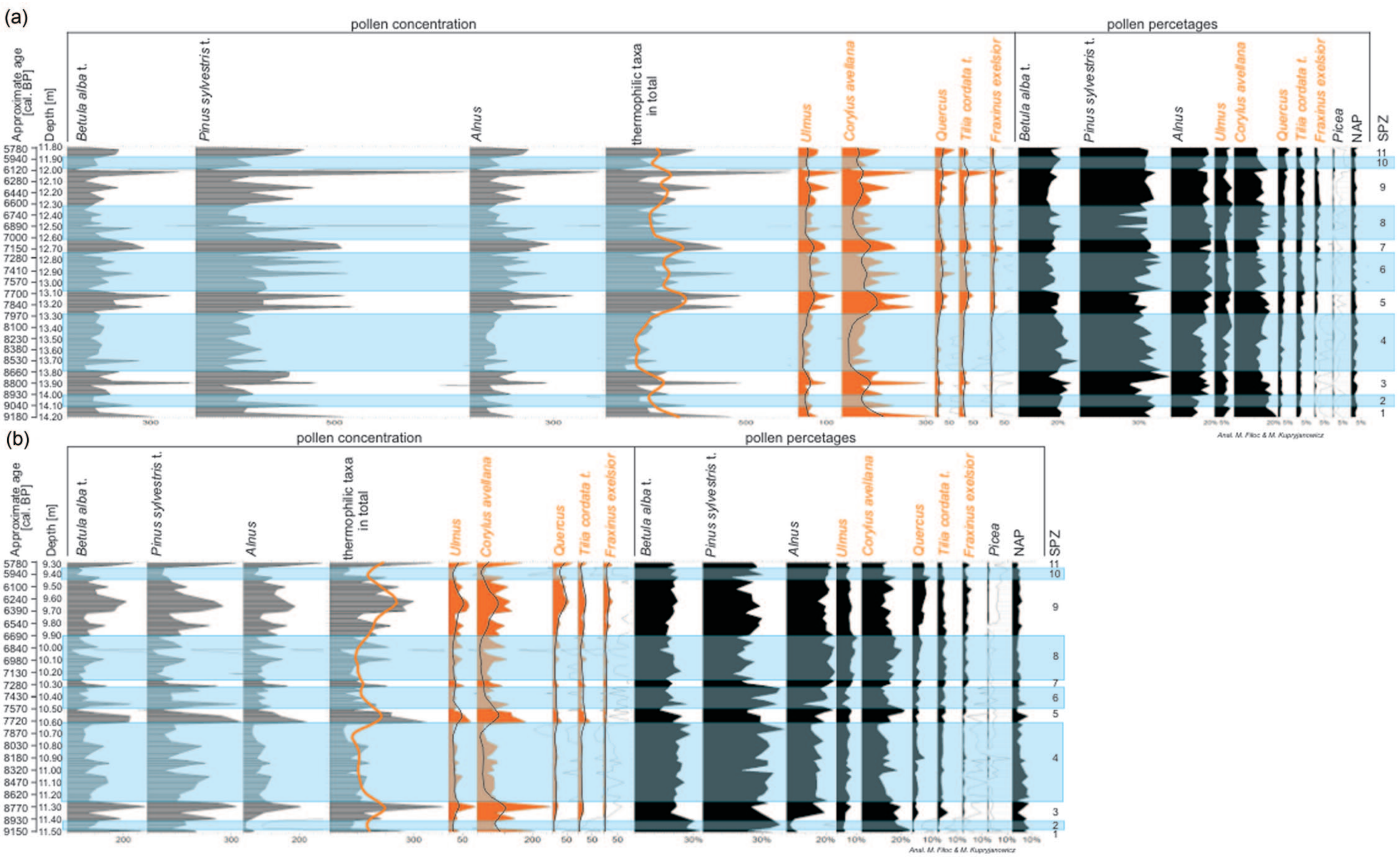

Figure 3. Simplified pollen concentration and percentage diagrams from the Atlantic part of the studied profiles (selected pollen curves): (a) Lake Suchar Wielki and (b) Lake Suchar II. Orange and black lines in the diagram indicate total concentration of trees' pollen marks smoothened by 25%. Blue indicates stages reflecting the climate coolings. Depths are counted from the water surface. SPZ: special pollen zone.

Table 1. Characteristic of SPZs distinguished in the studied part of the Lake Suchar Wielki and Lake Suchar II profiles (Figures 3 and 6).

SPZ	Age (cal. BP)	Depth (m)		Description
		SW	SII	
1	9200–9050	14.20–14.12	11.51–11.50	Very high total concentration of thermophilous taxa, including mainly *C. avellana* and *Ulmus*; low concentration peaks of *Quercus, Tilia cordata* t. and *F. excelsior*.
2*	9050–8950	14.10–14.02	11.48–11.42	Depression in concentration of *C. avellana, Quercus, T. cordata* t. and *F. excelsior*, especially clearly visible in the SII profile.
3	8950–8700	14.00–13.80	11.40–11.27	Very high peaks of *C. avellana* and *Ulmus* concentration; increase in concentration of *Quercus, T. cordata* t. and *F. excelsior*; in the SII profile maximum of total concentration of thermophilous taxa.
4*	8700–7800	13.78–13.30	11.25–10.62	Very clear decline in concentration of *C. avellana* and *Ulmus*; less marked decrease in *Quercus* and *T. cordata* t; concentration of *F. excelsior* similar to previous stage.
5	7800–7600	13.26–13.10	10.60–10.50	Very high peaks in concentration of *C. avellana* and *Ulmus*; culmination of *Quercus* and *T. cordata* t.; concentration of *F. excelsior* slightly higher than two previous stages.
6*	7600–7250	13.06–12.80	10.45–10.32	Slight decrease in the concentration of *C. avellana* and almost all thermophilous trees, except *F. excelsior.*
7	7250–7100	12.78–12.66	10.30–10.26	Increase in concentration of *C. avellana* and all thermophilous trees, which is clearly visible in the SW profile, while in the SII profile is recognised only in single pollen spectrum.
8*	7100–6600	12.60–12.36	10.24–9.90	Decline in concentration of *C. avellana* and all thermophilous trees, very clear in the SW profile and less pronounced in the SII profile.
9	6600–6050	12.30–12.00	9.88–9.50	Rise in concentration of *C. avellana* and all thermophilous trees; in the SW profile maximum of total concentration of thermophilous taxa.
10*	6050–5900	11.96–11.90	9.48–9.34	Decline in total concentration of thermophilous taxa resulting from decrease in all individual taxa of this group of plants, more evident in the SII profile.
11	5900–5750	11.86–11.80	9.32–9.28	Increase in concentration of *C. avellana* and all thermophilous trees, more evident in the SII profile.

SPZ: special pollen zone.
*Stages reflecting the climate coolings.

mainly for mountain waters (Hoffmann et al., 2011), became the dominant diatom species.

In both investigated lakes, there was a decrease in the abundance of cladocerans, both planktonic and littoral, including those preferring warmer waters (e.g. *Pleuroxus* spp.). Moreover, species preferring cool waters of low trophic status occurred: *Alonopsis elongata* and *Rynhotalona falcata* in Suchar Wielki and *Alona intermedia* in Suchar II (Figure 4). There was a dominance of *Alonella nana, Alona affinis* and *Chydorus sphaericus*, and in Suchar Wielki also *Alona quadrangularis*, species known for their wide tolerance of environmental conditions.

Stage 3 – warming, ca. 8950–8700 cal. yr BP. The increase in the concentration of thermophilous taxa pollen (Figure 3) suggests an improvement in the thermal conditions. Considering percentage data, this is reflected by the increase in pollen values for hazel, elm and lime and a decrease in pine pollen values. The expansion of alder took place (increase in *Alnus* percentage values).

It can be concluded based on diatom remains that the pH of water in Lake Suchar Wielki stabilised, leading to increased trophic status (Figure 5). Higher trophy and probably the improvement of thermal conditions is also confirmed by the increase in the total abundance and changes in Cladocera in both studied sites (Figure 4).

Stage 4 – cooling, ca. 8700–7800 cal. yr BP. The second cold event was recorded again as a decrease in the pollen concentration of thermophilous taxa, including hazel, elm, oak, ash and lime (Figure 3). A slightly lower decrease was found for the pollen concentration of trees more tolerant to cold, such as pine, birch and alder. Because of this, pollen record shows increased percentage values for pine and/or birch pollen. This was the longest and most pronounced cooling in the whole analysed period. At this stage, the percentage values for hazel pollen decreased to 9%, while pollen values of pine and/or birch increased to 46% and 31%, respectively. Because this cooling was long (ca. 900 years), it can be concluded that such a palynological record reflects the actual changes in the composition of forests at that time, illustrated by at least a partial reduction in the acreage of hazel. Alder also responded to climatic changes in that period (both concentration and percentage values of its pollen decrease). This probably resulted from the changes in water levels which were often recorded during the 8.2-ka cold event (Magny, 2004; Magny et al., 2007).

Cladocera assemblages reveal at that time two to three short-term phases indicating deteriorated temperature (Figure 4). They are marked by the increase in abundance and/or appearance of cold-tolerant Cladocera species (*A. elongata, R. falcata, A. intermedia* and *Paralona pigra*; cf. Nevalainen et al., 2013). Similar changes were found for diatoms as a 3-fold increase in the concentration and share of Chrysophyceae cysts (Table 2, Figure 5), which can be indicative of climate cooling. Interestingly, *K. oblongella*, characteristic for cold waters, disappeared at that time. This may indicate that the temperature decrease was significant enough to limit even the growth of this diatom.

During cooling, a decline in the abundance of taxa preferring higher temperatures was observed (Bosmina *longirostris* in Suchar II and *Pleuroxus trigonellus* and *A. guttata* ver. *tuberculata* in Suchar Wielki). In Suchar Wielki, the most profound change was the decline in *A. quadrangularis*, which previously was a dominant species. The other large-bodied taxa, known for their high tolerance to low temperatures (Nevalainen et al., 2013) – *A. affinis* – tolerated the changes much better and partially compensated for the declining *A. quadrangularis*. Also, in Suchar II the increase in *A. affinis* is marked at the end of this stage (Figure 4). During this stage, two phases of increased production of ephippia were identified, being in good agreement with the decline in total Cladocera abundance. Large differences in the p/l ratio (0.2–0.8 Lake Suchar Wielki and 0.2–0.9 for Lake Suchar II) may indicate changes in the water level.

Stage 5 – warming, ca. 7800–7600 cal. yr BP. A strong increase in pollen concentration, both of thermophilous taxa and pine, birch

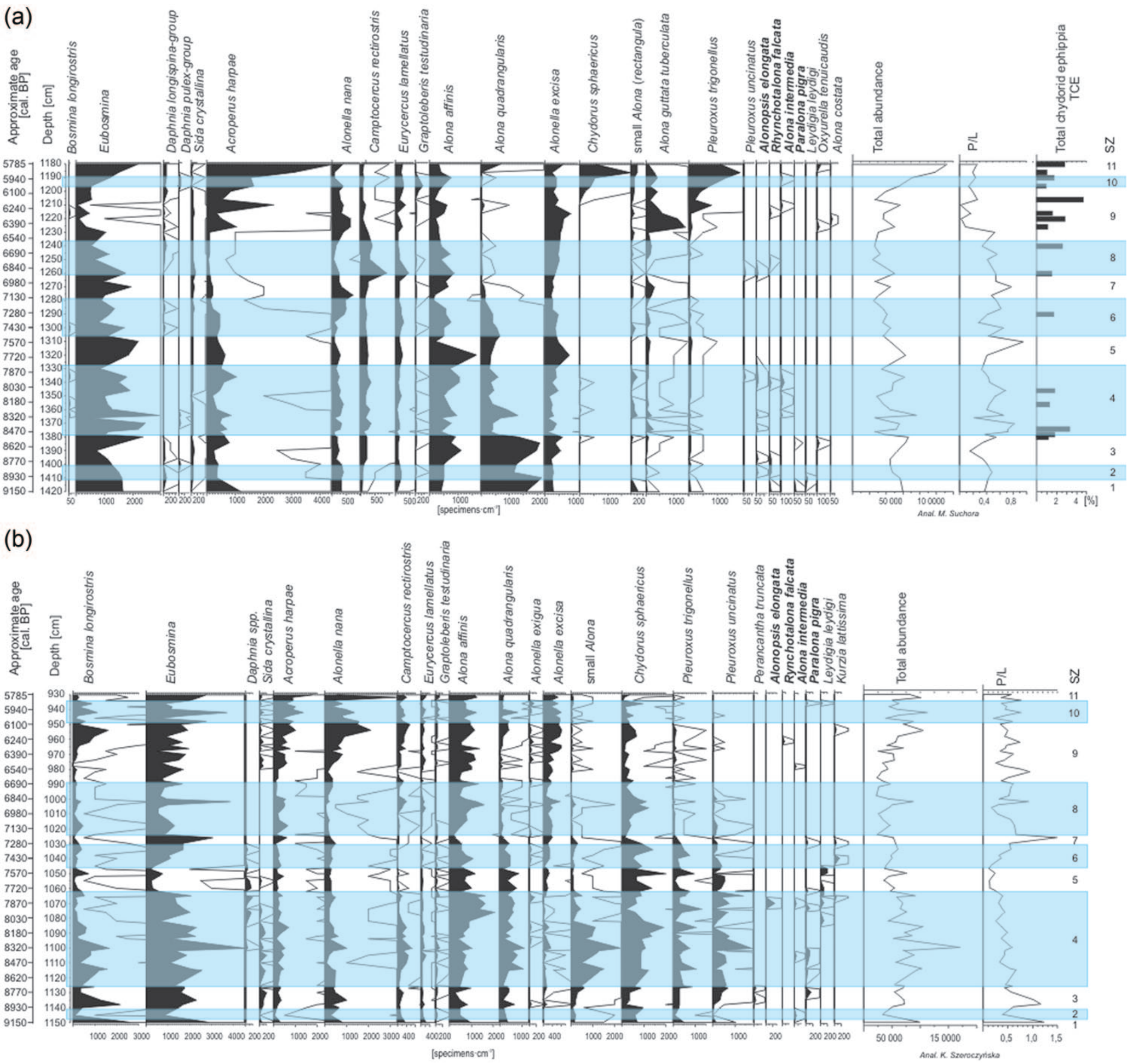

Figure 4. Cladocera total abundance diagram from the Atlantic part of the studied profiles: (a) Lake Suchar Wielki and (b) Lake Suchar II. Blue indicates stages reflecting the climate coolings. Depths are counted from the water surface. SZ: special zone.

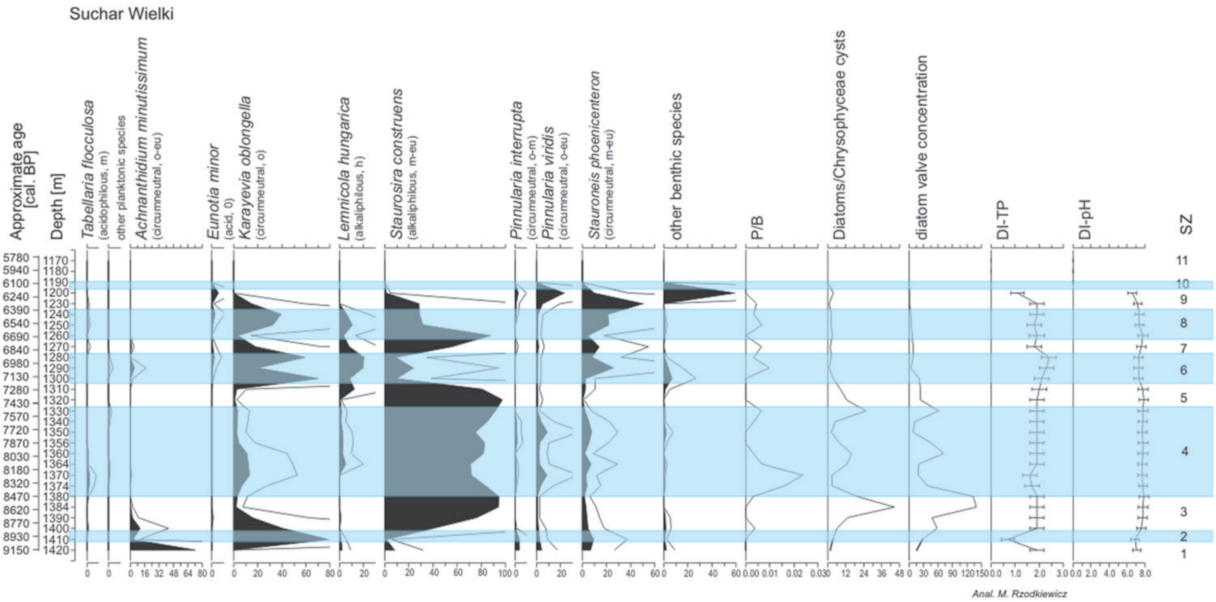

Figure 5. Diatom percentage diagram from the Atlantic part of the Lake Suchar Wielki profile. Blue indicates stages reflecting the climate coolings. o: oligotraphentic; o-m: oligo-mesotraphentic; m: mesotraphentic; m-eu: meso-eutraphentic; eu: eutraphentic; h: hypereutraphentic; o-eu: oligo to eutraphentic; P/B: planktonic/benethic. Depths are counted from the water surface. SZ: special zones.

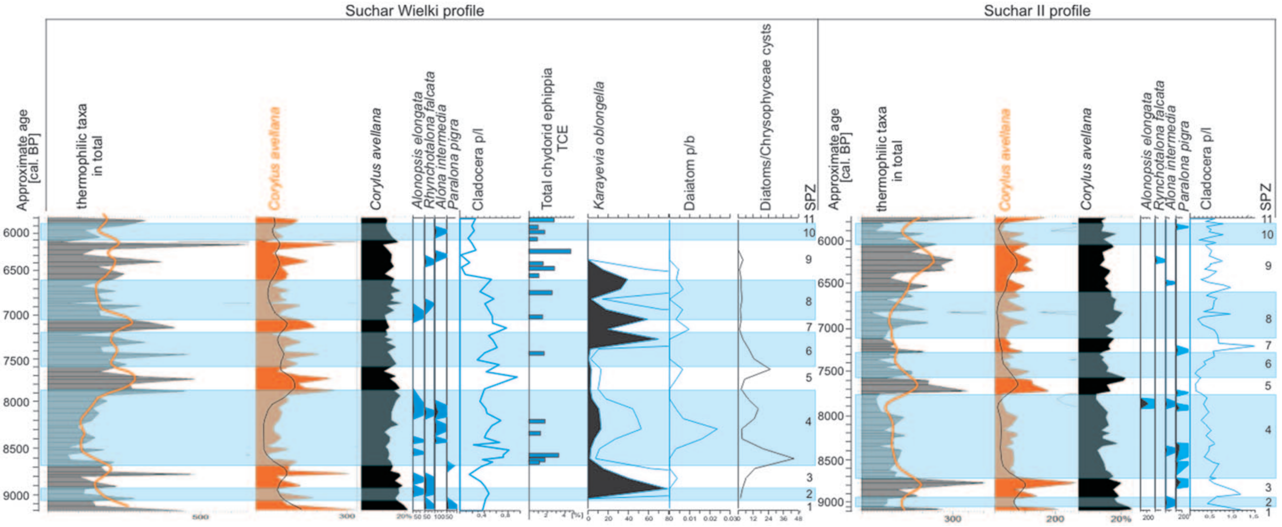

Figure 6. Correlation of the pollen, Cladocera and diatom records of cold Atlantic oscillations registered in the profiles from Lake Suchar Wielki and Lake Suchar II. Blue indicates stages reflecting the climate coolings. Depths are counted from the water surface.

and alder (Figure 3), documents an improvement of the thermal conditions.

Gradual warming of the lake water is illustrated by the decrease in concentration of Chrysophyceae cysts (Figure 5).

The composition of Cladocera assemblages is different in each of the studied lakes, which may indicate the increasing role of local factors in shaping their development. The total abundance of Cladocera increased in Suchar Wielki, mainly because of the expansion of planktonic taxa (*Eubosmina*), while in Suchar II total abundance decreased, primarily because of the marked decline in the number of planktonic Cladocera (*B. longirostris* and *Eubosmina*; Figure 4). In both lakes, the abundance of *Alonella excisa* increased, and the expansion of this species was associated with humic waters.

The changes in Cladocera communities could be related to warming, but it seems that the response to this warming was rather indirect – increased temperature could lead to drying and initiate water humification, frequently associated with the shrinking of the open water zone following the expansion of mire. The response of cladocerans (indicating contrasting trends in changes of water level during that period) may suggest that cladocerans responded to these factors, but open water zone had to reduce more in the smaller basin – Suchar II. Moreover, a marked decrease in the water pH of Lake Suchar Wielki reconstructed based on diatom data occurs later, only at the time of the subsequent warming (stage 7).

Stage 6 – cooling, ca. 7600–7250 cal. yr BP. The next colder period is reflected in the pollen record from both lakes, again by the decrease in the concentration of mesophilous taxa (Figure 3). Significant fluctuations in the concentrations of these taxa in subsequent pollen spectra suggest that this could have been a time of very dynamic climate changes.

The changes in Cladocera composition are not coherent, especially with regard to planktonic taxa, which are mainly responsible for the overall changes in total Cladocera abundance (Figure 4). In Lake Suchar Wielki, because of a decline in planktonic *Eubosmina*, there was a decline in total Cladocera abundance, whereas in Suchar II the high increase in the abundance of *Eubosmina* and *B. longirostris* resulted in an increase in total Cladocera abundance. A more coherent trend was found for littoral communities – the downward trend concerned *A. quadrangularis* and *P. trigonellus* in Suchar II: disappearance/decline in sediment-associated and preferring more eutrophic waters *Leydigia leydigi* and of *Pleuroxus* spp. This may indicate worsening conditions for sediment-associated taxa (*Pleuroxus uncinatus, A. quadrangularis*), and also a decline in the temperature and trophy of waters. This confirms a significant increase among *K. oblongella* diatoms associated with cold water.

Stage 7 – warming, ca. 7250–7100 cal. yr BP. Another stage was a short but marked signal of improved conditions for pollen production by all mesophilous taxa, and also by pine, birch and alder, which are tolerant to lower temperatures, and also positively respond to warming (Figure 3). The concurrent changes in the concentration of pollen produced by all trees and shrubs are camouflaged by the changes in percentage pollen values.

The changes observed in Cladocera composition – mainly clear increase in *Eubosmina*, decline in *Pleuroxus* spp. and *Ch. sphaericus* (Figure 4) – are reaction to decline in trophy rather than increase in temperature. However, amelioration of climate conditions may indicate lack of Cladocera ephippia as well as cold-preferring taxa. On the other hand, a decrease in the share of cold-preferring diatom *K. oblongella* also indicates an increase in temperature.

Stage 8 – cooling, ca. 7100–6600 cal. yr BP. There is a general decrease in the concentration of pollen produced by thermophilous taxa (Figure 3). However, strong fluctuations in the concentration suggest that this could have been another period of very dynamic climate changes, and thus florescence and pollen production by these trees. Again, the decrease in the concentration of pollen for other trees camouflages changes in pollen values.

A low concentration of Cladocera remains was registered (Figure 4). Both sites experienced a decline in the dominant planktonic taxa – *Eubosmina*. There is a decline in *Graptoleberis testudinaria, Alonella exigua, P. trigonellus* and *P. uncinatus*, species having their optima in warmer lakes (Nevalainen et al., 2013), and also cold-tolerant *Alonella nana*. Dominant littoral species in the sediments of Lake Suchar II are *Ch. sphaericus* and *A. affinis* – known for their resistance to unfavourable environmental conditions such as low temperatures, nutrients and pH (Bjerring et al., 2009; Flössner, 2000; Whiteside, 1970). At the onset of this stage, in the sediments of Lake Suchar Wielki, cold-tolerant *Rhynchotalona falcata* and *A. elongata* are present. Also, the share of *K. oblongella* increased. In both lakes, a decline in the abundance of *A. quadrangularis* with the concurrent growth of *A. affinis* is noted, as well as a high proportion of *Alonella excisa* – a

Table 2. Characteristics of Cladocera and diatoms' assemblage changes in subsequent warmer and colder stages determined based on the change in concentration of pollen distinguished in the studied part of the Lake Suchar Wielki and Lake Suchar II profiles (Figures 4–6).

SP	Age (cal. BP)	Lake Suchar Wielki			Lake Suchar II	
		Depth (m)	Description of changes in Cladocera assemblages	Description of changes in diatoms' assemblages	Depth (m)	Description of changes in Cladocera assemblages
1	9200–9050	14.20–14.12	High total abundance; high frequency of *Eubosmina, A. harpae* and *A. quadrangularis*.	Dominance of periphyton (100%) mainly represented by *S. construens*. Oligoeutrophic conditions.	11.51–11.50	High total abundance; high frequency of *B. longirostris* and *Eubosmina*; relatively high proportion of *A. nana, Ch. sphaericus* and *A. affinis*.
2*	9050–8950	14.10–14.02	Decrease in total abundance; among planktonic taxa small decline in *Eubosmina*. Decline in most littoral taxa (mainly those preferring warmer waters – *A. quadrangularis, P. trigonellus* and *small Alona*). Stable values of common, but cold-tolerant taxa: *A. affinis, A. nana* and *E. lamellatus*. Among littoral taxa a marked decline in *A. quadrangularis* and disappearance of *A. rectangula* and decline in *P. trigonellus*. Among littoral taxa dominance of *A. quadrangularis, A. affinis, A. nana* and *A. harpae*. Appearance of *R. falcata* and *A. elongata*, preferring cold, low-trophy waters. Slight increase in common but cold-tolerant taxa: *A. affinis, A. nana* and *E. lamellatus*. No ephippia of *Cladocera*.	Dominance of periphyton continues. Change in diatom composition in favour of *K. oblongella*, characteristic of cold-water basins and rivers. Change into oligotrophic conditions. Increase in the ratio of diatoms/Chrysopohyceae cysts, which can signify deteriorating conditions for growth.	11.48–11.42	Decrease in total abundance; among planktonic taxa a substantial decline in the abundance of *B. longirostris*; lower and also noticeable decline in *Eubosmina*. Decline in most littoral taxa except *Ch. sphaericus*. Among littoral taxa dominate *A. affinis, A. nana* and *Ch. sphaericus*. Decrease in *P. uncinatus* preferring higher temperatures; appearance *of A. intermedia* preferring cold waters.
3	8950–8700	14.00–13.80	Increase in total abundance; decline in *Eubosmina* and *A. nana* frequency; peaks of *A. quadrangularis, A. affinis* and *A. excisa*.	Dominance of periphyton represented mainly by *S. construens*. Trophic conditions improve slightly, leading to the dominance of mesoeutrophic and oligotrophic species, next change into mesoeutrophic.	11.40–11.27	Increase in total abundance; high peak of *B. longistris* frequency; rise in *P. uncinatus*; decrease in *A. affinis* and *Ch. sphaericus*.
4*	8700–7800	13.78–13.30	Distinct decline in *A. quadrangularis*. Symptoms of cooling marked three times: at 13.70–13.80 m – decline in abundance; temporary disappearance of *D. longispina*; appearance of *D. pulex*; decline in *P. trigonellus* and *A. quadrangularis*; high abundance of *A. affinis*; presence of *ephippia*; at 13.56–13.50 m – lower abundance of *Eubosmina*, decline in *Daphnia*, presence of *A. intermedia*, presence of *ephippia*; at 13.40–13.30 m – presence of *A. elongata, R. falcata* and *A. intermedia*. Decline in *D. longispina*, single appearance of *D. pulex* preferring lower trophy of waters.	Periphyton continues to dominate and is represented by *S. construens* and *K. oblongella*. Mesoeutrophic diatoms dominate. The ratio of diatoms/Chrysopohyceae cysts increases three times: at 13.85–13.80 m increases to 45.0 and declines at 13.55 m increases to 18.5 and declines at 13.30 m increases to 30 m.	11.25– 10.62	High total abundance of Cladocera, with several fluctuations. Dominance of *Eubosmina, Ch. sphaericus*, small *Alona, A. affinis, A. quadrangularis* and *Pleuroxus* spp. Symptoms of cooling marked twice: at 11.25–10.95 m – presence of *P. pigra* and *A. intermedia* at 10.75–10.62 m – appearance of *A. elongata*; presence of *P. pigra* and *A. intermedia*; decline in *Ch. sphaericus, B. longirostris* and *A. excisa*; among littoral species shift to dominance of large-bodied *Alona* spp. (*A. affinis* and *A. quadrangularis*).
5	7800–7600	13.26–13.10	Increase in Cladocera abundance, mainly because of increase in *Eubosmina* and *A. excisa*.	Periphyton accounts for 100% of diatom community. *S. construens* is a dominant species. Trophy remains unchanged – mesoeutrophic species dominate. The ratio of diatoms/Chrysopohyceae cysts declines.	10.60–10.50	Decline in total Cladocera abundance because of marked decline in planktonic taxa (*Eubosmina, B. longirostris*) with subsequent rise or constant abundance of littoral taxa: *Ch. sphaericus, A. quadrangularis, A. nana* and *A. excisa*.

Table 2. (Continued)

SP	Age (cal. BP)	Lake Suchar Wielki			Lake Suchar II	
		Depth (m)	Description of changes in Cladocera assemblages	Description of changes in diatoms' assemblages	Depth (m)	Description of changes in Cladocera assemblages
6*	7600–7250	13.06–12.80	Decline in total Cladocera abundance, mainly because of the decline in planktonic *Eubosmina*; in the littoral zone the downward trend concerned *A. quadrangularis* and *P. trigonellus*. In the middle of the phase an increase in *A. nana*.	Change in species composition: the share of *S. construens* decreases, but the share of *K. oblongella* and *S. phoenicenteron* increases. At the depth of 12.80 m the share of *S. phoenicenteron* decreases but the shares of *K. oblongella* and *L. hungarica* increase.	10.45–10.32	Increase in total Cladocera abundance and percentage of planktonic species, mainly because of high abundance of *Eubosmina*. Disappearance of *L. leydigi* and (temporal) *C. rectirostris*; decline in *Pleuroxus* spp.; reappearance of *A. exigua* and *K. lattissima*.
7	7250–7100	12.78–12.66	Increased abundance of Cladocera; peak of *Eubosmina*; decline in *P. trigonellus* and *A. quadrangularis*; rise in *C. rectirostris* and *A. affinis*.	The share of *S. construens* increases again and it occurs with *S. phoenicenteron, K. Oblongella* and *L. hungarica*.	10.30–10.26	Final disappearance of *Daphnia*; very high peak of *Eubosmina* frequency. Decline in *A. exigua, Ch. sphaericus* and *Pleuroxus* spp.
8*	7100–6600	12.60–12.36	Low total abundance. Gradual decline in *Eubosmina*; decline in *A. harpae* and *A. nana*; maximum of *C. rectirostris* and *A. affinis*; very low abundance of *A. quadrangularis*; presence of *G. testudinaria, P. uncinatus, P. trigonellus* and also *R. falcata, A. elongata*; increase in *A. excisa* and *A. guttata*.	Species composition is similar to that in the previous stage, but the shares of *K. oblongella, S. phoenicenteron* and *L. hungarica* increase.	10.24–9.90	Decreasing trend in total abundance. Marked decline in planktonic Cladocera. Decline in *G. testudinaria, A. exigua, A. nana, P. trigonellus* and *P. uncinatus*; dominant species in littoral are *Ch. sphaericus* and *A. affinis*. Decline in *A. exigua, P. uncinatus* and *G. testudinaria* (species having their optima in warmer lakes). Decline in *A. quadrangularis* with concurrent growth of *A. affinis*. High proportion of *A. excisa*.
9	6660–6050	12.30–12.00	Increase in total Cladocera abundance; marked decline in planktonic Cladocera; maximum frequency of *A. guttata*, high proportion of *A. excisa* and *A. nana*; rise in *A. harpae*; decrease in *C. rectirostris* and *A. affinis*. Single findings of *A. intermedia* and *R. facata*.	Dominance of periphyton. Its share declines towards the ceiling; at the depth of 12.00 m the shares of *P. viridis* and *E. minor* increase. pH does not change, but at the depth of 12.00 m is more neutral. Dominance of oligoeutrophic species accompanied by mesoeutrophic ones.	9.88–9.50	Systematic increase in total abundance, including both littoral and planktonic taxa; maximum frequency of *A. nana*; increase in *A. harpae* ans *A. excisa*. Decline in *Ch. sphaericus*, small *Alona* and *A. quadrangularis*. Single findings of *A. intermedia* and *R. falcata*.
10*	6050–5900	11.96–11.90	Increase in *Eubosmina, A. harpae, Ch. sphaericus, P. trigonellus P. uncinatus* and *A. affinis*; decline in *A. nana*; presence of cold-tolerant *A. intermedia*.	*Disappearance* of diatoms (see section 'Mid-Holocene environmental changes').	9.48–9.34	Decrease in total abundance; decrease in frequency of *B. longirostris* and *A. nana*; presence of *P. pigra*.
11	5900–5750	11.86–11.80	Increase in total abundance of Cladocera. Increase in planktonic (*Eubosmina* and *Daphnia* spp.) as well as some littoral taxa including mainly *A. harpae, P. trigonellus* and *Ch. sphaericus*. Slight increase in *A. nana*. Fall in *A. affinis*; reappearance of *A. quadrangularis*.	*Absence* of diatoms (see section 'Mid-Holocene environmental changes').	9.32–9.28	Increase in total abundance of Cladocera, Increase in *Eubosmina, A. harpae* and *A. nana*.

SP: special zone.
*Stages reflecting the climate coolings.

possible indicator of ongoing humification. A clear dystrophication in Lake Suchar Wielki is also indicated by a significant decrease in diatom-inferred pH and the complete disappearance of diatoms in stage 10 (Figure 5). Moreover, the Atlantic/Sub-Boreal interface was a transition into the dystrophic state also in Lake Suchar II (for more details, see Drzymulska et al., 2015).

Stage 9 – warming, ca. 6600–6050 cal. yr BP. The concentration of thermophilous taxa increases, as well as that of pine, birch and alder, which masks the improvement in thermal conditions (Figure 3). This indicates that during that period warming caused no significant changes in forest composition.

Relatively clear changes are seen in Cladocera assemblages. An increase in total Cladocera abundance with a marked decline in planktonic Cladocera in Lake Suchar Wielki was recognised (Figure 4), which may indicate a lowering of water level, or an overgrowing of the lake by aquatic vegetation. At the same time, at Lake Suchar II an increase in both planktonic and littoral taxa resulted in a relatively constant p/l ratio. The maximum frequency of *Alonella nana* in Lake Suchar Wielki, as well as *A. guttata* var. *tuberculata* together with a high proportion of *Alonella excisa* suggest a lowering of pH, which is confirmed by the values of diatom-inferred pH. This was also accompanied by a very distinctive increase in *Acroperus harpae.* During this warm phase, single occurrences of *A. intermedia* and *R. falcata* were noted, which may be related to the change in in-lake edaphic conditions. In diatom assemblages, the share of *K. oblongella* decreased, as in the earlier warmer phases.

Stage 10 – cooling, ca. 6050–5900 cal. yr BP. The concentration of thermophilous taxa pollen decreased (Figure 3). In the area near Lake Suchar II, a decreased concentration was also observed for other trees, which may suggest more pronounced local changes in climate influencing pollen production by trees. This is most likely associated with a slight increase in humidity, intensifying this periodic cooling.

The frequency of *Alonella nana* decreased at that time in both lakes, and two species preferring lower temperatures occurred: *A. intermedia* (Suchar Wielki) and *P. pigra* (Suchar II; Figure 4). Diatoms disappeared and no longer occurred in the analysed part of the profile, nor above it (Rzodkiewicz, unpublished data).

Stage 11 – warming, ca. 5900–5750 cal. yr BP. The concentration of all pollen taxa, including thermophilous ones, strongly increased (Figure 3). This signals the onset of another period with more favourable climatic conditions promoting florescence and pollen production.

Also, the increase in the total abundance of Cladocera indicates better thermal and edaphic conditions in lakes (Figure 4). The increase in planktonic (*Eubosmina* and *Daphnia* spp. at Suchar Wielki and *Eubosmina* at Suchar II) as well as some littoral taxa points to favourable conditions for this group of organisms.

Discussion

Cold oscillation at the beginning of the Atlantic chronozone

At the end of the Boreal chronozone, ca. 9200–9050 cal. yr BP, hazel domination ends in the vicinity of Lakes Suchar Wielki and Suchar II. The hazel's importance was maintained in forests of the Wigry region till ca. 8800 cal. yr BP (Kupryjanowicz, 2007). At this time, pine and birch dominated in the tree stands of this area, but increasing numbers of trees with higher thermal requirements began to appear. The moist habitats were being gradually occupied by alder. Next, at the beginning of the Atlantic chronozone, ca. 9050–8950 cal. yr BP, the invasion of mesophilous taxa had stopped. Moreover, in the vicinity of Lake Suchar II the expansion of alder was interrupted, which probably indicates drier conditions. Furthermore, changes in aquatic communities document a decline in temperature with the appearance of low-trophy and cold-water taxa.

Similar climate changes at that time have also been observed in other parts of Europe. In the record of Cooney Lough, Ireland, two cool episodes occurred – ca. 9200–9000 and 8900–8700 cal. yr BP (Ghilardi and O'Conell, 2013). During these events, a decrease in the pollen concentration and percentage share of hazel and an increase in birch were recorded. Moreover, the record of Crag Cave, Ireland, noted speleothem ca. 8800 cal. yr BP (McDermott et al., 2001). In the Central Europe – Austrian Alps, in the bogs Krummgampen and Brunnboden signals of climate worsening have been placed between 9300 and 9100 cal. yr BP (Kofler et al., 2005). Exactly in the same period, cooling was observed also on the East European Plain (Novenko and Olchev, 2015). In southern Europe, on the Ic Ponor bog, Romania, a decline in elm, hazel and oak coupled with a maximum of birch was recorded between 9350 and 9250 cal. yr BP (Grindean et al., 2015).

The dates of these fluctuations are partly consistent with the changes described by us in the study area. These changes may be a delayed reaction to the 9.4-ka cold event (Bond et al., 1997), or they could have a relationship with outburst ice lakes in North America ca. 9200 cal. yr BP (Teller et al., 2002) or with a solar minimum ca. 9000 cal. yr BP (Neff et al., 2001).

8.2-ka event

The most significant mid-Holocene cooling in the study area occurred ca. 8700–7800 cal. yr BP. This anomaly corresponds probably to the 8.2-ka event (e.g. Bond et al., 1997). Similar changes, noted in the pollen record from nearby Lake Linówek, were dated on the period between ca. 8450 and 8050 cal. yr BP (Gałka et al., 2014).

The changes in concentration and percentage share of thermophilous species were the most common record of the 8.2-ka event in the European continent. Nevertheless, not all plants reacted the same everywhere. The record from Cooney Lough, Ireland, shows a decrease in hazel and oak and an increase in pine and birch pollen concentration ca. 8400–8100 cal. yr BP (Ghilardi and O'Conell, 2013). In Scandinavia, the pollen record from Lake Flåfattjønnain registered a decline in the concentration of alder and pine between 8500 and 8150 cal. yr BP (Paus, 2010). In lakes Topptjønna and Ristjønna, the cold episode was recorded as the expansion of alder around 8400–8300 cal. yr BP (Paus et al., 2011). Records from lakes Flarken and Igelsjön noted a decreased share of hazel, alder and elm pollen between 8200 and 8000 cal. yr BP (Seppä et al., 2005), while in Lake Arapisto, changes for the same taxa were recorded ca. 8400–7950 cal. yr BP (Sarmaja-Korjonen and Seppä, 2007). Further south of Europe, in the vicinity of Lake Højby Sø, Denmark, there was a pronounced decline in both percentage share and concentration of hazel, alder, oak and lime pollen between ca. 8250 and 7950 cal. yr BP (Hede et al., 2010; Rasmussen et al., 2008). In the annually laminated sediments of Lake Rouge, Estonia, a decrease in percentage share and concentration of hazel, alder, elm and lime pollen took place at 8400–8080 cal. yr BP (Veski et al., 2004). Further south of Europe, the record from Bog Egelsee, Switzerland, indicates the replacement of thermophilous deciduous forests by mesophilous silver fir-beech forests between 8350 and 7700 cal. yr BP (Wehrli et al., 2007). In the records of bogs Krummgampen and Brunnboden, Austria, there was a reduction in Cyperaceae and pine pollen production ca. 8160–7940 and 7960–7790 cal. yr BP (Kofler et al., 2005). Furthermore, the record from bog Brunnboden indicated a decreased pollen influx of hazel, lime and elm. Even further south of Europe – Romania, in the pollen record of Preluca Tiganului and Steregoiu lakes, a reduction in deciduous trees and shrubs was noted, with a slight expansion of spruce around at 8600–8000 cal. yr BP (Feurdean, 2005; Feurdean et al., 2008). In a record from the Ic Ponor bog, a decline in thermophilous taxa occurred between 8250 and 8140 cal. yr BP, together with an increase in the share of spruce (Grindean et al., 2015). In Eastern Europe, in a record of the Braunis, Lithuania, ca. 8200–7900 cal. yr BP, the percentage share of hazel and alder pollen declined, and the share of pine and birch increased (Gryguc et al., 2013). On the East European Plain, a cooling period was observed ca. 8500–8100 cal. yr BP (Novenko and Olchev, 2015).

In the vicinity of Lakes Suchar Wielki and Suchar II ca. 8700 cal. yr BP, a decline in the share of thermophilous taxa was accompanied by an increase in the percentage share of birch and pine pollen. The decline in the share of hazel was often accompanied by an increase in the share of birch (Seppä et al., 2005; Veski et al., 2004), or birch and pine (Ghilardi and O'Conell, 2013; Hede et al., 2010; Kofler et al., 2005; Tinner and Lotter, 2001). The increase in the percentage share of birch and pine and their still high concentration at the study area suggest that these two taxa are the most frost-resistant tree taxa in Europe during Atlantic period.

Importantly, the changes in water level of both studied lakes indicate changes in humidity, which may have occurred during the 8.2-ka cooling. In the study area, the share of pine increased first, and next the share of birch increased. It may be associated with the occurrence of humid phase during this cooling – two small increases in the water level took place ca. 8400 and 7880–7840 cal. yr BP in both studied lakes, and other small increase ca. 8300 cal. yr BP only in Lake Suchar II, as it is indicated by the increase in the p/l Cladocera ratio. The moist-dry pattern of the 8.2-ka event has already been described in the literature (e.g. Ojala et al., 2008; Paus, 2010; Rasmussen et al., 2008). For example, in the Rødalen alpine area cold oscillation 8.2 ka began with wetter winters, and next there was a shift to dry winters (Paus, 2010).

Moreover, during the 8-2 ka oscillation, the record of cladocerans and diatoms in the Lake Suchar Wielki pointed to the three colder phases, and the record of cladocerans in the Lake Suchar II pointed to the two colder phases (Table 2). These phases occurred at the beginning, at the end as well as in the middle of this event. Interestingly, these stages correspond to the deepest declines in hazel concentration.

The dynamic nature of the 8.2-ka event could be related to a sequence of freshwater influxes registered in Lake Agassiz (Nesje et al., 2004), or marked minima in solar activity (Björck et al., 2001).

Together with 8.2-ka event in Europe, the water level increases, decreases or remains unchanged. In Lake Suchar Wielki, diatoms' data indicate a low water level, while Cladocera results indicate a generally high water level, with two to three fluctuations and a tendency towards its lowering only at the end of the phase. However, the p/l ratio in periods when factors other than habitat changes caused by increase or decrease in water level (here – the climatic factor) had their effect should be interpreted very carefully, because changes noted in the structure of the Cladocera population could be attributed to the lower adaptability of the taxa-poor group of planktonic cladocerans compared with much more diversified littoral cladocerans, in which the decline in the abundance of some taxa is compensated by the increase in the number of more adaptable ones. In addition, the dominance of littoral forms over planktonic is typical in dystrophic lakes even today, despite their considerable depth (Zawiska et al., 2013). Regardless of these uncertainties, our findings provide data supporting the moist-dry pattern of 8.2 ka. It should be noted, however, that the decline in the share of planktonic cladocerans observed at the end of this stage was small compared with those in subsequent stages (e.g. stage 8 in Suchar II; stage 9 in Suchar Wielki). Additionally, in nearby Lake Purwin, data indicate that the water level increased between 8600 and 7300 cal. yr BP (Gałka and Apolinarska, 2014). On the other hand, in a similar time (8300–7880 cal. yr BP) a lowering of the water level occurred in the Ic Ponor peat bog, in Southern Europe (Grindean et al., 2015). Furthermore, the water level of mid-European lakes increased ca. 8300–8050 cal. yr BP, which indicates wetter conditions (Magny, 2004; Magny et al., 2007). Grindean et al. (2015) point out that the event 8.2 ka has been observed in most records from Europe characterised by cool and wet conditions (in mid-latitude zone between 58 and 43° N acc. Magny et al., 2007), cool and dry climate in Central Europe and below this zone or lower summer temperatures, when hydrological changes were not observed (e.g. Grindean et al., 2015; Kofler et al., 2005 and references therein). Above the zone described by Magny et al., in Lake Arapisto there was a higher water level (Sarmaja-Korjonen and Seppä, 2007), in the vicinity of Lake Flåfattjønnain could be a moist and next dry phase (Paus, 2010). Moreover, in the whole of Central Europe flooding episodes in river valleys took place ca. 8400–7700 cal. yr BP, which also suggests an increased water level during event 8.2 ka (Starkel et al., 2013).

Cooling is marked very clearly in the aquatic environment of both studied lakes. Chrysophyceae cysts and cold-preferring cladocerans appeared, and there was a decrease in the concentration of aquatic organisms; *A. elongata* typical for northern areas, indicating a decrease in water temperature and low trophy (Hessen and Walseng, 2008), appeared concurrently during the 8.2-ka event also in Lake Charzykowskie (Mirosław-Grabowska and Zawisza, 2014; Szeroczyńska and Zawisza, 2011) and Lake Linówek (Gałka et al., 2014). Furthermore, this Cladocera taxa occurred in Lake Suchar Wielki during earlier, Preboreal cold climate oscillations (Fiłoc et al., 2016).

The observed changes in Cladocera assemblages during the most distinctive coolings might also be attributed to decreased trophy. However, the lack of change in diatom-inferred TP suggests that the climate played a main role in shaping aquatic communities. Moreover, the appearance of the sexual pattern of Cladocera reproduction documented by the presence of subfossil ephippia additionally supports climatic forcing.

Cold events during the late-Atlantic chronozone

The next colder phase ca. 7600–7250 cal. yr BP is indicated by the decreasing concentration and percentage share of the thermophilous taxa pollen, mainly hazel and elm, in record of Lake Suchar II. In the record of Lake Suchar Wielki, the decrease in pollen concentration was not so significant as with other oscillations. During this time, the increased concentration of pine pollen, combined with Cladocera data about a decrease in water level, could indicate drier conditions.

In other parts of Europe, such changes were observed in a similar period. In Northern Europe, cooling was dated at ca. 7500 cal. yr BP in the pollen profile from Cooney Lough, Ireland (Ghilardi and O'Conell, 2013). In the Southern Europe, Romania, colder oscillation occurred between ca. 7700 and 7400 cal. yr BP (Grindean et al., 2015). At that time, glacier advances also took place (Figure 2).

The increase in the concentration of thermophilous taxa indicates a short, but significant improvement in climatic conditions ca. 7250–7100 cal. yr BP.

Nevertheless, in the vicinity of study area, the pollen concentration of thermophilous taxa again decreased ca. 7100–6600 cal. yr BP. In Europe, thermophilous taxa concentration decline was recorded at that time also from Cooney Lough, Ireland, between 7100 and 6700 cal. yr BP. In the records of Lakes Topptjønna and

Ristjønna, Norway, tree pollen percentage values and total concentration declined (Paus et al., 2011). In bogs Brunnboden and Krummgampen, Austria, a colder period was recorded ca. 6750 cal. yr BP, although colder summers occurred in this area already from 7100 cal. yr BP (Kofler et al., 2005). The Romanian record from Preluca Tiganului documents decreased temperatures ca. 6800–6400 cal. yr BP, and in the Steregoiu record a decrease in temperature occurred ca. 6900–6700 cal. yr BP (Feurdean et al., 2008). Also in Ic Ponor bog between ca. 6800 and 6600 cal. BP, a cold period is recorded (Grindean et al., 2015).

The improvement in climatic conditions was evident in the increase in the concentration of all thermophilous taxa present in the region, ca. 6600–6050 cal. yr BP.

Next, colder stage registered in the study area was dated to ca. 6050–5900 cal. yr BP. It could be associated with the Bond event dated to 5900 cal. yr BP (Bond et al., 2001). The chironomids records of Lakes Topptjønna and Ristjønna indicated cooling ca. 6400–6100 cal. yr BP. However, in the pollen record there are no changes (Paus et al., 2011). Nevertheless, in the Eastern Alps, a cooling was recorded ca. 6250 cal. yr BP (Kofler et al., 2005). More to the south of Europe, at Steregoiu site, Romania, temperature decrease was registered around 6100–5900 cal. yr BP (Feurdean et al., 2008). Moreover, a decline in deciduous trees started at 6000 cal. yr BP in some other places in Romania (Feurdean et al., 2012, 2013; Grindean et al., 2014, 2015).

The impact of the middle-Holocene climate oscillations on hazel development

According to the data of many palynological reports, the decreased concentration of hazel and thermophilous trees (elm, lime, oak and ash) in pollen records defines coolings. Among these taxa, hazel in the European continent responded most strongly to climate deterioration, limiting its pollen production (Feurdean et al., 2005; Gałka et al., 2014; Ghilardi and O'Conell, 2013; Gryguc et al., 2013; Hede et al., 2010; Rasmussen et al., 2008; Sarmaja-Korjonen and Seppä, 2007; Seppä et al., 2005, 2007; Veski et al., 2004; Tinner and Lotter, 2001). It is an oceanic thermophilous shrub, which requires long growing seasons and warm early springs. The data indicate that *Corylus* needs accumulation of heat before they begin bloom, which depends on the air temperature (Frenguelli et al., 1992). The production of its pollen is negatively affected by frost, which can kill the catkins, but both drought and heavy rain can be equally deleterious to the reproduction of hazel (Tallantire, 2002). The impact on the dynamics of pollen season *Corylus* has especially air temperature, in the period preceding the pollen season. Furthermore, *Corylus* is the taxon that starts flowering early in spring, in Central Europe often in February/March (Myszkowska et al., 2010). During the 8.2-ka event, temperatures were low, both in the winter and the summer, and the growing season was short. Similar phenomenon was observed in profile Højby Sø, Denmark (Hede et al., 2010). This had a negative effect on pollen production by hazel and other thermophilic taxa. Moreover, modern research on the intra-annual variability of flowering monitored by pollen traps in Denmark also indicated a positive correlation between temperatures during the flowering season and pollen accumulation rates for *C. avellana, Quercus robur* and *Fraxinus excelsior* (Nielsen et al., 2010). Additionally, it has been shown that there can be a positive correlation between annual mean temperature and annual pollen accumulation rates of *Corylus* in the following year (Nielsen et al., 2010). Nevertheless, it can be observed that our study and those from other parts of Europe clearly show the significant sensitivity of hazel to cold climate changes. Furthermore, in our research this is confirmed by the decrease in pollen production by hazel, five times in the period under review. This means that hazel and other thermophilic trees have a low threshold of response to climate change; but depending on the intensity of these changes, the response will be different. In our study, during the 8.2-ka event both the production of pollen and the percentage share of the hazel decreased. However, the four other colder oscillations are reflected mainly in the decreased pollen concentration. This indicates the importance of various combinations, such as changes in temperature, together with the season of the year or with changes in humidity.

Conclusion

The multi-proxy analyses of sediments from two lakes, Suchar Wielki and Suchar II, covering the period ca. 9200–5750 cal. yr BP, reflect the influence of climate on vegetation and aquatic communities in NE Poland (Figure 6). At this time, five coolings affecting terrestrial and lake ecosystems were identified: ca. 9050–8950, 8700–7800, 7600–7250, 7100–6600 and 6050–5900 cal. yr BP. These fluctuations were not just a local or regional phenomenon, but they are events affecting all of Europe.

The cold event corresponding to the 8.2-ka event lasted in East Suwałki Lakeland for ca. 900 calendar years, ca. 8700–7800 cal. yr BP. A climate deterioration at that time resulted in changes in pollen productivity (reflected by pollen concentration) and in the share of various tree taxa (reflected by percentage values of pollen). Moreover, a temperature effect was defined in the aquatic communities of both studied lakes.

The changes in vegetation during mid-Holocene coolings older (9050–8950 cal. yr BP) and younger (7600–7250, 7100–6600 and 6050–5900 cal. yr BP) than 8.2-ka event were illustrated in studied lake profiles only by the decreased pollen concentration of thermophilous taxa; percentage share of these taxa is not marked as a decrease. This suggests that all these oscillations have a smaller impact on environment than the 8.2-ka event. They probably concerned only few seasons with longer and colder winters, which affected the production of pollen and the occurrence of cold-preferring species in the aquatic environment.

The percentage composition of pollen spectra does not reflect minor and short changes in climate, which do not lead to changes in the taxonomic composition of plant communities, but only have an adverse effect on the condition of plants forming these communities reflected in the lower intensity of their flowering and pollen production. Therefore, such climatic events should be recorded based on the analysis of pollen concentration (or influx) in sediments. Only longer cold events, lasting for ca. a thousand year, could lead to a reduction in the area of thermophilous taxa and then to changes in the composition of plant cover.

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Fiłoc M., Kupryjanowicz M., Szeroczyńska K., Suchora M., Rzodkiewicz M. 2017. Environmental changes related to the 8.2 ka event and other climate fluctuations during the Middle Holocene – evidence from two dystrophic lakes in NE Poland. *The Holocene* DOI: 10.1177/0959683617702233.

Magdalena Fiłoc: opracowanie koncepcji badań; wykonanie analizy palinologicznej i interpretacja uzyskanych wyników; opracowanie koncepcji artykułu; przygotowanie tekstu manuskryptu; opracowanie większości rycin i tabel.

Mirosława Kupryjanowicz: opracowanie koncepcji badań; interpretacja wyników analizy pyłkowej; opracowanie koncepcji artykułu; przygotowanie tekstu manuskryptu.

Krystyna Szeroczyńska: wykonanie analizy Cladocera osadów z profilu Suchar II; opis i interpretacja uzyskanych wyników dla analizy Cladocera.

Magdalena Suchora: wykonanie analizy Cladocera osadów z profilu Suchar Wielki; opis i interpretacja uzyskanych wyników; opracowanie rycin i tabel ilustrujących wyniki analizy Cladocera.

Monika Rzodkiewicz: wykonanie analizy okrzemkowej osadów z profilu Suchar Wielki; opis i interpretacja uzyskanych wyników; opracowanie rycin i tabel ilustrujących wyniki analizy okrzemkowej.

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