A Late Holocene Lake-Level Lowstand:
A Case Study on Lake-Level Changes at Uddelermeer, the Netherlands

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Abstract

There have been many changes in climate conditions throughout the Quaternary, even before mankind was a factor influencing the climate. The natural forcing mechanisms responsible for these climate shifts require further study, and particularly the effects of solar forcing and its associated amplification mechanisms are poorly understood. As changes in atmospheric circulation patterns, which might be induced by changes in solar activity, may result in lake-level fluctuations, this study attempts to reconstruct past lake-level change at Uddelermeer, the Netherlands. This lake meets the optimal basin criteria set by Harrison and Digerfeldt (1993) as it is sensitive to changes in effective precipitation and as it has a continuous sediment record covering the entire period from the Late-Glacial to the present. Ground-penetrating radar and palynological analysis on three sediment cores recovered from the lake were used to determine the intensity and timing of lake-level change. Ground-penetrating radar imaging shows a gap in the sediment record indicating that lake-levels were roughly 2.35 meters lower than present during at least one period. A comparison of a pollen record from a littoral core with a record from a central core shows that a *Botryococcus* peak at the onset of the Subatlantic is present in both cores. However, increases in other algal groups and human impact indicator taxa occur in the late Subatlantic in the central core, whereas the occur almost immediately after the *Botryococcus* maximum in the littoral core. The time covered by the hiatus is therefore estimated to span the time from the onset of the Subatlantic to just before a *Cannabis* peak, i.e. 850 B.C. to 1500 A.D. As Uddelermeer relies on groundwater for its water supply, which by itself is reliant on effective precipitation, this study suggests that either precipitation was lower or evaporation was higher in North-West Europe during this 2,350 year long period.

Introduction

The Quaternary (2.5 million years ago – present) is characterized by many rapid changes in climate that resulted in a sequence of glacial and interglacial periods. The Holocene interglacial period started approximately 11,500 years ago and lasts until the present day. Even though Holocene climate conditions are relatively stable, climate change did occur in the past and mechanisms that acted in the past probably still influence Earth's climate today. Nevertheless, recent climate changes are often attributed to anthropogenic disturbances, such as agriculture, deforestation, landscape fragmentation and, most importantly, modern industry. Human impact on the environment, however, may provide insufficient explanation for the entirety of contemporary climatic changes. Combined with the occurrence of natural mechanisms driving climate change during the absence of mankind, this hints at climate change as being influenced by natural processes as well.

Some of the past changes in climate (e.g. Little Ice Age) have been shown to coincide with changes in ^{14}C production rates caused by fluctuations in total solar irradiance (TSI)(Blaauw *et al.,* 2004). These changes in climate include changes in hydrology and other environmental factors (van Geel *et al.*, 1996; Ineson *et al.*, 2011; Magny, 1993). However, changes in solar irradiance are often relatively small, and may seem unlikely to account for all of the observed changes in environmental conditions, as current climate models are unable to explain these climatic shifts. Several amplification mechanisms have been suggested to explain how small changes in TSI could have large-scale effects on Earth's climate, including how changes in ozone production by variations of UV irradiance may result in shifts of atmospheric circulation cells (van Geel *et al.*, 1999) and how cosmic rays are linked to cloud formation (Carslaw *et al.*, 2002).

Changes in atmospheric circulation lead to changes in many related factors, such as wind strength. One such shift in wind strength has been observed around the time of the Younger Dryas cold period ca. 12,700 years ago, and is suggested to be linked to changes in circulation over Europe and the North Atlantic Ocean (Brauer *et al*., 2008). Moreover, Harrison and Digerfeldt (1993) have shown that changes in lake-levels over the last 16,000 years may be partially explained by the fluctuations in the Westerlies and the subtropical high pressure cell.

It is only recently that evidence for a possible causal relationship between regional atmospheric circulation shifts and solar irradiance was shown in a study by Martin-Puertas *et al.* (2012). A correlation, rather than causality, between changes in atmospheric circulation and solar forcing resulting in climate change has been suggested extensively in the past (e.g. Bond *et al.*, 2001; Van Geel *et al.*, 1999; Svensmark & Friis-Christensen, 1997; Schuurmans & Oort, 1969; Rind & Overpeck, 1993). Despite these studies, still relatively little is known about past precipitation patterns, and thus about atmospheric circulation, over Europe. Two important climatic variables, moisture balance and temperature, may be determined via the palaeoecological analysis of lake sediments, as local vegetation history may accurately reflect changes in the two (Shuman *et al.*, 2001; Shuman *et al.*, 2005).

Shuman *et al*. (2001) were able to show how the combination of sedimentological and palynological analyses can be used to infer lake-level changes. In the first step of their study, they used GPR data to identify buried shorelines in a lake's sediment body.

Over time, sediment will accumulate in layers on the lakebed ranging from one shore to another. When lake water levels are lowered, shore locations shift further inward and sedimentation patterns change accordingly to the shifting shores. Any increase in water level may once again submerge the shores and allow for the accumulation of sediments to continue in conditions similar to the starting situation. When this occurs, any sediment deposited during the period of low water levels is only present in the depression between the former shores. Younger sediments will thus be deposited over the other sediments as a blanket. This process is illustrated in figure 1. Changes in lake depth may be quantified by using ground-penetrating radar

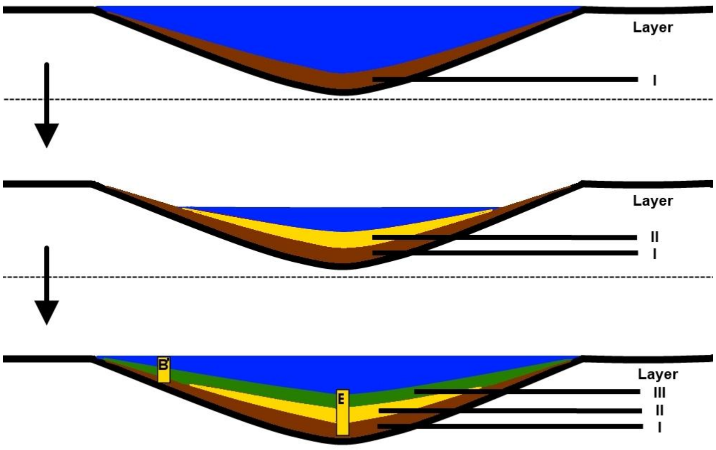

Figure 1. This figure shows how sediment may be deposited over time (I, II & III) with a fluctuating water surface level over time. At site E, a complete sediment record is available, while littoral core B' contains a hiatus (absence of layer II) due to low water levels during time of deposition.

(GPR) to determine the approximate depth of each layer or former shoreline.

In step 2 of the Shuman *et al.* (2001) approach, palynology is used to identify the timing and duration of lake-level changes. A more complete record of sediment, vegetation change and other macro-remains is expected to be present in the deepest parts of the lake due to the continuous supply of sediments from the environment over the years. Cores taken further from the centre, however, may contain hiatuses due to the fact that these places may not have been submerged for the entirety of the lakes history (i.e. times of low water levels). By comparing littoral cores to the central core taken from the deepest part of the lake, it can be determined what parts of the record are missing, when these periods occurred and thus when water levels were different from what they currently are.

Many of the observed changes in factors such as lake and shore vegetation, sediment composition and sediment limit may be subject to alternative interpretations unrelated to climate change as a cause for fluctuating lake-levels (Digerfeldt, 1986). Combining the different kinds of evidence (e.g. pollen stratigraphy, chironomids, sediment layers), however, may provide an explanation which relates the observed changes in water table to climatic changes.

Lakes are excellent archives of environmental and climatic change as their sediments record changes in vegetation (e.g. through fossil pollen) and climate. Pollen analysis on a littoral core from a lake with continuous sedimentation and a high sensitivity to precipitation changes can be used to produce data on lake-level changes, potentially as the result of climate change.

This study aims to improve knowledge about regional hydrological changes and connections with past changes in climate (e.g. temperature, precipitation patterns) by reconstructing the timing and magnitude of past lake-level changes via the analysis of fossil pollen and sediments, respectively. This may provide essential clues to climatic change on the European continent, primarily concerning paleohydrology and precipitation patterns. Detailed studies such as these are underrepresented in respect to the time period on which they focus, as there are few quantitative data available on climate change in Holocene North-West Europe.

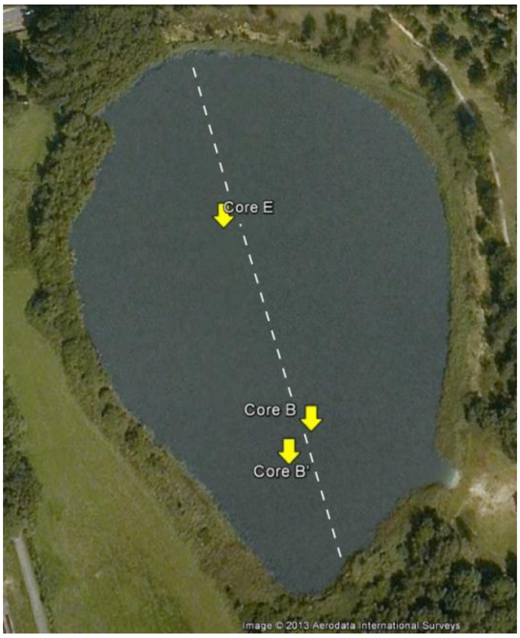

Figure 2. Aerial view of the Uddelermeer site. This image shows the locations of the coring sites (Core E, B and B') and the transect along which ground-penetrating radar was applied.

Site Description

Lake Uddelermeer (52°14'45.37"N 5°45'41.53"E) is a pingo-remnant situated close to Amersfoort, the Netherlands. The lake is located atop the Drenthe and Twente formations, and is located on the slope of two Saalian push moraines. The gentle slopes of the lake allow for lateral movement of the shoreline and its location between push moraines makes it highly sensitive to changes in precipitation.

At present, excess groundwater enters from the east and exits it to the west.

This lake was selected for the present study due to its high sensitivity to changes in precipitation as well as its continuous sedimentation since the Late-Glacial (Bohncke, 1999), both optimal basic criteria according to Harrison & Digerfeldt (1993).

Methods

Sedimentology

Nine sediment cores were taken from lake Uddelermeer during two field work periods, in April and May 2012, respectively. The cores UDD-A, UDD-B, UDD-C and UDD-D were taken in April of 2012, while additional cores UDD-A', UDD-B', UDD-C', UDD-E and UDD-F were taken a month later (figure 2). Cores UDD-A, -B and –C were incomplete due to the inability to acquire the top 1.50 m at that time, and three additional 3 m long cores (UDD-A', -B' and –C') were taken a month later in May to complete these sequences. Cores B and B' have been analyzed for their pollen content, and are treated as separate records rather than as a single core, as they were located ca. 21 m apart. Core B was acquired with a modified Bohncke corer in 1 m long segments, whereas core B' was taken using a Niederreiter piston corer as a 3 m long segment. All cores were taken along a south-north transect (figure 2).

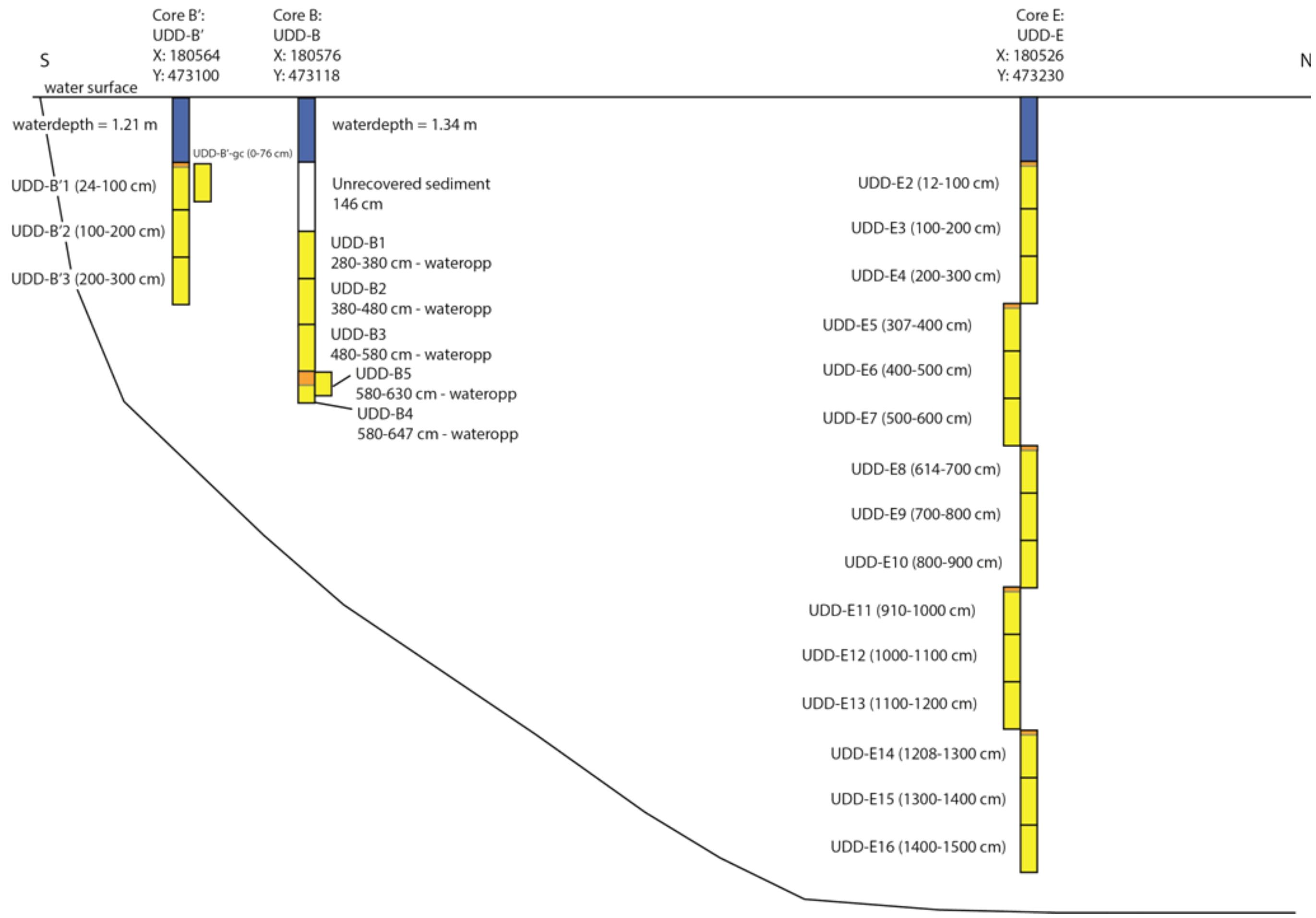

Figure 3. Locations of the three cores used in this study are shown along with their coordinates (UTM Dutch Grid) along with their codes and corresponding depths of each core segment.

Ground-Penetrating Radar

GPR imaging was used to determine at what depth a hiatus occurred within the B and B' cores, as well as being used to reconstruct how far lake-levels had dropped during the hiatus period. The GPR device of TNO/Deltares was used to accomplish this at frequencies of 100 and 200 Mhz, respectively. The GPR was applied along the same south-north transect along which the cores were taken (figure 2).

Pollen Analysis

The biostratigraphy of littoral cores B and B' was compared to that of the central core E, which was taken from the deepest part of the lake (figure 1). Core E was counted by Stefan Engels and Rogier van Oostrom in the framework of an ongoing research project and it spans the entire sediment sequence from 16 m sediment depth to the sediment-water interface.

Core B is 3.5 m long, spanning 1.5 to 5.0 m sediment depth. In contrast core B' consisted of 3 m length from 3.0 m sediment depth to the sediment-water interface. (figure 3).

0.79 cm^3 samples from the sediment cores were prepared for pollen analysis according to Faegri & Iversen (1964). 17 out of a total of 41 samples from core B were analyzed, whereas 13 out of 30 samples were analyzed for core B' (table 1). During the analysis, a minimum pollen sum of 300 was maintained. The pollen sum consisted of all taxa included in the trees and shrubs, human impact indicators and other upland herbs. Moore *et al.* (1991) and Beug (2004) were used along with the extensive reference collection available at the University of Amsterdam for the identification of pollen.

Pollen diagrams were constructed for cores E, B and B' using Tilia for Windows (Grimm, 2011) and were subsequently compared to each other to locate and date the hiatus. A Constrained Incremental Sums of Squares (CONISS) analysis was used to provide a statistical basis for the assigning of zones. Zones were then assigned optically to certain intervals within the pollen diagrams. Each of these zones represents a certain period of time (e.g. Preboreal, Boreal) and its corresponding age is given in uncalibrated ^{14}C years in the remainder of the report.

Chronology

To provide a tentative chronology to the record, seven pollen stratigraphic horizons and their uncalibrated ^{14}C ages were used: the *Juniperus*, *Betula* and *Pinus* peaks (±14,100 BP; Allerød), the consecutive increase in Ericales, Cyperaceae, Poaceae, *Artemisia* and monolete fern spores (±12,800 BP; Younger Dryas), the second peaks in *Betula* and *Pinus* along with a decrease in NAP (±10,300 BP; Preboreal), the decrease in *Betula* and the introduction of *Corylus* (±9,000 BP; Boreal), the introduction and increase of *Quercus* and *Alnus* pollen above 10% (±7,500 BP; Atlantic), the introduction of *Fagus* along with increases in Poaceae, *Rumex*, Ericales and *Botryococcus* (±5,000 BP; Subboreal), and the decrease in AP along with the increases in *Fagus* and Ericales (± 2,800 BP; Subatlantic). Two distinct subzones can be distinguished in the Subatlantic: one without and

Table 1. Pollen counts of cores B' and B. Shown are the core code, the corresponding sediment depth, number of taxa found, the number of pollen in the pollen sum and the total amount of pollen found per sample.

Core	Depth	Taxa	Sum	Total	Core	Depth	Taxa	Sum	Total
UDD-B'	5	41	358	402	UDD-B	151	28	365	392
UDD-B'	35	42	362	394	UDD-B	171	33	551	605
UDD-B'	65	42	398	448	UDD-B	191	31	330	373
UDD-B'	85	42	364	411	UDD-B	211	37	442	483
UDD-B'	105	30	371	412	UDD-B	231	29	335	372
UDD-B'	125	33	411	453	UDD-B	255	29	347	398
UDD-B'	155	34	409	457	UDD-B	275	28	392	410
UDD-B'	175	36	378	400	UDD-B	285	36	445	476
UDD-B'	205	26	338	347	UDD-B	305	25	339	356
UDD-B'	225	28	349	384	UDD-B	335	29	375	396
UDD-B'	255	27	347	422	UDD-B	355	23	327	346
UDD-B'	275	31	364	451	UDD-B	375	23	363	417
UDD-B'	295	25	349	444	UDD-B	405	27	365	492
					UDD-B	425	29	355	564
					UDD-B	455	27	350	489
					UDD-B	485	21	316	341
					UDD-B	505	30	363	491

one with intensive anthropogenic activity. This activity is clearly visible as an increase in Cerealia, *Secale*, *Cannabis*, *Fagopyrum*, *Pediastrum*, *Scenedesmus* and *Tetraedron minimum*.

These zones are well-recognized all throughout North-West Europe and their ages are well documented for the Netherlands (Van Geel *et al.*, 1980, 1989; Hoek, 1997), and thus provide an accurate and reliable date for each zone.

Statistical Analysis

A Principal Component Analysis (PCA) was performed to compare the pollen spectra of the littoral cores with the central core. The PCA was performed in Canoco For Windows (Ter Braak & Smilauer, 2002) using the pollen counts of the taxa included in the pollen sum for each sample. A square-root transformation was performed on the data prior to the analysis.

The data from core E was first used in the analysis to provide the timeline which was to be the basis for the analyses of cores B and B'. A PCA was then performed for the combinations E-B and E-B', in which the data from either core B or B' was marked as supplementary (therefore excluding them from the formation of the axes).

Results

Ground-Penetrating Radar

GPR imaging shows several hiatuses in the lake's sediments. This study focuses on the most recent one (figure 4).

The GPR image shows that the position of core E is near the lake's deepest part, and that it contains a complete record of all past change. Cores B and B' contain a hiatus and are thus missing part of the record. Using the water depth (±1.34 m) as a unit of measurement, the depths at which the hiatus occurs within each core has been calculated to be ±1.03 m and ±0.88 m for core B and core B', respectively. As B' consists of the top 3.0 m of sediment, it encompasses the hiatus depth. Core B spans 1.5-5 m sediment depth, and therefore does not cover the hiatus that is seen in the GPR data.

By locating the point at which the hiatus is no longer present (figure 4), the location of the former shoreline during that time could be established. By again using current water depth as a unit of measurement, the sediment depth of this old shoreline was estimated to be ±1 m. Based on these observations, the northern and southern shoreline likely shifted ±20 m and ±90 m inward, as a result of a maximum lake-level decrease of ±2.3 m. This lake-level decrease is a maximum, since no correction was applied for the compaction of the sediment.

Pollen Analysis

The three cores all cover most of the Holocene and Late-Glacial. Core E contains the most complete record (figure 5), ranging from the end of the Older Dryas to the present. Core B (figure 6) starts in the Allerød interstadial, but ends in the early Subboreal due to the missing top 1.5 m. Core B' (figure 7) provides a more complete record of the Holocene in this respect, as it ranges from the Younger Dryas to the Subatlantic.

Core E shows low abundances of *Betula* and *Pinus* at the onset of the record, along with a peak in Poaceae. Especially the low amounts of *Pinus* combined with the peak in NAP observed seem to indicate that this represents the Older Dryas stadial. This is further

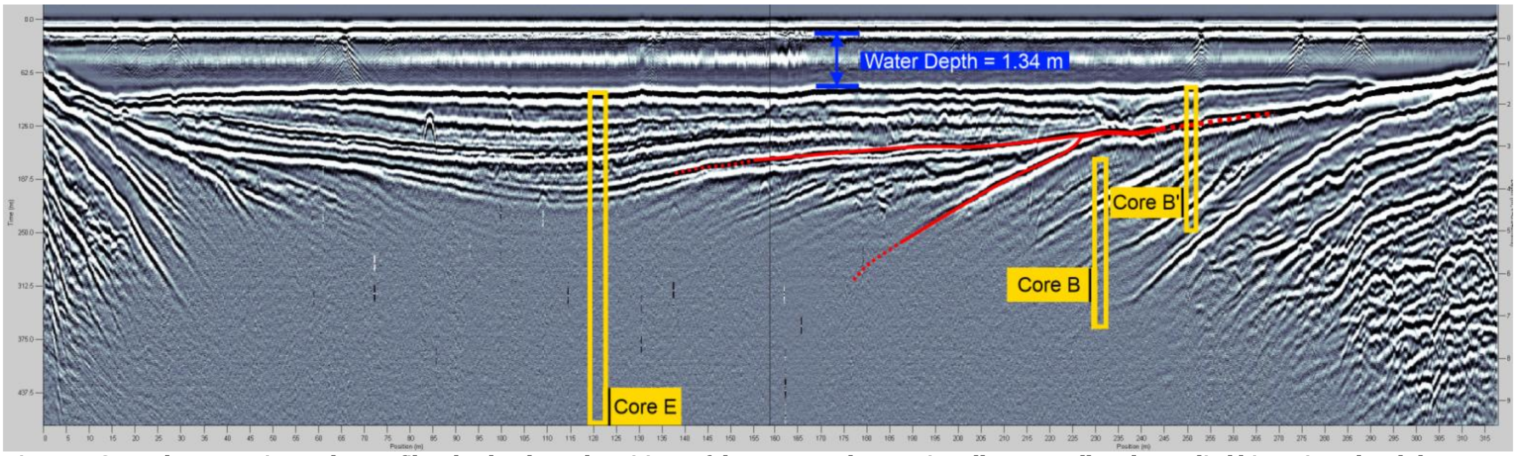

Figure 4. Ground-Penetrating Radar Profile. The depths and positions of the cores can be seen in yellow, as well as the studied hiatus in red and the water depth (blue). Each of the lines that are visible in this image represents a layer of deposited sediment. This image represents the transect as depicted in figure 2 from the northern shore of the lake (left) to the southern shore (right).

supported by its position just before increases in AP (AP) indicative of interstadial conditions.

Cores E and B both show peaks in *Juniperus* and *Betula* (>50%) during the Allerød (14,100 – 12,800 BP) and increases in the abundance of *Pinus*. Whereas the percentage of *Pinus* in core B steadily increases with time, core E shows a peak of *Pinus* (±60%) early on. *Salix* abundances in these two cores are also highest during the Late-Glacial. Furthermore, core B shows peaks in *Pediastrum* and *Scenedesmus*, along with a decrease in non-arboreal pollen (NAP) from ±40% to ±20%. Especially the peaks in juniper, birch and pine are indicative of the Allerød interstadial (14,100 – 12,800 BP).

During the Younger Dryas period (12,800 – 10,300 BP), all records show increases in monolete fern spores (>5%), Cyperaceae (>20%) and Ericales (≥5%). At the same time, *Artemisia* and *Salix* become more abundant in core B, while *Equisetum* becomes more widespread in the B' and E cores. Cores B' and E contrast each other as NAP abundances rise to ±30% in E, but fall from ±40% to ±20% in core B'. The relatively high abundance of NAP, along with the presence of heath and ferns, are characteristic of the Younger Dryas stadial in North-Western Europe (12,800 – 9,000 BP).

At the onset of the Holocene, all cores show increases in arboreal pollen (AP), *Betula*, and *Pinus*. The abundance of AP increases to ± 90% in all cores, and peaks of *Pinus* pollen are as high as 60%. Core E shows a maximum in *Betula* pollen (>70%), as opposed to core B' in which birch eventually declines to abundances lower than 30% of the pollen sum. Core B' also shows an unusually early introduction of *Corylus* and *Ulmus*. However, the peaks in *Pinus* and AP in core E, along with a strong decline in *Artemisia* and Ericales, indicate that this interval corresponds with the Preboreal (10,300 – 9,000 BP).

The next zone is characterized by the introduction of *Corylus* and *Ulmus* in cores E and B', after which *Corylus* rapidly expands (>30% in core B). All cores show an appearance of *Quercus*, which reaches values of ≥10% soon after, concurrent with a strong decrease of *Betula* (<10% in core E). A decrease in pine pollen (<20%) is witnessed in core B' along with the decrease of birch. During this same period, *Alnus* first appears in cores B and B'. As *Betula* has severely decreased at this point and *Corylus* has entered the record, this part of the record reflects the Boreal period (9,000 – 7,500 BP).

After the Boreal, all cores show a decline of pine pollen, as well as an increase of oak and alder. *Pinus* reaches levels lower than 5%, while *Quercus* and *Alnus* increase to values of ≥20%. Alder increases rapidly, especially within core E, in which alder first appears in this period of time as well. Core E also shows a decrease in *Ulmus* as well as in AP which are lowered to <5% and ±85%, respectively. Core B shows an increase in *Botryococcus* during the same period in which *Isoetes* first occurs in core B'. These changes, especially the decrease of pine pollen and the increase of alder and oak, are strong indicators suggesting that this zone represents the Atlantic period (7,500 – 5,000 BP).

After the Atlantic, all cores show increases in *Isoetes* (≥5%), *Littorella* (±5%), Ericales (5-15%), *Sphagnum* (<5%), NAP (≥15%) and the introduction of *Fagus*. Furthermore, cores B' and E show large peaks in the abundance of *Botryococcus* towards the end of this period, whereas core B shows a strong increase in this group of algae instead of a large peak. Core B also shows an increase in alder at the beginning of this zone. The presence of *Isoetes*, *Littorella* and *Sphagnum*, along with increases in Ericales and *Sphagnum* places this zone in the Subboreal (5,000 – 2,800 BP). The early Subboreal is also where the record of core B ends due to the missing top 1.5 m.

The top layers of cores B' and E first show increases in *Rumex* and *Fagus* followed by increases in *Cannabis* (>20%), Cerealia, *Secale*, *Fagopyrum* and Ericales (±20%). Maxima in *Potamogeton*, *Pediastrum*, *Scenedesmus* and *Tetraedron minimum* also occur in both cores, however they appear relatively early in core B'. The increases in cultivated plants (i.e. *Cannabis*, *Secale*, *Fagopyrum*) occur throughout the entire Subatlantic in core B', whereas they occur at the end of the record in core E. Just before the rise in Ericales observed in both cores, core E shows a short period of time in which there is a decline in Ericales to ± 10%. Both of these cores also show an overall decrease of AP to ±20%, with a decline in alder, oak, hazel and birch (<10%, <10%, <5% and <5%, respectively). The strong decline of AP and the increase in *Fagus* abundance are indicators of the start of the Subatlantic, while the increase in cultivated plants

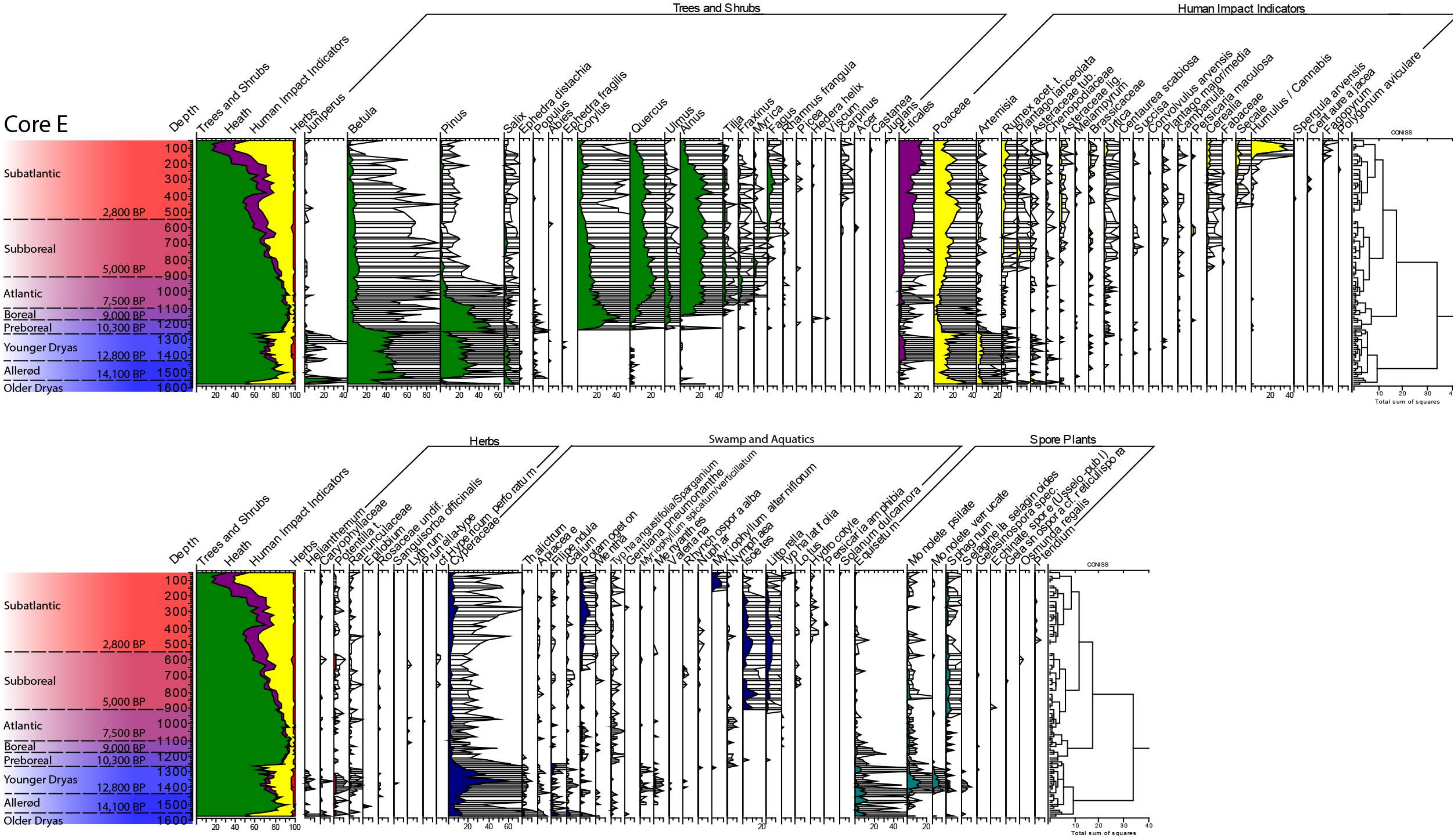

Figure 5. Pollen diagram of core E.

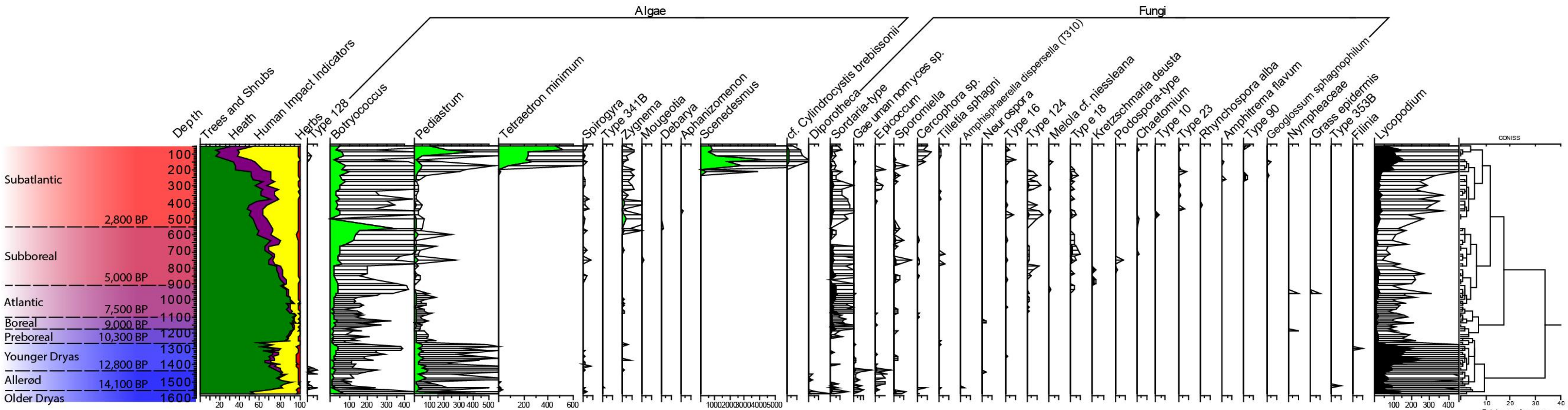

Figure 5. Core E continued.

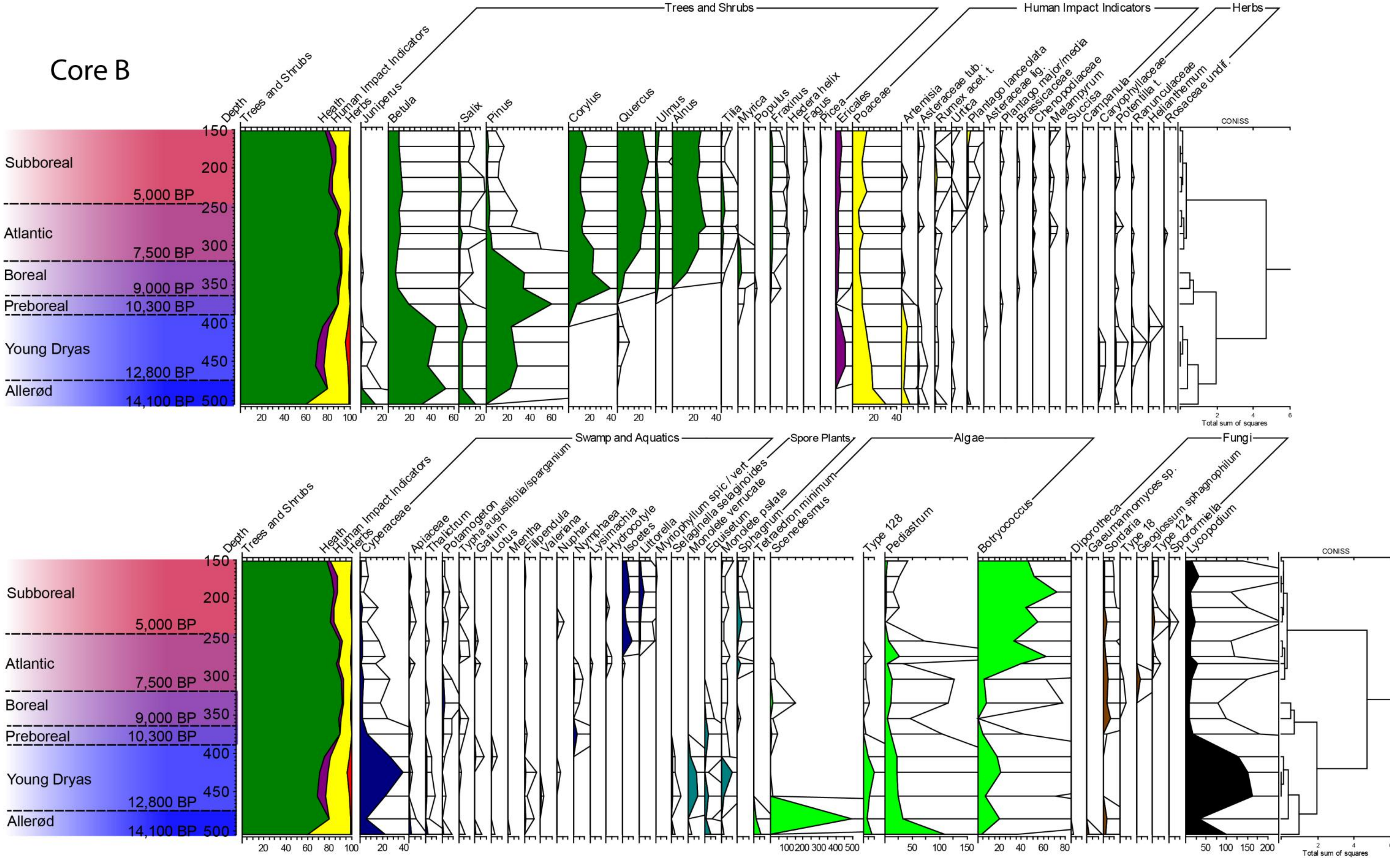

Figure 6. Pollen diagram of core B.

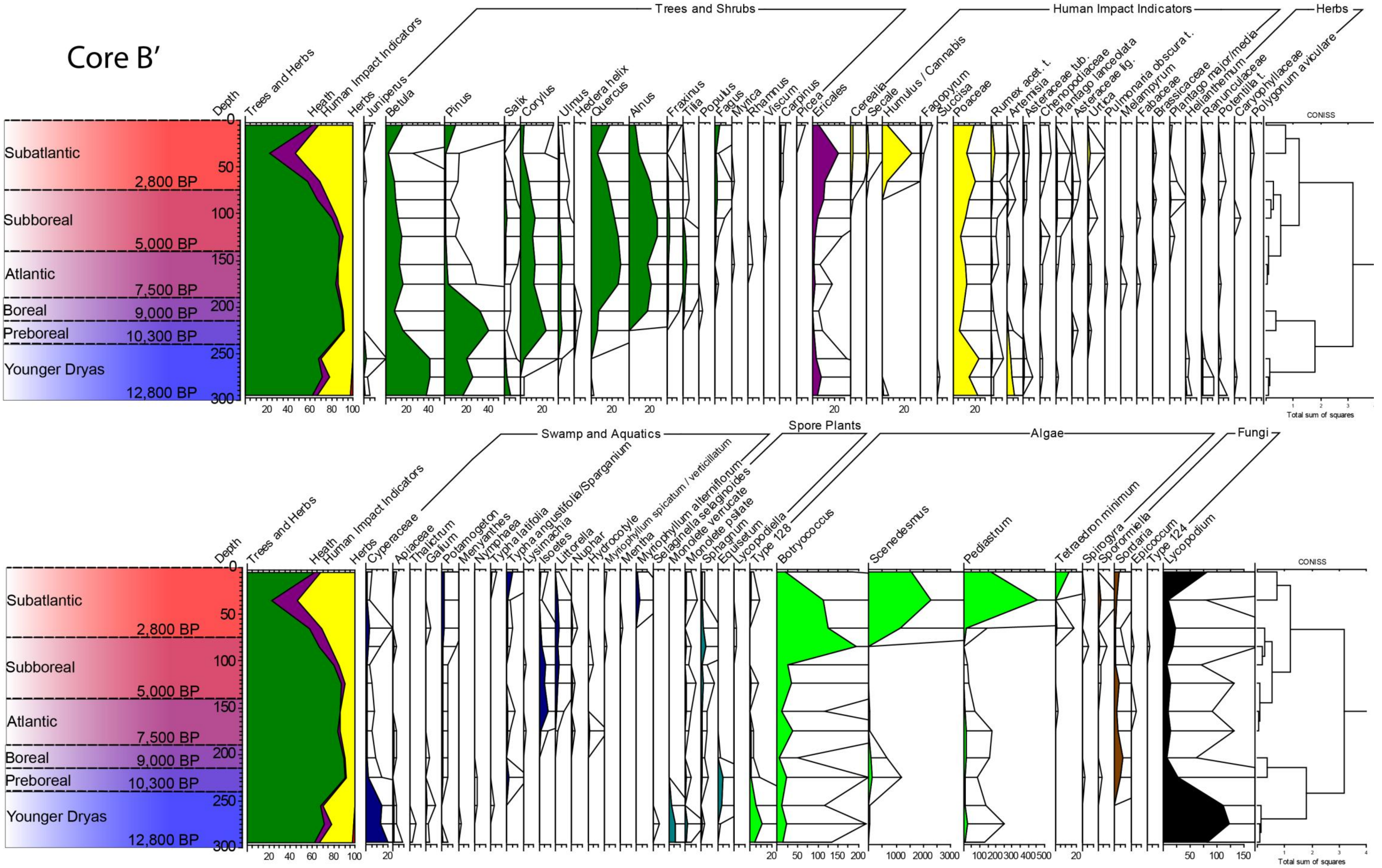

Figure 7. Pollen diagram of core B'.

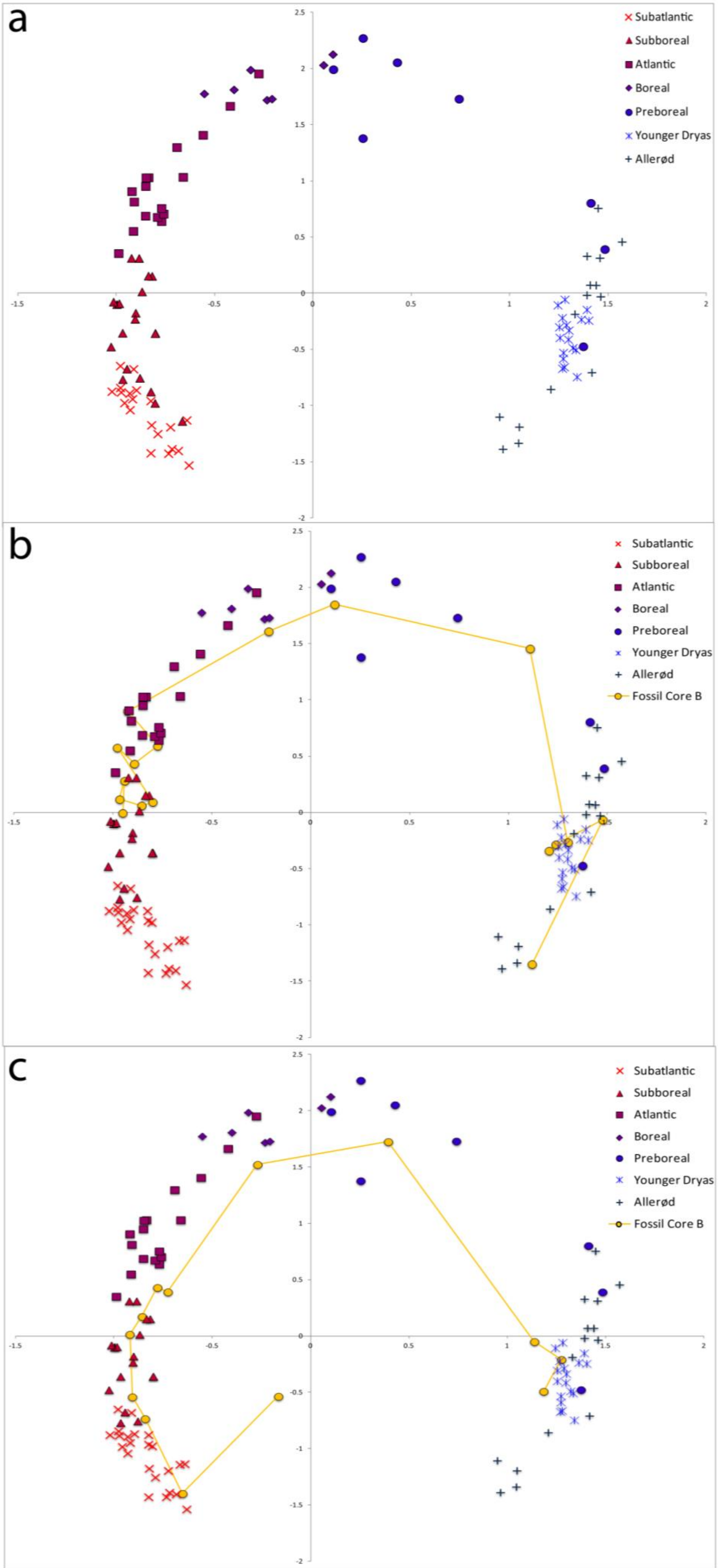

Figure 8. Principal Component Analyses of (a) core E, (b) core E versus core B and (c) core E versus core B'.

and algae later on are characteristic for the late Subatlantic.

Statistical Analysis

A Principal Component Analysis (PCA) of core E (figure 8a) shows that the samples within each zone group closely together and that each period of time transitions into the next according to the established chronology. The first four axes explain respectively 53.1, 20.6, 9.1 and 3.4% of all variance found within the data. The Allerød and Younger Dryas are both part of the Late-Glacial and only show slight differences on the first two axes of the PCA as samples from both zones are located next to each other. The Preboreal acts as a transitional phase from Late-Glacial to Holocene conditions, and this is shown by the PCA as well. The Boreal and Atlantic are periods of time in which a lot of change occurred in the form of new taxa arriving in the environment. This is well reflected once more, as both periods are well-defined in the figure. The differences between the Subboreal and Subatlantic are substantial, but not as dramatic as those in the Boreal and Atlantic. The PCA also shows a slight overlap between the Subboreal and Subatlantic periods, but their positions correspond with the timeline nonetheless.

When the data from core B is added to the PCA of core E as a supplementary variable, it clearly follows the timeline set by the PCA of core E (figure 8b). Furthermore, as the samples from the top of core B are similar to those of the Subboreal in core E, this PCA reinforces the idea that the core B record is cut off at the first half of the Subboreal.

When the same analysis is performed using cores E and B' (figure 8c), core B' seems to follow core E's timeline, except for one outlier at the very end. This outlier is caused by an unexplained increase in AP in core B' which is not witnessed in core E.

Discussion

Summary

All cores show a similar vegetational development during the Holocene corresponding with the known changes starting in the Late-Glacial and continuing to the present. Over time, the overall number of arboreal plants decrease in favour of herbaceous taxa and plants indicative of human impact on the environment. During the late Subboreal, algal blooms are related to the eutrophication of lake Uddelermeer. The eutrophication and the abundant algae correspond with human activity (e.g. agriculture) in the late Subatlantic. This argument is reinforced by the increase in cultivated plants (e.g. buckwheat, rye and hemp) and the decline of trees. These all point towards human activity, such as agriculture, logging and an increased nutrient flow into the lake itself.

While the general trends in each of the cores are similar, there are some slight differences. Some of the differences in abundances may relate to the position of the cores, as some plants have properties which cause an uneven distribution across the lake. These include some of the aquatic plants that have preferences for certain depths or the different buoyancies for the pollen of some taxa (e.g. *Pinus*).

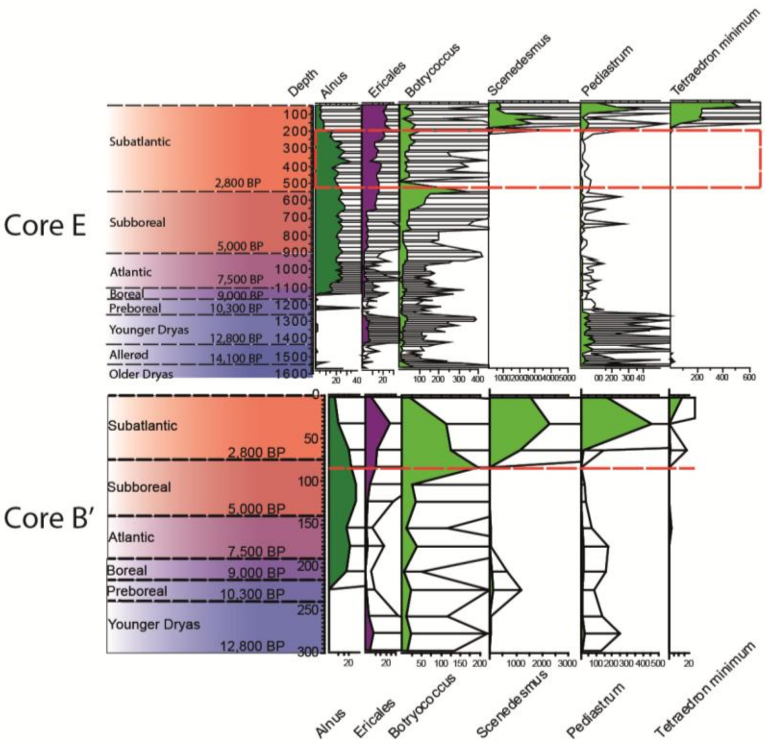

Figure 9. A comparison of a selection of taxa in cores E and B'. The red frame and line indicate where the hiatus is located.

Besides variation in taxa abundance, there is also some temporal variation in the pollen diagrams. This variation is not necessarily related to actual differences in timing, but may have to do with the resolution of the analysis. Examples of this are the early presences of hazel and elm in core B', as opposed to cores E and B. The early entry of hazel and elm in core B' during the Preboreal may partially be explained by the resolution of the pollen diagram. A lower resolution may lead to the pollen diagram not accurately reflecting the actual point of appearance of taxa. The presence of an additional hiatus at this point of the record could provide an alternative explanation. The latter seems likely as there are strong differences between core B' and E, showing circumstances uncharacteristic for the Preboreal.

Dating the hiatus

Ground-penetrating radar places the start of the hiatus in core B' pollen record at ~0.88 m sediment depth which dates back to the Subboreal-Subatlantic transition ±2,800 years ago. There are several differences between cores E and B' at this depth (figure 9), which is indicative of a hiatus and further supports the GPR data. In core E, *Alnus* shows a peak between ~4 and ~2.5 m sediment depth, whereas the presence of alder continuously decreases during the Subatlantic period in core B'. The opposite is observed for Ericales. It increasing continuously throughout the Subboreal and Subatlantic in core B', while core E shows a short period in which Ericales declined (~4-~2.5 m sediment depth). Furthermore, *Fagus* abundance rises in the same depth interval of core E, yet *Fagus* shows little change in core B' until the very end of the Subatlantic. These taxa seem to suggest that the hiatus in core B' correspond to the sediment interval between 4 and 2.5 m sediment depth in core E. However, due to the relatively low resolution of core B' compared to that of core E, it could simply be that these changes go unnoticed in the littoral core.

The peaks in *Botryococcus*, *Pediastrum*, *Scenedesmus* and *Tetraedron minimum* provide more robust evidence for the presence of the hiatus. I assume that algae are homogenously distributed throughout the lake. A *Botryococcus* peak is observed in both cores at the Subboreal-Subatlantic transition (~5.5 m sediment depth in core E), but the occurrence of peaks in the other algae is very different between cores. Core E shows a strong increase in *Scenedesmus* at ±2 m sediment depth and subsequent increases in *Tetraedron minimum* and finally *Pediastrum*. However, the peaks in these algae occur directly after the peak in *Botryococcus* in core B'. Moreover, the increase in cultivated plants (i.e. Cerealia, *Secale*, *Cannabis* and *Fagopyrum*) is present in the top ±0.5 m and ±2m of cores B' and E, respectively. This, along with the later peaks in algae, suggests that sediment record of core B' was interrupted shortly after the peak of *Botryococcus* and resumed just before the peaks in cultivated plants (e.g. *Cannabis*) and the other algae. These indicators of the start and end of the hiatus correspond with the period of time covered by ±3.5 m in core E (~5.5-~2 m sediment depth). The beginning of the hiatus seems to correspond with the start of the Subatlantic roughly 2,800 years ago. The end of the hiatus cannot be accurately dated, but seems to occur just before the peak in *Cannabis* in core E. A report on Uddelermeer by Sjoerd Bohncke (VU University, Amsterdam) places the peaks in *Cannabis* at roughly the 16th century. A German study by Dörfler (2013) and a French study by Lavrieux *et al*. (2013) indicate that *Cannabis* reaches maximum abundances during the modern age (starts at ±1500 A.D.) and during either the 14th, late 15th or late 18th century, respectively. Therefore, a rough estimate of the end of the hiatus is placed at approximately the 15th century. As the onset of the Subatlantic in calendar years is ca. 700 B.C., this would mean the hiatus covers about 2,350 years (850 B.C. – 1500 A.D.).

Statistical Analysis

The results of the Principal Component Analysis (core B' against core E; figure 8c) seem to suggest the presence of a hiatus at the Subboreal-Subatlantic transition in core B', but there is no statistical way to prove this objectively. A hiatus in the PCA would normally be visible with samples from core B' not covering the complete record of core E. However, since all major time periods zones are recognized in both cores (excluding the Allerød interstadial in core B'), it is not possible to tell where the hiatus is located based purely on PCA data. However, the taxa included in the PCA (i.e. the pollen sum) offer no good evidence of a hiatus as was stated before. The algae were excluded from the PCA, but they show the strongest evidence of the presence of a hiatus. The absence of the algae from the PCA may explain why we are not able to recognize a hiatus in the PCA.

Regional implications of a late Holocene lake-level lowstand at Uddelermeer

The hiatus covered by the 5.5 – 2m depth interval in core E suggests that there were large changes in local hydrology during the time of deposition. Because the water supply of the lake depends on regional groundwater levels, it can be assumed that the region received less precipitation during this time. Alternatively, regional groundwater levels depend on effective precipitation and higher levels of evaporation might also have resulted in lake-levels lowering.

The Westerlies provide North-West Europe with much of its precipitation. Therefore, if lower lake-levels were caused by a decrease in precipitation, these drier conditions occurred not only regionally, but would be expected to affect a large part of North-West Europe. It would have affected a multitude of modern-day countries, including Great Britain, parts of Scandinavia and the Netherlands among others.

This study shows that lake-levels at Uddelermeer were lower than present-day during a period of ca. 2,350 years, starting at the onset of the Subatlantic (850 B.C.; 2,800 cal BP).

A study on Lake Bysjön, South Sweden, by Digerfeldt (1988) used sediment limit changes recorded in the lake and the reworked minerogenic matter content of the sediment to reconstruct past lake-level fluctuations. His results suggest a fluctuating climate with a culmination of dry conditions from ca. 4,900-4,600 BP to ca. 2,900-2,600 BP, followed by a rise in lake-levels until a lowering took place somewhere inbetween 1,800 and 1,200 BP.

In a study by Gaillard *et al.* (1991) at Bjäresjösjön, South Sweden, several increases and decreases in water levels have been observed over the past ca. 2,700 years. Using pollen analytic methods proposed by Digerfeldt (1986), they demonstrated three increases in lake-levels (700-300 B.C.; 650-1150 A.D.; 1050-1300 A.D.) along with two lake-level lowering events from 0 to 650 A.D. and 1400 to 1600 A.D. The first increase in the water table, which led to the lake's creation, at ca. 700 B.C. may have been caused by either climatic or human impact factors. Gaillard *et al.* deem a climatic cause (i.e. drier or wetter climate) plausible for this first increase as well as for all subsequent changes. Their findings seem to confirm the changes found by Digerfeldt (1988).

Lake-level fluctuations at Ljustjärnen, central Sweden, were reconstructed by Almquist-Jacobson (1995) by studying changes in sediment composition, changes in the distribution of aquatic macrophytes, unconformities in the stratigraphy, the juxtaposition of several lithostratigraphic facies and fossil pollen. Her reconstruction shows three fluctuations over the last ca. 3,200 years: a rise of lake-levels at ca. 3,200 BP, followed by a lowering at ca. 2,000 BP and a final increase at around 300 BP These results are roughly similar to the findings from the aforementioned studies in southern Sweden, but seem to indicate regional differences.

A comparison of several studies allowed Magny (1993) to reconstruct Holocene lake-level fluctuations in the Jura and northern subalpine ranges, Switzerland. The results show that this region experienced high water levels, or transgressive phases, during several major periods: 1,865-1,050 B.C., 850 B.C.-18 A.D., 1-200 A.D., 500-1,000 A.D. and a phase which began after ca. 1,100 A.D. These transgressions were interrupted by three regressions, the first of which lasted from 1 to 200 A.D. The remaining two regressions occurred somewhere during the latest of the transgressions (i.e. after 1,100

A.D.). This reconstruction seems to differ greatly from those in Sweden, as is to be expected.

Another study on Swiss past lake-level change was performed by Mahler in 2009, in which she compared data from 12 studies. These studies made reconstructions using lake sediments and analyzing the texture, lithology, morphotypes of carbonate concretions, mollusc shells, macro-remains from aquatic and terrestrial plants, and the geometry of the sediment layers. These were dated using radiocarbon dating, dendrochronology, archaeological dating, isotope stratigraphy and pollen stratigraphy. The results presented by Mahler show six periods of alternating lower and higher lake-levels during the last 3,150 calendar years. These periods are from 3,150-3,000 (low), 2,750-2,300 (high), 1,550-1,250 (low), 1,100-950 (high), 975-950 (low) and 650-250 (high) cal. BP. The dating of higher lake-levels seems roughly similar to those observed by Magny (1993) due to some overlap between the dates, but there seem to be several differences as well. The most distinct of these differences are the multiple periods in which lake-levels were lower that seem to be missing from Magny's record.

Whereas the previous studies were limited to specific regions, a study by Holzhauser *et al.* (2005) focused on lake-level fluctuations across West-Central Europe using datasets from other studies which used the same parameters as mentioned in the study by Mahler (2009). They showed that lake levels were higher from 1,550-1,150 B.C., lower from 1,150-800 B.C., higher again from 800-400 B.C. and lowered once more during 250-650 A.D. The two lowstands along with the highstand from 800-400 B.C. seem to correlate well with the low and high lake-levels seen in Switzerland (Mahler, 2009), and with some of the periods seen in Sweden (Gaillard *et al.*, 1991).

Magny (2004) explored Holocene climate variability by studying mid-European lake-level fluctuations from a data set of 26 lakes in the Jura mountains, the northern French, Pre-Alps and the Swiss Plateau, containing 180 radiocarbon, tree-ring and archaeological dates. The results provide evidence of an unstable Holocene climate with nine phases of higher or lower lake-levels within the last 2,750 years. These phases alternate between higher and lower lake-levels. The period from 2,750-2,350 cal. BP consists of many high lake-levels, followed by a period with lower lake-levels from 2,350-1,800 cal. BP, higher lake-levels from 1,800-1,700 cal. BP, lowering again from 1,700-1,300 cal. BP, a subsequent rise from 1,300-1,100 cal. BP, a lowering from 1,100-750 cal. BP, an increase from 750-650 cal. BP, a brief lowering of lake-levels from 650-550 cal. BP and a final rise in lake-levels at 1,394 A.D.

These previous studies on lake-level fluctuations in Europe show that higher lake-levels occurred from ca. 2,800 – 2,100 cal. BP, followed by a period of lower lake-levels between ca. 2,000 and 1,200 cal. BP and finally a period from ca. 1,100 to 400 cal. BP showing both increases and decreases in lake-levels depending on the lake's location (Gaillard *et al.*, 1991; Mahler, 2009; Holzhauser *et al.*, 2005; Magny, 1993, 2004; Almquist-Jacobson, 1995; Digerfeldt, 1988). However, most of these studies use data from lakes located in either Scandinavia or Switzerland, which may not be representative of events in the Netherlands. Furthermore, the resolution of core B' may be too low to provide enough detail to allow an accurate comparison to the aforementioned studies.

Many lake-level increases are observed at the onset of the Subatlantic, likely caused by increases in effective precipitation. Hypothetically, an alternative explanation for the lowering of the lake-level would be that the increase in precipitation led to higher lake-levels and the lake consequently broke through the surrounding wall. This would have led to water flowing out of the lake, possibly leading to the lake-level lowering observed in the present study.

Further research could assist in providing a more reliable dating of the time in which lake-levels were lower. The research possibilities include a further increase of the resolution of core B', dating using ^{14}C or the use of additional proxies (e.g. fossil chironomids). The data acquired in this study has been made available for use in an overarching multi-proxy study on the effects of solar forcing on European climate (NWO research grant 863.11.00), in which it will be possible to use the produced data for the reconstruction of precipitation patterns over North-West Europe. Furthermore, the data produced by the overarching study may eventually be used to validate climate models. This study, along with the multi-proxy study, will provide high-resolution environmental data (i.e. lake-levels, surrounding vegetation, and inferred climate change) and may lead to new insights in Holocene precipitation fluctuations.

Conclusions

In this study, a reconstruction of a late Holocene lake-level lowstand at lake Uddelermeer was made. This lake is a pingo-remnant located near Amersfoort, the Netherlands, sensitive to changes in groundwater tables. This is due to its position between two push moraines, which provide it with its water. The reconstruction was made by combining sedimentological with palynological methods: ground-penetrating radar and pollen analysis, respectively. Pollen analysis was done on two littoral cores and one central core. Due to their locations, the central core (Core E) contains a complete record, while littoral cores (Cores B and B') are incomplete.

Ground-penetrating radar images show that lake-levels were ±2.3 meters lower at some time during the Holocene. Palynological data from core E and core B' suggest that the hiatus occurred during the period of time contained by sediments from ±5.5 to ±2 meters deep in core E. Several differences were observed between the pollen records of these cores. A peak in several algal taxa (i.e. *Scenedesmus*, *Pediastrum* and *Tetraedron minimum*) following a *Botryococcus* maximum was seen in core B', whereas core E showed that there was a lot of space inbetween these peaks. These ±3.5 m roughly correspond with a period of 2,350 years. During these years, lake Uddelermeer received less water from the surrounding environment. Due to the dependency on effective precipitation as a water supply, it is likely that less precipitation arrived at the lake. As it is improbable that such a decrease in precipitation was confined to the region surrounding this lake, it is likely that a large part of North-West Europe experienced lower amounts of precipitation at that time.

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