“How and when did human activity influence the natural vegetation around the Nieuweveen pingo remnant during the Middle and Late Holocene.”

Human impact on the natural vegetation during the Middle and Late Holocene at the Nieuweveen pingo

Master Thesis

Author: Vincent van Doorn
Date: 19-03-2023
Student number: 5893747
1st supervisor: dr. Timme H. Donders
2nd supervisor: dr. Wim Z. Hoek

Inhoud

Abstract

The Nieuweveen pingo is one of the many pingos present in the Eastern part of the Netherlands. But it is unique thanks to the large and continuous sedimentary record. Preliminary research of the Nieuweveen core showed very little human impact present at this site. Therefore, the aim of this research is to determine how and when human influence impacted the natural vegetation around the site. 45 samples were taken from the Nieuweveen core and the pollen were extracted and analyzed. Based on the obtained pollen record it became clear that humans influenced the area since 5500 cal. yr. BP. However, clear human impact on the environment around the Nieuweveen site did not happen until around 3500 cal. yr BP, which is extremely late. Comparisons with other well-known pingo remnants such as the Hijkermeer pingo, Mekelermeer pingo and Uddelermeer pingo show that the human impact on the Nieuweveen site was also very limited compared to other parts of the Netherlands. As a result the vegetation around this site gives a clear picture of the natural vegetation during most of the Holocene. Small scale farming, deforestation and establishing of settlements all influenced the area. Although some had more impact than others. Furthermore, changes in temperature and precipitation between 4200 cal. yr BP and 3200 cal. yr BP were also important contributors to some of the changes in the natural vegetation, such as a rapid and sudden increase and later on a decline in *Betula.*

1. Introduction

Sedimentary archives may contain remains of past vegetation and the human impact on them. During the early and early middle Holocene, the impact of humans on the vegetation in the Netherlands was very limited, but since the later part of the middle Holocene and especially the later Holocene the human impact on the vegetation increased. This increased human impact resulted into a higher regional variation in the landscape during the latter half of the Holocene (van Beek et al., 2015). It is well known that agriculture developed relatively early in the northern Netherlands and had a large impact on the natural vegetation, but the precise chronology of the influence of agriculture on the vegetation in the north of the Netherlands is not well known and requires more archives and studies (Engels et al., 2016). One of the sedimentary archives which contains a lot of information on the past vegetation in the region is the Nieuweveen pingo remnant, which is located near the city of Hardenberg in the province of Overijssel, the Netherlands. This site has been cored in 2020 and contains a 18-m long section of organic deposits of which approximately 6.5m is of Holocene age, which is exceptionally deep for a pingo core (Hoek et al., not yet published). Pilot research from students of the University of Utrecht on the sediment infill and pollen content of the Nieuweveen pingo remnant has revealed a remarkably low amount of human influence on the landscape. To reconstruct the natural vegetation and research how it was influenced by human activities it is important to understand how the vegetation developed during the Holocene. Furthermore, it is important to understand how human influence on the vegetation developed and in which way they influenced the vegetation.

1.1 Vegetation history of NE Netherlands

In the Atlantic period (8-5 ka BP) large parts of the NE Netherlands were covered by deciduous forests, these forests primarily consisted out of oak (*Quercus*). However elm (*Ulmus*), lime (*Tilia*) and ash *(Fraxinus*) were also frequently occuring (van Beek et al., 2015). At the forest edges and sandy ridges a more shrub like vegetation composition occurred, which were dominated by hazel (*Corylus*) and bracken (*Pteridium*) (van Beek et al., 2015). On nutrient poor and sandy soils, which had slowly disappeared, pine still occurred. However, these trees gradually disappeared during the Atlantic period. On coversand plains, small open spaces could be found, which were covered with heath (van Beek et al., 2015). In early stages of the Subboreal period (5-2.5 ka BP) large deciduous forest occurred. Although Oak (*Quercus)* still dominated these forests, lime (*Tilia*) and elm (*Ulmus*) were decreasing (van Beek et al., 2015). At the end of the Subboreal period beech (*Fagus*) started to occur. In NW Europe there appears to be a direct link between human influence and the occurrence of beech (Pott, 1997), this suggests that the occurrence of beech should be limited in areas with little human influence, like the area around the Nieuweveen pingo remnant. Human impact on the environment caused the formation of woodland openings (van Beek et al., 2015). This led to open vegetation consisting out of heath, herbs and smaller shrubs. Compared to the Atlantic period the amount of pines has decreased significantly and only survived on nutrient poor soils (van Beek et al., 2015). During this period ribwort plantain (*Plantago lanceolata*), an important indicator for human activities, appeared, which grows in areas with open grass vegetation. In wetter places willow (*Salix*) starts to occur (van Beek et al., 2015). During the Roman Period a decrease in trees and an increase in heather and grasses occurs, this coincides with the first appearance of cereal pollen and arable weeds (van Beek et al., 2015). The pine forests have been completely cleared and are replaced with hazel (*Corylus*). The deciduous forest are still dominated by oak (*Quercus*), but the occurrence of beech (*Fagus*) in these forest has significantly increased. Heathlands have developed on the poor sandy soils (van Beek et al., 2015). By the Middle Ages (1000 BP) large areas were deforested. The remaining forest were dispersed and open. The landscape was more open with scattered areas of shrub. Heathlands became more numerous and increased in size (van Beek et al., 2015).

1.2 Human settlement history

In the Late Paleolithic (10 ka BP) human influence on the environment was very limited. They lived in small groups of hunters and gatherers, which roamed the land (van Beek et al., 2015). There settlements were mainly located near ice pushed ridges and coversand landscapes, which had a high biodiversity and enabled the exploitation of a variety of landscapes (Deeben et al., 2006). Hardly anything is known on the Early Neolithic (7300-6200 BP) human impact. There are some finds of stone axes dating to this time period, which suggests some sort of woodcutting. But this was most likely very limited and therefore had not much of an impact on the vegetation (Raemaekers, 1999). However, the human impact during the Middle Neolithic (6200-4850 BP) is clearly visible in the palynological records (Spek, 2004). During the Middle Bronze age (3500 BP) increasing numbers of small scale woodland openings appeared as a result of woodcutting, which is supported by findings of both bronze and stone tools and well preserved settlements (Bos and Zuidhoff, 2011). The massive deforestation, which corresponds to the Middle Roman Empire (2000-1700 BP), is absent at the study site. This area was never formally part of the Roman empire. Furthermore, there was a change in the settlement system. Single farmsteads were slowly substituted by fixed, nucleated settlements and agriculture became more prevalent (Bos and Zuidhoff, 2011; Jørgensen et al., 2020).

1.3 Pollen indicators of human activity

The current landscape of the Earth surface is a result of the combined effects of past climate change and human activities (Li et al., 2008). In which way the ecosystem and landscape have changed under the influence of human impact is an important factor for the reconstruction of past environments. To gain an accurate paleoenvironmental reconstruction, the impact of human activities must be considered. However, the impact of humans on the environment is often hard to detect and quantify and as a result its effect on the paleo records is often uncertain and complex (Li et al., 2008). Nevertheless, pollen analysis can be used to determine how the natural vegetation looked like before human activities in the area and reveal the rate, trend and scale of the various changes in the vegetation after humans occupied the area and started to disturb the vegetation. Furthermore, the occurrence of certain species and pollen types can be used to determine human activities in the area like forest clearance and agriculture (Behre, 1986).

1.3.1 Decline in arboreal pollen

A decrease in tree pollen can be caused by human activities, climate change or both (Li et al., 2008). Human impact would usually result in a decrease of one or multiple specific tree pollen types in different sites. As a result of climate change you usually see a decline in many types of different trees on a large spatial scale (Li et al., 2008). One of the most well studied cases related to human impact is the elm decline. The decrease in *Ulmus* pollen can be found in many sites all over Europe around 5100 year BP. Besides around 5100 year BP this event was found during many periods such as 5500 - 4950 year BP, 4600 year BP, 4470 - 3945 year BP, 4050 – 3750 year BP and 2950 – 2650 year BP (Li et al., 2008; Hirons & Edwards, 1986). In Europe a decrease in tree pollen often indicates the replacement of woodland by farmlands and pastures. This replacement is marked by the rise of cereal pollen and several cropland weeds, which consisted mostly out of *Aster*, *Plantago*, *Ambrosia* and Gramineae (Birks et al., 1988; Li et al., 2008). A decrease in influx of tree pollen in combination with the occurrence of open landscape pollen is usually an indicator of the occurrence of deforestation.

1.3.2 Pioneer plant pollen

According to Li et al (2008) ''a high influx and concentration of light-demanding pioneer species like *Alnus*, *Betula*, *Corylus* and *Pinus* after high pollen values of species like *Tilia*, *Fraxinus* and *Quercus* indicates a disturbance in the forest and points towards human activity''. A research of Chambers & Price (1988) shows that in some cases the *Alnus* and *Corylus* pollen do not show a decline or rise. It is suggested that this is caused by the removal of hazel and alder trees for farming. When these plots were abandoned the hazel would regrow. Abandonment of these farmlands and pastures can result in extensive reforestation. Trees like *Pinus*, *Betula*, *Corylus* and in some cases *Populus* can quickly spread after burning or forest clearance (Chambers & Price, 1988; Li et al., 2008). A sudden increase of these tree species may be caused by human interference on the local vegetation.

1.3.3 Cropland weed pollen

The occurrence of cereal-type pollen together with certain cropland weed pollen can be used as an indicator of prehistorical agriculture activities (McAndrews & Boyko-Diakonow, 1989; Li et al., 2008). Many agricultural sites show cereal type pollen grains together with cropland weed pollen like *Portulaca*, *Plantago*, *Urtica* and *Rumex*, which indicates agriculture around that time. A species often found at the edges of these croplands is *Centaurea cyanus* (McAndrews & Boyko-Diakonow, 1989; Li et al., 2008).

1.3.4 Changes in pollen concentration and influx

Human activities like forest clearance result in a decrease of trees in the area. This causes the total pollen deposition in the area to decrease. As a result forest clearance can be observed in the influx and concentration diagram. The total influx and concentration will decrease as a result of the forest clearance in particular for open vegetation (Yang et al., 2005). However, Aaby (1989) suggests that the influx of pollen would increase due to small scale forest clearance at the initial stage of the disturbance. This is because the open canopy resulting from the clearance would not only favour blooming flowers but also enhance the overall pollen dispersal. Although intensive deforestation would quickly result in a decrease of pollen influx and concentration.

1.3.5 Nitrophilous plants and pastoral weeds

Manuring as the result of grazing may increase the growth of nitrogen rich preferring plants such as *Cerastium arvense*, *Solanum nigrum*, *Artemisia*, *Peganum*, *Datura* and Chenopodiaceae, which can be found near settlements, croplands and pastures (Hjelle, 1999; Li et al., 2008). Pollen of *Rumex*, *Plantago lanceolata* and *Asteraceae* are commonly found near pastures and mowing lands in the northern parts of Europe (Hjelle, 1999).

1.3.6 Pollen spectra patterns for human impacted vegetation

Deforestation was the main type of human impact on the vegetation by the early farmers in forest regions (Behre, 1986; Li et al., 2008). The slash and burn strategy used by the early farmers in the Netherlands meant that they only cultivated the land for a certain amount of time before abandoning this land, because the cultivation of the land reduced the fertility and therefore it become less suitable for farming after a certain amount of time. This change in pollen deposition due to deforestation and agriculture caused by the first farmers is called Landnam (Iversen, 1973; R. Bakker, 1993). This fallow land often formed the basis for vegetation regeneration and was a signal that farmers moved somewhere else (Li et al., 2008). Pollen records may contain the entire process of human impact related to agriculture on the landscape: the deforestation to make room for farming, the cultivation of crops on the created plots, the abandonment of the land after the fertility decreased and the regeneration of the original forest. Li et al (2008) divided these processes into 5 different stages (Figure 1).

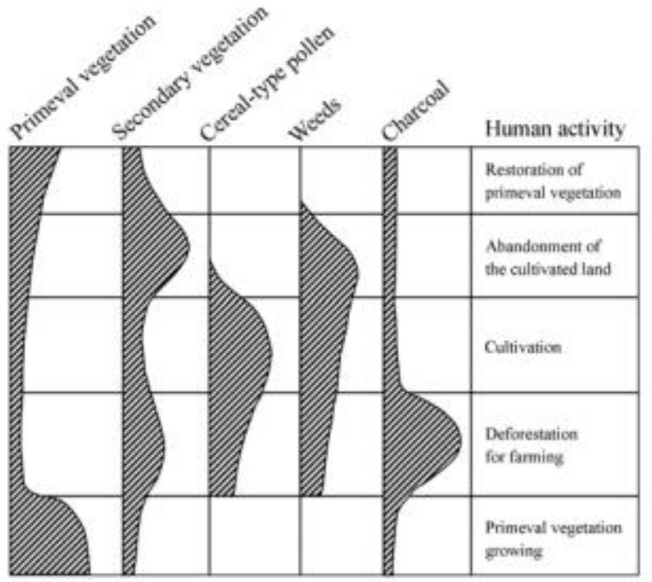


Figure 1, Patterns of pollen spectra for different stages related to human activity (li et al., 2008)

Stage 1: a period in which the original vegetation grows. High amounts of competitive and shade tolerant tree pollen like *Fraxinus*, *Tilia*, *Quercus*, *Picea*, *Alnus* and *Ulmus*. This suggest that there was limited disturbance caused by human presence on the vegetation.
Stage 2: a period of deforestation to create open plots for farming. Since the early farmers only cleared small parts of the forest for farming there is not a massive decrease in tree pollen. However pollen of secondary forest such as *Corylus*, *Betula* and *Pinus* together with other types of vegetation which grow underneath these trees like *Thalictrum*, *Artemisia*, *Sanguisorba* and spores of ferns show a clear increase. In some cases weed pollen and cereal type pollen may occur within this stage. However, the most important feature of this stage is the occurrence of the tree pollen.
Stage 3: This stage is characterized by the cultivation of crops. Due to this cultivation cereal type pollen and anthropogenic weeds occur in the pollen plot and they can become quite high depending on the intensity of the cultivation.
Stage 4: This stage marks the abandonment of the farm land. This abandonment results in a decline of cereal type pollen, which can be quite abrupt, and an increase in ruderal pollen, like *Plantago*, *Rumex* and *Asteraceae* and an increase in tree pollen like *Corylus*, *Betula* and *Pinus*.
Stage 5: This stage is characterized by the restoration of the original vegetation. Tree pollen like *Fagus*, *Carpinus*, *Fraxinus*, *Tilia*, *Quercus*, *Picea*, *Alnus* and *Ulmus* increases, whereas secondary forest pollen like as *Corylus*, *Betula* and *Pinus* declined.

1.4 Pollen analysis in NE Netherlands

Pollen analysis is a popular method of studying the Quaternary vegetational and climatic history. This method uses the numbers and kinds of pollen in samples, which are collected in vertical series from sediment deposits and peat (Davis, 1963). The results obtained from these samples are usually presented in a pollen diagram. In this diagram the percentage value of each pollen and spore type are shown against the height or age of the samples. These pollen percentages are presumed to show the percentage of vegetation types that grew around the site during the deposition of the sediment (Davis, 1963). The basic assumption around the pollen analysis method is that under the general circumstances the number of a specific type of pollen deposited per unit of time at a certain point in time is directly related to the total abundance of that species in the vegetational composition of the site. (Davis, 1963). However, pollen diagrams do not show the numbers of deposited pollen, but their proportion in the total pollen obtained from the sediment record. Certain species disperse more pollen than other types and therefore this method is not valid. Nevertheless can this be used for quantitative studies on past vegetation.

In North eastern Netherlands several studies have been performed with pollen analysis. Bijlsma (1983) researched the Nieuweveen site in 1982, he took several deep cores and made a pollen diagram. His research focused on the late Glacial. These cores show a thick layer of peat, mainly sedge peat, between 0cm and 330cm. Between 175cm and 270cm the peat contains wood remains. Around a depth of 350cm the sediment shows a transition from peat to gyttja. Deeper in the core there are sand layers present. These sand layers can be found at a depth of a 880-890cm, 1010-1020cm, 1030-1040cm, 1270-1280cm, 1420-1430cm, 1440-1450cm, 1505-1515cm, 1540-1550cm, 1610-1620cm, 1690-1700cm and 1780-1790cm. This core shows two peat layers within the gyttja layer at a depth of 1350-1380cm and 1480-1505cm. These peat layers are most likely remnant of younger peat layers which fell into the bore hole as a result of the coring. The transition from gyttja to a continuous sand layer can be found at 1840cm. Figure 2 shows the pollen diagram from Bijlsma (1983), this diagram shows at the top a thin layer of Holocene sediments until a depth of 750cm. A thick layer of younger Dryas sediments can be found between 750cm and 1760cm. This thick layer is followed by a thin layer of Allerød and Bølling. The pollen diagram shows an increase in *Betula* pollen at a depth of 1810cm and another increase at a depth of 800cm. *Pinus* also shows an increase around 1810cm, whereas *Salix* shows a decrease. The other pollen stay somewhat constant throughout the profile.

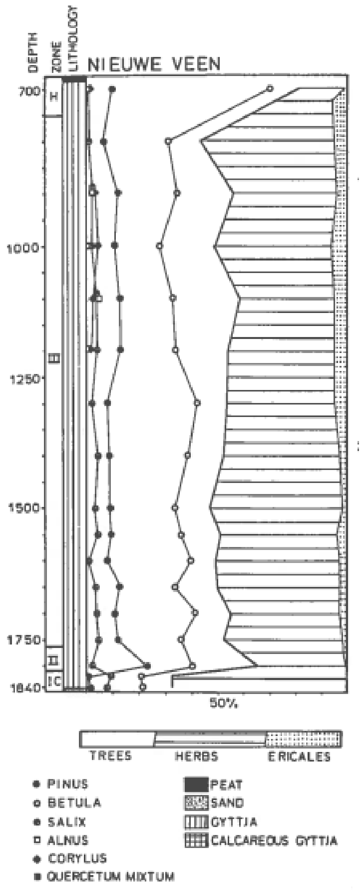


Figure 2, Nieuweveen pollen diagram (Bijlsma, 1983)

R. Bakker (2003) studied Gietsenveentje, which is located near the Gieten (53˚00’88’’N, 6˚74’80’’E), roughly 52 kilometres from the Nieuweveen site. 4 cores were taken from this site and the lithology varies slightly within each core. The general trend in the lithology is layer of homogeneous humic substance, followed by a thick layer of *Sphagnum* peat, a thin layer of *Sphagnum* peat with *Eriophorum*, a thicker layer of detritus gyttja, a thin layer of detritus gyttja with sand and loam and at the bottom of the core Pleistocene subsoil sand. The pollen diagram of R. Bakker (2003) shows that at a depth of 470-465cm *Betula* dominates with high amounts of *Pinus*. At a depth of 465-445cm *Betula* decreases and *Pinus* and *Corylus* increase. At a depth of 445-405cm *Alnus* and *Quercus* appear and quickly become the most common types. At a depth of 405-376cm *Alnus*, *Ulmus* and *Fraxinus* reach high values and *Fagus* and *Picea* appear for the first time. *Calluna* also increases. At a depth of 376-285cm *Quercus* and *Alnus* are dominant. *Fraxinus* reaches high values and *Calluna* and *Rumex acetosa* show an increase. At a depth of 285-210cm *Alnus* becomes dominant and *Corylus* reaches max value. *Plantago lanceolata* and *Rumex acetosa* increase as well as Ericaceae. At a depth of 175-125cm the trees stay constant, only *Fagus* increases. From 130cm *Alnus*, *Corylus* and *Quercus* decreases, while *Calluna* sharply increases. At a depth of 125-64cm *Alnus* and *Corylus* decrease, while *Fagus* reaches its highest value. Ericaceae reaches almost zero. From 64cm onward agricultural indicators such as Cerealia-type and *Centaura cyanus* increase.

1.5 Research aims

The natural vegetation in the Netherlands during the early and mid-Holocene is well known and described (Van Zeist, 1967; Zagwijn, 1994; van Beek et al., 2015; Engels et al., 2017). However, the exact timing of the introduction of agriculture in the Netherlands is less well known. Furthermore, the way agriculture developed and spread throughout the Netherlands varies wildly, because the ecology and environment differs a lot throughout the Netherlands (Louwe Kooijmans, 1993b; Bogucki, 1996). As a result, the effect of the development of agriculture on the natural vegetation is relatively unknown. Therefore, this research will try to answer the following research question:

"How and when did human activity influence the natural vegetation around the Nieuweveen pingo remnant during the Middle and Late Holocene."

To find an answer to the research question several sub questions need to be answered:

- What was the natural vegetation during the Middle and Late Holocene like?
- Which changes in the pollen record are regional changes and which are local changes.
- How did agriculture develop in Europe and the Netherlands specifically?
- In which way did humans practice agriculture in the Netherlands
- How did humans impact the vegetation around their settlements

The aim of this research is to reconstruct the vegetation cover around the Nieuweveen pingo remnant for the period between the Middle and Late Holocene and determine how this natural vegetation has been influenced by human activity. This will be done by analyzing pollen and NPP's (Non-Pollen palynomorph), which may indicate human influences like grazing by using dung fungi, obtained from the Nieuweveen core between 9000 BP, to ensure a clear view on the natural vegetation in the area before human impact first occurred, and 2000 BP, which is the top of the core. The results will be compared to results from other research both from areas with much human influence and areas with almost no human influence within NW Netherlands, key sites for these comparisons are Uddelermeer (Engels et al., 2016), Hijkermeer (Zagwijn, 1956) and Mekelermeer (Bohncke, 1991). Furthermore, archaeological data, mainly in the form of papers on the development of agriculture, human settlements and different cultures and their interaction, will be used to explain and support changes within the pollen record. Based on the data, comparisons and literature a conclusion can be made on how the natural vegetation was influenced by human activity.

1.6 Pingos

The Netherlands, especially the province of Drenthe and Friesland, contains hundreds of round and oval lakes and fens. Most were partially or completely filled with gyttja and peat and dredged later on (de Gans, 2008). Most of these round and oval lakes and fens are pingo remnants. The most famous pingo remnants in the Netherlands are those of Uddelermeer, Mekelermeer and Hijkermeer. The Nieuweveen site is also a pingo remnant, therefore it is important to understand the processes involved in the formation of a pingo. A pingo can only form in an environment covered with permafrost. The formation of pingos is the result of an injection of water into near surface permafrost, which is the result of a pressure gradient in ground water (Harris & Ross, 2007). The formation of ice lenses, which are the initiators of the formation of pingos, occurs underneath the permafrost. However, the way and the location these ice lenses form can differ. The conditions under which these ice lenses grow determine what kind of pingo will form. Pingos are subdivided into two different categories: Hydraulic pingos and hydrostatic pingos (Hornum et al., 2020).

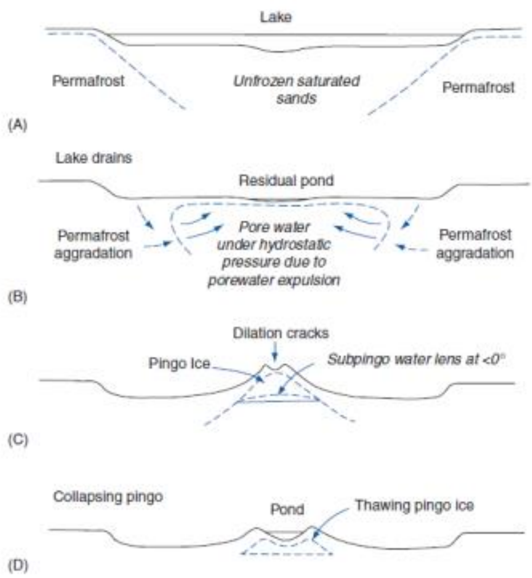


Figure 3, schematic overview of the formation of a hydrostatic pingo (Harris & Ross, 2007)

Hydrostatic pingos, often referred to as closed system pingos, form in old lake beddings. Figure 3 shows the growth of a hydrostatic pingo schematic. When the depth of a lake reaches below the active layer of the permafrost, lenses of unfrozen sediment may occur. This usually occurs in lakes which do not completely freeze during winter. When these criteria are met the lake prevents the sediments on the bottom from freezing. As a result these lenses of unfrozen sediments are able to sustain within the permafrost (Harris & Ross, 2007). Such a lens of unfrozen sediments is called a talik (Rowland et al., 2011). However, when the lake is dried up or drained the talik is no longer protected from the cold and it will start to freeze. The permafrost surrounding the lake slowly moves towards the center down the sides of the lake. As a result, the permafrost pushes the water ahead. This water moves upwards at the center of the lake, where the permafrost is relatively thin because this path contains the least resistance for the water. When this water reaches the active layer it freezes and it forms the ice core of the pingo (Gurney, 2001). Hydrostatic pingos usually only occur within regions with continuous permafrost layers. However, in some cases an impermeable layer of clay may be sufficient enough instead of a permafrost layer (Mackay, 2011). Hydrostatic pingos usually occur alone in an area.
Hydraulic pingos, often referred to as open system pingos, form in areas where there is a clear difference in elevation (Scholz & Baumann, 1997).

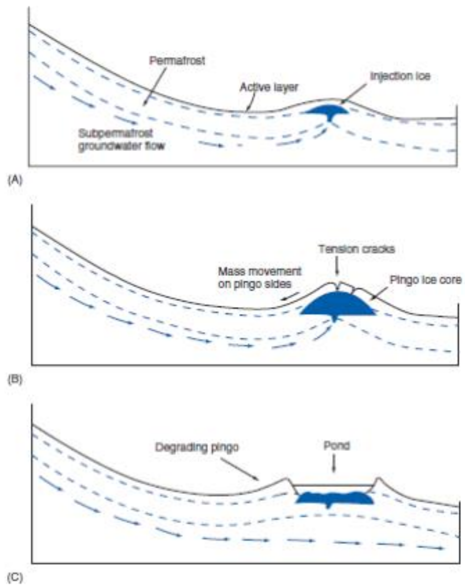


Figure 4, schematic overview of the formation of a hydraulic pingo (Harris & Ross, 2007)

Figure 4 shows the schematic formation of a hydraulic pingo. Elevation differences in mountainous areas can cause a pressure gradient. This pressure gradient causes the upwelling of groundwater (Flemal, 1976). The water from rain or the melting of ice enters the ground at high altitudes from beneath a glacier or underneath permanent snow (Flemal, 1976). As a result of the pressure gradient it surfaces at a lower elevation, where the permafrost usually is weaker. The water will move upwards throughout the weak spot in the permafrost and freezes (Flemal, 1976). This water forms the ice core of the pingo. As a result of the necessary difference in elevation these pingos usually form at the base of a hill or mountain (Scholz & Baumann, 1997). Where hydrostatic pingos only occur as a single pingo in the area, hydraulic pingos usually occur in groups, because of the upwelling of ground water (Yoshikawa, 1993).
The Nieuweveen pingo was most likely a hydrostatic pingo (closed-system pingo). According to De Gans (1981) and R. Bakker (2003) most of the northeastern part of the Netherlands contains till, deposited during the glacial period, on the water divides. As a result open system pingos cannot grow because the till rules out water supplying the groundwater from other source areas, which is necessary for open system pingos. Furthermore, the Netherlands lacks the necessary elevation difference for the formation of hydraulic pingos.
The pingo will continue growing until the water source has dried out. However, even though the pingo may not grow anymore, the ice core will remain. Eventually the pingo will become unstable and collapse on itself (Mackay & Burn, 2011). This collapse can be caused by two different mechanisms: Mechanical failure and climate change.
When the water underneath the pingo freezes it expands. This expansion causes a crack to form in the pingo surface. This crack exposes the ice core in the pingo. As the ice core in the pingo keeps growing, the crack will widen and the ice core will be exposed even further. This causes the ice core to be less well protected against the sun and heat. The ice core will start to thaw and forms a summit crater, which potentially can fill up with melt- and rainwater to form a summit lake (Mackay, 2011). There is also another possible form of mechanical failure. This type of failure occurs when the input of water into the pingo exceeds the potential of the water to freeze. As a result, a water lens can form within the pingo. The hydraulic pressure of this water lens causes the pingo surface to rupture and expose the ice core (Mackay, 2011). This exposure causes the ice core to melt and the pingo to collapse. This collapse can be fully completed in a couple of decades (Mackay, 2011).
Climate is another important factor in pingo collapse. As long as the climate is stable, permafrost conditions will remain and therefore pingos will grow, reach their maximum height and collapse (Mackay, 1988).
When the ice core is completely melted and the pingo collapsed, a circular depression with a surrounding wall of debris is left. The circular depression is then filled with water, forming a lake (Mackay, 1988). During the Holocene most these lakes gradually fill with peat. In some cases, the peat can continue to grow even after completely filling up the depression. Depending on environmental conditions and the layout of the landscape a blanket bog or a raised bog can form (Blackford, 2000).

The depth of the pingo can be used as an indicator of the minimum depth of the permafrost. Since pingos can only grow in areas covered with permafrost and the ice cores grow underneath the active layer of the permafrost, the permafrost layer must have been at least the depth of the ice core (Mackay, 1988). It is difficult to reconstruct the age of the pingo and to determine when it collapsed. There is no material left from during the formation of the pingo, making it difficult to date. However, it is clear that the pingo is older than the sediments of the surrounding wall (Mackay, 1988). Furthermore, it can be stated that the collapse of the pingo happened before the infill of the depression. It is important to note that this is only true for the youngest infill of the depression, since the oldest infill can already happen when there is only a summit depression before the pingo truly collapses(Mackay, 1988). Therefore the age of the pingo activity can be dated between the age of the sediments of the surrounding wall and the youngest sediment infill in the depression (Kluiving et al., 2010). The infill of these depressions are very valuable for paleoclimate reconstructions as they often provide a continuous record. As is the case with the Nieuweveen pingo remnant, which provided a continuous pollen record used for this research. Most of the pingos in the Netherlands were formed during the Upper Pleniglacial. During a period of discontinuous permafrost conditions. Continuous growth of the ice core eventually resulted into the rupture of the pingo skin (De Gans, 1982; Kluiving et al., 2010). During the onset of the Bølling warm interval the temperature began to rise, causing the degradation of these pingos. This led to the formation of hundreds of small lake basins in the Northern and Eastern part of the Netherlands (De Gans, 1982; Kluiving et al., 2010). Therefore, most of these pingo remnants contain Lateglacial and Holocene sediments (Kluiving et al., 2010).

1.7 Hydrosere

As previously mentioned in chapter 1.6 the collapsing of a pingo can form a circular depression, which is filled with water, resulting in a lake. When this lake is filled with organic material, a succession of plant communities can be observed. This succession takes place from the middle of the lake towards the edge and follows each other up at the same location. The different vegetation types that succeed each other have a set succession (Stouthamer et al., 2015). This succession can be seen in figure 5. Hydrosere, the change from a water body to land, can be distinguished into two situations: nutrient rich waters (eutrophic waters) and nutrient poor waters (oligotrophic waters) (Stouthamer et al., 2015). The production of organic material is faster in nutrient rich waters, compared to nutrient poor waters. The growth of algae and plants in oligotrophic waters is very limited and the organic material that is formed during the decomposing of these organisms lay down on the bottom of the lake in small layers, forming a dy

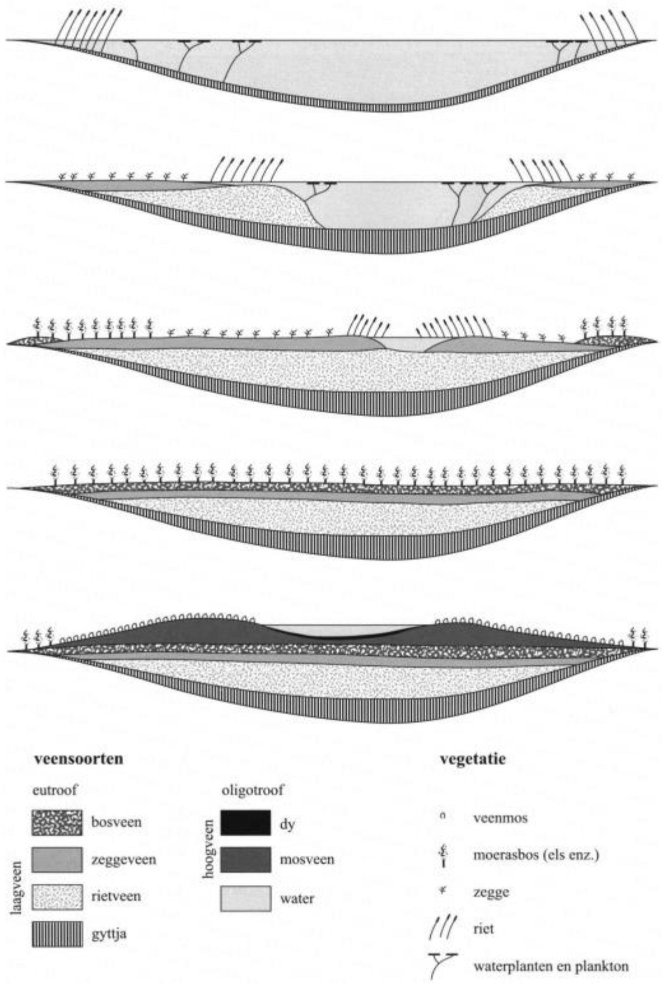


Figure 5, hydrosere of a lake (after Visscher, 1949)

(Stouthamer et al., 2015). A dy is a form of gyttja that forms in oligotrophic waters and consist out of almost pure humus (Stouthamer et al., 2015). Plenty of algae growth takes place in eutrophic lakes. Some of these algae are able to take up calcium (Stouthamer et al., 2015). When these organisms die and settle down at the bottom, in combination with the calcium, gyttja is formed. This gyttja slowly fills in the lake. When the infill of the lake by gyttja has reached the point that the bottom of the lake near the edge of the water body is around 2m deep reed can grow on the shore (Stouthamer et al., 2015). Reed is a vegetation type that produces a lot of organic material each year. This material quickly fills up the lake and the peat formed in this period is called reed peat (Stouthamer et al., 2015). When the lake is filled up to a water depth of 0.5m, sedges start to dominate the environment and sedge peat forms (Stouthamer et al., 2015). When the hydrosere continues the water body is almost completely dried up and in slowly transitions from an eutrophic environment into a mesotrophic environment (Stouthamer et al., 2015). This transition is caused by the dilution of the nutrients in the water by rainwater. In this mesotrophic environment trees start to grow, *Alnus* in a nutrient rich environment and *Betula* in a nutrient poor environment (Stouthamer et al., 2015). Moss grows along the stems of these trees. These mosses keep the ground and the leaves, which fell down on the ground, as well as any decaying wood humid (Stouthamer et al., 2015). This enhances the formation of peat, which in this stadium is called woodland peat. After this stage the hydrosere has finished and the water body is fully filled in and transformed into land. At this point the peat formation is usually finished, however, with the climate of the Netherlands with plenty of rain the peat formation usually continues (Stouthamer et al., 2015). Lower parts of the terrain are filled with rainwater and the peat retains the water. As a result the water table rises locally above the surrounding groundwater table, which is determined by regional factors. As a result the nutrients in the peat diminish and *Sphagnum* starts to grow (Stouthamer et al., 2015). This *Sphagnum* causes the vegetation around it to change and disappear, causing the *Sphagnum* to become dominant. This can create a raised bog on top of a fen (Stouthamer et al., 2015).
The Nieuweveen site shows two high peaks in *Sphagnum*, but besides those two peaks *Sphagnum* was never really abundant in the pollen diagram. This suggest that Sphagnampeat never formed in this site and Nieuweveen remained a fen. However, it is important to note that the *Sphagnum* spores in the Nieuweveen site were very hard to see. Most of the spores were really bleach, almost transparent, making it difficult to see those spores on the slides. Furthermore, the two *Sphagnum* peaks are observed in slides which were really clean and contained very little organic material making it easier to see those spores, whereas the other slides within the peat layers contained high amounts of organic material obscuring the slides. This made it very difficult to see those almost transparent *Sphagnum* spores. Therefore two scenarios need to be taken into account. Once scenario where Nieuweveen became a fen and a scenario where it became a raised bog. However, it this point a fen seems most likely the case for the Nieuweveen site.

1.8 Peatlands

The occurrence, rate and nature of peat accumulation is strongly determined by optimal moisture and temperature conditions (Roland et al., 2014). This is clearly highlighted by the global distribution of these peatlands, as observed by Barber and Charman (2003). This shows that peatlands are clearly impacted by climate. Therefore, peatland studies are interesting as archives of past climate, resulting in clear and continuous records of vegetation, hydrology, temperature etc. (Roland et al., 2014). This is also the case for the Nieuweveen site. The lithology shows that the Nieuweveen core contains a thick layer of peat, which holds a huge amount of information of a big part of the Holocene. However, to interpret these data it is important to understand how peatlands are formed and capture this environmental and climatic information.
Peatlands are often described as an area where the rate of decay of plant material is

exceeded by production of plant material. The growth of peat is a result of the disturbed decay rates due to wet or cold conditions together with high productivity during the growing season (Roland et al., 2014). Two different hydromorphological types can be distinguished in peatland systems: Ombrotrophic peatlands, often called bogs, have precipitation as their main water source. The water table within ombrotrophic peatlands is determined by precipitation and evaporation. Therefore ombrotrophic peatlands are heavily influenced by climate (Roland et al., 2014). On the opposite, minerotrophic peatlands, often called fens, are dependent on runoff and groundwater next to precipitation for their water supply. This means that changes in climate do not affect this type of peatland as much as with ombrotrophic peatlands and therefore changes in the water table cannot directly be linked to variations in climate (Roland et al., 2014).
Paleoclimate data from peatlands commonly focused on two different aspects. The first one is the location and timing of the start of the peat accumulation. This is regarded as a signal of a shift from warmer and drier conditions to wetter and colder conditions (Gorham et al., 2007). Studies focusing on this aspect can use all peatland sites, ombrotrophic or minerotrophic. However, there are many local factors which impact the start of peat accumulation such as vegetation, hydrology and substrate (Roland et al., 2014). As a result it is difficult to point out a specific climatic variation that caused peat to accumulate at a site. Therefore it is better to use regional records, which show simultaneous peat accumulation over several sites to determine climate variations (Roland et al., 2014). The second aspect centers on the diversity of peat composition and the elements that indicate changes in precipitation and temperature over time (Barber & Charman, 2003; Roland et al., 2014). Raised bog are most used in palaeohydrological reconstructions because of their high accumulation rates. Besides the high accumulation rates, raised bogs have another feature which sets itself above the other types of bogs, like blanket bogs. Raised bogs have a rather consistent peat accumulation rate. They accumulate about 10-20 years/cm, whereas other bog types like blanket bogs accumulate 20-50 years/cm and these accumulation rates can vary each year (Blackford, 2000; Barber & Charman, 2003; Roland et al., 2014). Raised bogs possess a unique convex profile sets them apart from the groundwater table's influences. Consequently, the water supply for these raised bogs relies entirely on atmospheric sources. Occasionally, runoff from the raised bog may give rise to a lagg-zone at the periphery of the bog system. Nevertheless, this phenomenon does not impact the water table depth on the surface of the raised bog (Roland et al., 2014). Howie & Tromp – van Meerveld (2011) describe a lagg-zone as ‘’A transition zone at the margin of a (usually raised) bog receiving water from both the bog and the surrounding mineral ground, often characterized by fen or swamp vegetation, transitional water chemistry, and shallow peat of relatively low hydraulic conductivity’’. Ombrotrophic raised bogs are ecosystems, which are mostly acidic, anoxic and nutrient poor (Roland et al., 2014). These ecosystems are formed by the continuous accumulation of dead plant material (Roland et al., 2014). *Sphagnum* generally dominates these acidic, anoxic, nutrient poor ecosystems although other families like Ericaceae and Cyperaceae are also commonly found (Roland et al., 2014). The presence of *Sphagnum* causes acidification of the surrounding environment. *Sphagnum* takes up certain nutrients like potassium from the environment and releases hydrogen ions. This process acidifies the environment, making it less habitable for other plant species. As a result, *Sphagnum* becomes even more dominant, since this species is capable to sustain highly acidic environments (van Breemen, 1995). *Sphagnum* cannot regulate water loss; therefore this species is highly dependent on favorable conditions. Therefore, a positive water table and favorable climate conditions are of great importance for the formation and growth of a raised bog (Roland et al., 2014). Because of this reliance on precipitation, regions were ombrotrophic raised bogs are capable of forming and growing are sparse. These regions need to experience a high precipitation rate which exceeds the evaporation and runoff in the

area (Roland et al., 2014). Therefore, these type of peatland systems are often found in northwest Europe. Based on the occurrence of *Sphagnum* spores in the pollen record during the peat phases as well as the location of the site, it is possible that the Nieuweveen site was also a sphagnum peat site. However, the lack of high amount of *Sphagnum* spores and a hiatus as a result of the degradation of peat, which you would expect since there is no raised bog present at the moment, raises the question whether Nieuweveen was a raised bog or that it stayed in a interphase between raised bog and a fen.

1.9 Peatlands as archives of climatic change and human impact

Climate change has become one of society's most major issues. The uncertainty and potential risk as a result of climate change has spurred an interest in abrupt climate changes. Past changes in climate, recorded within peat layers can be used to determine the effects of changes in precipitation and temperature on the vegetation. Therefore, peat records can help society to determine the effects of the current climate change and help society prepare for what is to come. Climate plays an important role in the bog surface wetness (BSW). At first it seems that prolonged, increased rainfall influences BSW. However, a study from Barber et al. (2000) showed that different sites located at varying distances from each other and with varying altitudes, but with comparable precipitation levels showed different BSW. The only variable from these sites were temperature, indicating that temperature is a dominant driving force. Furthermore, Barber and Langdon (2007) conducted a study in which they compared various BSW records dating back to the mid-Holocene with temperature records. The temperature data were derived from chironomid data collected from several lakes, providing an average July temperature. The analysis revealed a correlation between the shifts in BSW and changes in temperature. This suggests that variations in BSW coincided with fluctuations in temperature during the mid-Holocene period. Charman et al. (2009) suggests that BSW should be considered a function of both temperature and precipitation.

The climate record, which is archived in the peat and can be observed by using different forms of proxies, is a representation of biological and chemical responses to changes in the bog surface wetness over time. Therefore, it can be stated that changes in BSW is a result of changes in the atmospheric moisture balance (Roland et al., 2014). Peat based stable isotope analysis may help to better understand the key drivers, which change the BSW. This technique could record shifts in temperature and precipitation. This allows for a comparison between isotopic records and BSW proxies. However, the forcing of these changes in temperature and precipitation are still controversial (Roland et al., 2014). Two major drivers are proposed: solar variability and ocean forcing. Support for solar forcing comes from various records and proxy data like ice cores, lake varves, and glacier fluctuations, indicating evidence of solar irradiance variability. Ocean forcing also plays a crucial role in influencing climate patterns and environmental conditions (Barber et al., 2008). Although precipitation and temperature changes in northwestern Europe are more likely driven by variations in the North Atlantic, changes in BSW has been linked to changes in oceanic forcing by several studies (Bond et al., 2001; Blundell & Barber, 2005). However, changes in oceanic forcing are linked to solar variability, which creates a complicated relationship between the two and their impact on the BSW (Roland et al., 2014). Raised bog records, which are mostly complete and span across a long time period, can be used to determine dominant periodicities. The Holocene peat based paleoclimatic archive from northwest Europe contains many well documented climatic changes as well as the introduction of human activity in the area. Many of these events, both human impact and climatic impact have been studied thoroughly with the help of peat records, such as 2.8 kyr event (Van Geel et al., 2014), the introduction of agriculture in Europe (Andrič, 2007), the 8.2 kyr event (Pross et al., 2009) and the little ice age (Hotchkiss et al., 2007). However, the 4.2kyr event, which is one of the major abrupt climatic changes in the mid-Holocene remains comparatively underrepresented (Kleijne et al., 2020). Unfortunately most of the peat records in the

Netherlands have been excavated for the use of fuel from 2000 cal. yr. BP. Furthermore, in some places the peat layers were superficially burned by the buckwheat culture (Casparie, 1972; Dupont, 1986). Furthermore, appendix 1 shows a clear decrease of humidity in the core around 70cm. The humidity reaches values below the indicative value of 90% based on the LOI (Loss on ignition). This suggests drying of the peat and possibly oxidation.

2. Study site

The Nieuweveen pingo remnant (52˚33’49’’N, 6˚40’00’’E) is located near the city of Hardenberg, close to the border between Germany and the Netherlands. It has an elevation of about 10.4m a the current sea level. Figure 6 shows the location and elevation of the pingo remnant. The Nieuweveen pingo remnant is one of the many pingo remnants that can be found in the eastern part of the Netherlands, often found as circular or oval depressions in the landscape. The Nieuweveen pingo is nearly circular with a diameter of 350 m. The infill of the pingo remnant consists out of 19 meter thick organic material (Bijlsma, 1983). The depression that was formed in fluvioperiglacial deposits consists out of fine sands, which is alternated by layers of silt. These layers of silt are most likely a result of lake deposits (Bijlsma, 1983). The sides of the depression contain older coversands I, deposits of the Beuningen complex and older coversands II (Bijlsma, 1983).

Small rivers laid down sand during the early and middle Pleniglacial. These sand deposits mixed with the loam and peat layers. These fluvioperiglacial deposits can be found all over the area, mostly between the ice pushed ridges (Bijlsma, 1983). During the late Pleniglacial the whole area was covered with aeolian sands. These aeolian sands are often fine grained and contain thin layers of loam. This type of coversand is called older coversand I (Bijlsma, 1983). On top of the older coversand I layer, the Beuningen complex can be found. The base of this Beuningen complex contains arctic soil. This arctic soil developed in the older coversand I, which was cryoturbated. Overlaying this arctic soil is a layer of coarser deposits. This coarser deposit contains large ice wedge casts (Bijlsma, 1983). The top of the Beuningen complex contains a thin eolized pebble band. This pebble band is called the Beuningen gravel bed (Bijlsma, 1983). On top of the Beuningen complex older coversand II can be found. This aeolian deposit has the same lithology as the older coversand I (Bijlsma, 1983). In the Late Weichselian a new layer of coversand was deposited. This layer of

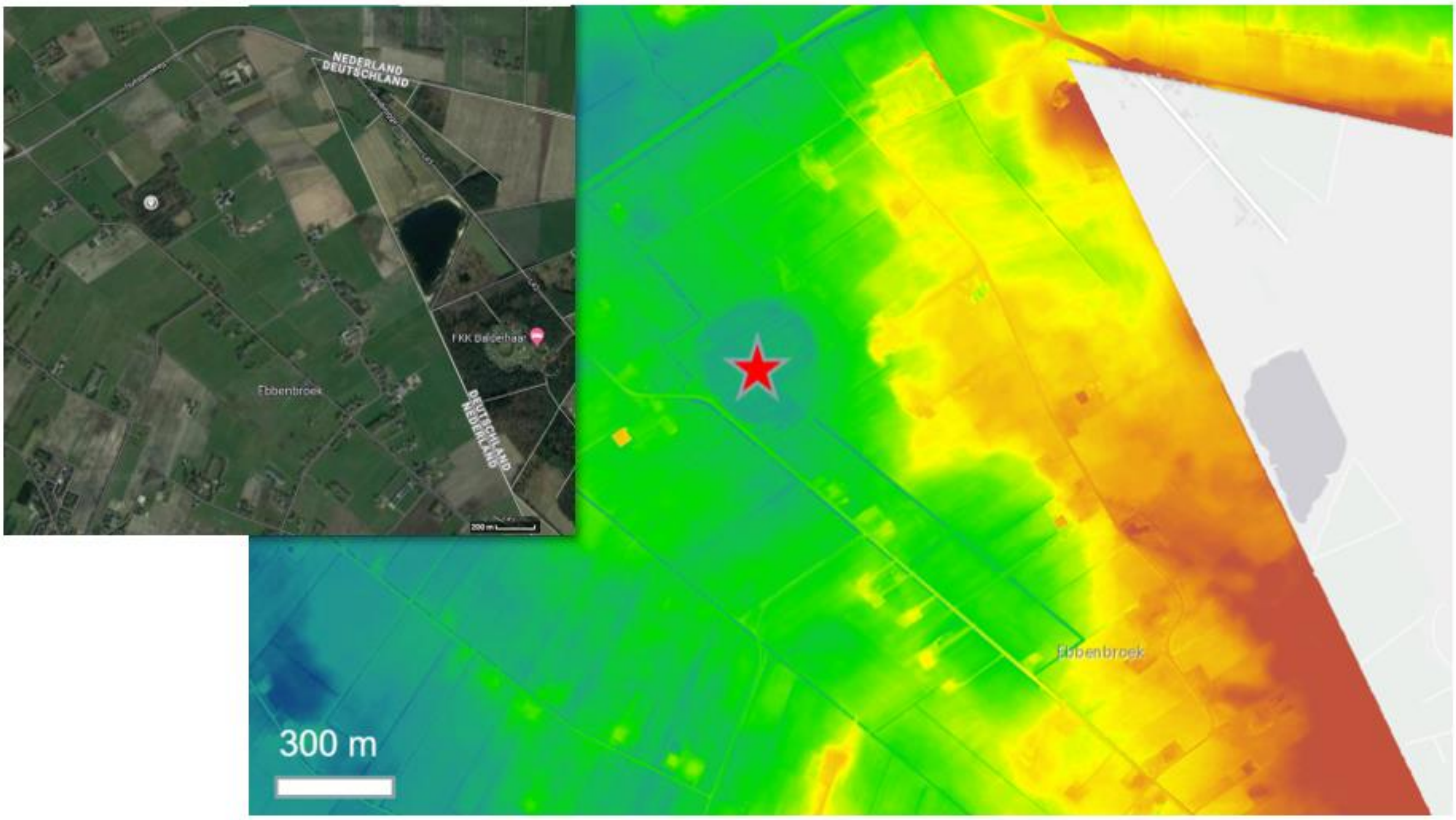


Figure 6, Google Earth view of the location of the Nieuweveen pingo remnant and an elevation map of the surrounding area coversand is coarser than the Pleniglacial coversands. This younger coversand contains fine gravel and there is no loam layer present (Bijlsma, 1983). During the Holocene the area was an almost flat plain. This plain was originally covered with Holocene peat. This peat has been dug out during the last centuries to be used as fuel (Bijlsma, 1983). Figure 7 shows the cross section of the Nieuweveen pingo as described by Bijlsma (1983).

Appendix 2 shows topographic maps, obtained via topotijdreis.nl. These maps show that before 1932 the landscape consisted out of a widespread peatland, which was called ‘’de Nieuwe Venen’’. This peatland remained that way until 1932. The map of 1932 shows the first presence of peat pits. The peat pits in the northern part of de Nieuwe Venen disappear 3 years later in 1935. These peat pits in the northern part of de Nieuwe Venen appear again in 1955, whereas the peat pits in the southern part disappear around this time. In 1975 the first trees appear on the northern part of de Nieuwe Venen, where the peat pits were. In 1987 this area is completely covered by these trees. In 2005 a part of the trees appears to be removed. In 2011 another part of the trees has been removed. The map of 2020 shows no alternations happening after 2011. At present the area is mostly used as farmland, either as a pasture or as field. The Nieuweveen pingo remnant is also located in a pasture. The area surrounding the pingo remnant is scarcely populated, only a few farms are present.

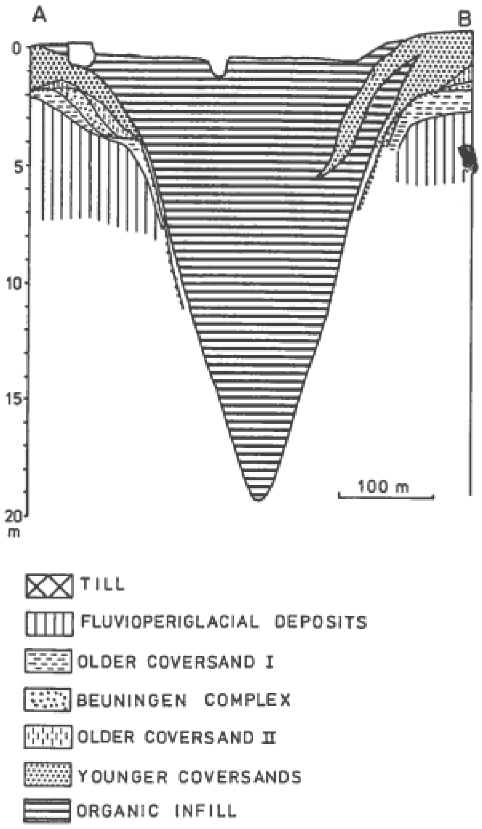


Figure 7, cross section of the Nieuweveen pingo remnant (Bijlsma, 1983)

3. Methods

3.1 Coring Nieuweveen NWV-20

The coring of NWV-20 has been performed on the 14th and 15th of October 2020, at the centre of the Nieuweveen depression as described in Hoek et al., (not yet published). The coring is performed by Arjan van Eijk, Stan Schouten, Timme Donders and Wim Hoek. As has been discussed in chapter 1.4 and chapter 2, Bijlsma already took a core at this location. Based on his data the location of the NWV-20 core has been decided. This core was taken several meters away from his core, at the centre of the depression, which is also the location where it is expected that the depression is the deepest. This location seems to contain an infill of 18 meters.
To prevent contamination with material from the borehole a Livingstone piston-corer was used. This method prevents contact between the core and the younger material in the borehole while retrieving the core from the hole. This method is very useful while coring below groundwater levels, but less for materials above groundwater level. Therefore, before using the Livingstone piston-corer, a borehole must be made below groundwater level with a gouge auger. However, it is almost certain that by doing this, younger material ends up at the bottom of the borehole. After groundwater level is reached, the Livingstone piston-corer is used. The corer is let down a few centimetres above the last coring, which was 80cm for the NWV-20 core. The core is pushed down into the hole until exactly a depth of 180cm. At this point the core contains about 100cm of material, with on top a few centimetres of contamination. The corer is hoisted from the borehole and the core is pushed out of the corer. This core is wrapped in a 110cm PVC pipe with plastic foil to prevent drying. Once again the corer is placed above the borehole and let down a few centimetres above the bottom of the hole. The corer is pushed into the soil until exactly 280cm. Once again the core contains about 100cm of material, with on top a few centimetres of contamination. The corer is hoisted from the borehole and the core is pushed out of the corer. A total of 18 cores have been taken for a total of 1780cm of material.

3.2 Pollen preparation

The cores were stored in a freezer and freeze dried before the pollen preparation. Circa 1 cm^3 of core material is taken from the core in a 10cm interval, with the exception for clear lithological changes. In case of a clear lithological transition, a sample was taken just below and above the lithological transition. This resulted in a total of 45 samples divided over 474 cm of core. Each sample was placed in a 15ml tube and filled with distilled water to prevent oxidation. In case of calcareous sediments, which can be tested on the core by adding a drop of hydrochloric acid to see if the core reacts, 5% hydrochloric acid can be added to dissolve the calcareous compounds. To remove the 5% hydrochloric acid, distilled water is added to the tube. After each step the samples are centrifuged for 1 minute at 2000 rotations per minute and decanted. This washing is done twice to ensure no 5% acetic acid is left in the samples. To each sample a total of 4 ml *Lycopodium clavatum-spore* (circa 8000 *Lycopodium spores*) solution is added to enable pollen concentration calculations. Furthermore, 5 ml 5% potassium hydroxide (KOH) solution is added to each sample to remove any humic substances present. These samples were heated in a stove for 60 minutes at a temperature of 70˚C. After the heating, each sample is sieved over a 200µm filter to remove large particles from the suspension. The residue is removed from the sieve and thrown away. The filtrate is moved into a 15ml tube and after each step 10ml of distilled water is added to the tubes and the samples were centrifuged for 1 minute at 2000 rotations per minute and decanted. After decantation these steps are performed once more. This to ensure that the remaining 5% potassium hydroxide (KOH) solution is removed and the

sample is well mixed with water.
For the acetolysis step, a 1:9 mixture of sulfuric acid (H_2SO_4) and acetic anhydride ($(CH_3CO)_2O$), it is important to remove the water from the samples, because the acetolysis mix can react with water. To ensure all water is removed from the sample, 5ml of glacial acetic acid is added. After each step the samples are centrifuged for 1 minute at 2000 rotations per minute and decanted. After decantation 5ml of glacial acetic acid is added again. To break down the organic compounds 4ml of acetolyses mix was added to each sample and homogenized. The samples were acetolysed for 10 minutes at a temperature of 100˚C. Once the samples have reached a temperature of 100˚C they are vortexed once. After 10 minutes the samples are once again centrifuged. After the samples are centrifuged the acetolyses mix is decanted. To ensure that all of the acetolyses mix is removed from the samples the tubes are filled with distilled water and centrifuged. This step is performed twice. 4 ml of sodium polytungstate liquid with a density of 2.0ρ was added to the samples and vortexed to ensure homogenisation. After the samples were vortexed they were centrifuged for 15 minutes at 2000 rotations per minute, to separate the pollen from the sediment and other particles from the samples. After the centrifuge a collar of pollen grains formed, which was decanted to a new tube and 10 ml of water was added. The same steps are performed again on the first tube with the residual material. After the centrifuge of the first tube a collar of pollen grains formed, which was decanted to a new tube and 10 ml of water was added. The new tubes are centrifuged for 5 minutes at 2000 rotations per minute. The old tubes are washed out with distilled water twice and the sodium polytungstate liquid is caught for recycling. After the samples are centrifuged they are decanted. Once again distilled water is added to the samples and they are centrifuged for 1 minute at 2000 rotations per minute. After the samples are centrifuged they are decanted. This step is performed 2 to 3 times. After the final decantation 1.5 ml of ethanol was added to the samples. Then the pollen samples were vortexed and the remain decanted into an Eppendorf cup. This Eppendorf cup was centrifuged for 5 minutes at 2000 rotations per minute. The content of the Eppendorf cups were decanted and replaced by glycerine. Finally, to ensure all ethanol was removed the cups were heated at 70˚C and left overnight so the remaining ethanol evaporated.

A few drops of the pollen sample is placed upon a heated slide. A small line of paraffin is added on the slide a couple of centimetres from the pollen sample. Then the cover glass is placed upon the pollen sample. The glycerine will flow along the cover glass and dry out, capturing the pollen sample between the cover glass and the slide.

3.3 Pollen and data analysis

45 slides were counted by using a light microscope. The obtained counts from the pollen, NPP and *Lycopodium* were entered into Tilia (version 2.6.1). This program was used to calculate pollen sum, which consists out of the total of Arboral, non-arboreal, heath and crop pollen, and make the pollen percentage diagram, concentration diagram (appendix 5) and influx diagram (appendix 6). These diagrams were then used for the interpretation. Two different percentage diagrams were made, one based on depth and one based on age. The age based percentage diagram was based on the age model.

3.4 Age model

Several organic samples, containing carbon, were sent to the Rijksuniversiteit Groningen for radiocarbon dating, 4 twigs and 1 seed of *Trapa natans*. The 5 twigs and a seed of *Trapa natans* were taken at a depth of 39-40, 111-112, 206-207, 314-315 and 393-394 cm. Furthermore, two palynological datings were used. The first continuous occurrence of *Corylus* and the first continuous occurrence of *Alnus*, which were taken from the pollen diagram and compared and supported by the accepted average first occurrence of these species in the region (Dupont, 1986; R. Bakker, 2003; Engels et al., 2016). The dates received from the Rijksuniversiteit Groningen were calibrated using CALIB Radiocarbon Calibration version 8.2. The 2nd sd range of these calibrated dates was calculated and used as set points within the age model. Since the depth and age of certain points in the core was known they could be used to calculate the sedimentation rate between these set points by dividing the difference in depth by the difference in age. With the sedimentation rate known the age model can be completed. This was done by linear interpolation between two depths. This resulted in a complete and continuous age model of the core.

4. Results

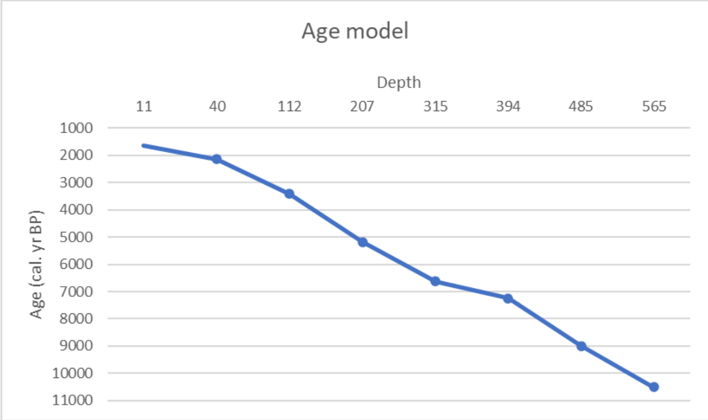


Figure 8, age model of the Nieuweveen core

4.1 Lithology

The master cores measures 1780 cm, this research only used the upper 500 cm of the core. The bottom of the sediment (Table 1) consists of fine detritus gyttja (500 – 330 cm) with a section where the fine detritus gyttja does not contain lamination (330 - 380 cm). At a depth of 393 cm and 412 cm a *Trapa natans* seed was found From 330 to 160 cm the sediment consists of fine detritus peat. This detritus peat layer is interrupted twice by a wood layer at 258 – 262 cm and 220 – 230 cm. Between 180 – 160 cm the detritus peat layer contains some minor wood remains, with a large chunk at 170 cm. Further upwards, the sediment consists of fibrous wood peat (160 – 10 cm), interrupted twice by a wood layer at 135 – 150 cm and 115 – 120 cm. Between 160 - 106 cm the fibrous wood peat contains some large wood remains.

4.2 Age depth model and sedimentation rate

The age depth model (Figure 8, Table 2) spans from 9200 to 1650 cal. yr BP (500 – 10 cm). This age depth model is based on C14 dating of 5 macrofossils found in the core and dating based of 2 pollen stratigraphic occurrences. 5 twigs were found at a depth of 39 – 40 cm, 111 – 112 cm, 206 – 207 cm. 314 - 315 cm and 393 – 394 cm. These twigs are dated at an age of 2154, 3410, 5132, 6611 and 7241 cal. yr BP.

Table 2, C14 dating calibrated with CALEBv8.2

Material	Lab-ID	14C Age (yr BP)	sigma	Calibrated age in cal. Yr BP (interval)
Twigs (AAA)	GrM-27311	2153	22	2139 (2106 - 2294)
Twigs (AAA)	GrM-27312	3185	22	3409 (3380 - 3445)
Twigs (AAA)	GrM-27363	4470	24	5178 (5042 - 5276)
Twigs (AAA)	GrM-27313	5811	27	6619 (6564 - 6663)
Seed (AAA)	GrM-27211	6324	35	7241 (7168 - 7278)

Table 1, lithology of the Nieuweveen core

10	20	peat	oxidized peat
20	47	peat	fiberous, laminated peat
47	68	peat	compacted, fiberous
68	70	peat	very fine (very little) fibers
70	77	peat	fine, fiberous peat
77	78	peat	very fiborous layer
78	98	peat	generally more fiborous, dark brown
85	106	peat	fiberous peat
106	160	peat	fiberous peat with large wood remains; large trunk between 115-120; large trunk between 139-150
160	180	peat	fine detritous peat with some minor wood remains; large chunk at 170
180	220	peat	fine detritous peat; countinous as above
220	230	log	log (greyish); salix? Wim is pretty sure
230	258	gyttja	coarse detritous gyttja; weak horizontal lamination
258	262	log	log (red); alnus?
262	277	peat	fine detritous peat
277	280	-	no sample
280	312	peat	fine detritous peat
312	330	peat	fiberous, coarse detritous peat
330	380	gyttja	fine detritous gyttja; no lamination
350	-	roots	roots
380	480	gyttja	fine detritus gyttja (all aquatic)
393	-	seed	trapa natans seed
412	-	seed	trapa natans seed
480	520	gyttja	fine detritus gyttja

Furthermore, two points were dated using the well-known first occurrence of certain species in the research area. The depth of 485 cm is dated at 9ka, based on the first occurrence of *Alnus*. The depth of 565 is dated at an age of 10.5ka, based on the first occurrence of *Corylus* (Dupont, 1986; R. Bakker, 2003; Engels et al., 2016). The average sample resolution is 145±56 years (mean±standard deviation).
The sedimentation rate is calculated using the ages of the previously mentioned depths. These sedimentation rates can be found in Table 3. Between 495 – 394 cm the sedimentation rate is 0.05 cm/yr. Between 394 – 315 cm the sedimentation rate is 0.13 cm/yr. Between 315 – 207 cm the sedimentation rate is 0,072998 cm/yr. Between 207 – 112 cm the sedimentation rate is 0,055168409 cm/yr. Finally, between 112 – 11 cm the sedimentation rate is 0,057324841 cm/yr.

Table 3, sedimentation rate of the Nieuweveen core

Top (cm)	Bottom (cm)	Sedimentation rate (cm/yr)
40	112	0,057324841
112	207	0,055168409
207	315	0,072997634
315	394	0,125496426
394	485	0,051719238

4.3 Pollen analysis

The pollen record (Appendix 3 & Appendix 4) consist of six pollen assemblage zones, based on changes in pollen composition and the first (continuous) occurrence of species. Figure 9 shows the most important pollen in the pollen diagram.

Zone-1 (9188 – 8807 cal. yr BP) - Arboreal pollen remain stable around 95%, suggesting closed forest conditions during this part of the Early Holocene. *Pinus*, *Corylus* and *Betula* pollen are dominant reaching 40, 30 and 18% respectively. Trees like *Quercus*, *Ulmus*, *Salix* and *Tilia* also occur, but in low abundance (<5%). Non-arboreal pollen stay around 4% during this zone and is dominated by Poaceae. At the end of this zone *Hedera* appears, indicating warmer temperatures. Heath makes up the remaining 1% of the pollen sum, consisting solely out of *Calluna*. Several aquatic pollen were found in the samples such as Nympheae, *Equisetum*, *Sparganium* and *Typha latifolia*, suggesting the occurrence of open, relatively deep, water in the area.

Zone 2 (8807 – 6540 cal. yr BP) – Arboreal pollen remain stable around 95%, suggesting closed forest conditions. In the beginning of this zone *Alnus* pollen rapidly increases from 1% to around 40%, whereas *Corylus* pollen decreases from 30% to around 13% at the end of the zone. *Betula* pollen rapidly decreases from 18% at the beginning of the zone to around 10% at the middle of the zone, after which it rapidly increases again to 18% at the end of the zone. *Pinus* pollen rapidly decreases from 40% to around 5-10% and remains stable till the end of the zone. Where *Tilia*, *Ulmus* and *Salix* remain stable compared to the previous zone (<5%), *Quercus* shows a significant increase from 4% at the beginning of the zone to 10% at the end of the zone. Furthermore, several species start to occur at the beginning of this zone such as *Fraxinus* and *Rhamnus frangula* (<5%). Non-arboreal pollen decreases to 3%. This group is still dominated by Poaceae, but several non-arboreal species appear at the beginning of this zone like Apiaceae, *Artemisia*, Asteraceae, *Gallium* and *Cannabis type*. Heath takes up 2% of the pollen sum, consisting out of *Calluna* and Ericaceae. Species like *Sparganium* and *Equisetum* are high at the beginning of the zone, but start to decrease and disappear towards the end of the zone, whereas species like *Typha latifolia* and Cyperaceae become more abundant towards the end of the zone. This all points towards an expansion of shore vegetation, which could be due to a lowering of the lake level. At the highpoint of these two species a peak in *Dryopteris* and *Thelypteris* spores can be observed.

Zone 3 (6540 – 3010 cal. yr BP) – At the beginning of this zone the Arboreal pollen decreases rapidly from 95% to 65%, due to a high peak in Heath pollen (34%). After this high

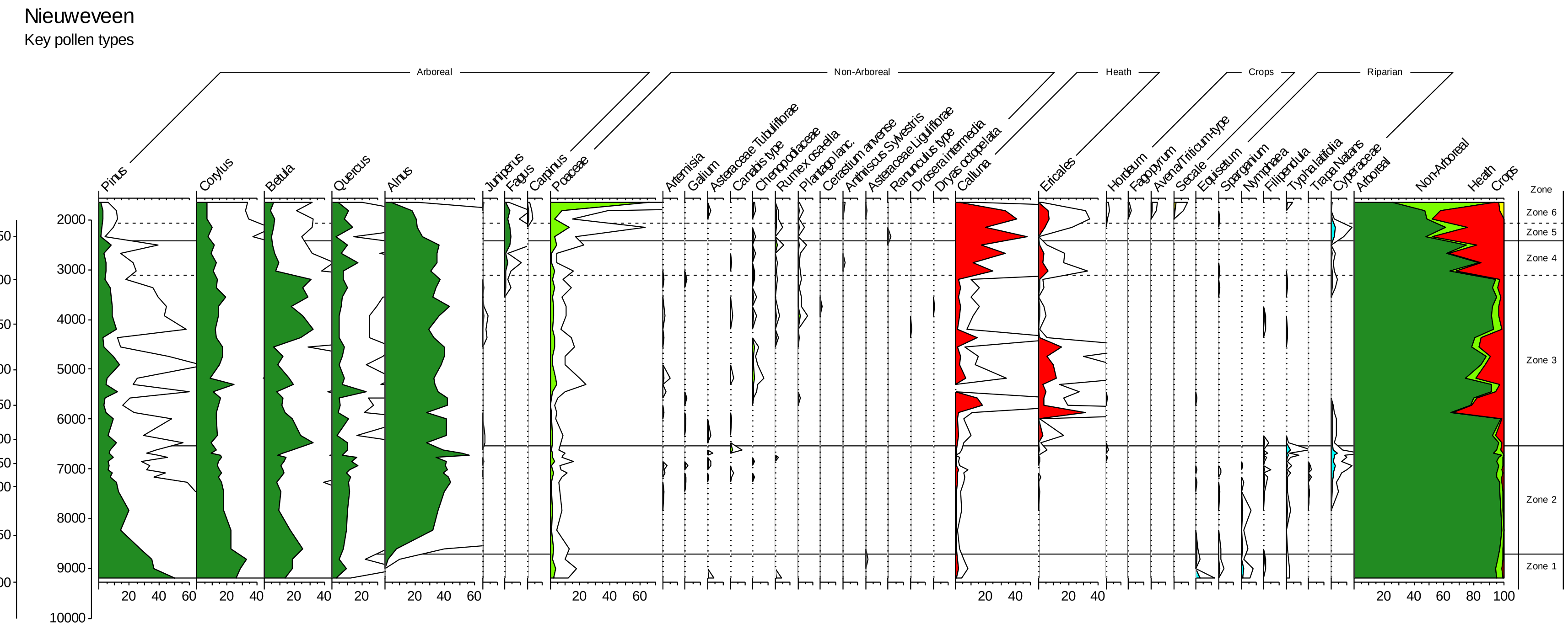


Figure 9, percentage diagram of selected pollen for Nieuweveen with a time scale (cal. yr BP) on a sediment depth scale (cm) peak in Heath pollen, the Arboreal pollen recovers back to 70-90%, whereas heath decreases to 10-20%. *Alnus* remains stable and dominant around 35%, whereas *Betula*, *Corylus* and especially *Quercus* show a decrease. Between 4280 – 3010 cal. yr BP arboreal pollen rapidly increase from 80% to 95%, whereas heath decreases from 15% to <5%. The increase of arboreal pollen is the result of a rapid increase in *Betula* pollen, which increases from around 12% to 25-30%. Non-arboreal pollen remain stable around 5% throughout the zone, Poaceae is still the dominant species. Around 5500 cal. yr BP the first human indicators, Chenopodiaceae and Brassicaceae, are continuously present in the diagram. Two other human indicators, *Plantago lanceolata.* and *Rumex*, are continuously present in the diagram from 4400 cal. yr BP onward. During the period of high *Betula* pollen and low heath pollen, *Drosera intermedia*, *Dryas octopelata* and *Jasmone montana* appear and they disappear at the same time as before the end of the zone. During this period *Juniperus* also occurs. At the start of zone 3 there is a high peak in *Sphagnum* spores and a small peak in *Pteridium* spores. Around 5300 cal. yr BP there is once again a high peak in *Sphagnum* spores and a small peak in *Pteridium*, *Thelypteris* and *Osmunda* spores. Around 3350 cal. yr BP *Fagus* occurs for the first time in the pollen record.

Zone 4 (3010 – 2410 cal. yr Bp) – Arboreal pollen drop significantly at the beginning of the zone and varies between 60-80%, *Alnus* is still the most dominant species and remains stable at 35%. *Betula* pollen dropped to <10% and *Pinus* pollen decreased <5%. *Quercus* pollen increased to around 10%, with a peak of 17%. At the beginning of the zone *Fagus* starts to occur in low abundance. Non-arboreal pollen remain stable around 3% throughout the zone, Poaceae is still the dominant species. At the end of Zone 3 heath was <5%, but at the beginning of this zone it has increased significant to around 20%. Within the heath group, *Calluna* is the dominant species with values of around 15%. During the peak in *Quercus* pollen, there is a small peak in *Sphagnum* spores and *Polypodium vulgaris* spores. Furthermore, Cyperaceae is present in low abundance.

Zone 5 (2410 – 2050 cal. yr BP) – Arboreal pollen have decreased significantly during this zone to a value of around 50%. *Alnus* is still the dominant species, but it decreased rapidly to 25% at the beginning of the zone. *Betula* pollen have decreased to 5% at the beginning of the zone and remained stable. *Corylus* pollen remain stable at 10% throughout the zone. *Fagus* has increased and remained stable at 4%. *Quercus* has remained stable around 10%. *Pinus* shows a significant decrease during this zone and only takes up 2% of the pollen sum. Non-arboreal pollen have increased to 5% of the pollen sum, Poaceae is still the dominant species. Heath pollen have increased to around 45% of the total pollen sum. Within the heath group, *Calluna* is the dominant species with values of around 40%. At the end of this zone a *Sphagnum* spore peak can be seen in the diagram.

Zone 6 (2050 – 1650 cal. yr BP) – Arboreal pollen remain stable at 50% throughout this zone. However, at the end of this zone arboreal pollen decrease rapidly to a value of 26%. *Alnus* remains the dominant tree species at 20%, but it decreases rapidly at the end of the zone to a value of 4%. *Betula* pollen remain stable throughout this zone at 5% and shows no decrease at the end of the zone. *Corylus* pollen decrease significantly at the beginning of the zone, from 10% to 6%, and remain stable throughout the zone, showing no decrease at the end. *Fagus* pollen remain stable throughout the zone at a value of 3% and show a rapid decline at the end of the zone to a value <1%. *Quercus* has remained stable around 10%, but shows a decrease at the end of the zone to a value of 4%. Around 1980 cal. yr BP *Carpinus* pollen occur for the first time and remain present throughout the zone. However, the *Carpinus* pollen never exceed 1% of the pollen sum. Non-arboreal pollen have increased to a value of 7% at the start of the zone, but at the end of the zone it increases rapidly to a value of 67%. This increase is a result of an increase in Poaceae pollen, which take up 66% of the total pollen sum at the end of the zone. At the beginning of the zone heath takes up

47% of the total pollen sum and slowly declines to a value of 39%. At the end of the zone heath decreases rapidly to a value of 3.3%. In the beginning of the zone *Calluna* pollen take up 40%, declining to 33% and ending at 2.7%. In the beginning of the zone Ericaceae pollen take up 7%, declining to 6% and ending at 0.5%. This zone also contains the first occurrence of several species of crops. At the beginning of the zone *Hordeum* appears, followed by *Avena/Triticum-type*, *Fagopyrum* and *Secale*. At the end of the zone Cyperaceae and *Typha latifolia* pollen occur. The rapid decrease of several tree species at the end of this zone and the increase of Poaceae, combined with the sudden occurrence of species like *Sparganium* and *Typha latifolia* might suggest the occurrence of a hiatus at the end of the zone. This is supported by the occurrence of *Fagopyrum*, which is a species commonly found in the last 500 years. Therefore it is highly likely that the hiatus is present somewhere between a depth of 30cm and 21cm, which corresponds to an age of 1979 cal. yr BP and 1822 cal. yr BP.

5. Discussion (Human impact)

Humans have always changed the nature around them throughout history. However, since the beginning of agriculture their impact on the nature around them increased severely. Deforestation to make space for small houses and later on larger settlements and villages or to make space for crop fields and pasture to have their animals graze on. The last few centuries humans even influenced the climate on earth. All these changes in nature are caught and can be seen in records, such as a pollen record. Every change in the environment gives a different signal in the record, some are difficult to see in the record, others have clear indicators. Nature around the Nieuweveen site is no exception. However, to understand how the vegetation around this site changes as a result of human impact it is important to know which changes in vegetation are a regional effect and which are local effects, since human impact on the vegetation may vary per site.

5.1 Comparison with other sites

The most famous pingo remnants in the Netherlands are those of Uddelermeer, Mekelermeer and Hijkermeer. Within these lakes peat never formed and as a result there never took any form of dredging place. These lakes form an exceptional geological archive, since the sediments are still intact, which goes all the way back from the present to the last ice age. These archives contain over 10.000 years with information on climate, water level, vegetation and human activity and can therefore be used to form reconstructions (de Gans, 2008). Since these lakes provide a complete record throughout the Holocene and captured the vegetational changes in this site since the last ice age they can be used to determine the regional changes in the Netherlands during this time period by comparing them.

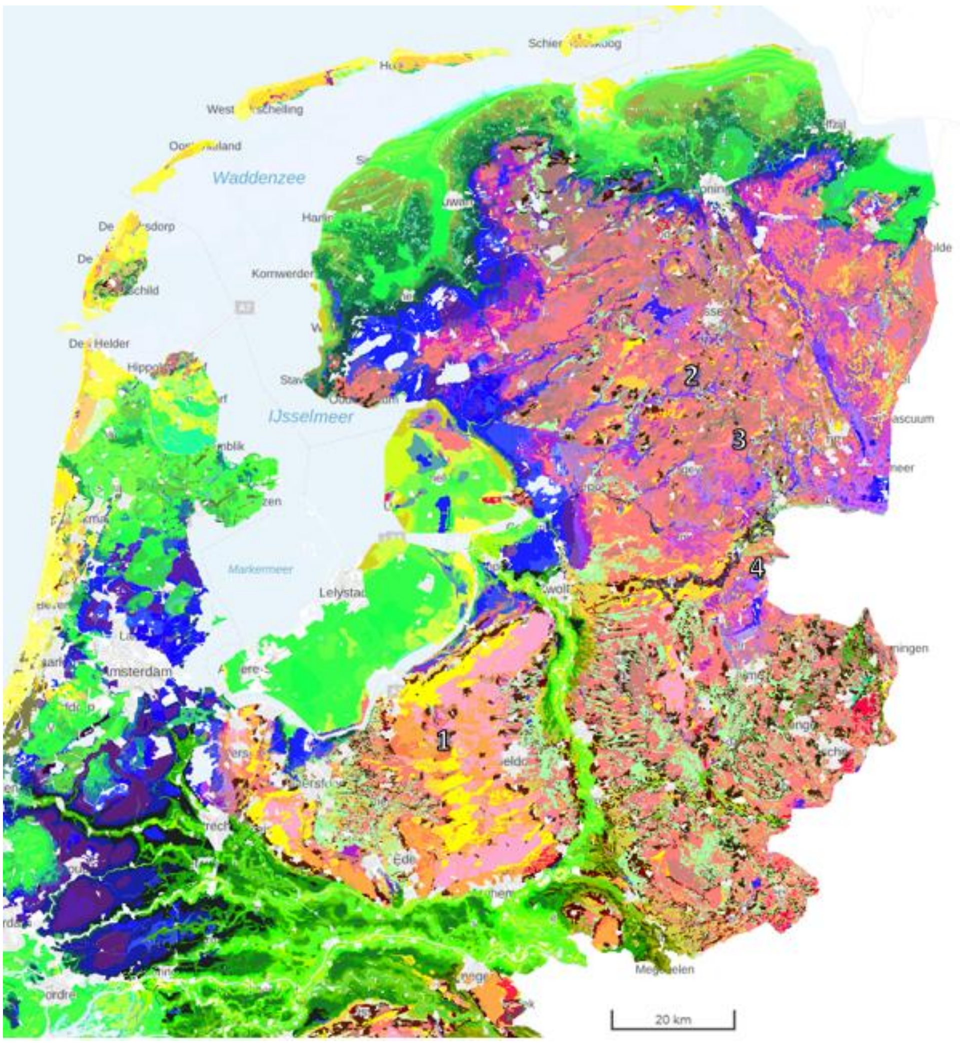


Figure 10, location of the different sites shown on a soil map. 1. Uddelermeer, 2. Mekelermeer, 3. Hijkermeer & 4. Nieuweveen

The same trends within the pollen diagrams from these lakes correspond to the regional changes in vegetation, whereas the differences between these sites most likely represent the local changes around these sites. This can be used to determine which changes in the pollen signal in the Nieuweveen site are regional changes and which changes represent local changes. Figure 10 shows the location of the different sites.

5.1.1 Uddelermeer

The Uddelermeer site is situated in the central part of the Netherlands (N 52°14′48″; E 5°45′40″). It is at a relatively low elevation and postioned between two push moraines which dating back to the Saalian time period (Engels et al., 2016). Because the Uddelermeer area is enclosed between these push moraines, it is a focal point for groundwater flow. As a result of this, this lake is very sensitive to changes in precipitation. Both the push moraines and the non-glacial sediments consists for the most part out of coarse grained gravelly sands (Engels et al., 2016). This hydrological and geological setting provided the right conditions for the formation of two pingo's during a period of permafrost in the Last Glacial Maximum. The large ice lenses underneath the pingo's and the surrounding permafrost melted after the LGM. As a result two basins were left behind which gradually altered into lakes of which Uddelermeer is the largest with a length of 300m and a water depth of 1.3 meter (Engels et al., 2016). The surface surrounding Uddelermeer is covered by Weichselian cover sands and a lot of intensive agriculture takes place in the area. West of the lake many *Alnus* trees can be found and a small wetland is situated to the north, northeast and southeast of the lake (Engels et al., 2016). The dating of the Uddelermeer site is relatively good. Especially the upper part of the core (4500 cal. yr BP – present) is reliable, due to a high amount of data points. However, the lower half of the sediment sequence (4500 cal. yr BP and 14.500 cal. yr BP) has to be treated cautiously. This part of the core is based on 5 data points, because there was very little organic material suitable for radiocarbon dating (Engels et al., 2016).

The Uddelermeer pollen diagram from Engels et al (2016) can be seen in figure 11.

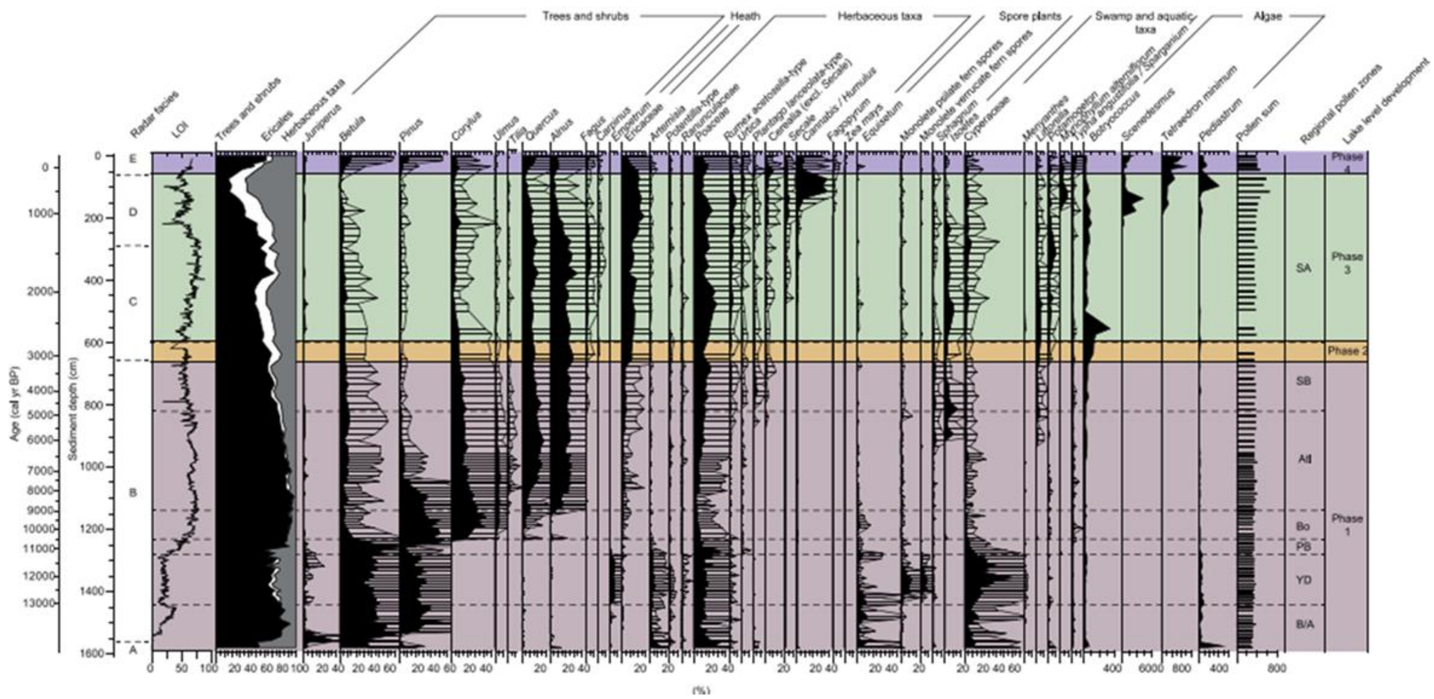


Figure 11, Uddelermeer pollen diagram (Engels et al., 2016)

5.1.2 Mekelermeer

The Mekelermeer site is located in the north eastern part of the Netherlands in the province of Drenthe, 20km west of the city of Emmen (N 52°77′08″; E 6°62′69″). The Mekelermeer pingo was deep and infill with sediments very slow, as a result peat never formed (de Gans, 2008). This makes this site rare, since almost all pingo remnants in the Netherlands contain a layer of peat on top of the gyttja layer. Besides the absence of a peat layer there is another factor which makes this site remarkable. The Mekelermeer site is surrounded by cover sands, but the infill itself does not contain cover sands even though the cover sands are about the same age as the melting of the pingo and the first infill. This is most likely caused by the height of the pingo itself. Apparently the hill was too high for covers and infill or the vegetation was too dense (de Gans, 2008). Compared to the radiocarbon dating of the Uddelermeer site, the Mekelermeer site is less reliable. The lower part of the core (9000 cal. yr BP – 14.000 cal. yr BP) contains 5 data points and is relatively reliable, although it does appear to have a hiatus marked by a sudden increase of age per cm. The upper part of the core (9000 cal. yr BP – Present) seems less reliable. It does not contain any radiocarbon datapoints and uses linear interpolation to create a chronology.

Figure 12 shows the Mekelermeer pollen diagram modified to show the same time period as the Nieuweveen site.

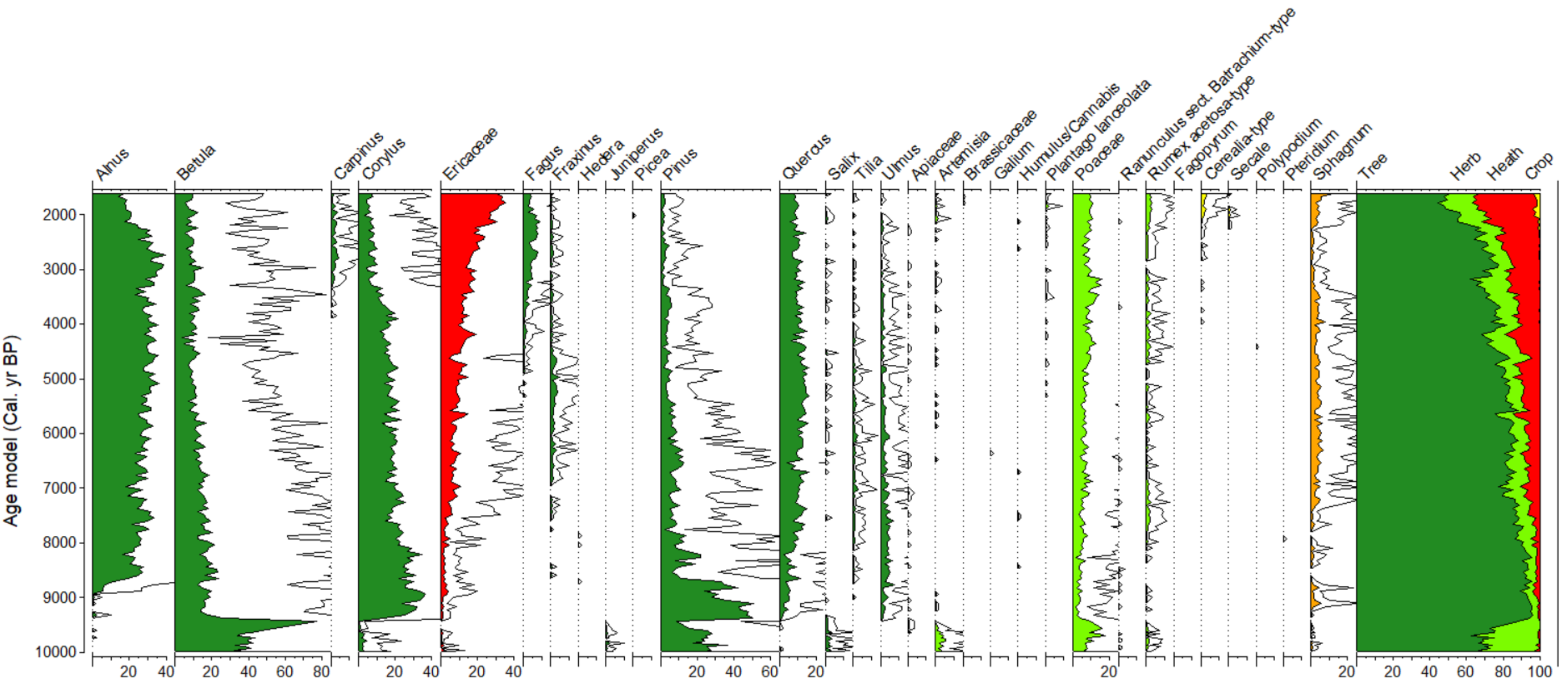


Figure 12, Mekelermeer pollen diagram (modified after Bohncke et al., 2008)

5.1.3 Hijkermeer

The Hijkermeer site is a pingo remnant and is situated in the north eastern part of the Netherlands in the province of Drenthe, close to the city of Assen (N 52°53’23’’; E 6°29′31’’). Hijkermeer is a small and shallow lake, measuring 200m in diameter and having a maximum depth of 1.6m. There are no river inlet and outlets present, which results in a minimized catchment area (Heiri et al., 2007). The Hijkermeer site has a relatively reliable age control and makes use of plenty of radiocarbon datapoints to reliably compare the Nieuweveen site with the Hijkermeer site.

The Hijkermeer pollen diagram from Donders et al (not yet published) is modified to show the same time period as the Nieuweveen pollen diagram and can be seen in figure 13.

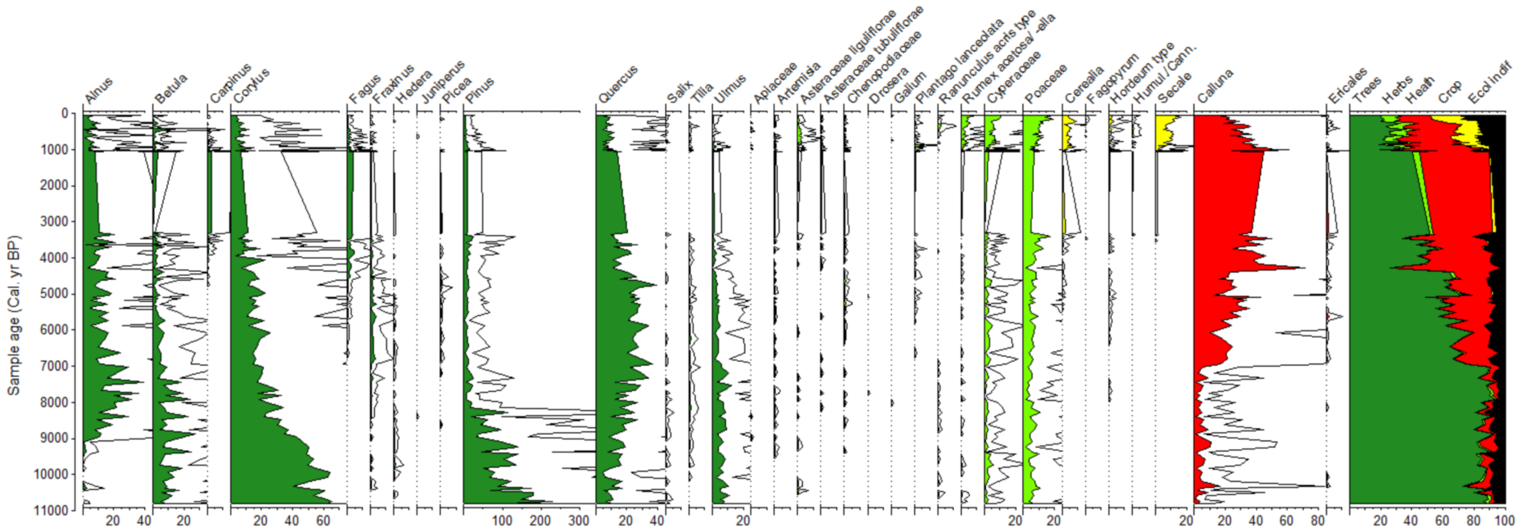


Figure 13, Hijkermeer pollen diagram (modified after Donders et al., (not yet published)

5.1.4 Local vs Regional changes

The pollen diagrams of Uddelermeer, Mekelermeer and Hijkermeer show the same trends in the lower half of the Holocene. The same trends can be seen in the Nieuweveen pollen diagram. Each diagram shows a rapid decline in *Pinus* pollen between 9500 cal yr BP and 7000 cal yr BP. At the same time a decline in *Corylus* pollen occurs. The same trend is observed in *Ulmus* pollen in all the diagrams. Between 9500 cal yr BP and 7000 cal yr BP a gradual increase in *Quercus* pollen can be observed in the diagrams. All sites show a sudden occurrence of *Alnus* around 9000 cal yr BP, which is followed by a rapid increase of *Alnus* pollen to a value of 40%. Both the Uddelermeer site and the Mekelermeer site contain very little NAP between 10.000 cal yr BP and 7000 cal yr BP after which the NAP slowly increases with a clear increase from 6000 cal. yr BP onward, this differs from the NAP found at the Nieuweveen site, which shows an increase from 6000 cal. yr BP. Which Non arboreal pollen types are dominant varies between sites, but in each site *Poaceae* is the most dominant arboreal pollen type. Based on these comparisons and the data from these sites it can be stated that the vegetational changes of these sites in the first of half of the Holocene (9500 cal yr BP – 7000 cal yr BP) is dominated by regional vegetational changes. The changes in vegetation are consistent between the different sites. Figure 14 shows a

comparison between the 4 sites with selected pollen, which are most relevant for the comparison.
After 7000 cal yr BP the sites begin the show different changes. All sites show an increase in *Plantago lanceolata* around 5000 cal yr BP, with an exception to the Hijkermeer site which shows this increase around 6500 cal. yr BP, but the percentage and consistency of *Plantago* varies wildly throughout the sites. However, from this data it is clear that humans started to disturb the vegetation in the Netherlands around this time period. Although the start of human disturbance on vegetation is occurring all over the Netherlands around the same time period, the amount of disturbance and how it effects the natural vegetation is site dependent. The Uddelermeer and Hijkermeer pollen diagrams show *Cerealia-type* as soon as humans begin to disturb the vegetation, as indicated by the *Plantago lanceolata* signal, around 5000 cal yr BP and 6500 cal. yr BP respectively. This suggests that at the start of human disturbance in the Netherlands and the early stages of agriculture crop cultivation took place around Uddelermeer and Hijkermeer. Around 2000 cal yr BP *Secale* starts to occur, indicating that the cultivation of this crop began in the area. During the middle ages the cultivation of crops intensified and humans begin to cultivate *Cannabis-type* or *Cannabis/humulus*.
Where Uddelermeer and Hijkermeer show clear human disturbance, the Mekelermeer pollen diagram does not. *Plantago lanceolata* first occurs around 5000 cal yr BP, which is consistent with the other sites, but it occurs in lower amounts and is less continuous. *Cerealia-type* occurs for the first time around 4000 cal yr BP, but only becomes continuous around 3000 cal yr BP. This suggest that although humans start to disturb the vegetation around 5000 cal yr BP, the first 1000 years most likely consist out of cattle grazing before the humans slowly start to cultivate crops around 4000 cal yr BP before the cultivation becomes more intensive around 3000 cal yr BP.
Based on this data it is clear that human disturbance on the vegetation in Uddelermeer and Mekelermeer began around 5000 cal yr BP, but the way it changed the vegetation is very local. However, Hijkermeer shows signs of human impact from 6500 cal. yr onward, which is very early based on what is known about the introduction of agriculture and human influence in the Netherland. The human impact trends from the Uddelermeer and Mekelermeer sites are also seen in the Nieuweveen pollen diagram. Human disturbance starts around 5500 cal

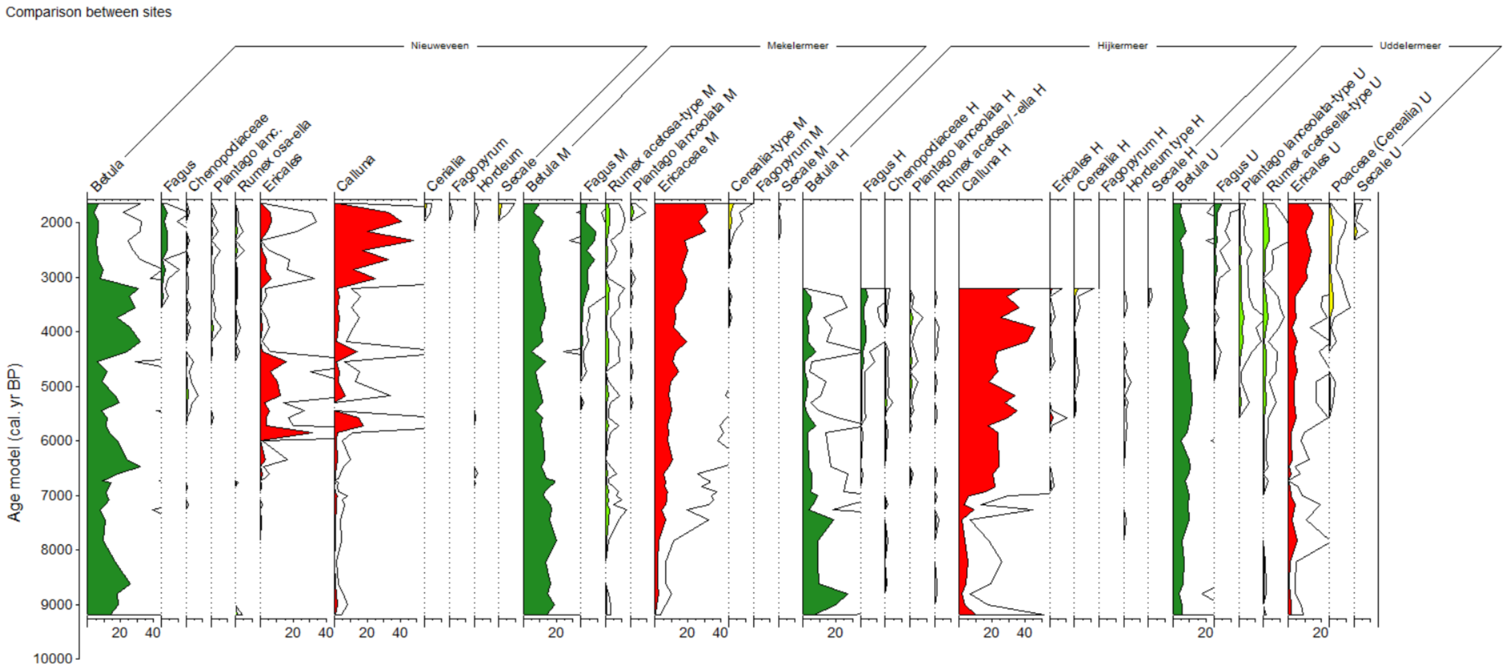


Figure 14, comparison between selected pollen types of the Nieuweveen site, Mekelermeer site (Bohncke et al., 2008), Hijkermeer site (Donders et al., (not yet published) and Uddelermeer site (Engels et al., 2016) yr BP as indicated by the first occurrence of *Plantago lanceolata* and the high and continuous presence of *Chenopodiaceae*, but *Plantago lanceolata* does not become continuous until 4500 cal yr BP. Unlike the Uddelermeer, Mekelermeer and Hijkermeer sites, the Nieuweveen site does not show a *Cerealia-type* signal together with the *Plantago lanceolata*, this indicates that this site was not used for the cultivation of crops but most likely for grazing by cattle. Cultivation of crops began around 2000 cal yr BP. The first occurrences of *Fagus* and *Carpinus* show similar trends between the sites, but the timing of the first occurrence of these species does vary. This suggest that the occurrence of these species is a regional vegetation change, but is influenced by human disturbance. It is known that these species are often linked to human impact (Pott, 1997). These species grow well on open spaces created by humans as a result of deforestation. However, the movement of these species from the south towards the Netherlands happened simultaneously (Rey et al., 2019). As a result the appearance of these species in the Netherlands happens around the same time and therefore can be considered a regional change. However, even though these species appear in the Netherlands region wide and around the same time period, they require open spaces to grow and thrive. The creation of these spaces is often driven by local factors, such as human influences like deforestation. As a result the appearance of *Carpinus* and *Fagus* are regional changes, which are driven by local changes. All the sites show an increase in Ericaceae around 3000 cal yr BP. This indicates that something changed in the climate or environment which allowed for this vegetation type to suddenly and rapidly increase. This is most likely caused by an increase in human impact during this time period and the resulting opening of the land, since around this time period human indicator species increase and the influx diagram (Appendix 6) shows a decrease in influx of tree pollen. One thing that is worth noticing in the Nieuweveen pollen diagram is the sudden and rapid increase in *Betula* pollen, between 4300 cal yr BP and 3200 cal yr BP, which coincides with a sudden drop in *Calluna* and *Ericales* pollen. This shift in vegetation is not observed in any of the other sites, which clearly indicates that this is a very local change in vegetation.

5.2 Development of agriculture

Early humans were hunter-gatherers, relying on nature to provide vegetation, nuts, fruits and animals for their survival (Gupta, 2004). These early humans did not establish permanent settlements like villages. Instead they adopted a nomadic lifestyle, moving their camps in response to changes in seasons and climate (Gupta, 2004). The first signs of animal domestication are found in the Palegawra cave, a site in the northeastern part of Iraq, and are dated around 14.000 BP (Gupta, 2004). Fossil bones suggest that during that time period humans might have used dogs for the hunting of wild animals (Morey & Wiant, 1992). The first cattle to be domesticated were sheep and goats. The first signs of this are found in southern and southwestern Asia (Allchin & Allchin, 1997). Remains of these animals found at sites linked to human occupation that are older than 10.000 BP show no sign of domestication, this suggests that around that time humans were still killing these animals (Allchin & Allchin, 1997). However, human sites, which are dated younger than 10.000 BP show greater abundance of skeletons of sheep and goats, including skeletons of younger sheep and goats. This suggests that these animals were kept by these early humans (MacDonald, 2003). At sites older than 9000 BP skeletons of sheep and goats are found even though these sites are located outside of the natural habitat of these species, suggesting full domestication of these animals and spreading of this practice throughout the world (MacDonald, 2003). Gupta (2004) suggests that humans transformed from hunting, to selective hunting and finally to herding as a result of the interaction with these herding animals. Over the past 10.000 years a diverse range of animals have undergone domestication. This benefited the growth and development of human populations greatly. The domestication of pigs and cattle in southwestern Asia between 9000 and 7000 cal. years BP resulted in greater availability of food. Hunting was less necessary since meat was more available. Furthermore, milk provided a fatty, nutrient rich drink throughout the year. A single cow could provide a large part of a village, making it a very useful animal to have around (Helmer & Vigne, 2007). Between 5000 and 3500 cal. year BP the horse and camel were domesticated in Central Asia, allowing humans to use these animals for heavy labour and quick travel (Gupta, 2004; Warmuth et al., 2012). The people of these cultures continued to rely primarily on hunting and gathering as their main food source, while using milk and meat as supplements. They did not yet establish permanent villages, instead they moved along with their herds during seasonal migration, following the availability of resources and adapting to changing environmental conditions (Gupta, 2004).

The domestication of plants started around the same time as the domestication of animals (Gupta, 2004). This domestication began in the tropical and subtropical regions of Asia, where there was enough precipitation to allow the growth of many plants in a small area without needing any additional watering. The earliest evidence for domestication of plants is found in southwestern Asia, on the Indian subcontinent. Several food plants like barley, wheat, lentils, rye, chickpeas and peas were all domesticated here between 11.000 – 9000 BP, although it quickly spread all over the world as a result of interaction between different cultures (Bogucki, 1996; Gupta, 2004).

The domestication of plants and animals was incredibly important for agriculture. Without agriculture the complex and technically innovative societies as we known them today could not have existed and humans would not have the capacity to maintain such a large population of humans. Furthermore, the development of agriculture allowed people to become sedentary and establish permanent living space, like towns and villages (Gupta, 2004).

5.3 Development of Agriculture in Europe

The movement of agriculture into Europe varies throughout the continent. The transition from hunting and gathering to agriculture took place many times all over Europe in completely different ways. In general the movement of agriculture into Europe and the following establishment of sedentary communities can be explained by two processes (Bogucki, 1996). In some cases farmers settled into a new area and brought along their domesticated plants and animals. In other cases hunters and gatherers gradually adopted agricultural knowledge and technology, eventually transitioning from their nomadic lifestyle to a fully sedentary one. In most cases the crops and animals were slowly integrated into the hunter and gather lifestyle patterns (Bogucki, 1996). The difference in time and way agriculture moved into different parts of Europe is a result of the difference among the regions of temperate Europe. Terrain, natural vegetation, drainage and soils all had an impact on the geographic patterns of the early farming communities (Bogucki, 1996). Large populations of hunters and gatherers lived often around coasts and estuaries, resulting in a more gradual adaption of agricultural knowledge and technology. Whereas the loess basins were thinly populated, but very fertile and dry. As a result these areas were often colonized by agricultural communities if they were able to moisturize the soil, bringing their crops and livestock along (Bogucki, 1996). The general spreading of agriculture through Europe can be seen in figure 15.

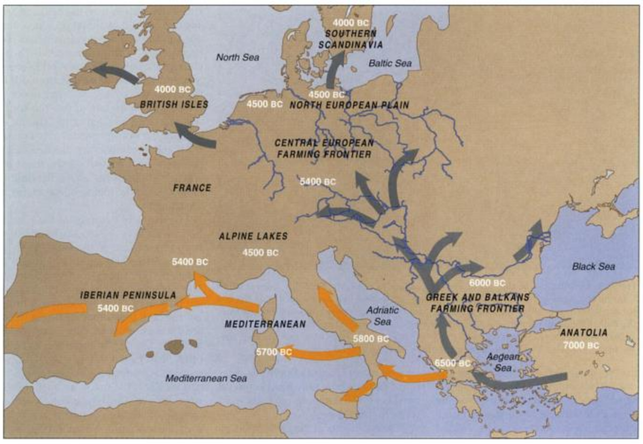


Figure 15, spreading of agriculture through Europe (Bogucki, 1996)

The first signs of farming in Europe can be traced back to Greece, after farmers crossed the Aegean sea with their crops and livestock between 9000 – 8000 year BP (Bogucki, 1996; Van Andel & Runnels, 1995). Early Neolithic sites in Greece show many similarities with early Neolithic Anatolian settlements. This suggests that agriculture spread from here into Europe (Bogucki, 1996; Van Andel & Runnels, 1995). After the arrival of the first farmers in Europe, signs of Neolithic settlements rapidly emerged on the alluvial plains of Thessaly and Macedonia. This indicates that these settlements were likely established by colonist, and the existing hunters and gatherers in the region had limited or no involvement in their establishment (Van Andel & Runnels, 1995). There are no alluvial planes present in southern Greece and therefore there are no signs of colonisation, instead the indigenous hunters and gatherers slowly adopted elements of the farming cultures (Bogucki, 1996). After agriculture got a foothold in Greece it spread into two different directions: westwards along the Mediterranean coast and islands and northwest following the major rivers into temperate Europe. Since the agricultural development around the Mediterranean had little to no impact on the agricultural development of the Netherlands, this chapter focusses on the northwest direction.

Around 8000 year BP farmers established settlements in the southern part of the Balkan. The early agricultural settlements in this part of the Balkan had to adapt to the more temperate climate (Bogucki, 1996). Sites show that pigs and cattle become more important than sheep and goats, while the farmers changed the grow season of crops like wheat and barley to summer rather than winter (Bogucki, 1996). These Balkan farmers were important for the transition of these new Neolithic settlements and way of agriculture into central and northern Europe (Bogucki, 1996; Van Andel & Runnels, 1995).

The early farmers encountered diverse soils and terrains in central Europe compared to south-eastern Europe. The domesticated plants adapted well to this new environment, thriving due to increased precipitation and more distinct seasonal differences (Bogucki, 1996). The terrain was covered with forests with species like oak (*Quercus*), linden (*Tilia*) and elm (*Ulmus*). These forest grew on a basin of fertile loess and many streams carved through the land. This made the terrain very attractive to early farming communities, who colonized these loess basins (Bogucki, 1996). These areas contained only a few settlements of indigenous foragers. The few foraging communities that lived on the loess basin were quickly absorbed within the farming communities or displaced into the surrounding areas. Foraging communities inhabited the regions north of the loess band, encompassing the North European plain and south of the loess band, the alpine foreland. The loess belt, stretching from eastern Germany to central France alongside the Alps, was where the farmers established their communities. The areas in which the foragers moved around become increasingly smaller after farming communities entered the loess band (Bogucki, 1996; Howell, 1987). The domesticated plants and animals slowly became a part of these foragers lifestyle about a millennium (6500 year BP) after the first farmers settled in the northern edge of the loess belt (Lorkiewicz et al., 2015). The knowledge and potential for agriculture was available during this period, however the foragers did not adopt this lifestyle until 6000 year BP (Bakels, 2009). Bakels (2009) suggests that this resistance of adopting agriculture is caused by the success of foraging in this area. Food was widely available. There were plenty of plants, which could be used as food, and enough animals in the area, therefore there was no immediate use for domesticated plants and animals. Agriculture came to these regions as a result of the interaction between the indigenous foragers in the area and the farming communities in the loess belt. Farmers never colonized the areas north of the loess belt, since the soil there was way less fertile and therefore it would have been inefficient to move out of the loess belt. It is suggested that these interactions consisted out of the exchange of forest products for crops (Bogucki, 1996). Around 5900 year BP there is a clear shift in one of the foraging communities to a more agriculture based community in the

North European plain. These Neolithic farmers are called the Funnel Beaker Culture and they are a group of the indigenous foragers that adapted agriculture, livestock and Neolithic technology into their lifestyle (Bogucki, 1996). The Funnel Beaker Culture were the last hunters and the first farmers in this area. The sites of this culture are found all over the North European plain, from the Netherlands to Poland and into Denmark and Sweden (Bogucki, 1996). What differentiate this culture from their precursors is the shift from a maritime economy (mainly fishing) to inland farming (Bogucki, 1996).
However, several sites in the Netherlands suggest another type of adaptation. The Netherlands was unattractive for agriculture and had limited amounts of suitable land for agriculture (Louwe Kooijmans, 1993b; Bogucki, 1996). Although the Netherlands was unattractive for agriculture there is plenty of evidence found which does indicate agriculture took place including crops and domesticated animal remains. Several sites have been found which appear to have been used as hunting stations. Furthermore, fish traps have been found in peat lands, which indicate that these areas have been used as short term winter fishing and fowling stations (Bogucki, 1996). Hunting, fowling and fishing were used to supplement the animal products and crops. This kind of lifestyle is called semi-agrarian and was commonly practiced in the Netherlands during this time period (Louwe Kooijmans, 1993a). It is clear that these sites belong to indigenous foragers who slowly changed from hunting and gathering to an agriculture based economy and adopted elements like crops and animals from farmers, who lived south of the Netherlands on more suitable land (Bogucki, 1996; Howell, 1987). This form of semi-agrarian lifestyle persisted way longer in the Netherlands, as a result of the climate and the terrain, compared to the surrounding areas. It continued for almost a millennium since the introduction of agriculture in the area. Around 5000 year BP the semi-agrarian communities were finally succeeded by a fully agriculture based economy (Bogucki, 1996; Louwe Kooijmans, 1993a).

5.4 Impact of Agriculture

The Funnel Beaker Culture did not cultivate their crops on permanent fields, instead they applied a slash-and-burn tactic, which resulted in short lived fields which also would quickly recover back to their natural state (Bogaard, 2004). Research shows that deciduous trees would quickly return after the creation of slash-and-burn fields (Bakels, 2014). However, there is also evidence pointing to a more permanent presence of agricultural fields although they were probably sparse since dry spaces suitable for arable farming in wetlands were often very small (Out, 2012). Nevertheless, agriculture, performed in any way, resulted into the opening up of the landscape. The first man-made or man enlarged forest clearings are probably hard to detect with pollen analysis (Bakels, 2014). As mentioned before, most fields were only small and temporary. Furthermore, they would quickly recover after abandonment of the plot. Size of the settlements and human population in the area play an important role in the opening-up of the forest. The size and the type of food produced also play an important role in determining the impact on the forest (Bakels, 2014). Some villages relied mostly on natural sources and to a limited extent on crop cultivation and animal care, whereas other sites relied heavily on crop cultivation, resulting on more and bigger plots and therefore a bigger impact on forest clearance. Furthermore, the effects of grazing by animals on the vegetation differs from the effect of the creation of fields for agriculture (Bakels, 2014).

5.5 Human impact at the Nieuweveen site

As previously mentioned in chapter 5.3 the Netherlands had an unattractive environment for crop cultivation during the early days of agriculture and the area surrounding the Nieuweveen site was no exception. The area consisted mostly out of peat swamps and the areas which were dry and located above the water levels were often nutrient poor or covered with sands, as can be seen in figure 16. As a result (intensive) agriculture was introduced several thousand years later in this area compared to other sites in the Netherlands. Interesting to note is that there are signs of early agriculture in the Hijkermeer site. The presence of a river near this site during that time period might have resulted in some fertile deposition, which made the land suitable for some small scale agriculture. To come to a clear conclusion more research might be necessary. Nevertheless, there are some possible indications of small scale agriculture and human land use in the Nieuweveen site. Furthermore, the landscape of the area prevented many forms of human impact, since the area was not well suited for living. Therefore it took centuries longer for humans to develop their capabilities further and really have an impact on the local vegetation.

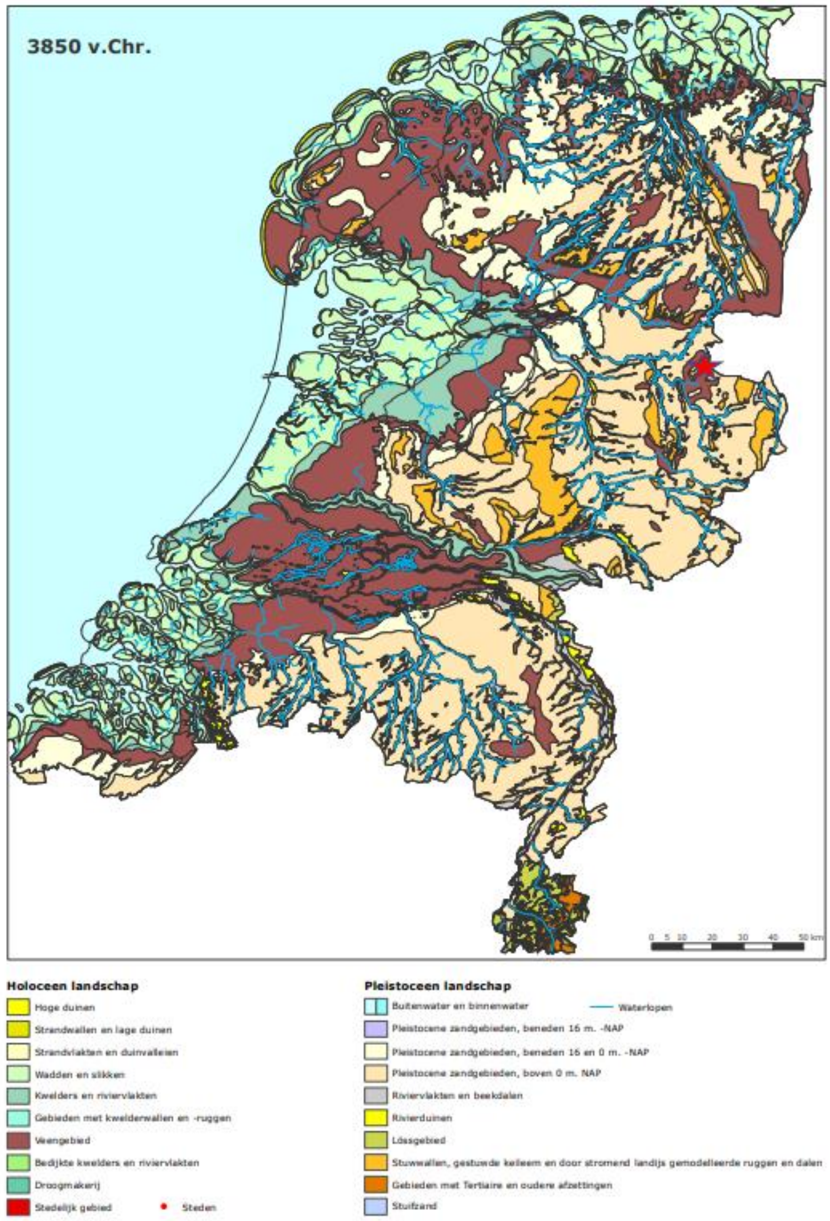


Figure 16, paleogeographic map of the Netherlands around 3850 BC (5800 yr BP) (Ministerie van Onderwijs, Cultuur en Wetenschap, 2020)

5.5.1 Small scale agriculture

At 3 different depths in the lower part of the studied Nieuweveen core a small peak in *Hordeum* can be found. These *Hordeum* pollen are found at a depth of 240cm, which is dated at 5584 cal. yr BP, a depth of 315cm, which is dated at 6611 and at a depth of 335cm, which is dated at 6770. The latter two of these depths are clearly not a result of agriculture. As stated by Bogucki (1996), agriculture entered the Netherlands around 6000 cal. yr BP. However, this does not mean small scale agriculture did not happen. But, there are no agricultural indicators present during the presence of these *Hordeum* pollen. There are no *Plantago lanceolata*, *Rumex* or Chenopodiaceae present. Therefore the *Hordeum* pollen, found at 315cm and 335cm, are not a result of crop cultivation, but more likely the result of a natural occurring grass species. It would at least take 500 more years before crop cultivation would start in the Netherlands. As a result these two sample depths can be disregarded. However, the *Hordeum* pollen found at a depth of 240cm is dated at an age of 5584 cal. yr BP. The *Hordeum* signal with different pollen types important as human activity indicators can be found in figure 17. This is well within the established range of first introduction of agriculture in the Netherlands. Therefore it is very much possible that this *Hordeum* peak is indeed a result of small scale agriculture. To determine whether or not this *Hordeum* peak is a result of early agriculture the 5 stages of agricultural impact by Li et al (2008) are used. This suggests that before 5584 cal. yr BP there should be a high percentage of shade tolerant species, followed by an increase in secondary forest as a result of deforestation. Shortly after 5584 cal. yr BP there should be an increase in ruderal pollen followed by a return to the original state of the forest before the start of agriculture in this area.

At a depth of 260cm, which is dated at an age of 5858 cal. yr BP, there is a decrease in tree pollen such as *Fraxinus*, *Tilia*, *Ulmus* and *Quercus*, while an increase in the secondary forest species *Corylus* is observed. Furthermore, a slight increase in fern spores can be observed. This corresponds to the first 2 stages of agricultural disturbance, as described by Li et al (2008). However, there is no clear decrease in *Alnus* pollen and no decrease in *Pinus* and *Betula* pollen.

At 5584 cal. yr BP there is a peak of *Hordeum*, which coincides with rural pollen types as *Plantago lanceolata*, *Chenopodiaceae* and *Galium*. Indicating agricultural use. This corresponds to stage 3 and 4 of the agricultural impact.

After 5584 cal. yr BP there is no more *Hordeum* signal, indicating that the land was no longer used for crop cultivation. Furthermore, *Artemisia* starts to occur and Chenopodiaceae increases, which indicates that the land around the site is restored or at least no longer used by humans. Finally, the influx diagram (appendix 6) shows a recovery of the tree species after 5500 cal. yr BP.

Although it is clear that this site has been used for the cultivation of crops around 5584 cal. yr BP. The trends in the different signals of pollen types shows a very long time span. There are several possible explanations for this disagreement.

As stated before by Boogaard (2004) the Funnel Beaker Culture did not cultivate their crops on permanent fields, instead they applied a slash-and-burn tactic, which resulted in short lived fields which also would quickly recover back to their natural state. It could be that the duration and area of these fields are too small to have a real impact on the surrounding vegetation, which results in not enough or not clear enough changes in the pollen signals for these multiple fields to be observed. Another possible explanation is an establishing of a settlement near the Nieuweveen site around 5900 cal. yr BP. As previously mentioned in chapter 5.3 the agriculture was introduced in

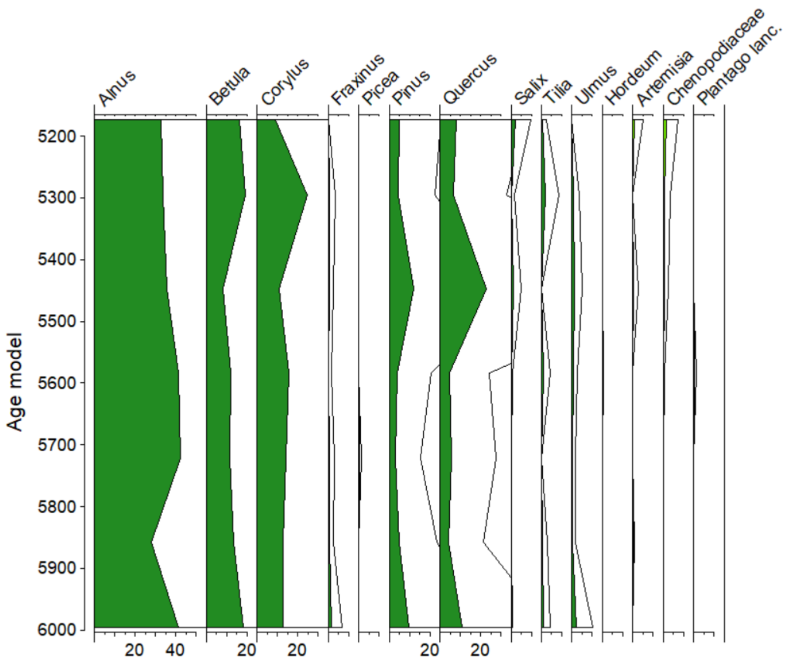


Figure 17, small Hordeum peak with important human activity indicators (cal. yr BP)

the Netherlands around 6000 BP, which would result in more permanent settlements. Therefore it is possible that changes in vegetation, which appear to indicate a slightly more open landscape is caused by the establishing of an early settlement. This suggested clearing of the landscape to create space to establish a settlement is supported by the influx diagram (Appendix 6). This figure shows a clear decrease in tree pollen around this time period. An early settlement in this area would also explain why the *Hordeum* signal is only observed in one sample and why there is only a small change in the vegetation around the site. Around this time period, humans were still semi-agrarian. Crop cultivation was not their main source of food and therefore they had very small fields, which they only cultivated for a short time period after which they abandoned the plot and moved their crop cultivation somewhere else. As a result this gives only a small signal in the pollen record, with little impact on the natural vegetation. Furthermore, in the area of Nieuweveen, as mentioned by Out (2012), dry spaces suitable for arable farming were sparse and restricted in size. Besides the fact that the spaces suitable for agriculture were restricted, humans in this time period often had their agricultural plots located far from their settlements. Therefore it is very well possible that these humans had agricultural plots before and after the one observed in the pollen record around 5584 cal. yr BP, but that these were located too far away from the Nieuweveen site to be caught in the pollen record because there was no suitable land available close enough to the Nieuweveen site, explaining why there is only one agricultural signal visible in the pollen record.
Based on the changes in the pollen signals, which corresponds with the 5 stages of agricultural impact, and the theoretical background of how the early farmers around this time period cultivated their land, established their settlements and the environment around the site at this time. The latter explanation seems most likely. However, the most definitive evidence for crop cultivation around 5584 cal. yr BP would be charcoal. Which would be a result of the slash-and-burn tactic often used by the Funnel Beaker Culture. Unfortunately, the organic content in these slides was to dense to be able to identify charcoal remains.

Between 1980 cal. yr BP and 1650 cal. yr BP the pollen record shows the occurrence of *Hordeum*, *Fagopyrum*, *Cerealia-type* and *Secale*, suggesting crop cultivation. This period falls within the occupation of the Roman empire in the southern part of the Netherlands. Although the area of the Nieuweveen site was not located within the occupied land, the knowledge and advanced tools they possessed heavily influenced the native people deep within Netherlands. Therefore it is very much possible that the farmers around the Nieuweveen site learned how to drain the wetlands and cultivate crops on this newly formed land (de Haas & Schepers, 2022). However, the sudden and strong increase in Poaceae during this time period as well as the presence of *Typha* latifolia, might suggest the presence of a hiatus. Furthermore, *Fagopyrum* is a species which is most commonly linked to agricultural activities from the past 500 years.

5.5.2 Grazing

As previously mentioned in chapter 4.3, Chenopodiaceae is continuously present from 5584 cal. yr BP onward. Around 4500 cal. yr BP *Plantago lanceolata* and *Rumex* show an increase and become consistent in the pollen record. This indicates an more open landscape. Besides these rural pollen there is an increase in *Artemisia* 4500 cal. yr BP as well, which is present until around 3000 cal. yr BP. Furthermore, there is a small peak in *Cerastium arvense*, which is a pollen type which is often indicative of pastures (Eriksson & Eriksson, 1997). Chenopodiaceae, *Artemisia* and *Cerastium arvense* are nitrophilous plants. The sudden and quite significant increase of these species indicate an increase in nitrogen content in the soil (Pöyry et al., 2016). Whereas *Plantago lanceolata* and *Rumex* are an indicator of open areas. These indicators of an open area in combination with the nitrophilous plants suggests grazing or mowing lands. Nevertheless, there is still the possibility for an agricultural plot. There is evidence that around 5000 cal. yr BP the early farmers in Europe had developed the use of manure to enhance the yield of their cultivated crops (Bogaard et al., 2013). This could explain the sudden increase in nitrophilous species. However, there have not been found any type of crop in the pollen record. Furthermore, the establishment of an agricultural field would have required a significant amount of deforestation. The influx diagram (Appendix 6) shows only a small decrease in the influx of tree pollen types. Therefore it is very unlikely that these pollen signals are caused by agriculture. On the opposite there is some evidence pointing towards the possibility of grazing by cattle. During this time period there were no possible natural sources to increase nitrogen content in the soil. So it is highly likely that this nitrogen increase is caused by manure. This is supported by the presence of the dung fungi sporormiella. Unfortunately, due to the high density of the slides only a limited amount of sporormiella has been observed. As a result it is difficult to make a distinction between cattle, which would result in high amounts of sporormiella and natural occurring grazers like deer, which would result in lower quantities of sporormiella. Around this time period the Funnel Beaker culture had fully adopted livestock in their lifestyle, which they often had grazing on designated fields often located a distance from the village (Lübke, 2007). At first these farmers often moved their animals from field to field to prevent exhaustion of the vegetation (Bogucki & Grygiel, 1983). Later on, the keeping of livestock developed and people were able to keep more animals. This made it more difficult for humans to move their animals from plot to plot. To be able to keep the animals at one spot the early farmers often used a natural meadow for their livestock to graze. When the herd grew an natural meadow or open forest was often not open enough. The animals had to spread more to have enough space to graze, which made it more difficult for the humans to keep their herd close together. Therefore, these natural meadows were often cleared to create more space to graze on (Doppler et al., 2017; Towers et al., 2017). As mentioned before the influx diagram does show a slight decrease in the influx of pollen diagram. It is known that the tree pollen slowly declined at the start of the Bronze age (around 4100 cal. yr BP in the Netherlands) as a result of human impact throughout the Netherlands (van den Bos et al., 2014; Groenewoudt, Van Haaster, et al., 2007). This increase in human impact was mainly caused by a substantial rise human population (Clarke et al., 2009). This coincides with the growing of the herds and the increased influx in the diagram (around 4000 cal. yr BP). The decrease in tree pollen occurred later than the first signs of grazing. Therefore it is likely that the *Plantago lanceolata* and *Rumex* signals, which in this case indicate a natural meadow, in combination with the nitrophilous species Chenopodiaceae, *Artemisia* and *Cerastium arvense* indicate an open landscape where the early farmers had their livestock graze. Around 4000 cal. yr BP the tree pollen influx declines. This is most likely caused by deforestation to clear the area to be able to keep more animals together on one plot for grazing to sustain the increased human population in the village.

5.5.3 Deforestation

By the end of the Neolithic period, the landscape around the Nieuweveen site and the eastern part of the Netherlands was primarily covered by forests. This started to change at the beginning of the Bronze age (van den Bos et al., 2014; Groenewoudt, Van Haaster, et al., 2007). An increase in human population and the following increase in human impact on the environment in the form of agriculture, herding and deforestation resulted in a change of vegetation (Clarke et al., 2009). At the start of the Bronze age this decline began very slowly, but later on this decline became more drastic. As these tree pollen start to decline throughout the Netherlands, species like Poaceae, *Rumex*, *Plantago lanceolata* and *Calluna* and Ericaceae show a general increase in abundance (Prummel, 1979; Groenewoudt, Van Haaster, et al., 2007). These changes are the starting signal for the establishment of large open fields in the form of meadows for grazing and arable land to cultivate crops in (open forest areas). Whereas the decrease in tree pollen in the sand ridges in the eastern parts of the Netherlands caused a presence of heathlands on the nutrient poor sandy soils (Groenewoudt et al., 2007; van den Bos et al., 2014). This decrease in tree pollen persisted throughout the Iron age and reached its minimum around 2500 cal. yr BP. Around 1500 cal. yr BP most deforested areas were covered again by trees, which coincides with the end of the Roman period.

These patterns of increase and decrease in tree pollen throughout the Eastern part of the Netherlands can also be observed within the Nieuweveen pollen diagram. Around 4500 cal. yr BP the presence of *Plantago lanceolata* and *Rumex* indicate a more open landscape. However this effect is not visible in the influx diagram (Appendix 6). Around 3800 cal. yr BP a slight decrease of influx of tree pollen can be observed from the diagram. This decrease coincides with the beginning of the Bronze age and the following increase in human population, which caused deforestation. It's very likely that around this time period the *Calluna* and Ericaceae pollen start to increase in abundance on the nutrient poor sandy soils as well, but these signals are obscured by the high abundance and influx of *Betula* pollen. This is further supported by the high amount of *Calluna* and Ericaceae pollen present after the period of high *Betula* abundance. Around 3100 cal. yr BP there is a fast and strong decline in tree pollen influx, suggesting high deforestation rates. This strong change in influx signals coincides with an increase of *Rumex* and *Plantago lanceolata* abundance, as well as a rise in the abundance of Poaceae. This suggests that the area did indeed become more open. Around 2500 cal. yr BP the abundance and influx of tree pollen reached its minimum, as is observed all over the eastern parts of the Netherlands (Groenewoudt et al., 2007). This minimum persisted until around 2100 cal. yr BP after which it slowly started to rise again. Interesting to note is the high abundance of *Quercus* around 3000 cal. yr BP and the consistent influx rate, which continued for a longer period compared to the other trees. This influx stayed consistent until around 2500 cal. yr BP, after which it quickly decreased to the same levels as the other tree pollen. This suggests that the oak trees might have purposefully been spared to be used as a source for food, while the other trees were felled (Deforce et al., 2009; Zhang et al., 2017).

Between 2000 and 1500 cal. yr BP the roman empire reached halfway into the Netherlands. It is well known that the Roman occupation had a severe influence on the natural vegetation. Although the Roman empire never reached the area of the Nieuweveen site, their influence reached deep into the Netherlands and their advanced way of life and knowledge drastically changed the way the natives lived. Unfortunately it is difficult to differentiate the specific impact of the Roman occupation on the vegetation from the overall trend of deforestation that occurred during the Iron Age (Prummel, 1979; Groenewoudt, Van Haaster, et al., 2007).

The low abundance and influx rate of tree pollen does not necessarily suggest a treeless landscape (van den Bos et al., 2014). It is possible that the land was used to grow trees used in timber. This would result in plots filled with relatively young trees, which would be too young to disperse pollen. During this time period *Alnus*, *Pinus* and *Fraxinus* were the main wood types used in construction (van Dinter et al., 2014). This is supported by the higher abundance of *Pinus*, *Alnus* and *Fraxinus* around 2500 cal. yr BP as well as a small peak in the influx diagram. The pollen record shows a decrease in abundance and influx rate for all the tree species, even though not all of these species were suited to be used in construction. During this time period wood was also used as fuel. This wood could be used for crafting, domestic use, cooking and some specific species were used during funerals and cremations (which type was different for each village) (Prummel, 1979; Groenewoudt, Van Haaster, et al., 2007). Therefore, it is possible that these tree species might have been used for other purposes.

5.6 Occurrence of Cannabis/Humulus

Cannabis and *Humulus* pollen look very similar and it is hard to distinguish between the two species underneath a microscope. Therefore, researchers often group the two together as *Cannabis* type or C-H pollen. Although the pollen may look similar, they may indicate very different environments and conditions. The first clear signal of *Cannabis* pollen in Europe originate from the Olduvai cold stage, which started around 1.8mya (McPartland et al., 2018). *Humulus* has been present in Europe far longer, the first signs of continuous presence of *Humulus* date back to the late Miocene, 6.1 – 5.3 mya, when it expanded from Asia to Europe. *Humulus* is usually found in warmer environments, whereas *Cannabis* prefers colder environments. Although *Cannabis* can withstand colder temperatures it may seem unlikely that *Cannabis* occurred in northern Europe during the Last Glacial Maximum and the following deglaciation. However, *Cannabis* is classified as an arctic forb (Binney et al., 2017). *Cannabis* is even capable of tolerating climate conditions north of 68˚N (McPartland et al., 2018). *Cannabis* even expanded towards northern Europe during the deglaciation. Northern Europe experienced post glacial isostatic rebound, leading to significant land uplift in certain areas, with some places rising by 300 meters. This uplift, combined with the formation of streams from glacial melt, resulted in the creation of alluvial ravines. These ravines cut through dry tundra and steppe, forming a disturbed landscape that was well suited for the growth of *Cannabis* (Berglund, 2004; Binney et al., 2017; McPartland et al., 2018). According to McPartland et al. (2018) collective data has shown that Europe was colonized by *Cannabis* during stadials and was replaced by *Humulus* during interstadials. During these interstadial periods, *Cannabis* retreated to interstadial refugia in eastern and southern Europe.

Study of McPartland et al. (2018) shows that during the Mid-Holocene Climatic Optimum (MHCO) (9000 – 5000 BP), *Cannabis* had retreated to two interstadial refugia in Europe: the Pontic steppe (Ukraine and Bulgaria) and along the Mediterranean coastline (Greece and Spain).

For this reason *Cannabis* had largely disappeared from Europe, during the Neolithic period, by the time that farmers and the knowledge needed for agriculture had arrived from the Middle East (McPartland et al., 2018). The domestication and cultivation of *Cannabis* was difficult and required a lot of knowledge. Furthermore, as mentioned before, *Cannabis* was not naturally wide spread during this time period. Therefore there were only three cultures which were capable of the cultivation and domestication of *Cannabis*: the Neolithic Greece culture, the Cardium Pottery culture (Mediterranean coastline) and the Bug-Dniester culture (Ukraine) (McPartland et al., 2018). However, no pollen signal indicating the cultivation of *Cannabis* is found within archaeological data of the cultures (Conolly et al., 2008). This means that either the farmers of these cultures, although they had the potential to domesticate and cultivate *Cannabis*, never started this process or they tried to domesticate and cultivate *Cannabis*, but quickly abandoned the cultivation.

The presence of C-H pollen, which is consistent with *Cannabis*, indicates that there were two cultures within the Copper Age that possessed the knowledge and potential to domesticate and cultivate *Cannabis* (McPartland et al., 2018). The Copper age is the transitional period between the Neolithic period and the Bronze age. These cultures are the Greek Chalcolithic culture and the Cucuteni-Tripolye culture (Ukraine) (McPartland et al., 2018). No evidence has ever been found for the domestication and cultivation of *Cannabis* by the Greek Chalcolithic culture. However, archaeological studies on sites from the Cucuteni-Tripolye culture have found significant findings, including the discovery of seeds of *Cannabis* and, although weaker but suggestive indications from pottery seed impressions (Long et al., 2016; McPartland et al., 2018).

During the Bronze age the cultivation become more widespread, not only in Europe but also in eastern China. During the Bronze age eight cultures had the potential to cultivate

Cannabis: the Netted Ware culture (Russia), Ezero culture (Bulgaria), Yamnaya culture (Ukraine), Corded Ware culture (North Europe - Netherlands to Baltic countries), Bell-Beaker culture (Western Europe), Terramara culture (North Italy), Aegean Bronze age culture (Agean sea) and the Mycenaean Greece culture (Southern Greece) (McPartland et al., 2018). Cultures started to actively trade and interact with each other during this time period, resulting in the sharing of information and cultivated seeds. This made it easier for cultures to start the cultivation of *Cannabis* and the fast spreading of this practice throughout Europe (Vandkilde, 2021).

During the Iron age *Cannabis* was cultivated on a large scale by many different cultures throughout all of Europe. In western Europe there are plenty of sites indicating cultivation of *Cannabis* like France, Germany, Great Britain, Switzerland and the Netherlands (McPartland et al., 2018). During the Roman period *Cannabis* become even more widespread. Macroscopic and pollen finding of *Cannabis* cultivation spread into new regions synchronous to the spreading of the Roman empire (Mercuri et al., 2002).

Both *Cannabis* and *Humulus* have been used by humans for a long time as they are both native to the northern hemisphere. The earliest use of *Cannabis* fibres predates the Neolithic, humans soaked the plants in lakes to make the fibres strong and resilient to make ropes out of them (McPartland & Hegman, 2017). Besides the fibres, humans also used the seeds from the hemp as food and as a source of oil. However, the use of *Cannabis* was small spread, many European Neolithic cultures preferred the use of flax (*Linum usitatissimum*). The cultivation of flax was already wide spread around that time and therefore easier and more efficient over the cultivation of *Cannabis* (McPartland & Hegman, 2017). During the Bronze age *Cannabis* became the most used source for fibre. *Cannabis* was cultivated by many different cultures throughout Europe and its fibre is stronger than that of flax (Kymäläinen et al., 2001), therefore many cultures switched to *Cannabis* as their source of fibre for ropes.

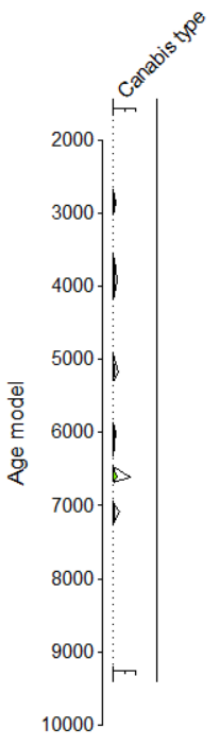


Figure 18, Cannabis/Humulus pollen diagram (Nieuweveen cal. yr BP)

During the Iron age humans also discovered the medicinal properties of *Cannabis*, Romans used it as a medicine against earache. Furthermore, a few hundred years earlier the Greek used the fibre from hemp to make clothes and burned the seeds during funerals to lighten the mood (Mercuri et al., 2002).

Humulus was far less used by ancient cultures. Many cultures ate its young shoots like asparagus and later on hop was used as a garden plant during the Roman period, but its use in brewing was only discovered in the middle ages. This is also the period in which hop cultivation become wide spread (Mercuri et al., 2002).

Figure 18 shows a diagram which contains the C-H pollen, in this diagram indicated as *Cannabis type*, from the Nieuweveen site. The first C-H pollen signal appears in the Neolithic period around 7000 cal. yr BP, followed by a small peak around 6500 cal. yr BP and a small signal around 6000 cal. yr BP. The next signal of C-H pollen appears in the Copper age around 5200 cal. yr BP. A more continuous signal of C-H pollen appears at the start of the Bronze age around 4100 cal. yr BP, which lasted till around 3500 cal. yr BP. During the Bronze age another signal appears around 3000 cal. yr BP and lasted till the start of the Iron age around 2700 cal. yr BP. Throughout the Iron age there are no

signals of C-H pollen found within the diagram.
By comparing the Nieuweveen site with the Uddelermeer site from the study of Engels et al. (2016) it becomes clear that the occurrence of *Cannabis type* varies wildly. Figure 19 shows the *Cannabis type* from Uddelermeer. This study made a clear distinction between *Cannabis* and *Humulus* and therefore the *Cannabis type* signal in this diagram consists mostly out of *Cannabis sativa*. *Cannabis* first appeared in low abundance during the middle of the Iron age around 2500 cal. yr BP at the Uddelermeer site. *Cannabis* sees a sudden and significant rise around 1000 cal. yr BP, Engels et al. (2016) suggest that this sudden appearance in high abundance of *Cannabis* after the Iron age in this record is caused by the deposition of pollen grains during the retting of hemp in the lake. Around the same time period the Hijkermeer site also shows a sudden appearance in high abundance of *Cannabis*. De Klerk et al. (1997) found 2 *Cannabis* pollen in the area of Leerdam around 2600 cal. yr BP. There are no further records of *Cannabis* signals in the Netherlands before this time period, which may suggest that cannabis never really got a foothold in the Netherlands.
Humulus, however, has been found in many different sites in the Netherlands. *Humulus* was almost continuously present in the area of Oss between 3000 and 6200 cal. yr BP (Cleveringa et al., 2000). Near the area of Zijderveld *Humulus* has been present almost continuously present between 9800 and 8000 cal. yr BP, after which it became less abundant but still often present until 3500 cal. yr BP (De Jong, 1970). *Humulus* is also found at the site of Horssen-Laagveld, where it is continuously present between 1000 and 1500 cal. yr BP and 3000 and 3500 cal. yr BP (Teunissen, 1990). According to the study of Van Geel (1978) at the area of the Engbertsdijksveen, which is located close to the Nieuweveen site, C-H pollen first appeared around 3800 cal. yr BP. However, they only become continuously present in the site around 2750 cal. yr BP. Around 2200 cal. yr BP the C-H show a sudden and significant rise in abundance, this suggest that this is a result of cultivation.

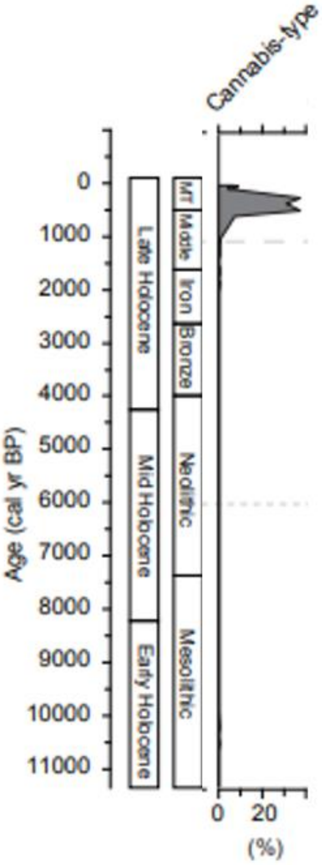


Figure 19, Cannabis/Humulus pollen diagram of Uddelermeer (modified after Engels et al., 2017)

When looking at figure 18 of *Cannabis type* at the Nieuweveen site it seems very unlikely that the C-H signals during the Neolithic period are that of *Cannabis*. As mentioned before *Cannabis* retreated to refugia in the Pontic steppe (Ukraine and Bulgaria) and along the Mediterranean coastline (Greece and Spain) (McPartland et al., 2018). This suggests that the C-H pollen in the Neolithic part of the diagram are *Humulus* pollen and not *Cannabis* pollen. During the Copper age there were only two cultures, which had the potential to cultivate *Cannabis*, but neither lived close enough to have an impact on the *Cannabis* signal in the Netherlands. Therefore it is most likely that the C-H signal during the Copper age in the Nieuweveen diagram is a *Humulus* pollen signal. The Corded Ware culture and Bell-Beaker culture were the first cultures in the Netherlands with the potential to cultivate *Cannabis* during the Bronze age. However, there are almost no sites in the Netherlands which show a *Cannabis* signal during this time period. When zoomed out even further, it becomes apparent that there are almost no sites with *Cannabis* in all of North-West Europe (Netherlands, Belgium and Germany). Whereas many different sites in the Netherlands show the presence of *Humulus* throughout all of the Holocene. This might suggest that although

the Corded Ware culture and Bell-Beaker culture had the potential to cultivate *Cannabis*, there might have been another limiting factor like environment or climate which made the cultivation of *Cannabis* impossible or not feasible. Furthermore, the cultivation of *Cannabis* often leads to a sudden and significant increase of pollen, as is seen in the Uddelermeer diagram. The Nieuweveen site does not show such a sudden and significant signal. The Iron age does not show any C-H signal in the diagram, whereas this is the period after which the cultivation of *Cannabis* became a widespread practice as a result of the conquest for territory by the Roman empire (Mercuri et al., 2002).
Altogether it seems highly unlikely that any of the C-H pollen signals in the Nieuweveen diagram consist out of *Cannabis* pollen. Based on information on the spreading of *Cannabis* and *Humulus*, the potential of cultures to cultivate *Cannabis,* the abundance of *Cannabis* pollen in the diagram and data obtained from other sites throughout the Netherlands and other parts of North-Western Europe, it seems most likely that the C-H pollen signal in the Nieuweveen diagram consists completely, or at least for the most part, out of *Humulus* pollen.
However, although the presence of *Cannabis* around the Nieuweveen site seems very unlikely. These facts do not rule out the possibility for small scale cultivation of *Cannabis* in the area. Furthermore, it is known that during the Bronze age settlements traded with both surrounding and far away located settlements or via traveling merchants (Vandkilde, 2021). Therefore the possibility remains that the *Cannabis type* pollen found in the core, after the beginning of the Bronze age (4100 cal. yr BP) are a result of deposition of pollen grains during the retting of hemp in the lake. Nevertheless, the cultivation or natural occurrence of *Cannabis* seems very unlikely.

6. Discussion (Natural changes)

Nature is always changing. Changes in precipitation, temperature, sunlight, wind etc can all cause vegetation to change and adapt. Climate is one of the major drivers for these changes. Gradual changes in climate and abrupt changes in climate can therefore been seen in a pollen record.

6.1 Filling of the Lake

As the pingo continued to accumulate ice and its height increased, cracks began to form in the ice layer covering the pingo. As a result of these cracks, sunlight was able to penetrate the layer covering the pingo. This sunlight caused the ice layer to melt slowly as well as the surrounding ground layer. The meltwater from the ice ran down the ping o, transporting molten pieces of the ground layer downwards. These pieces of ground were deposited at the foot of the pingo. As a result of elevated wall of ground formed around the foot of the pingo. As the ice core underneath the hill continued melting, the hill eventually became unstable and collapsed on itself. This formed a circular depression surrounded by a wall of ground, which was filled with meltwater. During the early Holocene, the temperatures began to rise significantly, and plants settled in the lake. Since these plants were submerged under water, they could not be decomposed after they died. As a result, peat began to form. These layers of peat slowly filled up the lake, until it was completely filled up. This process also occurred at the Nieuweveen pingo ruin.

Between 780cm and 330cm the lithology of the core shows the presence of gyttja, which is the first form of infill of a lake. Around 330cm the lithology shows a change from gyttja to peat, which is the next step in the hydrosere as discussed in chapter 1.7.

The filling in of the lake can also be seen by the sequence of aquatic species. The appearance, disappearance and abundance of these species show a clear correlation with the changing water depth, which is caused by the infill of the lake. Since the first signs of infill of pingo ruins usually date back to 12.000- 11.000 cal. yr BP (Mahlstedt et al., 2018) it can be assumed that the lake underwent at least 2000 years of infill before the first sample used in this research and therefore the lake must have originally been much deeper than reconstructed by using the aquatic vegetation. Figure 20 shows the aquatic species present in and around the lake. At the bottom of the core *Equisetum*, *Sparganium*, Nympheae, *Fillipendula* and *Typha latifolia* are present. It is known that *Equisetum* spores show no correlation with water depth, therefore the presence of *Equisetum* cannot be used to determine water level change in the lake (Edwards et al., 2000). Furthermore, *Typha latifolia*, *Sparganium* and *Fillipendula* grow along the shoreline of the lake or in the shallowest parts of the lake and therefore they cannot be used to determine the average water depth of the lake (Gurnell et al., 2013).

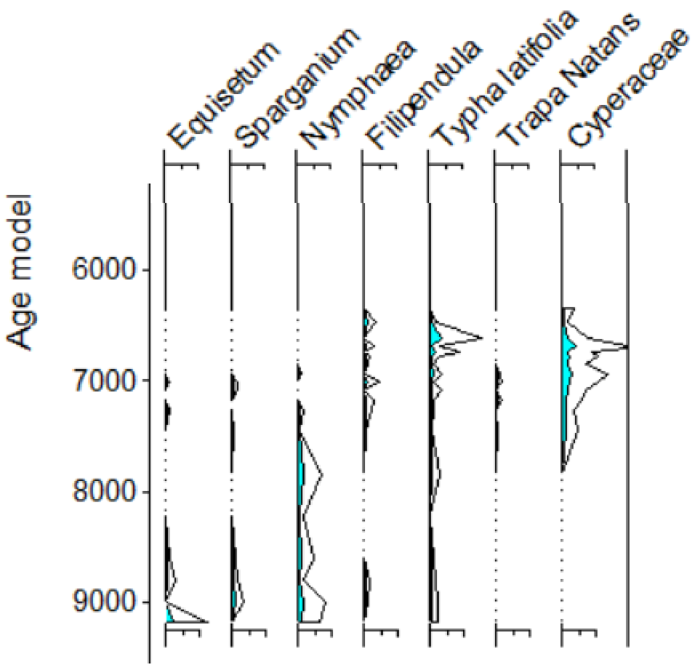


Figure 20, Aquatic species present in the Nieuweveen core until 6000 cal. yr BP

However, Nympheae does have specific needs which can be used to determine the water depth. Nympheae grows in moderate nitrogen, stagnant waters with a depth of 1.5 – 2.5m (Edwards et al., 2000; NDFF Verspreidingsatlas | Nympheae alba - Witte waterlelie, 2014). Therefore can be stated that at the bottom of the core, the water depth in the lake was at least 2.5 meters deep. Around 7453 cal. yr BP *Trapa Natans* appears in the pollen diagram. This species grows in nitrogen rich waters. The water depth can vary between 0.5 – 5m, but *Trapa* Natans prefers depths between 1 – 2m and is also most productive at this depth (NDFF Verspreidingsatlas | Trapa Natans - Waternoot, 2014; USDA, 2016; Schofield & Bunting, 2005). This is supported by a seed of *Trapa Natans* found at a depth of 393 and 412, which do not transport far from their point of deposition and is therefore an indicator of the local water depth. This suggests that the lake level changed from a minimum depth of 2.5m to a water depth of a maximum of 2m. Furthermore, it is interesting to note that Nympheae grows in nitrogen moderate waters, whereas *Trapa Natans* grows in nitrogen rich waters. This suggests that the nitrogen composition in the lake water increased. This increased nitrogen contents are most likely a result of the shallowing of the lake due to the infill with peat, which decreased the water column. During the decomposition of organic material nitrogen content increases and due to a smaller water column the concentration of nitrogen as a result of the decomposition is higher than in a larger water column (Tfaily et al., 2014). Around 6930 cal. yr BP the abundance of *Typha latifolia*, *Fillipendula* and Cyperaceae increases. As mentioned before these species grow on the shoreline of the lake or in the shallow parts of the lake along the shoreline. This indicates that the shoreline of the lake moved more inwards, indicating a further shallowing of the lake. This is supported by the lithology, which shows a change from gyttja to peat. As mentioned in chapter 1.7, this switch occurs when the water near the edge of the lake is a depth of above 2m, causing the formation of reed peat. Around 6474 cal. yr BP the aquatic plants completely disappeared from the pollen diagram, except for Cyperaceae this might suggest very shallow water or swamp like conditions (Gignac et al., 2004). This is also in line with the vegetation succession of a lake infilling. The disappearance of *Typha latifolia* and the occurrence of Cyperaceae shows the transition of reed peat to sedge peat. Around 5721 cal. yr BP Cyperaceae also completely disappeared from the pollen diagram and a huge increase in *Calluna* and *Ericales* can be observed in the pollen record. These species are pioneers who colonized the newly available land as a result of the filling of the lake. This vegetational reaction is often seen within areas where lakes have been filled in with peat layers (Sarmaja-Korjonen et al., 2006). Furthermore, the lithology around this time period shows the presence of wood remains in the peat. Notably a piece of *Alnus* wood at a depth of 258cm. As mentioned in chapter 1.7 *Alnus* is a species which occurs on the newly formed land and this would indicate that the lake has become very shallow and allowed trees to grow at the site.

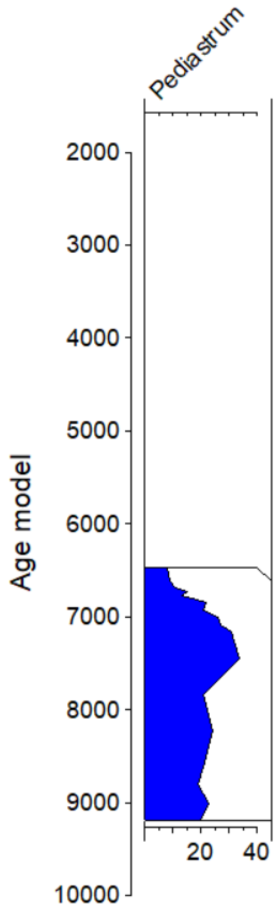


Figure 21, Pediastrum present in the Nieuweveen core. Data is shown in absolute values

Figure 21 shows the presence of *Pediastrum* next to the aquatic vegetation of the Nieuweveen site. Certain species of *Pediastrum* can be used to determine the depth of the water column in a lake (Whitney & Mayle, 2012). However, for this research no distinguishment has been made between the different species. Nevertheless the presence of these *Pediastrum* species support the presence of a lake (Kaufman et al., 2010). Whitney & Mayle (2012) suggest that the average preferred water depth for *Pediastrum* species is between 2 – 3m. Figure 21 shows the highest *Pediastrum* abundance at the expected depth of 2 – 2.5m, as reconstructed based on the presence of Nympheae and *Trapa Natans*, supporting this depth reconstruction.

6.2 Lagg-zone

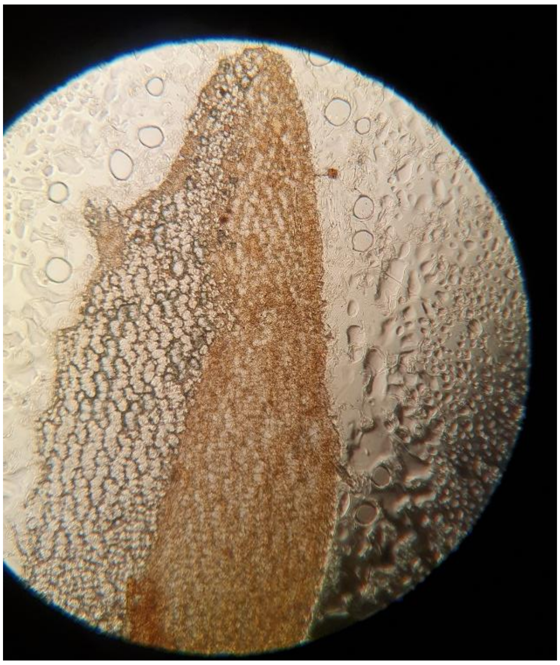


Figure 22, a moss leaf, which is expected to be of Sphagnum cuspidatum

Between 3200 and 4370 cal. yr BP there is a period of high abundance of *Betula* even though there is little to no change in abundance of other tree species. This period of high abundance is shows a sudden and very strong increase in *Betula* pollen at start of this period. At the end of this high *Betula* abundance there is a verry sudden and strong decrease of *Betula*. Simultaneously with the strong and sudden increase in *Betula* pollen the pollen record shows a strong and sudden decrease in *Calluna* and *Ericales* pollen. At the end of the high *Betula* period these species show a strong and sudden increase in abundance as the *Betula* pollen decrease. Furthermore, within this period there is a reoccurrence of several riparian species like *Sparganium*, *Fillipendula* and *Typha latifolia* as well as the pioneer species *Juniperus*. As well as the occurrence of species as *Drosera intermedia*. These signals and specific vegetation composition are an indicator for the presence of a lagg-zone (Howie & van Meerveld, 2018). Furthermore, preliminary research of the sphagnum leaves within the expected lagg-zone shows the presence of *Sphagnum cuspidatum*, which is a *Sphagnum* type often present in the transitional margins of a bog (Bakker & Van Smeerdijk, 1982) (Figure 22).
Howie & Tromp – van Meerveld (2011) describe a lagg-zone as ''A transition zone at the margin of a (usually raised) bog receiving water from both the bog and the surrounding mineral ground, often characterized by fen or swamp vegetation, transitional water chemistry, and shallow peat of relatively low hydraulic conductivity; the lagg transition may be sharp or diffuse (depending on the topography), or may not be present as a distinct feature''. In figure 23, two distinct types of lagg-zones are depicted graphically. The dotted line shows the transition from the acrotelm, which contains peat with living vegetation, to the catotelm, which consists of peat with only dead vegetation. This boundary is typically determined by the lowest water table level. As the ground water level drops towards the rand, which is the edge of the raised bog, it facilitates increased tree growth at the bog's margin (Howie & Tromp - van Meerveld, 2011). Runoff water collects between the bog and upland, which causes sedges and other fen vegetation to grow at the transition zone. In contrast to an upland lagg transition, where the runoff is more focused and concentrated, the runoff in a flat lagg transition spreads out over the surface. This leads to the establishment of larger shrubs and

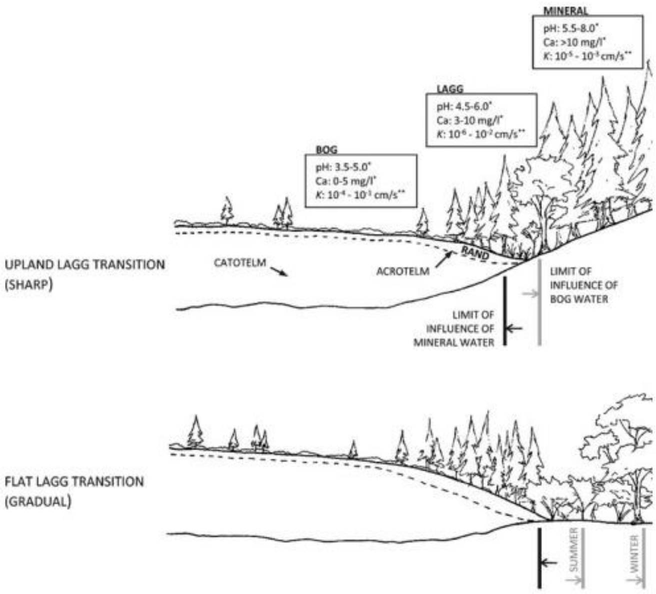


Figure 23, a schematic view of 2 different type of lagg transitions. The upper one shows an upland lagg transition. The lower one shows a flat lagg transition (Howie & Tromp - van Meerveld, 2011)

trees (Howie & Tromp - van Meerveld, 2011). Furthermore, in a flat lagg transition the bog water tends to spread further compared to the upland lagg transition, especially during the winter season. This strongly influences the vegetation composition at the bog margin (Howie & Tromp - van Meerveld, 2011). When an ombrotrophic peatland grows in size, it rises above the water table and it spreads outwards. This expansion leads to changes in the distribution of water and vegetation, with the minerotrophic vegetation being pushed to the edges. As a result a distinct border forms where the runoff water forms a small stream (Howie & Tromp – van Meerveld, 2011). This small stream may move outwards with the outwards movement caused by the growth of the bog (Howie & Tromp - van Meerveld, 2011). In time this stream deepens and it might experience an increase in flow rate. This causes the stream to become so deep and mineral rich that it limits the growth of *Sphagnum* and therefore the accumulation of peat, which will stop the spread of the bog (Howie & Tromp - van Meerveld, 2011). From the centre of the bog towards the lagg-zone the water table rises. In some cases it may even reach the surface level near the lagg-zone. (Moore, 1984; Damman, 1986; Howie & Meerveld, 2011).

The permeability of the catotelmic peat layer is very low, therefore most of the excess water flows through the acrotelm layer (Damman, 1986). This can result in rapid runoff during heavy rain. The dome shape of the bog causes the water to pass through the rand and lagg-zone, as a result it receives most of the water (Damman & Dowhan, 1981). This also means that the lagg-zone is highly reliant on the bog water. When there is a lack of precipitation the minor drainage features on the bog surface can dry up. This can cause the marginal stream to turn still or even dry out (Holden, 2005; Howie et al., 2009). Low runoff, during the summer, and high runoff, during the winter, can result in fluctuating conditions in wetness and nutrients, which restrict the growth of vegetation in the lagg-zone. Therefore the vegetational composition in the lagg-zone consist out of species which are capable of withstanding rapid changes in the water table and a wide variety and fluctuating nutrient conditions, like *Betula* (Howie & Tromp – van Meerveld, 2011).

Since the lagg-zone is only fed by rainwater, it is reliant on the bog water as well as the adjacent land. Therefore, the lagg-zone is more sensitive to changes in the surrounding land than the bog itself. As a result there are few lagg-zones left in developed and highly populated areas (Schouten, 2003; Howie & Tromp – van Meerveld, 2011).

The peat layers present in the lagg-zone is relatively shallow, usually <0.5m, therefore deeply rooted plants are able to make contact with the underlying soil (Howie & Tromp – van Meerveld, 2011). Dense trees and shrubs are often found within the lagg-zone, while sedges make up the understory (Howie & Tromp – van Meerveld, 2011). Surface water also flows faster in the lagg-zone compared to the centre of the raised bog, therefore the water is more aerated and allows for different species that are not tolerant for the stagnant bog water (Howie & Tromp – van Meerveld, 2011). The vegetation around the lagg-zone is strongly affected by the fluctuation, level and chemical quality of the runoff from the bog and adjacent land. Since the runoff from bogs are similar to the rainwater, the driving factor for the lagg species around the bog is the composition of the surrounding soil (Howie & Tromp – van Meerveld, 2011). As a result, the species around the lagg zone can vary wildly. Figure 24 shows a schematic view of the species surrounding the Burns bog lagg zone, which is located in Delta, British Columbia, Canada. This figure shows that the vegetational composition can vary.

Based on this theoretical background and the data from the pollen record it is possible that between 3200 and 4370 cal. yr BP a lagg-zone was present surrounding the Nieuweveen site. Since there are no large elevation differences near the Nieuweveen site, the flat lagg transition seems the most likely scenario. In this scenario the low summer runoff and the high winter runoff resulted in a fluctuating water table and a varying nutrient condition, which restricted the growth of vegetation in the lagg-zone. Due to these conditions many tree species were unable to settle in this area, whereas *Betula* thrived in these conditions. This caused the high *Betula* peak during this time period. These wet conditions made it especially hard for *Calluna* and *Ericales* to survive, resulting in a decrease in those species. As mentioned the vegetation around the lagg-zone is highly influenced by the water from the surrounding land and bog. This causes different lagg-zones to have different species. The presence of species as *Drosera intermedia* and *Dryas octopetala* as well as *Sphagnum cuspidatum* are typical indicators for lagg-zones in the Netherlands Bakker & Van Smeerdijk, 1982). Furthermore, is it likely that the reoccurrence of several riparian species like *Sparganium*, *Fillipendula* and *Typha latifolia* is caused by the presence of the runoff water in the lagg-zone. This water is well aerated and allows for these species to grow on the banks of the lagg-zone.

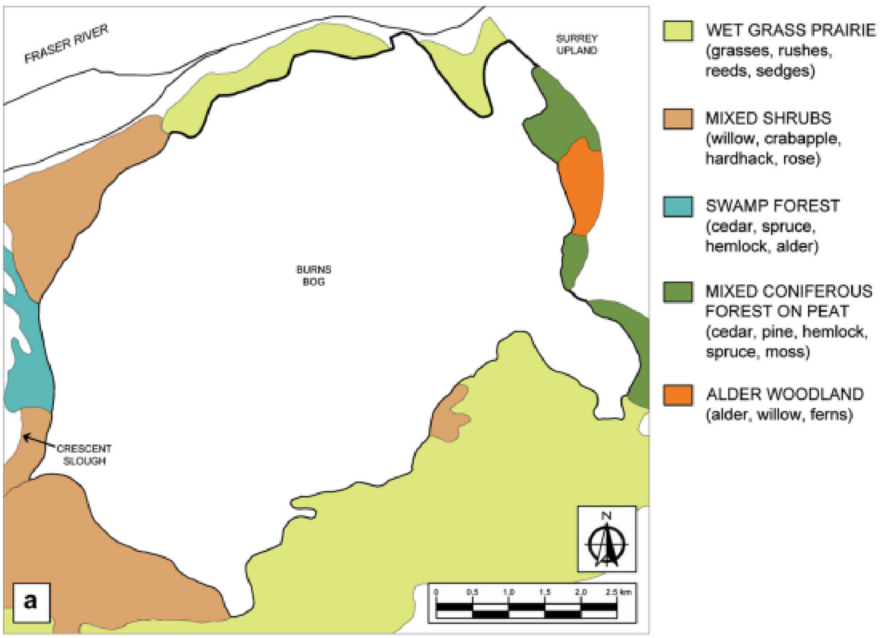


Figure 24, surrounding vegetation of the Burns bog lagg zone, showing that the vegetational composition surrounding the lagg can vary (modified after Howie & van Meerveld, 2018)

If we assume the scenario that a lagg-zone was present near the Nieuweveen site, only one question remains. Why did a lagg-zone form around 4370 cal. yr BP and why did it suddenly disappear around 3200 cal. yr BP.

6.3 Mid Holocene climatic changes

During the Holocene there were several short term but relatively rapid climatic shifts (Roland et al., 2014). During the Late Glacial and early Holocene, climatic events such as the Younger Dryas and the 8.2kyr event were frequently triggered by strong North Atlantic signatures. These events had a hemispheric impact and possibly affected the global climate (Alley et al., 2003; Daley et al., 2011; Roland et al., 2014). The deglaciation of the Northern hemispheric icesheets caused meltwater outbursts and icesheet surging, which resulted in these abrupt climate changes during the Holocene (Hemming, 2004; Teller et al., 2002). However, these climatic events continued after the mid Holocene, even without the presence of continental ice sheets. This made the cause of these climatic changes less well defined and less abrupt and more gradual in influence (Roland et al., 2014). Most evidence for the presence of the 4.2kyr event was found in North America, Africa and the region of Central Asia and presented a trend of colder temperatures and lower humidity. Therefore it has been thought for a long time that the 4.2kyr event was a mid to low latitude aridification event. But more research on the 4.2kyr climatic changes showed various effect all over the world (Roland et al., 2014; Walker et al., 2012). Roland et al. (2014) states that the 4.2kyr event can be characterized by a clear aridification event at the mid latitudes of Africa, Asia and North America. The west coast of South America shows a drying trend, but the continent is dominated by wetter conditions as is the North Atlantic. The climatic signal of the 4.2kyr event in Europe is more complex to define than in the rest of world. Nevertheless, two clear patterns can be distinguished throughout Europe. The southern part of Europe shows a clear dry event, whereas the northern part of Europe shows a clear wet event (Roland et al., 2014). The wet phase during the 4.2kyr event is documented in various peatland records throughout northern Europe. Besides the shift to wetter conditions, peat records obtained from southwestern Sweden show evidence of heightened winter storms and intensified precipitation (Jong et al., 2006). As mentioned before the cause of the 4.2kyr event is less well defined compared to the abrupt climatic changes in the Late glacial and early Holocene due to the absence of ice sheets and melt water pulses. However, researchers have identified 4 different potential causes to explain the start of the 4.2kyr event: Milankovitch forcing, solar variation, changes in the ocean/atmosphere circulation and changes in solar forcing. It is possible that the climate was affected by changes in orbital forcing although the variations in Milankovitch forcing were minimal during the mid and late Holocene (Booth et al., 2005; Roland et al., 2014).

Around 4200 cal. yr BP a change in solar forcing took place, which is supported by the correlation between the IRD3 cold event in the North Atlantic and the increased presence of cosmogenic isotopes (Bond et al., 2001; Roland et al., 2014). However, the models which work with solar forcing often result in a change in temperature. The 4.2kyr event resulted mostly in a change in precipitation and is therefore most likely a hydroclimatic event opposed to a temperature based event (Roland et al., 2014).

Although there has been increased volcanic activity around 4200 cal. yr BP there is no global scale volcanic signal present in the Greenland ice cores. Therefore it seems unlikely that theses volcanic activities caused a global climatic change (Bryson, 1989).

The most plausible explanation for the start of the 4.2kyr event is suggested to be variations in ocean-atmosphere circulation (Roland et al., 2014). Since the 4.2kyr event was a global event, the cause has to be on a global scale as well. It appears that the 4.2kyr event was triggered or at least amplified by changes in the ocean circulations of the North Atlantic (Roland et al., 2014). This period of wetter conditions remained until around 3250 cal. yr BP (Roland et al., 2014).

Between 3250 – 2300 cal. yr BP Europe experienced a series of shifts in conditions. However, it is characterized by more dry conditions between 3250 – 2800 cal. yr BP and more wet conditions between 2800 – 2300 cal. yr BP (Roland et al., 2014). Around 3250 cal. yr BP Europe is dominated by an overall shift to more dry conditions, which persisted until 3100 cal. yr BP. Around this time a shift to wetter conditions commences throughout Europe, which persisted until 2300 cal. yr BP. However, this period of wetter conditions is disturbed around 2800 cal. yr BP by a short lived dry period called the 2.8kyr event (Charman et al.,

2006; Roland et al., 2014).
The shifts to wet and dry conditions between 3250 – 2300 cal. yr BP coincide with changes in solar activity. Periods of high and low solar intensity are suspected to influence the temperature on earth and change local moisture conditions and the resulting moist sources. Therefore it is speculated that fluctuations in solar activity can shift the conditions on earth from wet to dry and the other way around (Blaauw et al., 2004; Speranza et al., 2003). However, there is still a lot of uncertainty surrounding these phenomena. Whether or not these solar cycles influenced the conditions on earth, based on the pollen data it is likely that there was indeed a shift in conditions.
Engels et al. (2016) found that the lake water level of the Uddelermeer lake was 2.5m lower than present between 3150 – 2800 cal. yr BP, supporting the idea of a drier conditions in the Netherlands. Whereas after 2800 cal. yr BP the water table of the Uddelermeer lake was at least as high as present, but possibly even 1.5m higher. The same water level fluctuations were found in several lakes in the French Alps between 3250 – 2600 cal. yr BP (Magny, 2006). Engels et al. (2016) points out that these variations in lake level can be attributed to two main factors. The first one is changes in atmospheric circulation, which could lead to alterations in the moisture source, affecting the lakes water supply. The second factor involves local influences such as erosional outflow events or increased human activity in the area (Engels et al., 2016). Their first hypothesis seems most likely. Changes in solar activity probably caused changes in atmospheric circulations, which changes the moisture source above Europe, which caused for drier and later on wetter conditions. Although it is definitely true that around 3000 cal. yr BP human activity quickly intensified throughout the Netherlands, which could have caused changes to the local hydrology, it seems less likely than changes in atmospheric circulation based on the fact that these lake level changes can be observed throughout Europe where human activity was already a strong influence on the local hydrology and vegetation for several centuries and in some cases even millennia, such as researches from Great-Britain (Charman et al., 2006; Mauquoy et al., 2008; Roland et al., 2014), France (Magny, 2006) and The Netherlands (Engels et al., 2016; This research).

As mentioned before a lagg-zone is formed as a result of rainwater runoff from the dome shaped raised bog, eroding the soil around the dome and creating a stream between the raised bog and the surrounding land. It seems highly likely that the increased precipitation as a result from the changed conditions during the 4.2kyr event created and sustained the lagg-zone. To sustain a lagg-zone a high winter runoff is required. These conditions were met between 4200 – 3200 cal. yr BP. The shift from wet to drier conditions around 3250 cal. yr BP resulted in decreased precipitation. Therefore there was not enough runoff to sustain the lagg-zone and in rapid disappeared. This is supported by the rapid decline of *Betula* pollen around 3200 cal. yr BP in the pollen record. Furthermore, the increased human influence in the area around this time period in the form of deforestation, which can be seen in the influx diagram (appendix 6) and as mentioned in chapter 5.5.3, could have contributed to the disappearance of the lagg-zone. The local groundwater table or soil composition can be changed by agriculture and deforestation. (Howie & Tromp – van Meerveld, 2011). As a result of this deforestation the runoff and soil composition might have changes, which affected the lagg-zone resulting in its disappearance. However, this leaves the question why the lagg-zone did not return after 2.8kyr, when there was a shift from dry to wetter conditions. This is most likely a result of a combination of human activity and peat decomposition. Changes in the nutrient and mineral composition of the lagg-zone or changes in runoff can drastically impact the rate of peat growth and decomposition (Howie & Tromp – van Meerveld, 2011). It could very well be that during the drier period of 3250 – 3100 cal. yr BP the rate of decomposition was relatively high, resulting in a loss of height in the raised bog. Due to this decreased height the runoff was not strong enough to create a new lagg-zone (Howie et al., 2009). Furthermore, the deforestation around that time might have altered the

groundwater table and soil composition, which could have affected the lagg-zone composition in case it still formed.
An alternate hypothesis is proposed by van Geel et al. (2014). They suggest that increased precipitation during cooler and wetter conditions might result in a swollen raised bog, with a elevated surface as a result of the rainfall. If this process continuous the bog can burst and the less compacted upper peat mud layers on top of the raised bog would flow down the dome. After this burst the bog surface is lowered and drained, this causes further decomposition of the peat and possibly even peat fires. Although this decrease in elevation of the raised bog could result in decreased runoff and disappearance of the lagg zone, it seems less likely than the previously proposed hypothesis of disappearance due to drier conditions and human activity.

This scenario, where a lagg zone is present around the Nieuweveen site, is supported by the presence of species like *Drosera* and a high abundance of *Betula* as well as the climatic data, which shows a shift in wet and dry conditions. However, this scenario is not supported by the lithology, which shows the presence of woodland peat whereas a raised bog consists out of *sphagnum* peat. It could be argued that this peat degraded after the lagg-zone disappeared, which, as mentioned before, is known to rapidly decline if the conditions are not favourable. However, this would cause a hiatus in the record, which is not visible around his time period. Furthermore, this scenario can only be true if the Nieuweveen site was a raised bog. Since the data does not align with this theory, it is important to look at another scenario where the Nieuweveen site never grew to a raised bog and remained a fen.

6.4 Desiccation/wetting

The pollen record shows a low amount of *Sphagnum spores*. As mentioned before in chapter 1.7, the *Sphagnum spores* were almost transparent and therefore hard to identify, making it difficult to determine the amount of *Sphagnum* present. The presence of a lagg-zone is only possible when there was enough *Sphagnum* peat present to form a raised bog. If there was indeed not enough *Sphagnum* peat present to form a raised bog another mechanism must have taken place to allow the increase of *Betula*. As mentioned in chapter 6.1 the lake eventually reaches a point where the infill is almost complete and the water is very shallow. As a result the water transitions from a eutrophic state

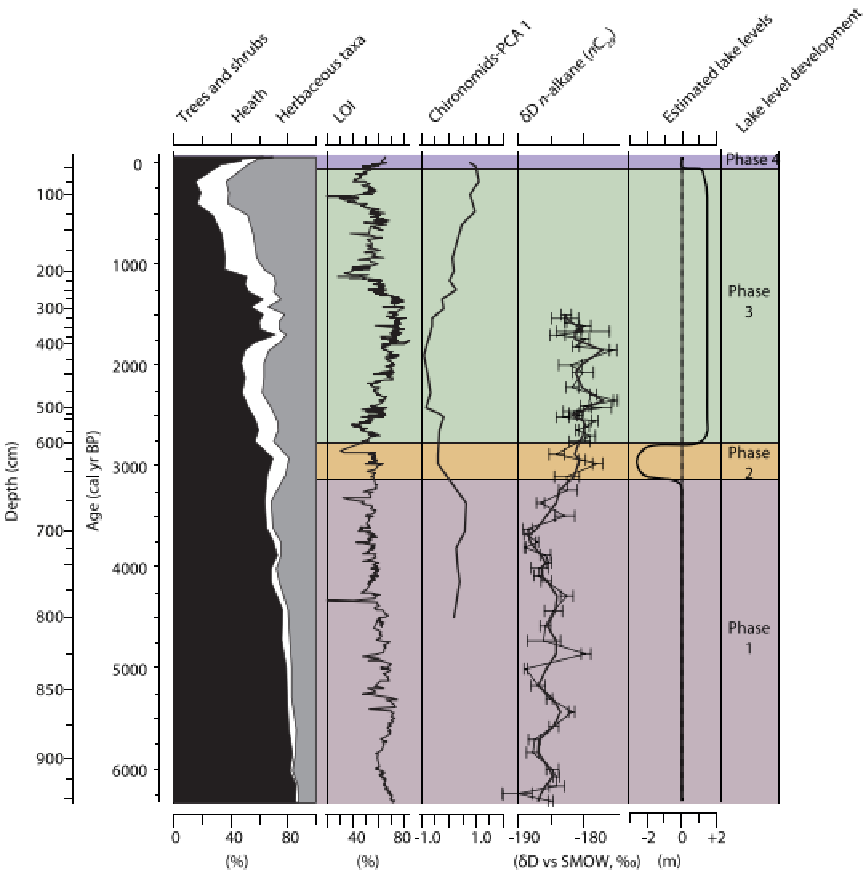


Figure 25, δD values of the Uddelermeer site (Engels et al., 2016) to a mesotrophic state (Stouthamer et al., 2015). At this point trees start to grow on top of the peat. The type of trees that start to grow at this location is dependent on the nutrients in the environment. If the environment is nutrient rich *Alnus* starts to grow and if the environment is nutrient poor *Betula* will grow. Figure 25 shows a summary of proxy records from Uddelermeer obtained from Engels (2016), around 4300 cal. yr BP the diagram shows a shift in δD values towards more negative values, which remains more negative until 3150 cal. yr BP. This shift to more negative values indicates an increase in precipitation around the Uddelermeer site. This shift to wetter conditions coincide with the shift to wetter conditions mentioned in chapter 6.3 between 4370 and 3250 cal. yr BP. Since this is a regional event it can be assumed that this increase in precipitation also took place around the Nieuweveen site. This shift to wetter conditions resulted in more precipitation and this increased precipitation resulted in a more wetter environment around the Nieuweveen site and a decrease in nutrients (Stouthamer et al., 2015). These conditions around the Nieuweveen site were perfect for *Betula*, which is well suited for these wetter conditions and lower nutrients (Howie & Tromp – van Meerveld, 2011). Whereas *Calluna* and *Ericales* become less abundant, since these species are not well suited for wet conditions. These *Betula* trees start to grow on top of the sedge peat. As mentioned in chapter 1.7 at the bottom of these trees moss starts to grow, which keeps the leaves and wood remains humid (Stouthamer et al., 2015). This enhances the formation of woodland peat. This formation of woodland peat is supported by the lithology, which shows the presence of large wood remains and trunks between 160cm and 106cm. These depths correspond with the duration of the *Betula* peak. Between 3150 and 2800 cal. yr BP figure 25 shows a more positive value for the δD, which suggest drier conditions. This is supported by a lake level lowstand at the Uddelermeer site. Besides drier conditions Engels (2016) also gives the possibility of a bog burst as a reason for the lake level lowstand. However, this seems unlikely for the Nieuweveen site, this would cause a loss of material and since there is no clear hiatus present in the record during this period this seems very unlikely. This drier condition resulted in less precipitation. As a result the environment around the Nieuweveen site became less wet and more nutrients were available. This gave space to other species beside *Betula* to grow there and prosper. Figure 25 shows a transition to wetter conditions around 2800 cal. yr BP, this coincides with the 2.8 event mentioned in chapter 6.3. However, even though there is a shift to wetter conditions there is no clear increase of *Betula* as is observed around 4370 cal. yr BP. This is most likely caused by the fact that around this time period the infill of the lake is completed and a wide variety of trees has grown on top of it. Therefore the environment is less susceptible to changes in nutrients and wetter conditions. This is supported by the lithology, which shows the presence of woodland peat. Since the environment is less wet, this also allows for *Calluna* and *Ericales* to become more abundant.

When looking at both the lagg-zone hypothesis and the sequence of wetting and desiccation of the soil, the latter seems most likely the case in the Nieuweveen site. This hypothesis does not require a raised bog, which would require a high amount of *Sphagnum* peat, and therefore suggests that the Nieuweveen site never grew past a fen. It is also supported by the lithology from the Nieuweveen site as well as the data from Engels (2016). Furthermore, it gives a clear explanation for the absence of a high *Betula* peak around 2800 cal. yr BP when the conditions shift back to wetter conditions. Therefore, the scenario that the site was almost near the end of the infill, while the climate shifted to more wetter conditions, which resulted in the growth of *Betula* trees and the formation of wood peat is most likely.

7. Conclusion

This research focused on the influence of human activity on the natural vegetation around the Nieuweveen pingo remnant located in the Northeastern part of the Netherlands, near the city of Hardenberg. The Nieuweveen pingo is one of the many pingo remnants in this area. However, this pingo remnant is one of the deepest pingos and contains a continuous record from the late glacial until the Holocene. This was done by analysing pollen obtained from the sediment core of the Nieuweveen pingo. This data was plotted in a pollen diagram. From the pollen diagram of the Nieuweveen pingo, it became apparent that throughout the Holocene the vegetation composition changed in several ways. From the pollen diagram increases, decreases, appearances and disappearances of pollen types can be distinguished. Some of these changes are a result of human influence while others are caused by natural changes. The first signs of agriculture can be found around 5500 cal. yr BP. Small deforestation and a *Hordeum* signal suggest small scale agriculture and settlement establishment. Later on a larger decrease in tree pollen influx can be seen, together with increased presence of *Plantago lanceolata*, *Chenopodiaceae* and *Rumex* suggesting an open landscape. This open landscape was most likely used for grazing of animals. Further deforestation took place from 3800 cal. yr BP onward. This deforestation can be seen in the influx diagram. It corresponds with the beginning of the Bronze age. Wood was used as fuel and to build houses. Furthermore, the increased population required more space. The Nieuweveen pollen record also shows the presence of *Canabis/Humulus type*. It based on the timing of the presence and the abundance as well as comparisons with other sites it seems most likely that this is not *Canabis*, but naturally present *Humulus*. Comparisons with other well preserved and relatively complete pollen records from Uddelermeer, Mekelermeer and Hijkermeer suggest that agriculture spread and developed slow and different throughout the Netherlands. This research shows that around the Nieuweveen site the human influence appeared extremely late compared to other sites and had very little impact on the vegetation. The natural vegetation is rather consistent throughout the sites until around 6000 cal. yr BP, which is roughly the time agriculture began to spread into the Netherlands. It also shows that human impact on the natural vegetation began really late around the Nieuweveen site. Besides changes in vegetation caused by human impact, changes caused by natural variations also occur. The high Betula peak in the pollen record seems to be caused by the infill of the lake. The shallow conditions of the lake in combination with climatic conditions, which caused high precipitation rates, resulted in an environment suited for *Betula* to grow. These changes in the depth of the lake, were roughly reconstructed by using the aquatic vegetation.

From this research it became apparent that many changes in the vegetation composition around the Nieuweveen pingo took place. Although some of the changes were caused by natural changes, human impact certainly has influenced the vegetation composition around the Nieuweveen pingo. Although the human impact in this area began really late compared to the rest of the Netherlands. This is most likely caused by the environment, which was not well suited for agriculture.

8. References

Aaby, B. (1988). The cultural landscape as reflected in percentage and influx pollen diagrams from tow Danish ombrotroplic mires. In *The Cultural Landscape: Past, Present, And Future*. Cambridge University Press.

Allchin, B. A. R. (1997). Origins of a civilization: the prehistory and early archaeology of South Asia. *Viking*, *1*.

Alley, R. B., Marotzke, J., Nordhaus, W. D., Overpeck, J. T., Peteet, D. M., Pielke, R. A., Pierrehumbert, R. T., Rhines, P. B., Stocker, T. F., Talley, L. D., & Wallace, J. M. (2003). Abrupt Climate Change. *Science*, *299*(5615), 2005–2010. https://doi.org/10.1126/science.1081056

Andrič, M. (2007). Holocene vegetation development in Bela krajina (Slovenia) and the impact of first farmers on the landscape. *The Holocene*, *17*(6), 763–776. https://doi.org/10.1177/0959683607080516

Bakels, C. (2009). *The Western European Loess Belt: Agrarian History, 5300 BC - AD 1000.* Springer Publishing.

Bakels, C. (2014). The first farmers of the Northwest European Plain: some remarks on their crops, crop cultivation and impact on the environment. *Journal of Archaeological Science*, *51*, 94–97. https://doi.org/10.1016/j.jas.2012.08.046

Bakker, M., & Van Smeerdijk, D. (1982). A palaeoecological study of a late holocene section from “Het Ilperveld”, western Netherlands. *Review of Palaeobotany and Palynology*, *36*(1–2), 95–163. https://doi.org/10.1016/0034-6667(82)90015-x

Bakker, R. (1993). Het Gietsenveentje, Gemeente Gieten (DR.): Unicum Of Probleemgeval? *Paleoactueel*, *5*, 35–38.

Bakker, R. (2003). *The Emergence of Agriculture on the Drenthe Plateau: A Palaeobotanical Study Supported by High-resolution 14C Dating*.

Barber, K. E., Chambers, F. M., & Maddy, D. (2008). Late Holocene climatic history of northern Germany and Denmark: peat macrofossil investigations at Dosenmoor, Schleswig-Holstein, and Svanemose, Jutland. *Boreas*, *33*(2), 132–144. https://doi.org/10.1111/j.1502-3885.2004.tb01135.x

Barber, K. E., & Charman, D. J. (2003). Holocene palaeoclimate records from peatlands. In *Global change in the Holocene*.

Barber, K. E., & Langdon, P. G. (2007). What drives the peat-based palaeoclimate record? A critical test using multi-proxy climate records from northern Britain. *Quaternary Science Reviews*, *26*(25–28), 3318–3327. https://doi.org/10.1016/j.quascirev.2007.09.011

Barber, K., Maddy, D., Rose, N., Stevenson, A., Stoneman, R., & Thompson, R. (2000). Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: new evidence for regional palaeoclimate teleconnections. *Quaternary Science Reviews*, *19*(6), 481–487. https://doi.org/10.1016/s0277-3791(99)00102-x

Behre, K. (1986). *Anthropogenic Indicators in Pollen Diagrams*. Routledge.

Belyea, L. R., & Clymo, R. S. (2001). Feedback control of the rate of peat formation. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *268*(1473), 1315–1321. https://doi.org/10.1098/rspb.2001.1665

Berglund, M. (2004). Holocene shore displacement and chronology in Ångermanland, eastern Sweden, the Scandinavian glacio-isostatic uplift centre. *Boreas*, *33*(1), 48–60. https://doi.org/10.1080/03009480310006961

Bijlsma, S. (1983). Weichselian pingo remnants (?) in the eastern part of the Netherlands. *Proceedings of the 4th International Conference on Permafrost*, 62–67.

Binney, H., Edwards, M., Macias-Fauria, M., Lozhkin, A., Anderson, P., Kaplan, J. O., Andreev, A., Bezrukova, E., Blyakharchuk, T., Jankovska, V., Khazina, I., Krivonogov, S., Kremenetski, K., Nield, J., Novenko, E., Ryabogina, N., Solovieva, N., Willis, K., & Zernitskaya, V. (2017). Vegetation of Eurasia from the last glacial maximum to present: Key biogeographic patterns. *Quaternary Science Reviews*, *157*, 80–97. https://doi.org/10.1016/j.quascirev.2016.11.022

Birks, H. H., Birks, H. J. B., Kaland, P. E., & Moe, D. (1988). *The Cultural Landscape: Past, Present and Future*. Cambridge University Press.

Blaauw, M., Van Geel, B., Mauquoy, D., & Van Der Plicht, J. (2004). Carbon-14 wiggle-match dating of peat deposits: advantages and limitations. *Journal of Quaternary Science*, *19*(2), 177–181. https://doi.org/10.1002/jqs.810

Blackford, J. (2000). Palaeoclimatic records from peat bogs. *Trends in Ecology & Evolution*, *15*(5), 193–198. https://doi.org/10.1016/s0169-5347(00)01826-7

Blundell, A., & Barber, K. (2005). A 2800-year palaeoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. *Quaternary Science Reviews*, *24*(10–11), 1261–1277. https://doi.org/10.1016/j.quascirev.2004.08.017

Bogaard, A. (2004). *Neolithic Farming in Central Europe: An Archaeobotanical Study of Crop Husbandry Practices*. Routledge.

Bogaard, A., Fraser, R., Heaton, T. H. E., Wallace, M., Vaiglova, P., Charles, M., Jones, G., Evershed, R. P., Styring, A. K., Andersen, N. H., Arbogast, R. M., Bartosiewicz, L., Gardeisen, A., Kanstrup, M., Maier, U., Marinova, E., Ninov, L., Schäfer, M., & Stephan, E. (2013). Crop manuring and intensive land management by Europe's first farmers. *Proceedings of the National Academy of Sciences*, *110*(31), 12589–12594. https://doi.org/10.1073/pnas.1305918110

Bogucki, P. (1995). The Spread of Early Farming in Europe. *American Scientist*, *84*(3), 242–253.

Bogucki, P., & Grygiel, R. (1983). Early Farmers of the North European Plain. *Scientific American*, *284*(4), 104–113.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., & Bonani, G. (2001a). Persistent Solar Influence on North Atlantic Climate During the Holocene. *Science*, *294*(5549), 2130–2136. https://doi.org/10.1126/science.1065680

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., & Bonani, G. (2001b). Persistent Solar Influence on North Atlantic

Climate During the Holocene. *Science*, *294*(5549), 2130–2136. https://doi.org/10.1126/science.1065680

Booth, R. K., Jackson, S. T., Forman, S. L., Kutzbach, J. E., Bettis, E. A., Kreigs, J., & Wright, D. K. (2005a). A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages. *The Holocene*, *15*(3), 321–328. https://doi.org/10.1191/0959683605hl825ft

Booth, R. K., Jackson, S. T., Forman, S. L., Kutzbach, J. E., Bettis, E. A., Kreigs, J., & Wright, D. K. (2005b). A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages. *The Holocene*, *15*(3), 321–328. https://doi.org/10.1191/0959683605hl825ft

Bos, J. A. A., & Zuidhof, F. S. (2011). Het landschap van de Borchert. In *Roel Brandt Stichting*.

Bryson, R. A. (1989). Late quaternary volcanic modulation of Milankovitch climate forcing. *Theoretical and Applied Climatology*, *39*(3), 115–125. https://doi.org/10.1007/bf00868307

Casparie, W. A. (1972). *Bog Development in Southern Drenthe (The Netherlands).* [Thesis]. Univ. Groningen.

Chambers, F. M., Kelly, R. S., Price, S. M., Birks, H. H., Birks, H. J. B., Kaland, P. E., & Moe, D. (1988). Development of the late prehistoric cultural landscape in upland Ardudwy, northwest Wales. In *The Cultural Landscape: Past, Present and Future*. Cambridge University Press.

Charman, D. J., Barber, K. E., Blaauw, M., Langdon, P. G., Mauquoy, D., Daley, T. J., Hughes, P. D., & Karofeld, E. (2009). Climate drivers for peatland palaeoclimate records. *Quaternary Science Reviews*, *28*(19–20), 1811–1819. https://doi.org/10.1016/j.quascirev.2009.05.013

Charman, D. J., Blundell, A., Chiverrell, R. C., Hendon, D., & Langdon, P. G. (2006). Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. *Quaternary Science Reviews*, *25*(3–4), 336–350. https://doi.org/10.1016/j.quascirev.2005.05.005

Clarke, D. L., Glynn, I., & Halstead, P. (2009). *Pattern of the Past: Studies in the Honour of David Clarke*. Cambridge University Press.

Cleveringa, P., Kuijper, W., Veldkamp, M. A., & Bakels, C. (2000). *Het pollendiagram Oss 45E/346* [Dataset].

Conolly, J., Colledge, S., & Shennan, S. (2008). Founder effect, drift, and adaptive change in domestic crop use in early Neolithic Europe. *Journal of Archaeological Science*, *35*(10), 2797–2804. https://doi.org/10.1016/j.jas.2008.05.006

Daley, T. J., Thomas, E. R., Holmes, J. A., Street-Perrott, F. A., Chapman, M. R., Tindall, J. C., Valdes, P. J., Loader, N. J., Marshall, J. D., Wolff, E. W., Hopley, P. J., Atkinson, T., Barber, K. E., Fisher, E. H., Robertson, I., Hughes, P. D., & Roberts, C. N. (2011). The 8200yr BP cold event in stable isotope records from the North Atlantic region. *Global and Planetary Change*, *79*(3–4), 288–302. https://doi.org/10.1016/j.gloplacha.2011.03.006

Damman, A. W. H. (1986). Hydrology, development, and biogeochemistry of ombrogenous peat bogs with special reference to nutrient relocation in a western Newfoundland bog. *Canadian Journal of Botany*, *64*(2), 384–394. https://doi.org/10.1139/b86-055

Damman, A. W. H., & Dowhan, J. J. (1981). Vegetation and habitat conditions in Western Head Bog, a southern Nova Scotian plateau bog. *Canadian Journal of Botany*, *59*(7), 1343–1359. https://doi.org/10.1139/b81-181

Davis, M. B. (1963). On the theory of pollen analysis. *American Journal of Science*, *261*(10), 897–912. https://doi.org/10.2475/ajs.261.10.897

de Gans, W. (1981). *The Drentsche Aavalley system - A study in Quaternary geology* [Ph.D thesis]. Vrije Universiteit Amsterdam.

De Gans, W. (1982). Location, age and origin of pingo remnants in the Drentsche Aa Valley area (the Netherlands). *Geologie En Mijnbouw*, *61*, 147–158.

de Haas, T., & Schepers, M. (2022). Wetland Reclamation and the Development of Reclamation Landscapes: A Comparative Framework. *Journal of Wetland Archaeology*, 1–22. https://doi.org/10.1080/14732971.2022.2072097

de Jong, J. (1970). Pollen and 14C Analysis of Holocene Deposits in Zijderveld and Environs [Dataset]. In *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek*.

de Klerk, P., Janssen, C. R., & Joosten, J. H. J. (1997). Patterns and process in natural wetland vegetation in the Dutch fluvial area: a palaeoecological study. *Acta Botanica Neerlandica*, *46*(2), 147–159.

Deeben, J., Brinkkemper, O., Groenewoudt, B. J., & Lauwerier, R. C. G. M. (2006). Een Federmesser-site van de Enterse akkers (Gemeente Wierden, Overijssel). *Nederlandse Archeologische Rapporten 22.*, 49–82.

Deforce, K., Bastiaens, J., van Calster, H., & Vanhoutte, S. (2009). Iron Age acorns from Boezinge (Belgium) : the role of acorn consumption in prehistory. *Archaologisches Korrespondenzblatt*, *39*(3), 381–392.

Doppler, T., Gerling, C., Heyd, V., Knipper, C., Kuhn, T., Lehmann, M. F., Pike, A. W., & Schibler, J. (2017). Landscape opening and herding strategies: Carbon isotope analyses of herbivore bone collagen from the Neolithic and Bronze Age lakeshore site of Zurich-Mozartstrasse, Switzerland. *Quaternary International*, *436*, 18–28. https://doi.org/10.1016/j.quaint.2015.09.007

Dupont, L. M. (1986). Temperature and rainfall variation in the holocene based on comparative palaeoecology and isotope geology of a hummock and a hollow (Bourtangerveen, The Netherlands). *Review of Palaeobotany and Palynology*, *48*(1–3), 71–159. https://doi.org/10.1016/0034-6667(86)90056-4

Edwards, M. E., Bigelow, N. H., Finney, B. P., & Eisner, W. R. (2000). Records of aquatic pollen and sediment properties as indicators of late-Quaternary Alaskan lake levels. *Journal of Paleolimnology*, *24*(1), 55–68. https://doi.org/10.1023/a:1008117816612

Engels, S., Bakker, M., Bohncke, S., Cerli, C., Hoek, W., Jansen, B., Peters, T., Renssen, H., Sachse, D., van Aken, J., van den Bos, V., van Geel, B., van Oostrom, R., Winkels, T., & Wolma, M. (2016). Centennial-scale lake-level lowstand at Lake Uddelermeer (The Netherlands) indicates changes in moisture source region prior to the 2.8-kyr event. *The Holocene*, *26*(7), 1075–1091. https://doi.org/10.1177/0959683616632890

Engels, S., van Oostrom, R., Cherli, C., Dungait, J. A. J., Jansen, B., van Aken, J. M., van Geel, B., & Visser, P. M. (2017). Natural and anthropogenic forcing of Holocene lake ecosystem development at Lake Uddelermeer (The Netherlands). *Journal of Paleolimnology*, *59*(3), 329–347. https://doi.org/10.1007/s10933-017-0012-x

Eriksson, S., & Eriksson, O. (1997). Seedling recruitment in semi-natural pastures: the effects of disturbance, seed size, phenology and seed bank. *Nordic Journal of Botany*, *17*(5), 469–482. https://doi.org/10.1111/j.1756-1051.1997.tb00344.x

Flemal, R. C. (1976). Pingos and Pingo Scars: Their Characteristics, Distribution, and Utility in Reconstructing Former Permafrost Environments. *Quaternary Research*, *6*(1), 37–53. https://doi.org/10.1016/0033-5894(76)90039-9

Gignac, L. D., Gauthier, R., Rochefort, L., & Bubier, J. (2004). Distribution and habitat niches of 37 peatland Cyperaceae species across a broad geographic range in Canada. *Canadian Journal of Botany*, *82*(9), 1292–1313. https://doi.org/10.1139/b04-081

Gorham, E., Lehman, C., Dyke, A., Janssens, J., & Dyke, L. (2007). Temporal and spatial aspects of peatland initiation following deglaciation in North America. *Quaternary Science Reviews*, *26*(3–4), 300–311. https://doi.org/10.1016/j.quascirev.2006.08.008

Groenewoudt, B., van Haaster, H., van Beek, R., & Brinkkemper, O. (2007a). Towards a reverse image. Botanical research into the landscape history of the eastern Netherlands (1100 B.C.—A.D. 1500). *Landscape History*, *29*(1), 17–33. https://doi.org/10.1080/01433768.2007.10594587

Groenewoudt, B., van Haaster, H., van Beek, R., & Brinkkemper, O. (2007b). Towards a reverse image. Botanical research into the landscape history of the eastern Netherlands (1100 B.C.—A.D. 1500). *Landscape History*, *29*(1), 17–33. https://doi.org/10.1080/01433768.2007.10594587

Groenewoudt, B., Van Haaster, H., Van Beek, R., & Brinkkemper, O. (2007). Towards a reverse image. Botanical research into the landscape history of the eastern Netherlands (1100 B.C.—A.D. 1500). *Landscape history*, *29*(1), 17–33. https://doi.org/10.1080/01433768.2007.10594587

Gupta, A. K. (2004). Origin of agriculture and domestication of plants and animals linked to early Holocene climate amelioration. *Current Science*, *87*(1), 54–59.

Gurnell, A. M., O'Hare, M. T., O'Hare, J. M., Scarlett, P., & Liffen, T. M. (2013). The geomorphological context and impact of the linear emergent macrophyte,*Sparganium erectum*L.: a statistical analysis of observations from British rivers. *Earth Surface Processes and Landforms*, *38*(15), 1869–1880. https://doi.org/10.1002/esp.3473

Gurney, S. D. (2001). Aspects of the genesis, geomorphology and terminology of palsas: perennial cryogenic mounds. *Progress in Physical Geography: Earth and Environment*, *25*(2), 249–260. https://doi.org/10.1177/030913330102500205

Harris, C., & Ross, N. (2007). PERIGLACIAL LANDFORMS | Pingos and Pingo Scars. *Encyclopedia of Quaternary Science*, 2200–2207. https://doi.org/10.1016/b0-44-452747-8/00106-x

Helmer, D., & Vigne, J.-D. (2007). Was milk a « secondary product » in the Old World Neolithisation process? Its role in the domestication of cattle, sheep and goats. *Anthropozoologica*, *42*(2), 9–40.

Hemming, S. R. (2004). Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Reviews of Geophysics*, *42*(1). https://doi.org/10.1029/2003rg000128

Hirons, K. R., & Edwards, K. J. (1986). Events At And Around The First And Second Ulmus Declines: Paleoecological Investigations In Co. Tyrone, Northern Ireland. *New Phytologist*, *104*(1), 131–153. https://doi.org/10.1111/j.1469-8137.1986.tb00641.x

Hjelle, K. L. (1999). Modern pollen assemblages from mown and grazed vegetation types in western Norway. *Review of Palaeobotany and Palynology*, *107*(1–2), 55–81. https://doi.org/10.1016/s0034-6667(99)00015-9

Hoek, W. Z., Donders, T. H., Schouten, S. J., & Van Eijk, A. M. (not yet published.). Ondersteboven: 14700 jaar invullingsgeschiedenis van het Nieuwe Veen bij Hardenberg, de diepste pingo-ruine van Nederland. Departement fysische geografie.

Holden, J. (2005). Peatland hydrology and carbon release: why small-scale process matters. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *363*(1837), 2891–2913. https://doi.org/10.1098/rsta.2005.1671

Hornum, M. T., Hodson, A. J., Jessen, S., Bense, V., & Senger, K. (2020). Numerical modelling of permafrost spring discharge and open-system pingo formation induced by basal permafrost aggradation. *The Cryosphere*, *14*(12), 4627–4651. https://doi.org/10.5194/tc-14-4627-2020

Hotchkiss, S. C., Calcote, R., & Lynch, E. A. (2007). Response of vegetation and fire to Little Ice Age climate change: regional continuity and landscape heterogeneity. *Landscape Ecology*, *22*(S1), 25–41. https://doi.org/10.1007/s10980-007-9133-3

Howell, J. M. (1987). Early Farming in Northwestern Europe. *Scientific American*, *275*(5), 118–127.

Howie, S. A., & Tromp - van Meerveld, I. (2011). The Essential Role of the Lagg in Raised Bog Function and Restoration: A Review. *Wetlands*, *31*(3), 613–622. https://doi.org/10.1007/s13157-011-0168-5

Howie, S. A., & van Meerveld, H. J. (2018). Laggs can develop and be restored inside a raised bog. *Wetlands Ecology and Management*, *26*(4), 635–649. https://doi.org/10.1007/s11273-018-9597-8

Howie, S. A., Whitfield, P. H., Hebda, R. J., Dakin, R. A., & Jeglum, J. K. (2009). Can Analysis of Historic Lagg Forms Be of Use in the Restoration of Highly Altered Raised Bogs? Examples from Burns Bog, British Columbia. *Canadian Water Resources Journal*, *34*(4), 427–440. https://doi.org/10.4296/cwrj3404427

Ingram, H. A. P. (1982). Size and shape in raised mire ecosystems: a geophysical model. *Nature*, *297*(5864), 300–303. https://doi.org/10.1038/297300a0

Iversen, J. (1973). Geology of Denmark III: The Development of Denmark's Nature since the Last Glacial. *Danmarks Geologiske Undersøgelse V Række*, *7*, 1–126. https://doi.org/10.34194/raekke5.v7.7020

Jong, R. D., Björck, S., Björkman, L., & Clemmensen, L. B. (2006a). Storminess variation during the last 6500 years as reconstructed from an ombrotrophic peat bog in Halland, southwest Sweden. *Journal of Quaternary Science*, *21*(8), 905–919. https://doi.org/10.1002/jqs.1011

Jong, R. D., Björck, S., Björkman, L., & Clemmensen, L. B. (2006b). Storminess variation during the last 6500 years as reconstructed from an ombrotrophic peat bog in Halland, southwest Sweden. *Journal of Quaternary Science*, *21*(8), 905–919. https://doi.org/10.1002/jqs.1011

Jørgensen, E. K., Pesonen, P., & Tallavaara, M. (2020). Climatic changes cause synchronous population dynamics and adaptive strategies among coastal hunter-gatherers in Holocene northern Europe. *Quaternary Research*, *108*, 107–122. https://doi.org/10.1017/qua.2019.86

Karjalainen, O., Luoto, M., Aalto, J., Etzelmüller, B., Grosse, G., Jones, B. M., Lilleøren, K. S., & Hjort, J. (2020). High potential for loss of permafrost landforms in a changing climate. *Environmental Research Letters*, *15*(10), 104065. https://doi.org/10.1088/1748-9326/abafd5

Kaufman, D. S., Scott Anderson, R., Hu, F. S., Berg, E., & Werner, A. (2010). Evidence for a variable and wet Younger Dryas in southern Alaska. *Quaternary Science Reviews*, *29*(11–12), 1445–1452. https://doi.org/10.1016/j.quascirev.2010.02.025

Kleijne, J., Weinelt, M., & Müller, J. (2020). Late Neolithic and Chalcolithic maritime resilience? The 4.2 ka BP event and its implications for environments and societies in Northwest Europe. *Environmental Research Letters*, *15*(12), 125003. https://doi.org/10.1088/1748-9326/aba3d6

Kluiving, S., Verbers, A., & Thijs, W. (2010). Lithological analysis of 45 presumed pingo remnants in the northern Netherlands (Friesland): substrate control and fill sequences. *Netherlands Journal of Geosciences - Geologie en Mijnbouw*, *89*(1), 61–75. https://doi.org/10.1017/s0016774600000822

Kymäläinen, H. R., Hautala, M., Kuisma, R., & Pasila, A. (2001). Capillarity of flax/linseed (Linum usitatissimum L.) and fibre hemp (Cannabis sativa L.) straw fractions. *Industrial Crops and Products*, *14*(1), 41–50. https://doi.org/10.1016/s0926-6690(00)00087-x

Li, Y., Zhou, L., & Cui, H. (2008). Pollen indicators of human activity. *Science Bulletin*, *53*(9), 1281–1293. https://doi.org/10.1007/s11434-008-0181-0

Litt, T. (1992). Fresh investigations into the natural and anthropogenically influenced vegetation of the earlier Holocene in the Elbe-Saale Region, Central Germany. *Vegetation History and Archaeobotany*, *1*(2). https://doi.org/10.1007/bf00206086

Long, T., Wagner, M., Demske, D., Leipe, C., & Tarasov, P. E. (2016). Cannabis in Eurasia: origin of human use and Bronze Age trans-continental connections. *Vegetation History and Archaeobotany*, *26*(2), 245–258. https://doi.org/10.1007/s00334-016-0579-6

Lorkiewicz, W., Płoszaj, T., Jędrychowska-Dańska, K., Żądzińska, E., Strapagiel, D., Haduch, E., Szczepanek, A., Grygiel, R., & Witas, H. W. (2015). Between the Baltic and Danubian Worlds: The Genetic Affinities of a Middle Neolithic Population from Central Poland. *PLOS ONE*, *10*(2), e0118316. https://doi.org/10.1371/journal.pone.0118316

Louwe Kooijmans, L. P. (1993a). The Mesolithic/Neolithic transformation in the lower Rhine basin. In *Case studies in European prehistory*. CRC Press.

Louwe Kooijmans, L. P. (1993b). Wetland Exploitation and Upland Relations of Prehistoric Communities in the Netherlands. *Flatlands and Wetlands: Current Themes in East Anglian Archaeology*, 71–116.

Lübke, H. (2007). From fish and seal to sheep and cattle: new research into the process of neolithisation in northern Germany. *Proceedings of the British Academy*.

MacDonald, G. M. (2003). *Space, Time and Life: the science of Biogeography.* Wiley.

Mackay, J. R. (1988). Pingo collapse and paleoclimatic reconstruction. *Canadian Journal of Earth Sciences*, *25*(4), 495–511. https://doi.org/10.1139/e88-050

Mackay, J. R. (2011). Pingos of the Tuktoyaktuk Peninsula Area, Northwest Territories. *Géographie physique et Quaternaire*, *33*(1), 3–61. https://doi.org/10.7202/1000322ar

Mackay, J. R., & Burn, C. R. (2011). A Century (1910-2008) of Change in a Collapsing Pingo, Parry Peninsula, Western Arctic Coast, Canada. *Permafrost and Periglacial Processes*, n/a-n/a. https://doi.org/10.1002/ppp.723

Magny, M. (2006). Holocene fluctuations of lake levels in West-Central Europe: Methods of reconstruction, regional pattern, palaeo-climatic significance and forcing factors. *Encyclopedia of Quaternary Geology*, 1389–1399.

Mahlstedt, S., Hüser, A., & Kegler, J. F. (2017). Mesolithic Settlement sites on the East Frisian Peninsula. Landscape history and development with regard to pingo scars as preferred settlement sites. *Quartär*, *65*, 115–127.

Mauquoy, D., Yeloff, D., Van Geel, B., Charman, D. J., & Blundell, A. (2008). Two decadally resolved records from north-west European peat bogs show rapid climate changes associated with solar variability during the mid-late Holocene. *Journal of Quaternary Science*, *23*(8), 745–763. https://doi.org/10.1002/jqs.1158

McAndrews, J. H., & Boyko-diakonow, M. (1989). Pollen Analysis of Varved Sediment At Crawford Lake, Ontario: Evidence of Indian and European Farming. *Quaternary geology of Canada and Greenland*, *1*, 528–530. https://doi.org/10.4095/131577

McPartland, J. M., Guy, G. W., & Hegman, W. (2018). Cannabis is indigenous to Europe and cultivation began during the Copper or Bronze age: a probabilistic synthesis of fossil pollen studies. *Vegetation History and Archaeobotany*, *27*(4), 635–648. https://doi.org/10.1007/s00334-018-0678-7

McPartland, J. M., & Hegman, W. (2017). Cannabis utilization and diffusion patterns in prehistoric Europe: a critical analysis of archaeological evidence. *Vegetation History and Archaeobotany*, *27*(4), 627–634. https://doi.org/10.1007/s00334-017-0646-7

Mercuri, A. M., Accorsi, C. A., & Bandini Mazzanti, M. (2002). The long history of Cannabis and its cultivation by the Romans in central Italy, shown by pollen records from Lago Albano and Lago di Nemi. *Vegetation History and Archaeobotany*, *11*(4), 263–276. https://doi.org/10.1007/s003340200039

Miller, G. H., Geirsdóttir, S., Zhong, Y., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Björnsson, H., & Thordarson, T. (2012a). Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophysical Research Letters*, *39*(2), n/a-n/a. https://doi.org/10.1029/2011gl050168

Miller, G. H., Geirsdóttir, S., Zhong, Y., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Björnsson, H., & Thordarson, T. (2012b). Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophysical Research Letters*, *39*(2), n/a-n/a. https://doi.org/10.1029/2011gl050168

Ministerie van Onderwijs, Cultuur en Wetenschap. (2020, 17 maart). *Paleogeografische kaarten*. Bronnen en kaarten | Rijksdienst voor het Cultureel Erfgoed. https://www.cultureelerfgoed.nl/onderwerpen/bronnen-en-kaarten/overzicht/paleografische-kaarten

Moore, P. D. (1984). *Mires: Swamp, Bog, Fen and Moor-General Studies. Ecosystems of the World 4A.*A. J. P. Gore , David W. Goodall*Mires: Swamp, Bog, Fen and Moor-Regional Studies. Ecosystems of the World 4B.*A. J. P. Gore , David W. Goodall. *The Quarterly Review of Biology*, *59*(3), 347–348. https://doi.org/10.1086/413982

Morey, D. F., & Wiant, M. D. (1992). Early Holocene Domestic Dog Burials From the North American Midwest. *Current Anthropology*, *33*(2), 224–229. https://doi.org/10.1086/204059

NDFF Verspreidingsatlas | Nymphaea alba - Witte waterlelie. (2014). Geraadpleegd op 30 juli 2022, van https://www.verspreidingsatlas.nl/0866

NDFF Verspreidingsatlas | Trapa natans - Waternoot. (2014). Geraadpleegd op 30 juli 2022, van https://www.verspreidingsatlas.nl/5262

Out, W. (2012). *Sowing the Seed?: Human Impact and Plant Subsistence in Dutch Wetlands During the Late Mesolithic and Early and Middle Neolithic (5500-3400 cal BC) (Archaeological Studies Leiden University Press)*. Leiden University Press.

Pott, R. (1997). Invasion Of Beech And Establishment Of Beech Forests In Europe. *Annali di Botanica*, *55*, 27–58.

Pöyry, J., Carvalheiro, L. G., Heikkinen, R. K., Kühn, I., Kuussaari, M., Schweiger, O., Valtonen, A., van Bodegom, P. M., & Franzén, M. (2016). The effects of soil eutrophication propagate to higher trophic levels. *Global Ecology and Biogeography*, *26*(1), 18–30. https://doi.org/10.1111/geb.12521

Pross, J., Kotthoff, U., Müller, U., Peyron, O., Dormoy, I., Schmiedl, G., Kalaitzidis, S., & Smith, A. (2009). Massive perturbation in terrestrial ecosystems of the Eastern Mediterranean region associated with the 8.2 kyr B.P. climatic event. *Geology*, *37*(10), 887–890. https://doi.org/10.1130/g25739a.1

Prummel, W. (1979). Environment and stock-raising Bronze Age and Middle Ages. *Palaeohistoria*, *21*, 92–107.

Rey, F., Gobet, E., Schwörer, C., Wey, O., Hafner, A., & Tinner, W. (2019). Causes and mechanisms of synchronous succession trajectories in primeval Central European mixed*Fagus sylvatica*forests. *Journal of Ecology*, *107*(3), 1392–1408. https://doi.org/10.1111/1365-2745.13121

Roland, T., Caseldine, C., Charman, D., Turney, C., & Amesbury, M. (2014a). Was there a '4.2 ka event' in Great Britain and Ireland? Evidence from the peatland record. *Quaternary Science Reviews*, *83*, 11–27. https://doi.org/10.1016/j.quascirev.2013.10.024

Roland, T., Caseldine, C., Charman, D., Turney, C., & Amesbury, M. (2014b). Was there a '4.2 ka event' in Great Britain and Ireland? Evidence from the peatland record. *Quaternary Science Reviews*, *83*, 11–27. https://doi.org/10.1016/j.quascirev.2013.10.024

Rowland, J. C., Travis, B. J., & Wilson, C. J. (2011). The role of advective heat transport in talik development beneath lakes and ponds in discontinuous permafrost. *Geophysical Research Letters*, *38*(17), n/a-n/a. https://doi.org/10.1029/2011gl048497

Sarmaja-Korjonen, K., Seppänen, A., & Bennike, O. (2006). Pediastrum algae from the classic late glacial Bølling Sø site, Denmark: Response of aquatic biota to climate change. *Review of Palaeobotany and Palynology*, *138*(2), 95–107. https://doi.org/10.1016/j.revpalbo.2005.12.003

Schofield, J. E., & Bunting, M. J. (2005). Mid-Holocene presence of water chestnut (Trapa natans L.) in the meres of Holderness, East Yorkshire, UK. *The Holocene*, *15*(5), 687–697. https://doi.org/10.1191/0959683605hl844rp

Scholz, H., & Baumann, M. (1997). An 'open system pingo' near Kangerlussuaq (Søndre Strømfjord),West Greenland. *Geology of Greenland Survey Bulletin*, *176*, 104–108. https://doi.org/10.34194/ggub.v176.5074

Schouten, M. G. C. (2003). *Conservation and Restoration of Raised Bogs: Geological, Hydrological and Ecological Studies*. Academic Service.

Spek, T., Spek, T., De Jong, A., & de Jong, A. (2004). *Het Drentse esdorpen-landscape: een historisch- geografische studie*. Wageningen Universiteit.

Speranza, A., van Geel, B., & van der Plicht, J. (2003). Evidence for solar forcing of climate change at ca. 850 cal BC from a Czech peat sequence. *Global and Planetary Change*, *35*(1–2), 51–65. https://doi.org/10.1016/s0921-8181(02)00091-7

Stouthamer, E., Cohen, K. M., & Hoek, W. Z. (2015). *De vorming van het land: geologie en geomorfologie*.

Teller, J. T., Leverington, D. W., & Mann, J. D. (2002). Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. *Quaternary Science Reviews*, *21*(8–9), 879–887. https://doi.org/10.1016/s0277-3791(01)00145-7

Teunissen, D. (1990). *Palynologisch onderzoek in het oostelijk rivierengebied; een overzicht* [Dataset].

Tfaily, M. M., Cooper, W. T., Kostka, J. E., Chanton, P. R., Schadt, C. W., Hanson, P. J., Iversen, C. M., & Chanton, J. P. (2014). Organic matter transformation in the peat column at Marcell Experimental Forest: Humification and vertical stratification. *Journal of Geophysical Research: Biogeosciences*, *119*(4), 661–675. https://doi.org/10.1002/2013jg002492

Towers, J., Bond, J., Evans, J., Mainland, I., & Montgomery, J. (2017). An isotopic investigation into the origins and husbandry of Mid-Late Bronze Age cattle from Grimes Graves, Norfolk. *Journal of Archaeological Science: Reports*, *15*, 59–72. https://doi.org/10.1016/j.jasrep.2017.07.007

USDA. (2015). *Weed Risk Assessment for Trapa natans L. (Lythraceae) – Water chestnut.*

van Andel, T. H., & Runnels, C. N. (1995). The earliest farmers in Europe. *Antiquity*, *69*(264), 481–500. https://doi.org/10.1017/s0003598x00081886

van Beek, R., Gouw-Bouman, M., & Bos, J. (2015). Mapping regional vegetation developments in Twente (the Netherlands) since the Late Glacial and evaluating contemporary settlement patterns. *Netherlands Journal of Geosciences - Geologie en Mijnbouw*, *94*(3), 229–255. https://doi.org/10.1017/njg.2014.40

van Breemen, N. (1995). How Sphagnum bogs down other plants. *Trends in Ecology & Evolution*, *10*(7), 270–275. https://doi.org/10.1016/0169-5347(95)90007-1

van den Bos, V., Brinkkemper, O., Bull, I. D., Engels, S., Hakbijl, T., Schepers, M., van Dinter, M., van Reenen, G., & van Geel, B. (2014). Roman impact on the landscape near castellum Fectio, The Netherlands. *Vegetation History and Archaeobotany*, *23*(3), 277–298. https://doi.org/10.1007/s00334-013-0424-0 van Dinter, M., Kooistra, L. I., Dütting, M. K., van Rijn, P., & Cavallo, C. (2014). Could the local population of the Lower Rhine delta supply the Roman army? Part 2: Modelling the carrying capacity using archaeological, palaeo-ecological and geomorphological data. *Journal of Archaeology in the Low Countries*, *5*(1), 5–50.

Van Geel, B. (1978). A palaeoecological study of holocene peat bog sections in Germany and The Netherlands, based on the analysis of pollen, spores and macro- and microscopic remains of fungi, algae, cormophytes and animals. *Review of Palaeobotany and Palynology*, *25*(1), 1–120. https://doi.org/10.1016/0034-6667(78)90040-4

van Geel, B., Heijnis, H., Charman, D. J., Thompson, G., & Engels, S. (2014). Bog burst in the eastern Netherlands triggered by the 2.8 kyr BP climate event. *The Holocene*, *24*(11), 1465–1477. https://doi.org/10.1177/0959683614544066

Van Geel, B., Heijnis, H., Charman, D. J., Thompson, G., & Engels, S. (2014). Bog burst in the eastern Netherlands triggered by the 2.8 kyr BP climate event. *The Holocene*, *24*(11), 1465–1477. https://doi.org/10.1177/0959683614544066

Van Zeist, W. (1967). Archaeology and palynology in the Netherlands. *Review of Palaeobotany and Palynology*. https://doi.org/10.1016/0034-6667(67)90171-6

Vandkilde, H. (2021). Trading and weighing metals in Bronze Age Western Eurasia. *Proceedings of the National Academy of Sciences*, *118*(30). https://doi.org/10.1073/pnas.2110552118

Walker, M. J. C., Berkelhammer, M., Björck, S., Cwynar, L. C., Fisher, D. A., Long, A. J., Lowe, J. J., Newnham, R. M., Rasmussen, S. O., & Weiss, H. (2012a). Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science*, *27*(7), 649–659. https://doi.org/10.1002/jqs.2565

Walker, M. J. C., Berkelhammer, M., Björck, S., Cwynar, L. C., Fisher, D. A., Long, A. J., Lowe, J. J., Newnham, R. M., Rasmussen, S. O., & Weiss, H. (2012b). Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science*, *27*(7), 649–659. https://doi.org/10.1002/jqs.2565

Warmuth, V., Eriksson, A., Bower, M. A., Barker, G., Barrett, E., Hanks, B. K., Li, S., Lomitashvili, D., Ochir-Goryaeva, M., Sizonov, G. V., Soyonov, V., & Manica, A. (2012). Reconstructing the origin and spread of horse domestication in the Eurasian steppe. *Proceedings of the National Academy of Sciences*, *109*(21), 8202–8206. https://doi.org/10.1073/pnas.1111122109

Whitney, B. S., & Mayle, F. E. (2012). Pediastrum species as potential indicators of lake-level change in tropical South America. *Journal of Paleolimnology*, *47*(4), 601–615. https://doi.org/10.1007/s10933-012-9583-8

Yang, X., Shen, J., Jones, R. T., Wang, S., Tong, G., & Zhang, Z. (2005). Pollen evidence of early human activities in Erhai basin, Yunnan Province. *Chinese Science Bulletin*, *50*(6), 569–577. https://doi.org/10.1007/bf02897482

Yoshikawa, K. (1993). Notes on open-system pingo ice, Adventdalen, Spitsbergen. *Permafrost and Periglacial Processes*, *4*(4), 327–334. https://doi.org/10.1002/ppp.3430040405

Zagwijn, W. (1994). Reconstruction of climate change during the Holocene in western and central Europe based on pollen records of indicator species. *Vegetation History and Archaeobotany*, *3*(2). https://doi.org/10.1007/bf00189928

Zhang, N., Dong, G., Yang, X., Zuo, X., Kang, L., Ren, L., Liu, H., Li, H., Min, R., Liu, X., Zhang, D., & Chen, F. (2017). Diet reconstructed from an analysis of plant microfossils in human dental calculus from the Bronze Age site of Shilinggang, southwestern China. *Journal of Archaeological Science*, *83*, 41–48. https://doi.org/10.1016/j.jas.2017.06.010

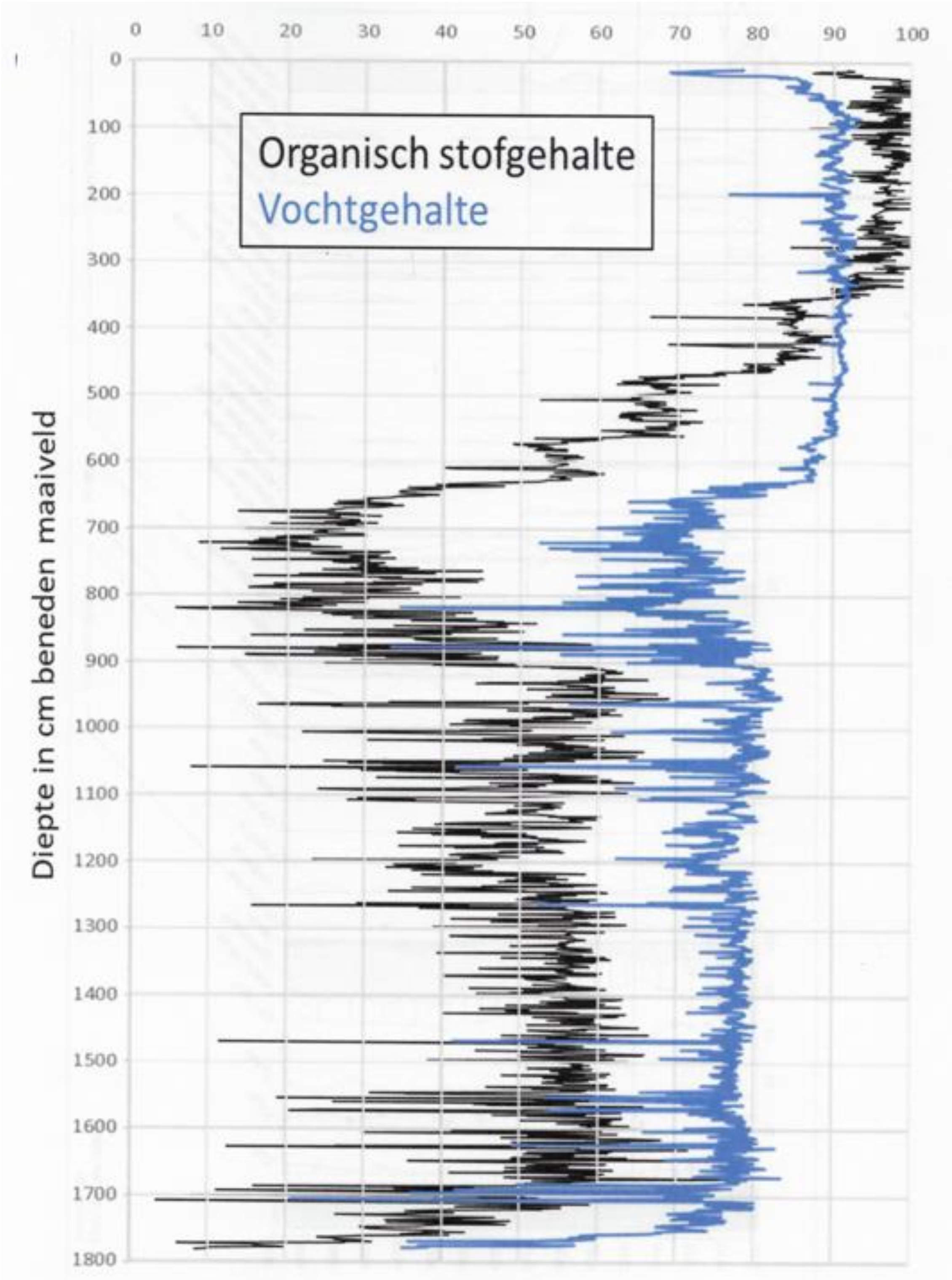
Zielinski, G. A. (2000a). Use of paleo-records in determining variability within the volcanism–climate system. *Quaternary Science Reviews*, *19*(1–5), 417–438. https://doi.org/10.1016/s0277-3791(99)00073-6

Zielinski, G. A. (2000b). Use of paleo-records in determining variability within the volcanism–climate system. *Quaternary Science Reviews*, *19*(1–5), 417–438. https://doi.org/10.1016/s0277-3791(99)00073-6

Zilhao, J. (1993). The Spread of Agro-Pastoral Economies across Mediterranean Europe: A View from the Far West. *Journal of Mediterranean Archaeology*, *6*(1), 5–63. https://doi.org/10.1558/jmea.v6i1.5

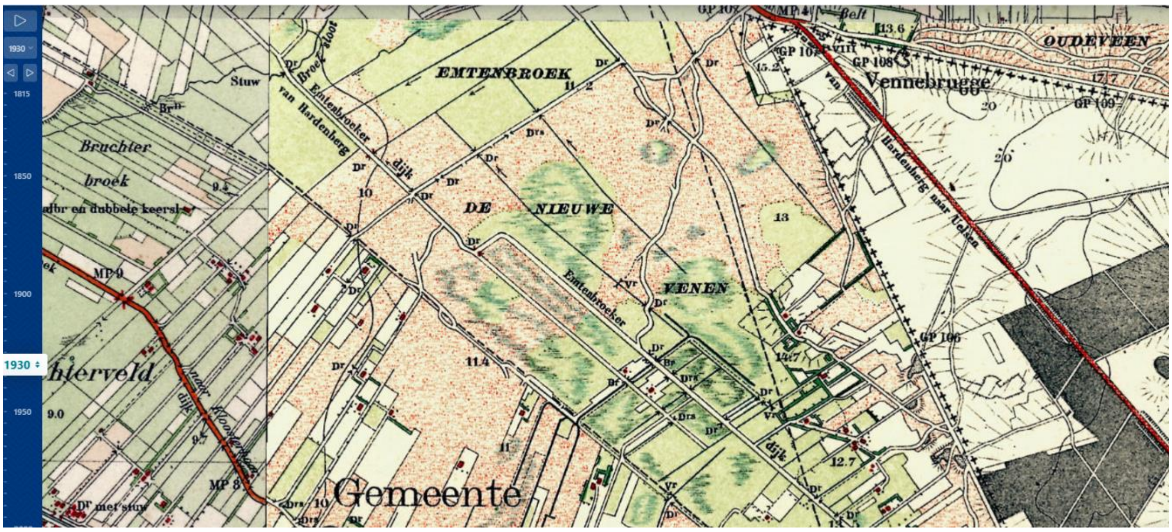
Zohary, D., Tchernov, E., & Horwitz, L. K. (1998). The role of unconscious selection in the domestication of sheep and goats. *Journal of Zoology*, *245*(2), 129–135. https://doi.org/10.1111/j.1469-7998.1998.tb00082.x

Appendix 1

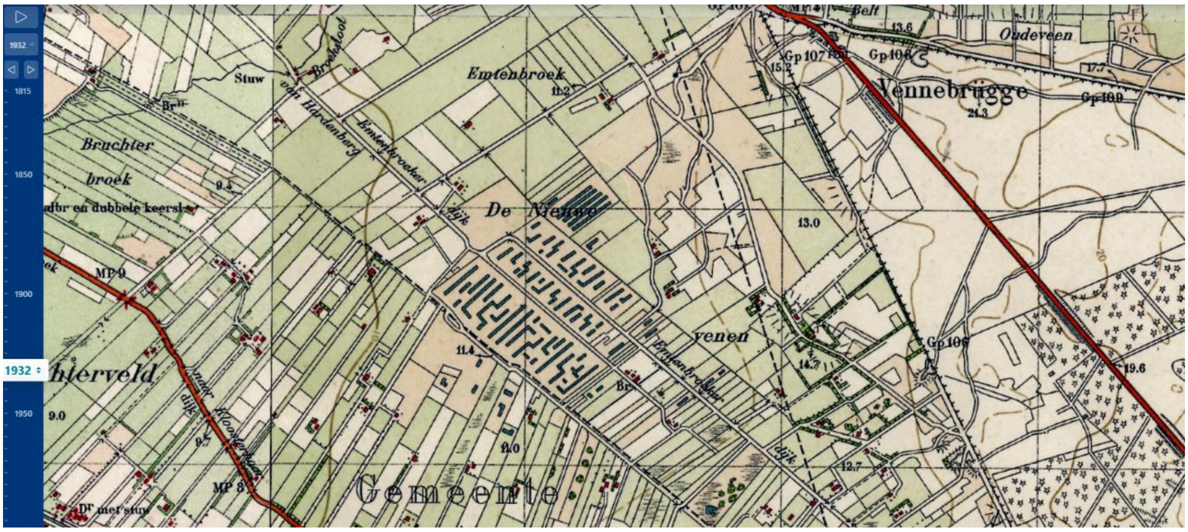


Hoek et al., (not yet published)

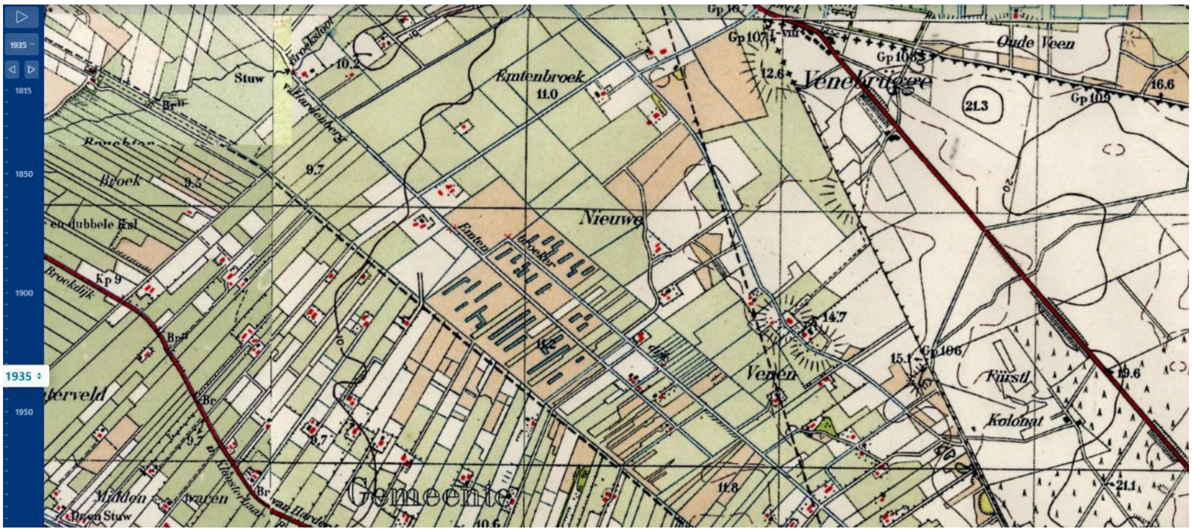
Appendix 2



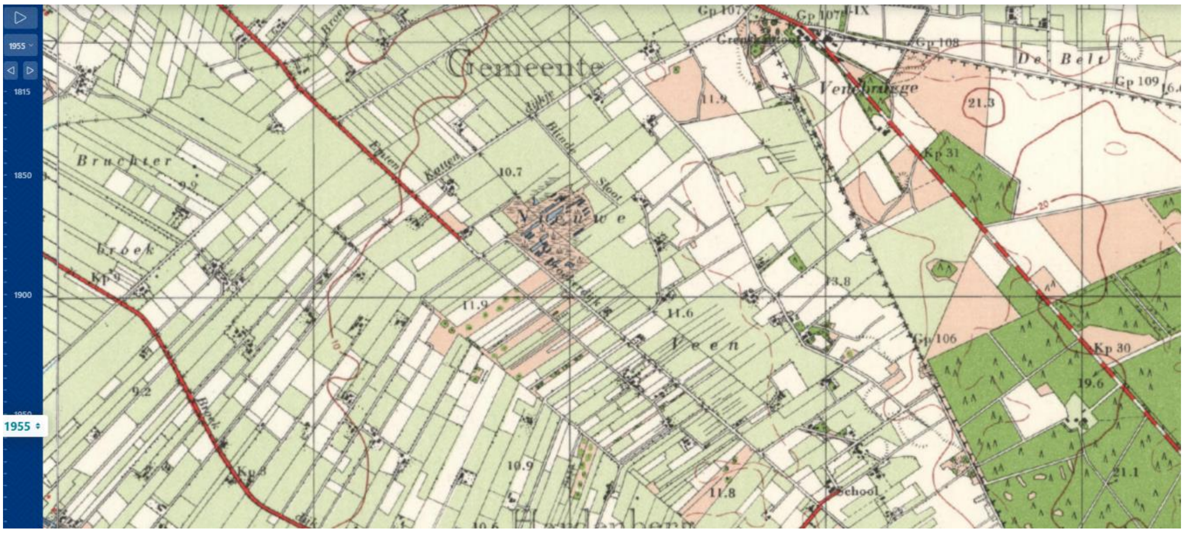
1930
1815
1850
1900
1950
Stuw
Bruchter
broek
EMTENBROEK
DE
NIEUWE
VENEN
OUDEVEEN
Vennebrugge
Gemeente

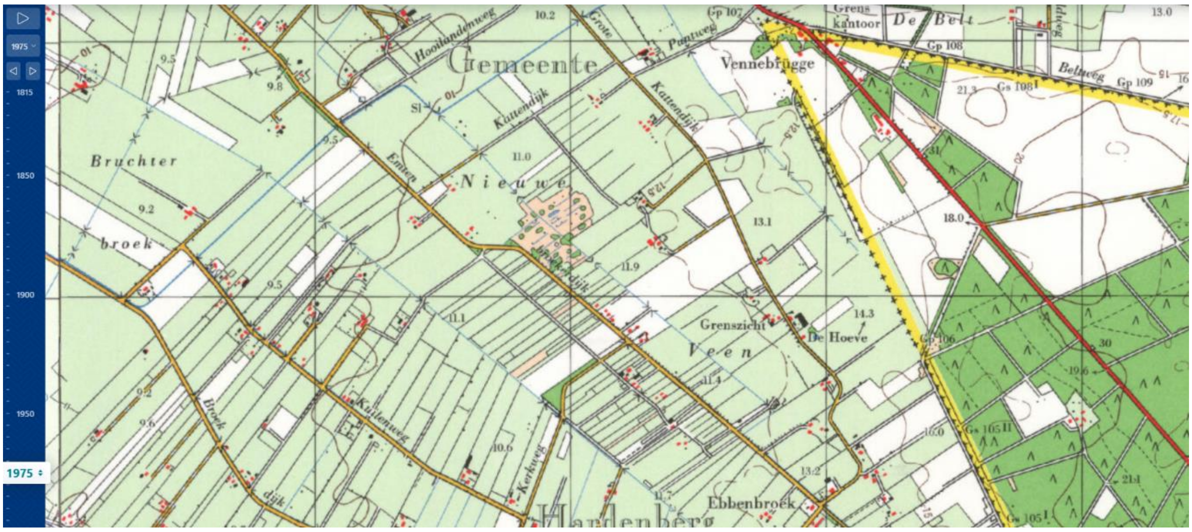


1932
1815
1850
1900
1950
Stuw
Bruchter
broek
Emtenbroek
De Nieuwe
venen
Oudeveen
Vennebrugge
Gemeente



1935
1815
1850
1900
1950
Stuw
Emtenbroek
Nieuwe
Venen
Oude Veen
Venebrugge
Kolonat
Gemeente


1955
1815
1850
1900
Gemeente
Bruchter
broek
Nieuwe
Veen
De Belt
Vennebrügge
School


1975
1815
1850
1900
1950
Gemeente
Bruchter
broek
Nieuwe
Veen
Vennebrügge
Grens kantoor
De Belt
Grenszicht
De Hoeve
Ebbenbroek
Kattendijk
Kuilenweg
Kerkweg


1987
1815
1850
1900
1950
Bruchter
broek
Nieuwe
Veen
Vennebrügge
Grenskantoor
De Belt
Beltweg
Grenszicht
De Hoeve
Ebbenbroek
Emtenbroekerdijk
Kattendijk
Kuilenweg
Kerkweg
Im Fürstenkamp
(Camping)


2005
Duitslandweg
Forellenhof
De Horizon
Kattendijk
Grote Kattendijk
Vennebrügge
De Belt
Bruchter
broek
Nieuwe
Gemeente
Hardenberg
Veen
Grenszicht
Kuilenweg
De Koelen
Kerkweg
Broek
dijk
Ebbenbroek
Olde Waterinkhoeve
Zandgroeve
Im Pürstenkamp
Beltweg
Gp 107
Gp 108
Gp 109
Gp 106
Gp 105

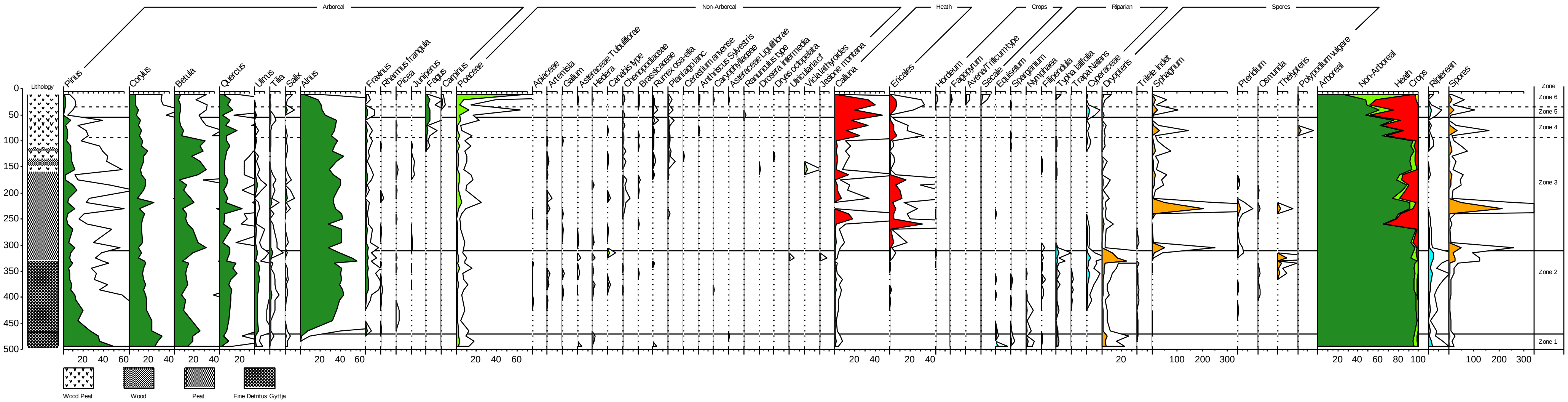

2011
Broeklanden
Forellenhof
Duitslandweg
Kattendijk
Grote Kattendijk
Vennebrügge
Venne-
brügge
Bruchter
broek
Nieuwe
Gemeente
Hardenberg
Veen
Grenszicht
Broekdijk
Kuilenweg
De Koelen
Kerkweg
Ebbenbroek
Olde Waterinkhoeve
De Wingerd
Gp 107 I t/mX
Gp 108
Gp 108 I
Gp 109
Gp 106 III
Gp 106 I
Gp 106
Gp 105 II
Gp 105 I
L43
Bad
0,2 km


2022
Broeklanden
Forellenhof
Duitslandweg
Kattendijk
Grote Kattendijk
Venne-
brügge
Nieuwe
Gemeente
Bruchter
broek
Hardenberg
Veen
Grenszicht
Zeldenrust
Broekdijk
Kuilenweg
De Koelen
Kerkweg
Ebbenbroek
Olde Waterinkhoeve
De Wingerd
Hoopsteeweg
Gpn 107 I en II
Gp 107
Gp 108
Gp 108 I
Gp 106 III
Gp 106 I
Gp 106
Gp 105 II
Gp 105 I
L43

Appendix 3

Nieuweveen

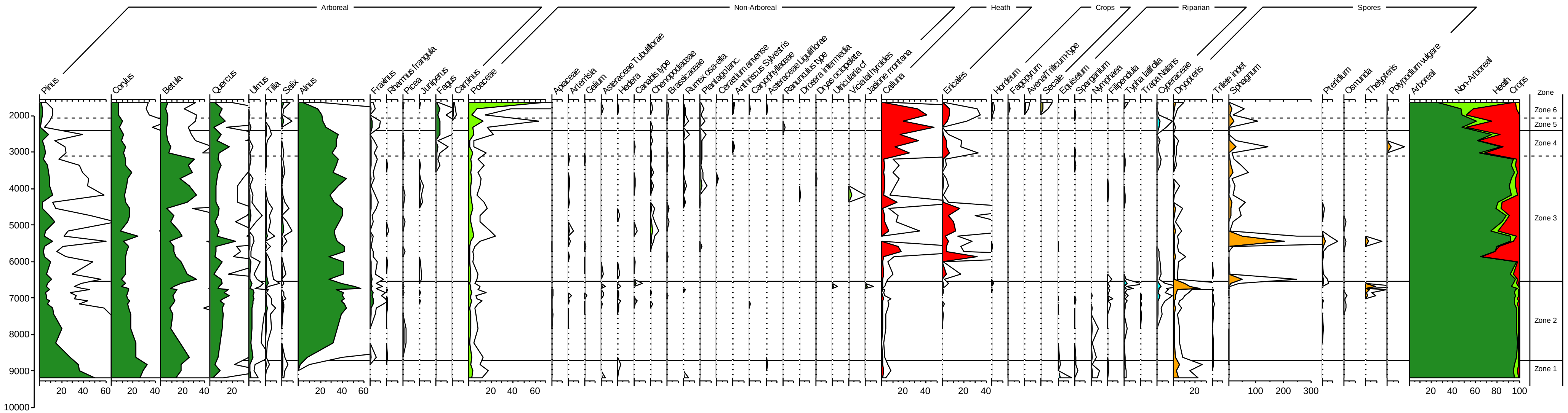
Depth diagram



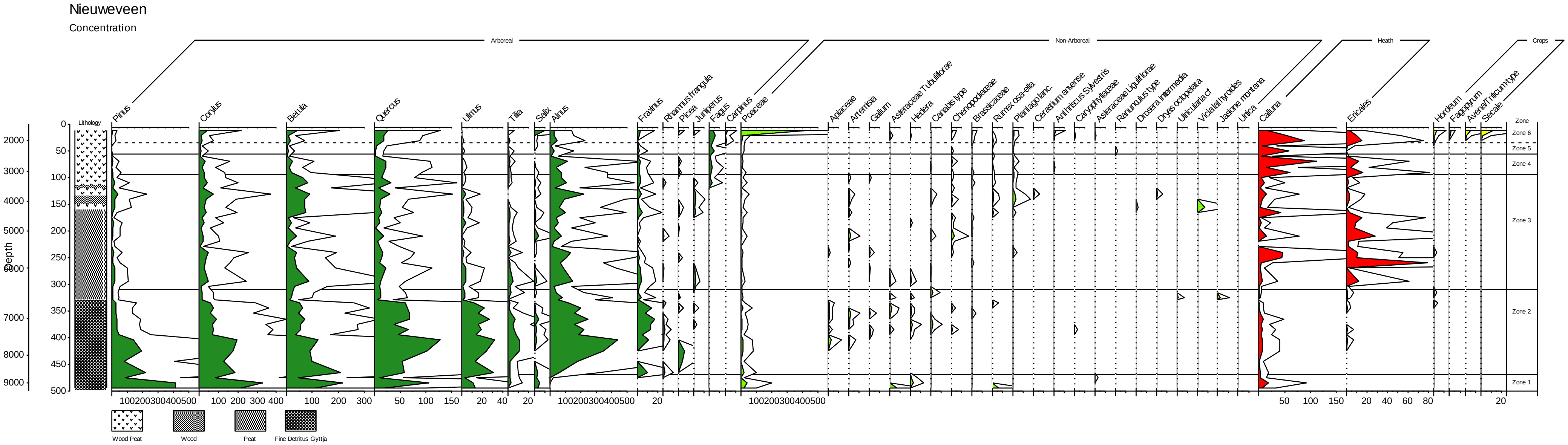
Appendix 4

Nieuweveen

Age diagram

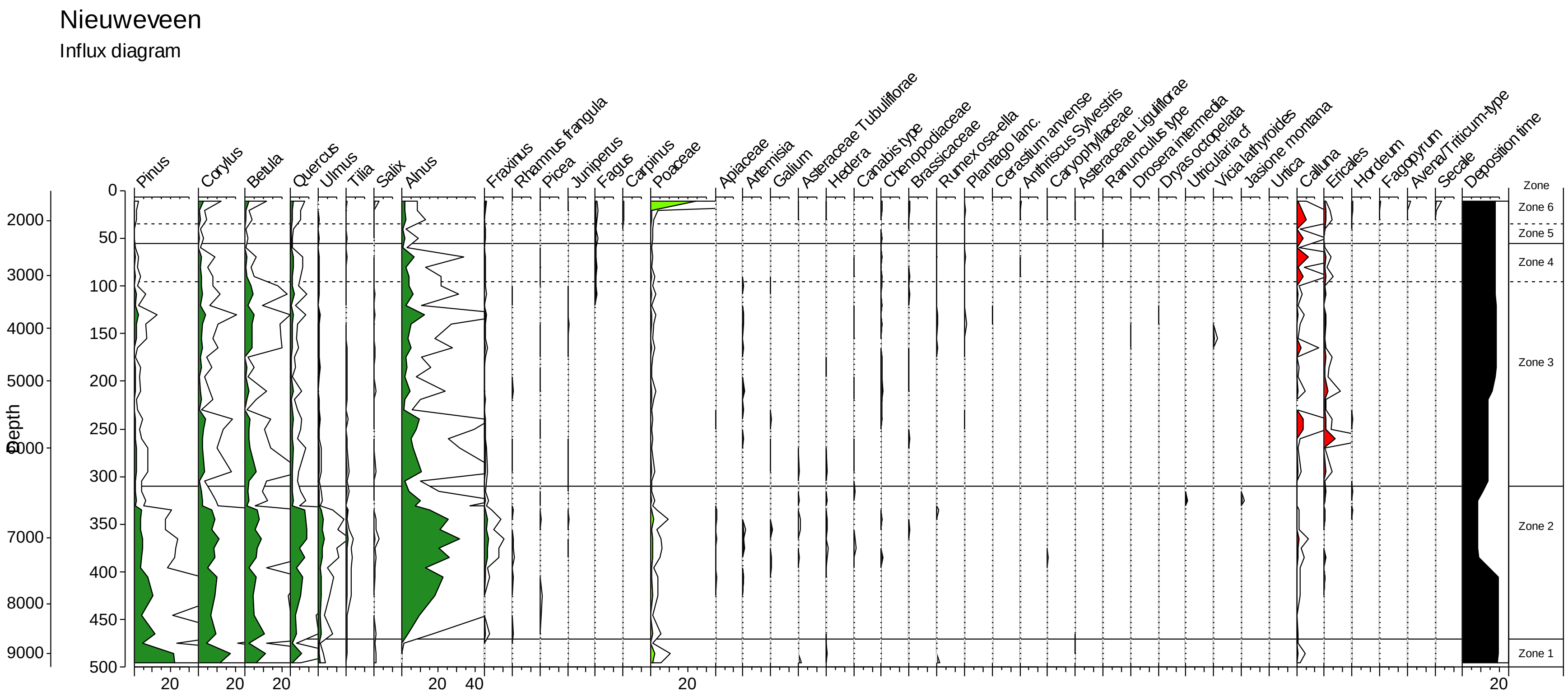


Apendix 5



Nieuweveen
Concentration
Arboreal
Non-Arboreal
Heath
Crops
Lithology
Pinus
Corylus
Betula
Quercus
Ulmus
Tilia
Salix
Alnus
Fraxinus
Rhamnus frangula
Picea
Juniperus
Fagus
Carpinus
Poaceae
Apiaceae
Artemisia
Galium
Asteraceae Tubuliflorae
Hedera
Canabis type
Chenopodiaceae
Brassicaceae
Rumex acetosella
Plantago lanc.
Cerastium arvense
Anthriscus Sylvestris
Caryophyllaceae
Asteraceae Liguliflorae
Ranunculus type
Drosera intermedia
Dryas octopetala
Utricularia cf
Vicia lathyroides
Jasione montana
Urtica
Calluna
Ericales
Hordeum
Fagopyrum
Avena/Triticum type
Secale
Zone
Zone 6
Zone 5
Zone 4
Zone 3
Zone 2
Zone 1
Depth
Wood Peat
Wood
Peat
Fine Detritus Gyttja

Apendix 6


Nieuweveen
Influx diagram
Pinus
Corylus
Betula
Quercus
Ulmus
Tilia
Salix
Alnus
Fraxinus
Rhamnus frangula
Picea
Juniperus
Fagus
Carpinus
Poaceae
Apiaceae
Artemisia
Galium
Asteraceae Tubuliflorae
Hedera
Canabis type
Chenopodiaceae
Brassicaceae
Rumex osa-ella
Plantago lanc.
Cerastium arvense
Anthriscus Sylvestris
Caryophyllaceae
Asteraceae Liguliflorae
Ranunculus type
Drosera intermedia
Dryas octopelata
Utricularia cf
Vicia lathyroides
Jasione montana
Urtica
Calluna
Ericales
Hordeum
Fagopyrum
Avena/Triticum-type
Secale
Deposition time
Zone
Zone 6
Zone 5
Zone 4
Zone 3
Zone 2
Zone 1
Depth
0
50
100
150
200
250
300
350
400
450
500
2000
3000
4000
5000
6000
7000
8000
9000
20
40