The vegetation development and drift-sand dynamics in the Kootwijkerveen, the Netherlands: the role of human impact and climate variability

Map from 1860. Retrieved from topotijdreis.nl.

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Abstract

After a period of reforestation during the Migration Period, population increase was accompanied by a strong intensification of agriculture. In the European sand-belt, this intensification of agriculture led to large-scale resedimentation of Weichselian coversand deposits, creating drift-sand areas. Several drift-sand deposits are located in The Netherlands, of which the areas in Drenthe (e.g. the Aekingerzand) and Gelderland (e.g. the Kootwijkerzand) are discussed in more detail. Since archaeological evidence of human settlement is present near the Kootwijkerzand, this site was chosen as a research area for this study. The drift-sand dynamics and vegetation development were reconstructed for the period 1-1500 AD, and the influence of climate and human settlement was assessed. In general, in this area, the anthropogenic influence on the vegetation development surpassed that of the climatic influence. However, a short phase of deforestation recorded in the first stages of peat growth could have been related to a decrease in precipitation. In this study only one phase of drift-sand influx was found, whereas in other studies several different phases were found. This could indicate that the influx of drift sand was variable throughout the area. A relatively closed woodland was present in the region until the human influence increased, creating open places with herbaceous vegetation and crop cultivation. The human impact increased further from the 10^{th} century onward, as can be inferred from an increase in cereal pollen percentages and the presence of cornflower. Locally, fluctuations of the groundwater table were observed, both in the bog itself and in the direct surrounding. Only during the final stage of peat growth a slight increase of drift-sand influx was found, simultaneously with the presence of an open environment and an increase in human impact indicators. After this, aeolian influx increased significantly in a short period of time, stopping peat growth. Sand drifting continued in this region until active reforestation from the 17^{th} century onward.

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1. Introduction

In Europe, a strong expansion of agriculture started around 900 AD as a result of population growth. This trend followed the Migration Period, during which a general depopulation and consequential reforestation took place in Europe. The expansion of agriculture often resulted in environmental deterioration, particularly when agriculture was intensified from the 12th century onward (Groenewoudt et al., 2007). Especially in environments where the soil was naturally sensitive to disturbance, such as coversand deposits, the impact of agricultural intensification was extensive. Eventually this environmental deterioration led to the start of sand drifting, a process in which wind erosion activates sandy deposits and covers large areas with a layer of sand (Koster, 2005). These sand drifting phases had a large impact, not only on the physical environment, but also on a social and economic level. Therefore, it can be relevant to investigate trends in the vegetation development preceding the onset of sand drifting phases in high detail, to determine the factors controlling this process.

According to Koster (1978) several environmental conditions have to be met in order for sand drifting to start. Firstly, the material which is present should be sensitive to wind erosion. This implies that fine-grained material is present at the surface, and that the material is well sorted. Secondly, the material should be dry enough for the wind to get grip on the material. Therefore, the groundwater level should be relatively low. Lastly, vegetation should not be present to protect the underlying sediment. In The Netherlands, minor phases of sand drifting are known to have coincided with increased human impact from the Neolithic onward, when partial deforestation took place (Groenewoudt et al., 2007; Spek, 2004). However, more intense sand drifting activity did not start until the expansion of agriculture from 900 AD onward (Koster, 2005; Tolksdorf & Kaiser, 2012). Although there is a wide consensus that the increase of human impact was the main trigger for the formation of drift-sand areas, it is argued that other factors, such as decreasing humidity, lowering of the groundwater level or temperature could also have played a role in the onset of sand drifting (Koomen et al., 2004; Koster, 2005).

Human impact on vegetation development already started before the expansion and intensification of agriculture from the 9th century onward. Centuries this agricultural expansion and major sand drifting started, the collapse of the Roman Empire (450 AD) in continental north-western Europe was followed by the Migration Period (450-525 AD) (Bos & Zuidhoff, 2015). During this period, also referred to as the 'Dark Ages', economic, cultural and demographic deterioration took place. Depopulation led to a decline in agricultural practices, especially south of the Roman frontier, but also in other parts of Europe. Consequently, reforestation took place. In the Netherlands, population numbers started to increase again from the 7th century onward and agriculture was intensified (Jansma et al., 2014). However, during the Middle Ages people did not use sustainable techniques for soil fertilization. Due to overexploitation and active removal of vegetation cover for fertilization purposes large areas of land were left fallow. One of the environmental conditions for sand drifting as proposed by Koster (1978) was hereby met. Occasionally, the sand drifting was so severe that it even led to forced abandonment of settlements (Koster, 1978).

Research that combines a detailed vegetation reconstruction with data on sand drifting and archaeological evidence in this specific period, around 900 AD, is scarce. It is of great importance to integrate knowledge from different fields of study in order to obtain a complete impression of the different mechanisms that led to this environmental change. The results of archaeological studies can help to give a historical and archaeological overview of the area, and therefore can add valuable knowledge to this study which mainly focuses on vegetation development. The Kootwijkerzand in the Veluwe area (The Netherlands) is an example of an area where the expansion and intensificaton of agriculture had a large impact on the environment and settlement. An extensive archaeological research has shown that people living in medieval settlements located in the Kootwijkerzand were forced to migrate because of the advancing drift sand in the area (Heidinga, 1984).

Therefore, this study aims to reconstruct the vegetation development and drift-sand dynamics in the Kootwijkerveen, the Netherlands, from 1 to 1500 AD. The second aim is to assess the role of anthropogenic as well as climatic influences on the vegetation development in this specific region. The Kootwijkerveen is chosen as research location since it still contains an undisturbed a peat sequence from the Late Subatlantic, which is rare in the Netherlands, and because it is located in close proximity to the largest inland drift-sand area of northwestern Europe: The Kootwijkerzand.

This research takes place within the context of the Dark Ages Project, an interdisciplinary project focusing on the interaction between environmental and cultural dynamics in northwestern Europe between 300 and 1000 AD. This study is part of and contributes to subproject C of the Dark Ages Project, the PhD research of drs. M.T.I.J Gouw-Bouman. Subproject C focuses on vegetation and climate change during the Dark Ages in The Lowlands, for example in river deltas and coastal plains. This includes reconstructing the interregional differences in vegetation development, and the assessment of the varying influence of human impact, landscape and climate on vegetation development (Jansma et al., 2014). I hope to contribute to this project by conducting this study and providing new data on vegetation development in the central Netherlands.

The Kootwijkerveen was chosen as a research area because of the ability to investigate the controlling factors in the onset of sand-drifting using different research disciplines. Research has shown that peat started growing in the Kootwijkerveen in the 3rd century AD and was overblown by drift sand in the 12th century AD (Koster, 1978). The Kootwijkerzand is located in the Veluwe area, where several other drift-sand areas are present on which a lot of research has been published. The aim of this study is to provide a detailed reconstruction of the vegetation development, especially of the phase shortly before the onset of the drift-sand phase in the beginning of the 11th century (Koster, 1978). The Kootwijkerveen is the ideal site since archeological as well as palynological data are available. Therefore, choosing the Kootwijkerveen as research location provides the opportunity to integrate the palynological research with the archeological and geomorphological data which is available from this region (Heidinga, 1984; Koster, 1978, 2005).

In order to achieve these aims, a core was taken during fieldwork in The Kootwijkerveen in October 2016. The objectives of this study are:

1) To reconstruct the vegetation development of the Kootwijkerveen between 1-1500 AD
2) To reconstruct the drift-sand patterns in the Kootwijkerveen region beween 1-1500 AD by quantifying the organic component of the sediment.
3) To determine the human population dynamics in this region between 1-1500 AD, using archaeological information from literature and human indicator pollen, spores and non-pollen palynomorphs from the sediment core from the Kootwijkerveen.
4) To compare the chronology of human population dynamics to the reconstructed vegetation development and drift-sand patterns.

5) To determine the temperature and precipitation patterns in Europe and The Netherlands between 1-1500 AD from literature.
6) To compare these temperature and precipitation patterns with the vegetation development and drift-sand dynamics of the Kootwijkerveen between 1-1500 AD.

This will be done via a literature study, and a core analysis using lithology, Loss On Ignition and palynological analyses.

The second chapter of this study will focus on the drift-sand dynamics in Europe, with special focus on local drift-sand areas in Drenthe and Gelderland (The Netherlands). Following this, the anthropogenic influences will be discussed in chapter 3, both on a regional and local scale. Chapter 4 will focus on climate fluctuations in the Late Roman Period and the Middle Ages, and in chapter 5 the vegetation development will be discussed both on a regional and a local scale. Following this literature study, the methods and materials that were used will be discussed in chapter 6. The results, discussion and conclusion will be provided in chapters 7, 8 and 9, respectively.

2. Drift-sand dynamics

2.1 Europe

The drift-sand areas in The Netherlands are part of the European sand-belt, which mainly consists of Weichselian coversand deposits (figure 1) (Castel, 1991). The European sand-belt ranges from Great Britain in the west to the Polish-Russian border in the east of Europe. The term 'coversand' describes the aeolian deposits which accumulated under periglacial and fluvio-periglacial conditions during the last glacial period. The term 'drift sand' is used to describe deposits formed due to re-sedimentation of coversand (Koster, 1982). Resedimentation is possible with winds >7,5 m/s, but the largest part is caused by winds > 10 m/s (Koster, 2009). While coversand typically lacks a distinct relief, drift-sand areas usually display a rather disordered dune relief of erosional and accumulational forms, varying in size and slope value (Koster, 2009).

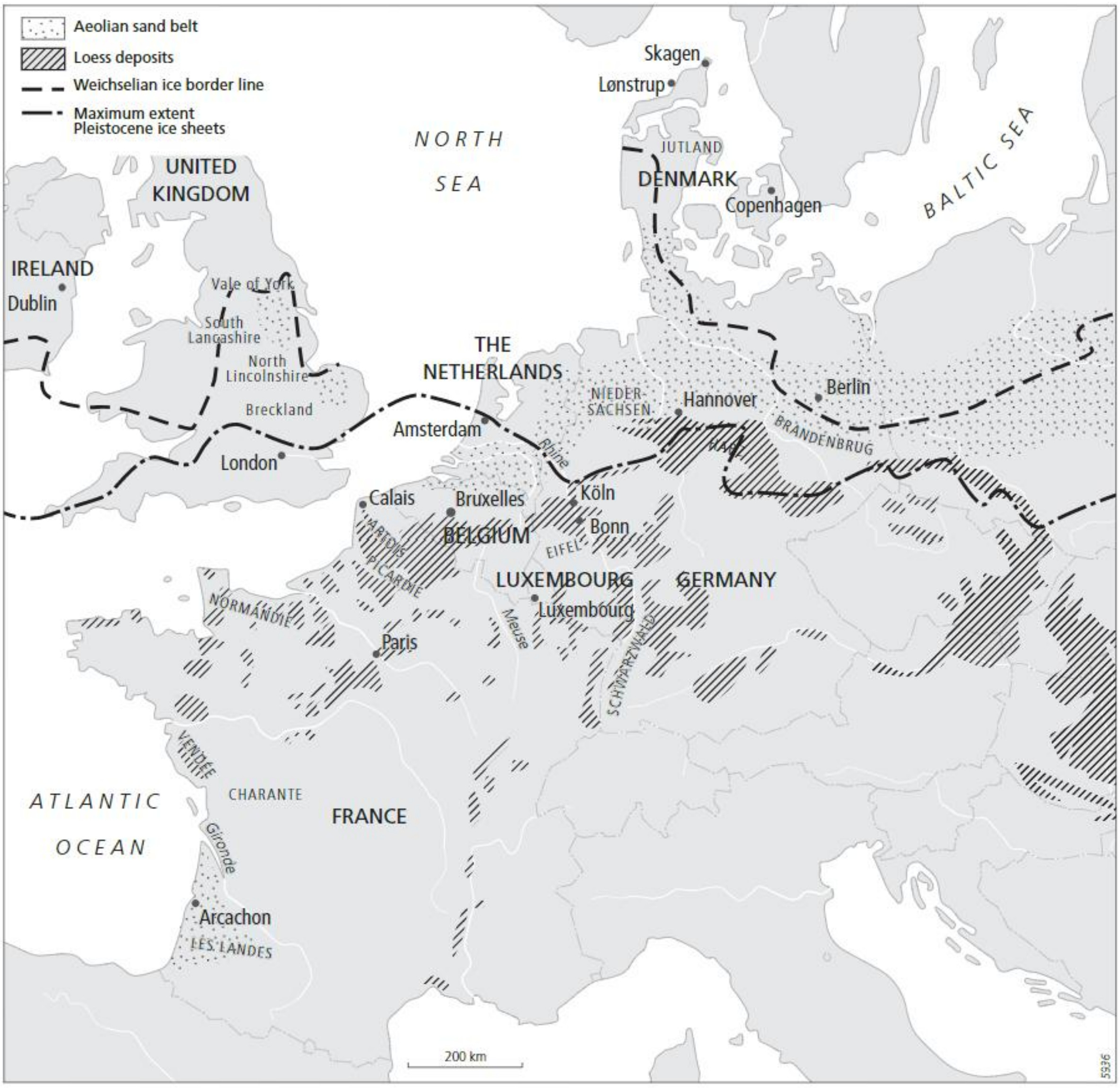

Figure 1. Extent of the European 'sand-belt'. In addition to aeolian deposits such as river dunes, cover and drift sands, European loess deposits are also shown. *Retrieved from Koster (2005).*

The aeolian activity in the European sand-belt was not constant through time. During the Late Pleniglacial, Old Dryas and Younger Dryas, aeolian activity increased, while in the Bølling and Allerød the increase in vegetation cover and soil formation led to a decrease in activity (Kasse, 2002; Schirmer, 1999; Tolksdorf & Kaiser, 2012). Although there is general consensus on the phases of aeolian activity during the Weichselian, the exact chronology of sand drifting during the Holocene is uncertain. Especially activity during the Boreal and early Atlantic is debated. This is mainly the result of incomplete Holocene archives due to later reworking of the drift-sand deposits. (Tolksdorf & Kaiser, 2012). The presence of drift-sand increases towards the eastern part of the European sand-belt, a trend which could have been caused by increasing aridity towards the east (Böse, 1991; Koster, 2009; Schwan, 1986).

There is general consensus that from the Neolithic onward, increased anthropogenic influence led to aeolian reactivation (Koster, 2009; Tolksdorf & Kaiser, 2012). During the late Neolithic and late Bronze Age periods of increased aeolian transportation took place. These reactivations were caused by a destabilization of the ecosystem by lower temperature and increasing drought combined with an increase in human impact (Hilgers, 2007; Kalis et al., 2003; Tolksdorf & Kaiser, 2012). Large scale sand drifting really started to occur on a larger scale when human impact on the environment increased around 900 AD (Koster, 2005; Tolksdorf & Kaiser, 2012).

Periods of temporal surface stability can be identified using palaeosols and buried peats, and are indicative of the maximum ages of subsequent aeolian activity (Tolksdorf & Kaiser, 2012).Clusters of palaeosols and buried peats from the Netherlands to Eastern Poland were dated at AD 650 and AD 1260. However, it should be mentioned that dating of palaeosols is not always reliable because of leaching of humic acids from overlying deposits. Clusters of luminescence dates were found in AD 1050 and AD 1300 in the western sand-belt, indicating periods of increased aeolian activity (Tolksdorf & Kaiser, 2012).

Agriculture was an important trigger for sand-drifting, since the protective vegetation cover was removed. From the 11^{th} century onward, agriculture was intensified in western-Europe. Removal of a protective vegetation cover in combination with the presence of relatively well sorted and dry coversand deposits led to large-scale wind erosion (Blume & Leinweber, 2004; Heidinga, 1984; Tolksdorf & Kaiser, 2012; van Mourik, Seijmonsbergen, Slotboom, & Wallinga, 2012). Occasionally, the population of the settlements located in these active drift-sand areas were forced to move because of this aeolian activity. Drift-sand areas actively kept forming until large scale reforestation using pine plantations in the second part of the last century. Especially in the countries surrounding The Netherlands nearly all the drift-sand areas became fixed as a result of active reforestation (Koster, 2005).

A large part of the currently active drift-sand areas in the European sand-belt can be found in The Netherlands, and are designated as protected areas (Koster & Castel, 1987). Only small areas in the central part of The Netherlands are still actively forming, helped by management focusing on preservation of these areas. Here, currently drift-sand areas comprise about 950 km^2, of which only 15/16 km^2 had active transport in 2009. In comparison, in 1980 40 km^2 was still actively moving (Koster, 2009). Nature conservation is actively involved in keeping these aeolian deposits from becoming fixed by controlling vegetation succession. Preserving these active drift-sand areas is of importance because of the distinct flora and fauna communities living in these areas, such as a number of rare lichen species and a diverse insect community (Koster & Castel, 1987).

In the Netherlands, drift-sand areas are located four main regions throughout the country. In the southern and eastern part, drift-sand areas such as the Loonse & Drunense

Duinen and the Lutterzand are present, respectively. In this study, the characteristics of two drift-sand areas will be investigated in more detail: the Aekingerzand in the northern and the Kootwijkerzand in the central part of the Netherlands (figure 2). Additionally, the factors that contributed to and controlled the development of the Kootwijkerzand drift-sand region will be studied in high detail.

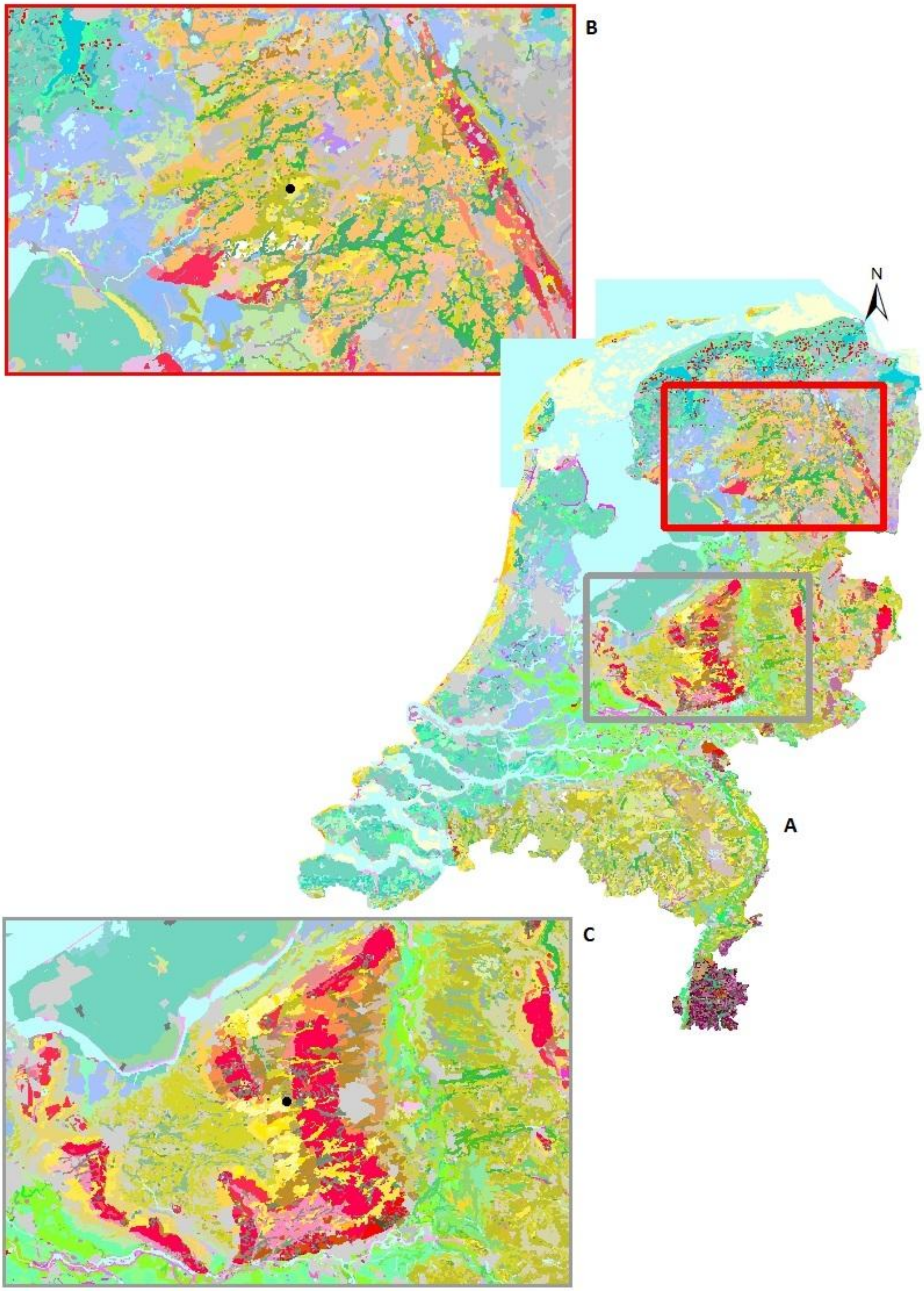

Figure 2. A: Geomorphological map of The Netherlands, demarcating drift-sand areas in B: Drenthe and C: Gelderland. The ice pushed ridges are indicated in dark pink (code '15B3') and the drift-sand areas are indicated in yellow and light yellow (code '4L9' and '2M16' respectively). The Aekingerzand (Drenthe) and the Kootwijkerzand (Gelderland) are both indicated with a black dot. *The figure was constructed by drs. M.T.I.J. Gouw-Bouman using GIS.*

2.2 Drenthe

One of the drift-sand areas in The Netherlands is located in Drenthe (figure 2). Several drift-sand deposits are present here. In Drenthe, the start of Holocene aeolian activity ranges significantly throughout the area. According to Castel (1991) the start of this transport ranges from 1100 AD to 1700 AD from west to east.

The current geomorphology of the region dates mainly from the Saalian, which lasted from 200 – 130 kyrs BP. During the Saalian glacial, the northern part of the Netherlands was covered with an ice sheet repeatedly. When the Saalian ice sheet retreated, all the unsorted material that was transported during glacier advance was deposited. As a result, a layer of till was left behind in the province of Drenthe, covering the area continuously, ranging from 25 m +NAP in the southeastern part to 15 m +NAP in the northwestern part of the province (Castel, 1991). A secondary groundwater table developed on top of the till layer, since water could not penetrate this layer (Castel, 1991). This contributed to the development of peat deposits in Drenthe.

The drift-sand deposits in Drenthe are characterized by the presence of plateau dunes. These dunes originally were low-lying, wet coversand depressions where peat development occurred. During phases of sand-drifting, these depressions preferentially captured the blown-in sand. Aeolian transport eventually led to relief inversion, since the original wet depressions built up into dunes and the surrounding coversand was eroded (figure 3). As a result, a landscape where plateau dunes alternate with flat blown-out areas is now present in Drenthe (Castel, 1991; Koster, 2009).

The peat which is present in these plateau dunes in Drenthe is especially suitable for research, since the drift-sand layer covering the peat sequence prevented large-scale excavation. In many of these plateau dunes relatively undisturbed peat sequence dating from the Subatlantic is still present, which is a rarely found in the Netherlands (Castel, 1991).

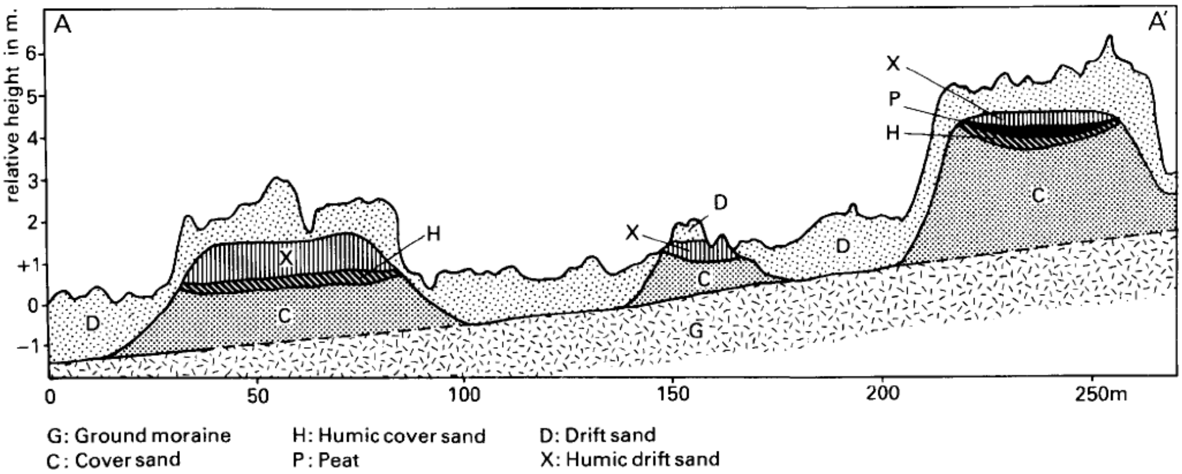

Figure 3. Cross-section of three plateau dunes in the province of Drenthe, The Netherlands. *Retrieved from Castel (1991).*

2.3 The Veluwe and Kootwijk

Various drift-sand areas are located in the Veluwe area, The Netherlands (figure 4). The orientation of these drift-sand deposits is predominantly WSW to ENE, corresponding to the prevailing direction of high wind speeds (Koster, 1978).

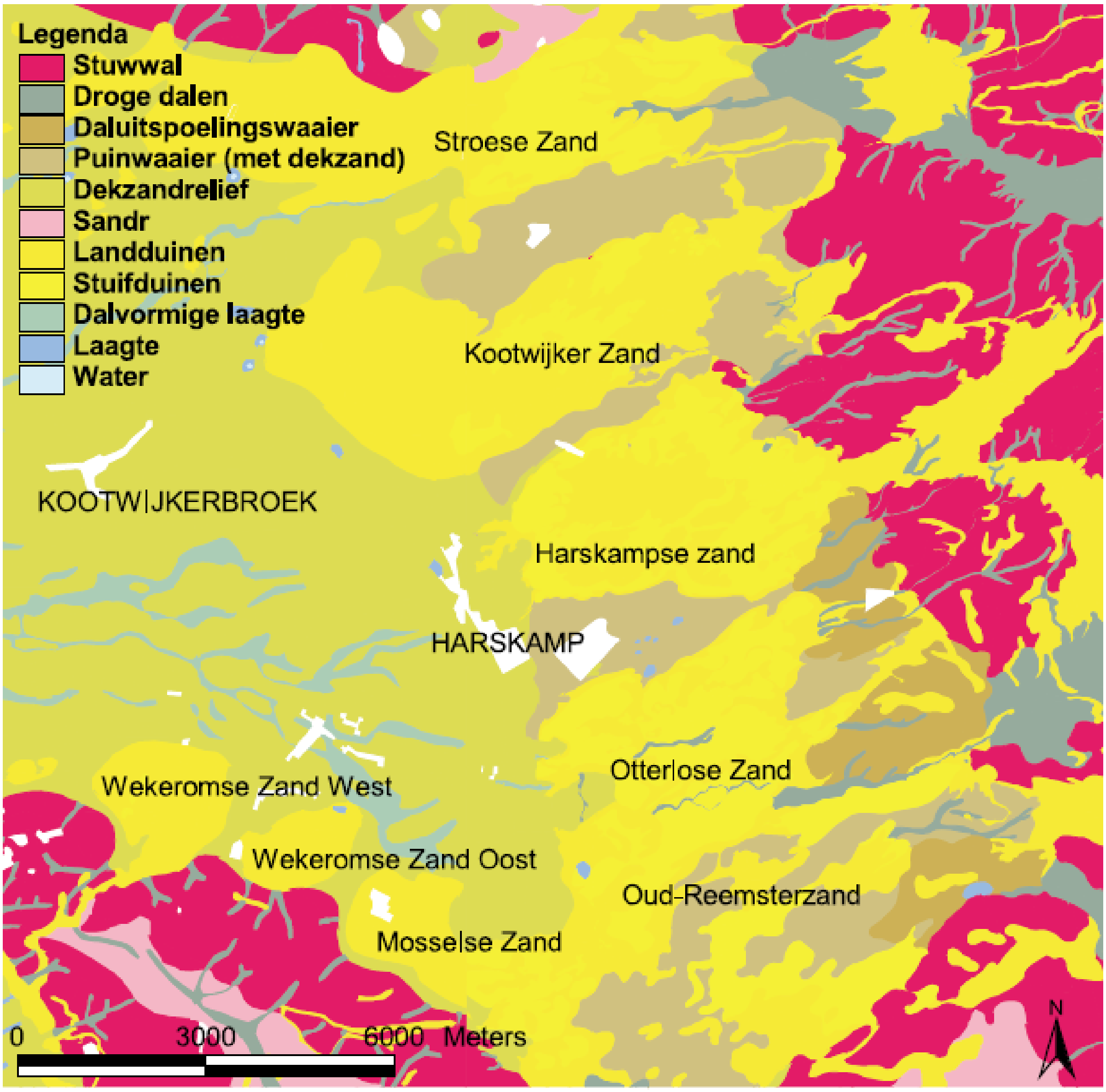

Figure 4. Drift-sand deposits on the soil map of the Veluwe area (central Netherlands). *Retrieved from Koomen et al. (2004).*

The Kootwijkerzand in the Veluwe area is the largest inland drift-sand area of northwestern Europe which is still active (Koster, 2009). Here, ice-pushed ridges formed in the Saalian surround several drift-sand formations, which were formed as a result of wind erosion on coversand deposits (figure 2) (Koster, 2009). The Kootwijkerveen is located north of the Kootwijkerzand (figure 5) and is characterized by the presence of a parabolic dune at the northeastern border of the bog (figure 6). The area is closely located to ice-pushed ridges, fluvioglacial units and coversand deposits, from which the drift-sand layer deposited on top of the peat originates (figure 7).

Podzol soils are common in coversand deposits of the Veluwe area. Peat formation in the Kootwijkerveen was enabled by the presence of a depression in the coversand and an impermeable B horizon which developed here as a result of podzolisation (figure 8). A podzol generally forms in sandy soils with a precipitation surplus. The upper horizon of the soil gets depleted of organic material, iron and aluminium. They leach down from the A and E horizon and are deposited in the B horizon, forming an impermeable iron pan layer (Castel, 1991; Koster, 1978). Infiltrating rainwater stagnated on this layer and peat started forming.

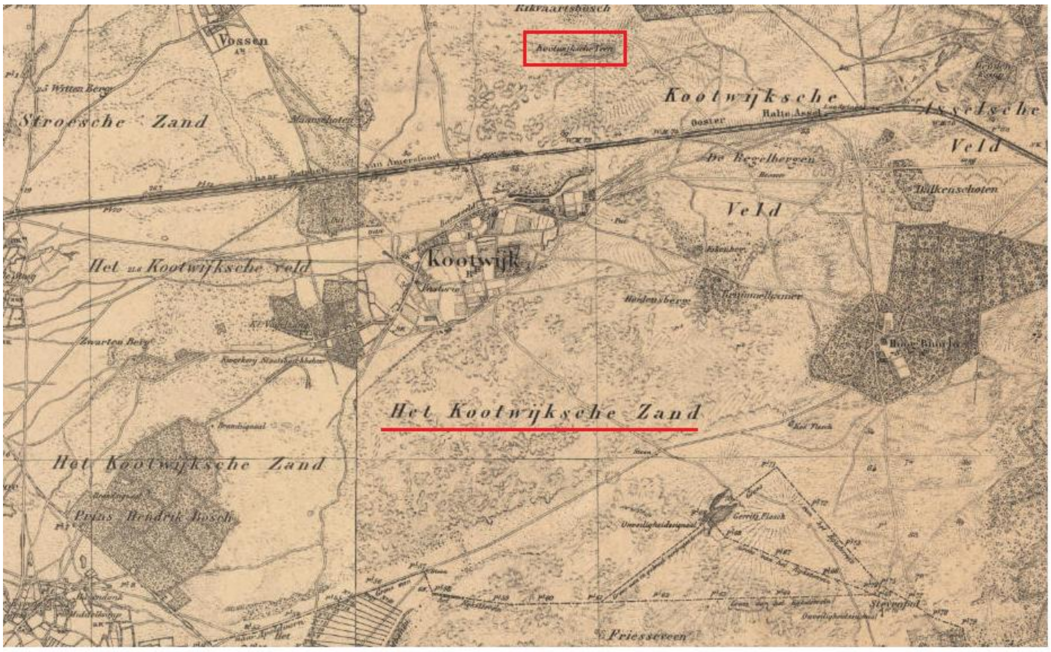

Figure 5. The location of the Kootwijkerzand (Het Kootwijksche Zand, underlined in red) and the Kootwijkerveen (red box) on a historical map from 1925. *Retrieved from: Kadaster, topotijdreis.nl*

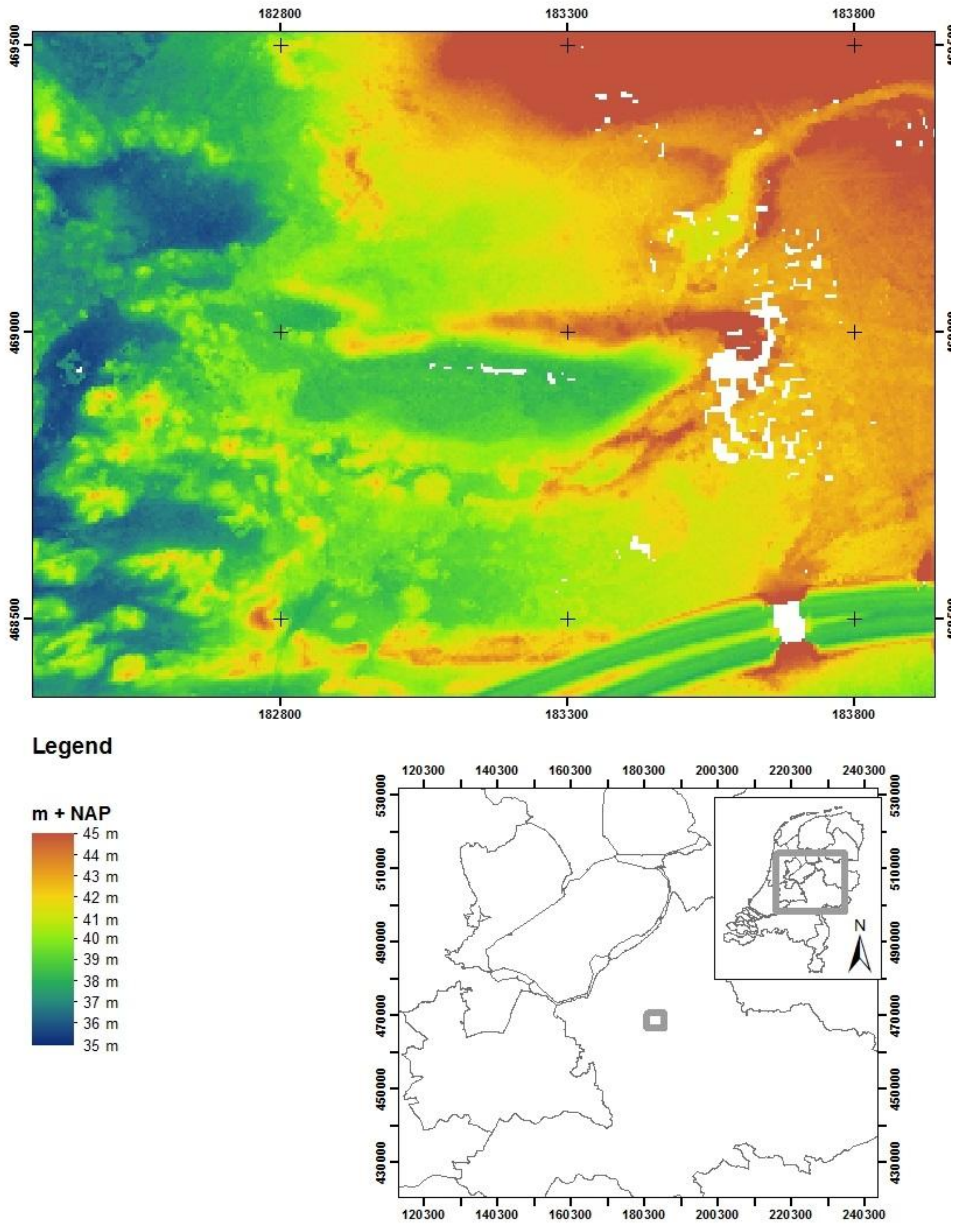

Figure 6. AHN map of the Kootwijkerveen, showing a parabolic dune bordering the northeastern side of the bog. The exact location of the Kootwijkerveen is indicated with a red dot. *The figure was constructed by drs. M.T.I.J. Gouw-Bouman using GIS.*

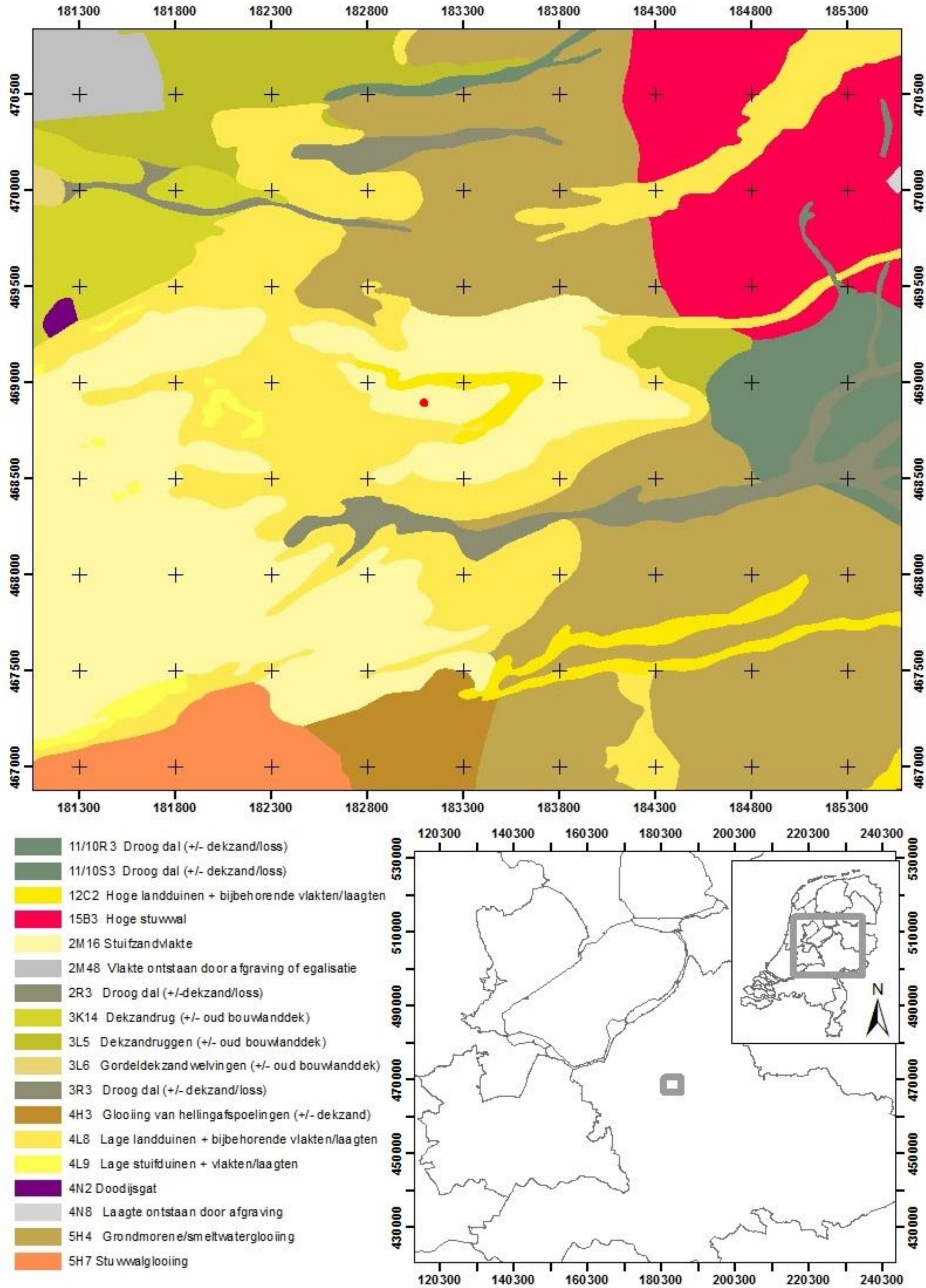

Figure 7. Geomorphological map of the Kootwijkerveen showing the different deposits in the area. The exact location of the Kootwijkerveen is indicated with a red dot. *The figure was constructed by drs. M.T.I.J. Gouw-Bouman using GIS.*

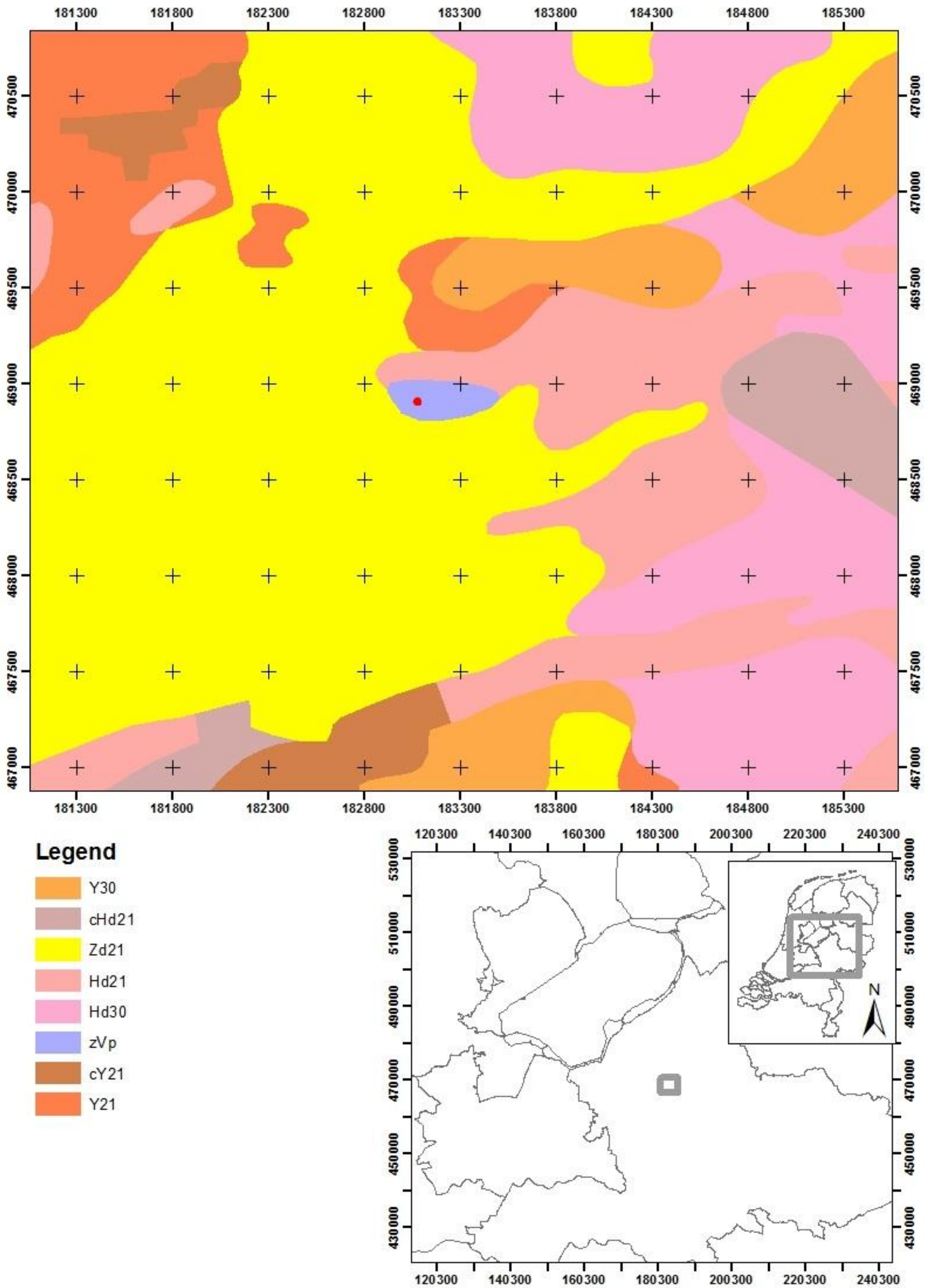

Figure 8. Soil map of the Kootwijkerveen area. The Kootwijkerveen is indicated with a red dot. *The figure was constructed by drs. M.T.I.J. Gouw-Bouman using GIS.*

All three preconditions for sand drifting to start were fulfilled in the Kootwijkerzand region during the Middle Ages (Koster, 1978). In this region, coversand deposits are present, which are fine-grained, well sorted and generally low in moisture. Furthermore, the protective vegetation cover was absent due to overexploitation starting from the 7th century AD (Heidinga, 1984; Koster, 1978).

During the Late Middle Ages (AD 1050-1450) there is evidence for an extensive increase in aeolian activity in the European sand-belt (Tolksdorf & Kaiser, 2012). In Kootwijk five major drift-sand events took place during the Middle Ages (Koster, 1978). The first half of the 7th century, middle of the 9th century, end of the 10th century, first half of the 11th century and finally the 12th century were characterized by increased aeolian transport (figures 9 and 10). The last drift-sand phase was so extensive that a thick layer of drift sand was deposited on top of the surface of the Kootwijkerveen. As a result, this peat deposit was protected from excavation. These phases were reconstructed by Koster (1978) by combining the ^{14}C dates from a core from the Kootwijkerveen with the mean peat growth at this location and the LOI data. These phases of aeolian transport are generally associated with land use changes and overexploitation due to increased human influence on the environment (Castel, 1991; Tolksdorf & Kaiser, 2012).

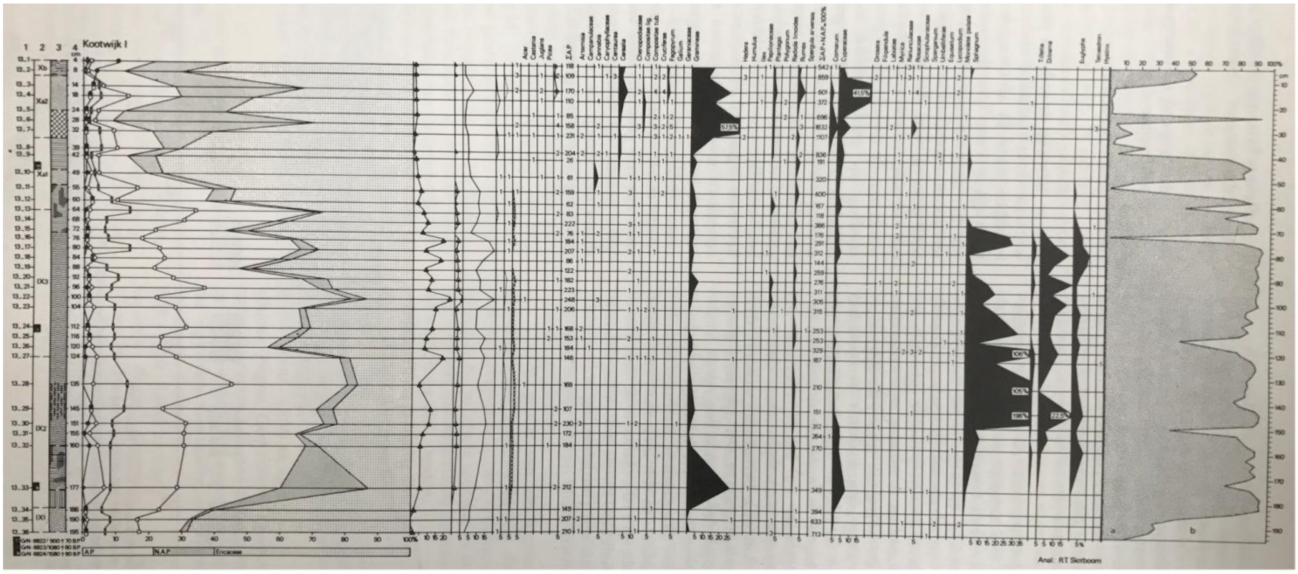

Figure 9. The pollen diagram from the Kootwijkerveen core, analyzed by Koster (1978). The phases of drift sand influx are visible in the right graph.

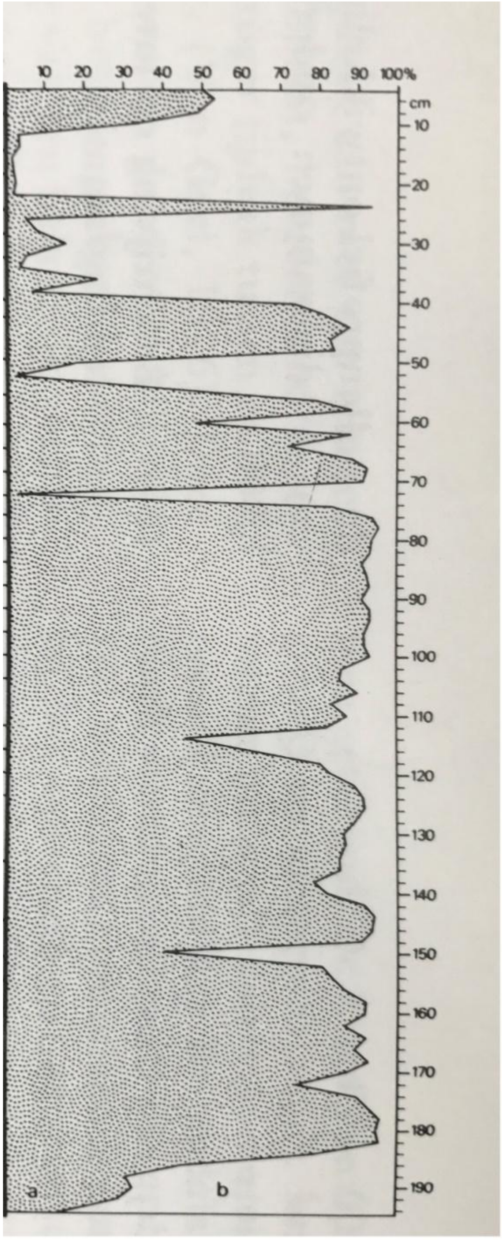

Figure 10. Detail of the diagram shown in figure 9. ‘A’ shows the percentage of weight loss at 950 °C, ‘B’ represents the ignition residue in percentages, The phases of drift sand influx are clearly visible. *Retrieved from Koster (1978).*

3. Anthropogenic influences

In order to determine the factors that contributed to the onset of sand drifting, it is important to reconstruct the history of the area as comprehensive as possible, preferably using different disciplines of research. Consequently, the Kootwijkerveen was chosen as a research area. Next to the potential to reconstruct the drift-sand dynamics and vegetation development, archaeological evidence is present here, providing the opportunity to reconstruct the anthropogenic influence in this specific area. By doing so, knowledge from different disciplines can be integrated and the interaction between them can be analyzed. In this chapter, first a general overview of human impact in Europe will be provided, from the Mesolithic onward. Following this, a more detailed reconstruction of human settlement in the area of Kootwijk is provided, focusing on the period from 1-1500.

3.1 Western-Europe

From the Mesolithic onward, human presence led to significant impact on its environment. In the Mesolithic, the impact from the hunter/gatherers was small in scale and localized (Tolksdorf & Kaiser, 2012). They used fire to modify the landscape and impacted the landscape by gathering food and construction material and removing vegetation. In the Atlantic, the hunter-gatherer cultures of the Mesolithic were replaced by the farming cultures of the Neolithic. Human impact on the environment increased as more forest was cleared for crop cultivation and pasture. As a result, aeolian resedimentation increased during the Neolithic (Tolksdorf & Kaiser, 2012). Tree-ring based reconstructions show increased tree felling from the late Iron Age to the Roman Age (~300 BC – 200 AD). A deforestation maximum was recorded in 250 AD, when the Western Roman Empire reached its greatest expansion (Buntgen et al., 2011). Reduced tree felling dates were found during the Migration Period. Depopulation led to a decline in agricultural practices, as a result of which reforestation could take place (Buntgen et al., 2011). From the 7th century onward population numbers started to increase again as a result of stabilized borders and economic prosperity, and agriculture was expanded accordingly (Buntgen et al., 2011; Jansma et al., 2014).

The expansion and intensification of agriculture in The Netherlands, in the 9th and 12th century, respectively, had a large impact on the environment. Not only did crop cultivation itself led to soil degradation, but fertilizing the poor sandy soils had a negative effect as well. The most important method of fertilizing the soil for crop cultivation was the use of sods in plaggen practice. Plaggen practice is a method used in traditional agriculture, and refers to the use of heather sods combined with manure to improve the penetrability, moisture holding capacity and nutrient content of the soil. From the 10th century onward the use of heather sods enabled cultivation of both nutrient-depleted soils due to overexploitation and relatively nutrient poor fine grained coversands. First only coarse grained, relatively nutrient rich deposits on the ice pushed ridges could be used (Blume & Leinweber, 2004; Heidinga, 1984; Koster, 1978; Tolksdorf & Kaiser, 2012; van Mourik et al., 2012). On agricultural fields crops were cultivated during part of the season, leaving the soil fallow for a relatively short period. Due to the plaggen practice fallow areas were created for much longer periods of time. In order to provide 4 ha with heather sods, it was necessary to cut an area of 3 ha. Only after several years the area fully recovered into heath land again (Heidinga, 1984; Pape, 1970). As a result, cutting heather sods impeded the natural vegetation succession and therefore the regeneration of woodland (Heidinga, 1984).

The plaggen practice was considered to be an important process for crop cultivation in the whole western sand-belt from the 10th century onward (Behre, 1981; Blume & Leinweber, 2004; Tolksdorf & Kaiser, 2012; van Mourik et al., 2012). Archaeological evidence shows that plaggen practice was used in the Veluwe area approximately from the 10th century onward (Heidinga, 1984). However, Spek (2004) argues that in Drenthe the use of plaggen fertilization did not start before the 15th century, much later than previously thought. Following this, it can be argued that the start of aeolian sand drifting was not always correlated to the start of the plaggen practice. Nevertheless, it is clear that after the onset of the process, aeolian transport was maintained as long as the vegetation cover remained absent and the groundwater table was low. Wind erosion formed oval-shaped sand drift cells in the central Veluwe, ensuring constant movement sediment (Heidinga, 1984; Koster, 2009).

Apart from the influence of the plaggen practice, other factors also had an impact on the environment, such as cattle farming and traffic. From the Late Middle Ages onward, traffic and drovers' roads for flocks of sheep created zones where sediment was loosened and vegetation was removed. Additionally, sheep farming prevented the natural regeneration of the forest (Heidinga, 1984). Furthermore, also agricultural fields that were left fallow were a hazard for sand drifting. Especially in the first year, when grasses or weeds were not abundantly present, the risk of aeolian transport was large (Heidinga, 1984).

In the province of Drenthe, several archaeological studies have been carried out, creating the opportunity to relate human impact to phases of increased aeolian activity already from the Neolithic onward (Harsema, 1984). According to Van Gijn & Waterbolk (1984), the area has been more or less continuously inhabited since the Bronze Age. However, the habitation history of many settlements between the 2nd and 10th century is uncertain. In historical archives names of villages are mentioned from the 10th century onward, and from these archives it can also be inferred that the number of villages increased from the 14th and 15th century (Castel, 1991). Furthermore, in the western part of Drenthe the increase in Medieval aeolian transport began much earlier than in the eastern part, 1100 AD compared to 1700 AD, respectively. This could imply that the western part of Drenthe was inhabited most densely in the Early Middle Ages, causing an earlier onset of sand drifting (Castel, 1991).

3.2 Kootwijk

In The Netherlands, archaeological evidence of permanent settlement locations from the Early Middle Ages is rare. In the 1970's an archaeological study focused on the Kootwijkerzand area during the Roman period and Medieval period. According to Heidinga (1984), the area was already inhabited from the Neolithic onward. Flintstone dated to 2500 BC and pottery debris dated to 1700 BC was found at this specific site. The site selection of suitable areas for farming was presumably based on local differences in soil humidity, indicated by the presence of vegetation and soil texture. Occupation from the Neolithic to the Roman period is represented by a few isolated finds. Therefore, it is not clear whether the area was occupied constantly (Heidinga, 1984).

At the end of the Late Roman Period (2nd – 3rd century) the first settlement with a permanent character was founded in this area (Kootwijk 3) (figure 11). This settlement was small and consisted of a few houses only. Between the 4th and the 6th century AD, the Migration Period, no archaeological evidence of human occupation was found. This period was followed by two other settlements in the 6th and 7th century with small clusters of houses and farmsteads (Kootwijk 4 and 5). Noticeable was the fact that 80% of the pottery that was found during the archeological study was imported from outside this area, indicating relative wealth. It was found that the eastern and southern part of these settlements were heavily affected by drift-sand sedimentation, although the timing is not known (Heidinga, 1984). Kootwijk 2 was founded around 750 AD. The buildings of Kootwijk 2 were characterized by a more organised structure than Kootwijk 4 and 5, the occupation was more concentrated in one spot instead of the presence of small clusters of houses. It is estimated that around 50-150 people inhabited this settlement, 52 farmhouses were found during the excavation (figure 12).

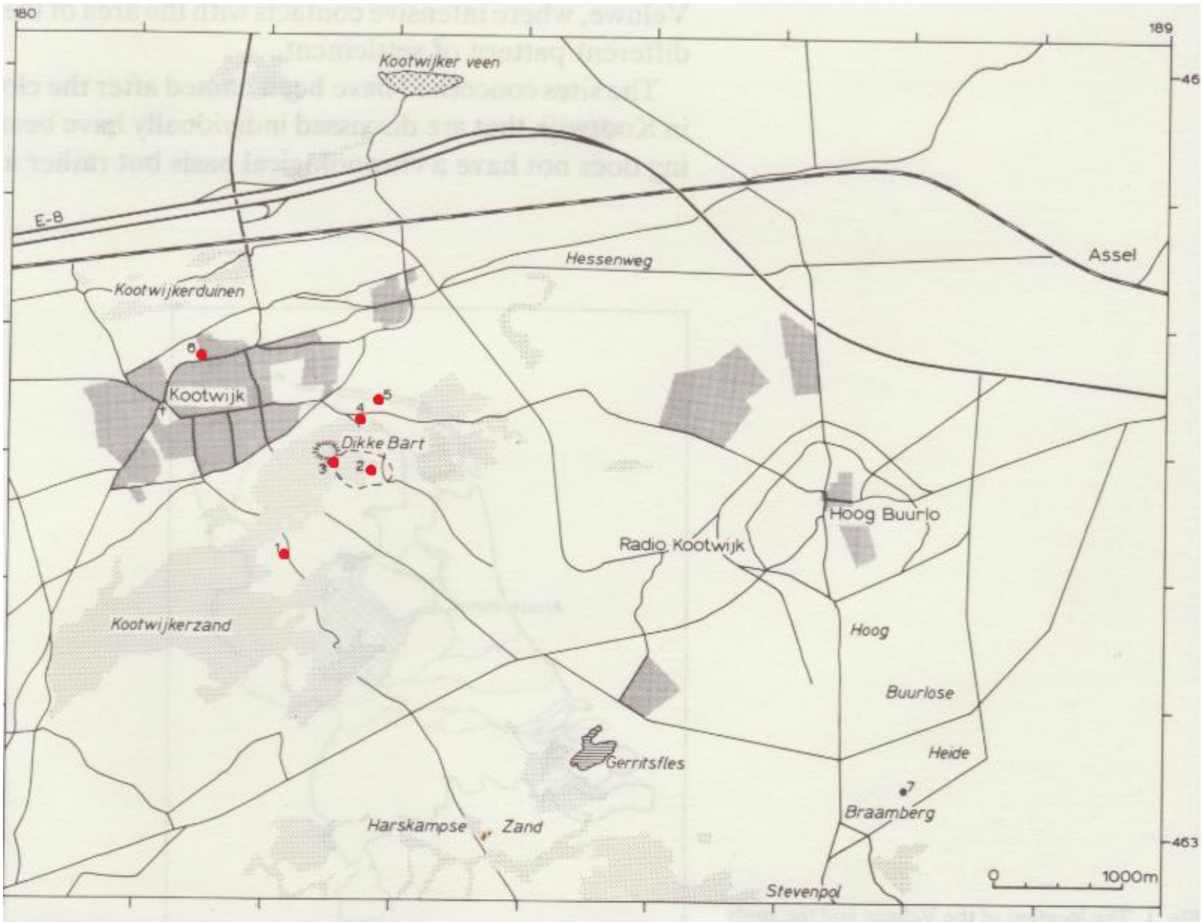

Figure 11. Locations of the Roman and Medieval settlements (in red) in the area near Kootwijk, The Netherlands. *Retrieved from after Heidinga (1984).*

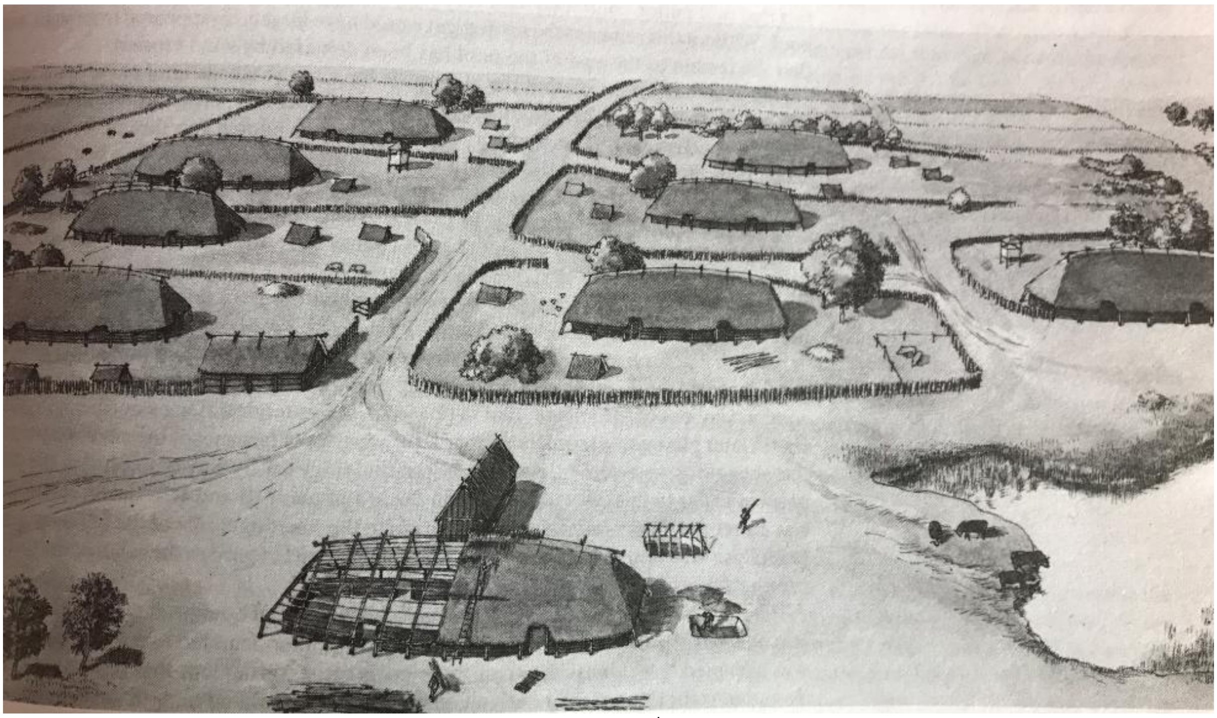

Figure 12. Impression of the village of Kootwijk 2 in the mid 8th century. *Retrieved from Bloemers et al. (1981).*

During the archeological excavation, evidence for a dry period around 1000 AD was found. Near Kootwijk 2 a pool formed due to water stagnation on the B horizon. This pool presumably attracted the larger community to settle in this specific location since water in the surrounding area was scarce. According to Heidinga (1984) a 40 year long dry period around 1000 AD caused the pool to dry up, forcing people to retrieve their water elsewhere. In his study Heidinga bases the presence of this dry period on tree ring data from central Germany, indicating growth stagnation due to moisture shortage, and a study of the soil-moisture curve of a peat deposit in northwest-England (Lamb, 1977; Barber, 1981). However, in general, evidence of this 40 year dry period has not been found widely in palynological records and lithological analyses of peat sections in northwest Europe encompassing this period (Heidinga, 1984; Koster, 2009).

During archaeological research it was found that half of Kootwijk 2 was covered with drift sand before 1000 AD. Traces of ploughing were found on fields already covered with a layer of sand, indicating the presence of aeolian activity while Kootwijk 2 was still inhabited. Also, wells filled with sand were found, including traces of attempts to dig out the sediment. Furthermore, it was found that fences that were first used for cattle, later served to protect the settlement from sand blowing in. This was concluded from finding fences with sand blown-up against one side of it (Heidinga, 1984).

After forced migration from Kootwijk 2, a scattered settlement pattern followed (Kootwijk 1 and 6) (Groenman-van Waateringe & van Wijngaarden-Bakker, 1987; Heidinga, 1984). As sand-drifting continued, Kootwijk 1 was abandoned and habitation concentrated on the area adjacent to the region where drift-sand deposition was most intense, Kootwijk 6. Based on written sources, it can be assumed that the current village of Kootwijk originated from Kootwijk 6 and was inhabited from the 12th century onward. In the Late Middle Ages, Kootwijk was one of the main villages in the area together with Essen and Kootwijkerbroek. To minimize the threat of sand drifting, active reforestation took place from in the 18th and 19th century (Castel & Koster, 1987).

4. Climate

In addition to the anthropogenic influence on vegetation development during the Late Roman Period and Middle Ages, climate oscillations could also have been important. A sudden change to drier conditions as the primary trigger for the onset of sand drifting was proposed by Heidinga (1984), based on archaeological data. However, from other archives this shift is not evident. In palynological research hazel (*Corylus*) and pine (*Pinus*) are genera which could show such a change in climate, since they respond positively to drier conditions (Dupont, 1986; B. Van Geel, 1978). Evidence for such a change to drier conditions was not found in pollen data from peat sections in northwestern-Europe encompassing this period. Therefore, it is assumed that this dry period was either restricted and did not have an effect on the vegetation community, or that it was a local event (Castel, 1991; Koster, 2009; Tolksdorf & Kaiser, 2012).

Between 1 and 1500 AD distinct climate oscillations have been found. In an overview of temperature proxy data by Ljungqvist (2009) from the extra-tropical Northern Hemisphere (90-30 °N) the Roman Warm Period (RWP) (1 - 300 AD) and Dark Age Cold Period (DACP) (300-800 AD) are visible in a considerable number of records (figure 13). Summer precipitation reconstructions from tree-ring data in Europe show that while during the beginning of the Roman Period the precipitation was above average, a dry period occurred in the 3rd and 6th century AD. Precipitation started to increase again from the end of the 6th century AD and reached levels comparable to the beginning of the Roman Period by the 8th century AD (Buntgen et al., 2011). The Medieval Warm Period (MWP) (800 – 1300 AD) can be recognized in the majority of the climate records shown in Ljungqvist (2009). During this period it was relatively humid, no large fluctuations are identified in the summer precipitation (Buntgen et al., 2011).

According to Ljungqvist (2010) the second century, during the RWP, was the warmest century from the last two millennia before the onset of anthropogenic climate change. Overall, the amplitude of temperature variability between the warmest and coldest century reconstructed for the last two millennia is 0,62 °C (Ljungqvist, 2010; Moberg et al., 2005).

While the increase in temperature during the RWP and MWP led to glacier retreat in the Alps, the Little Ice Age (LIA) (AD 1300-1900) resulted in an increase in glacier extent. The decrease in temperature during the LIA was coupled to wetter summers (Buntgen et al., 2011). Cooling in the LIA appeared to be more significant than the temperature decrease during the DACP. Furthermore, the DACP showed more temporal temperature variability than the LIA, and could therefore be less pronounced in low resolution temperature records (Holzhauser et al., 2005; Ljungqvist, 2009, 2010; Mangini et al., 2005).

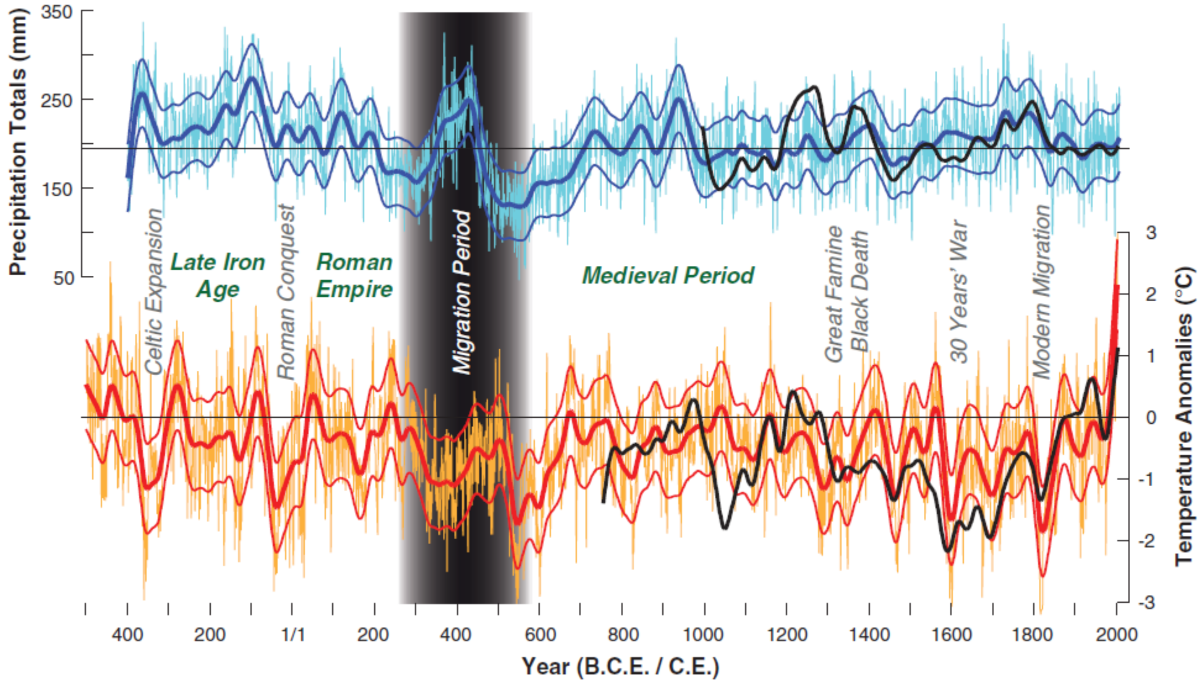

Figure 13. European summer precipitation totals (mm) (top) and summer temperature anomalies (bottom) with respect to the mean temperature in 1901-2000. The black lines indicate the independent precipitation and temperature reconstructions from Switzerland and Germany. The error bars indicate the root-mean-square deviation. *Retrieved from: Buntgen et al., 2011.*

In this study, the climatic oscillations are considered to be of minor importance compared to the anthropogenic influence in the onset of drift-sand sedimentation. In general, drift-sand sedimentation started earlier than the climatic shift from the MWP to the LIA. Pollen data from peat sections encompassing this period do not show a vegetation change which corresponds to a cooler climate (Castel, 1991; Koster, 1978). However, it is possible that the anthropogenic signal suppresses a possible climate signal, and therefore is not apparent from the pollen record.

5. Vegetation

In this chapter the a general overview of the vegetation development in the Holocene will be provided. Additionally, the vegetation development from records near Kootwijk will be discussed in detail, focusing on the period from 1-1500 AD. Consequently, the results of these records can be compared to the vegetation development that is found in the Kootwijkerveen. This could help to get a more complete impression of the regional vegetation development and could possibly provide an age indication of the different stages in the vegetation development of the Kootwijkerveen.

5.1 The Netherlands

When the temperature rose after the end of the last glacial, tree species that survived in refugia in the south of Europe could expand their range. Species that resided in these refugia included thermophilous trees such as birch (*Betula*), hazel, oak (*Quercus*), elm *(Ulmus*), lime (*Tilia)*, alder (*Alnus*) and ash (*Fraxinus*) (Kolstrup, 1990; Bennet et al., 1991; Birks & Willis, 2008; Bos & Zuidoff, 2015). In the early Preboreal (c. 9000 BC), birch expanded, followed by pine in the Late Preboreal (c. 8200 BC). At the start of the Boreal (c. 7800 BC), hazel occurs in the Netherlands for the first time after the end of the last glacial. The immigration of hazel was quicky followed by oak, elm and lime. As a result, mixed oak forests developed and coniferous forests dominated by pine decreased in extent (Bos & Zuidoff, 2015).

During the Atlantic (7000-3800 BC), relatively large percentages of elm and ash pollen were first observed in pollen diagrams of the Netherlands (de Mulder et al., 2003). During the Atlantic a deciduous forest, consisting of oak, lime, elm and hazel was abundantly present throughout the Netherlands. In the undergrowth of this stable climax forest ivy (*Hedera helix*), mistletoe (*Viscum album*) and holly (*Ilex*) were present (Bos & Zuidoff, 2015). In the Atlantic period a high tree-pollen percentage was found in pollen diagrams, equal to or exceeding 90% (Groenewoudt et al., 2007; Koster, 2009).

The transition from the Atlantic to the Subboreal period (c. 3700 BC) can be recognized in pollen diagrams by the marked decrease in lime and elm pollen percentages (figure 14). The marked elm decline could have been caused by elm disease which was transmitted by beetle species (Iversen, 1973). Additionally, the Subboreal (3700-1000 BC) is characterized by the expansion of beech (*Fagus*). While during the Atlantic a stable and diverse climax forest was present, during the Subboreal the increase of human disturbance led to an increase in fragmentation of the forest. Consequently, the diversity of habitat types and species richness increased (Iversen, 1973). Intensified human activity led to an increase of small-scale woodland openings which where grassland, heathland and shrub vegetation could develop.

From the early Subatlantic (Iron Age, 800 – 12 BC) onward the AP/NAP ratios started to decrease, a trend which continued until the Roman period. Simultaneously, hornbeam (*Carpinus*) first appears in pollen diagrams from the Netherlands (de Mulder et al., 2013). The decrease in arboreal pollen coincided with the rise in cereal (Cerealia) pollen and an increase of human indicator species, such as cornflower (*Centaurea cyanus*) and buckwheat (*Fagopyrum esculentum*). From the start of the Roman period (12 BC – 450 AD), a general trend toward deforestation occurred in the Netherlands (Bos & Zuidoff, 2015). Birch increases slightly while the downward trend of lime and elm, which had already started, continued (Iversen, 1973). Before the Roman Period, rye (*Secale cereale*) was very scarcely found in the Netherlands. It was not a cultivated crop yet, and occurred as an arable weed. Rye started to appear more frequently from the Roman Period onward, but only from the beginning of the Middle Ages it really started to increase significantly and was used for crop cultivation widely (Van Zeist, 1976; Behre, 1992; Lauwerier et al., 1999).

During the Migration Period (450-600 AD) reforestation occurred on a large scale. A decrease in human impact led to natural vegetation succession and woodland could regenerate (Janssen, 1974; Koster, 1978). During the Late Middle Ages (AD 1050-1450), extensive areas in The Netherlands were deforested, since agriculture was expanded and intensified. The area for crop cultivation and plaggen practice increased at the expense of woodland. Accordingly, the area of heathlands, grasslands and shrub vegetation increased (Koster, 1978; van Beek et al., 2015).

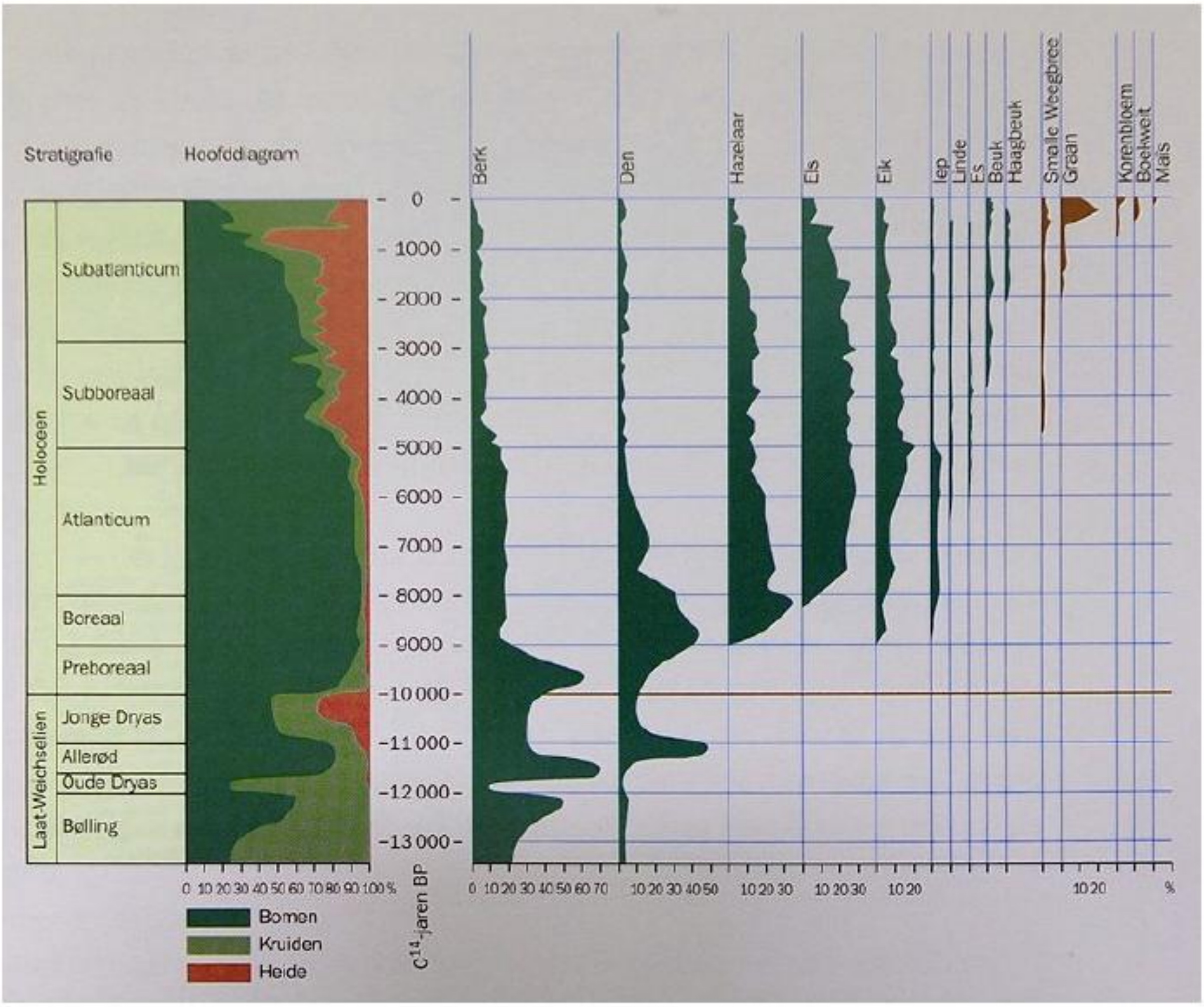

Figure 14. General pollen diagram of the Netherlands, covering the Late-Glacial and the Holocene. Left, the pollen zones are indicated. Note: cereal ('Graan') is referring specifically to rye. *Retrieved from de Mulder et al, 2013.*

As the human impact on its environment increases, indicators of this human presence can be found in the pollen assemblage. These are pollen types of plants that people cultivated for consumption, to make utensils with, that do well in open areas or that can be found in nutrient rich areas. These types can grow as arable weeds, and certain pollen types, such as plantain (*Plantago*), are found in areas which are frequently subjected to treading. Finding hemp pollen (*Cannabis*) could be an indicator for the retting of hemp, provided that there is a water body available locally. Retting of hemp in water was done in order to produce fiber. However, since its pollen morphology closely resembles that of hop (*Humulus*), the presence of this pollen type could also originate from the presence of hop in the undergrowth of the forest. In The Netherlands, the occurrence of *Cannabis/Humulus* type pollen increases from 500 AD onward, but does not reach maximum percentages until 800-1200 AD (Koster, 1978). Also cornflower is closely coupled to human presence, since it occured in rye fields as an arable weed. From approximately the 10th and 11th century AD, a combination of rye, cornflower and buckwheat was often found in areas which were influenced by human presence (Bos & Zuidhoff, 2015; Koster, 1978). Dock (*Rumex*), mugwort (*Artemisia*), species of the goosefoot family (*Chenopodiaceae*) and the composite family (*Asteraceae*) are examples of species that are closely associated with crop cultivation. They are found as arable weeds and grow in nutrient rich conditions. Furthermore, an increase of plantain pollen percentages is usually closely associated to human presence, since they are resistant to treading.

5.2 Kootwijk

Near the Kootwijkerveen, several pollen records are available that can provide information on the regional vegetation development. In 1978 a palynological study has been conducted in the Kootwijkerveen itself (Koster, 1978). However, the details on drift-sand influx into the Kootwijkerveen still remained unclear because of the absence of details provided in this study. Furthermore, since this study was carried out approximately 40 years ago, there is a strong need for an updated pollen and LOI record in order to optimally determine the interregional differences in the vegetation development of north-western Europe during the Dark Ages Project. In 1987, following the archaeological excavation led by Heidinga (1984), palynological investigations of wells, turves and sandy infills of sunken huts were conducted. However, this contained mostly material with a poor pollen preservation such as sandy samples poor in humic content, which led to selective corrosion and a low pollen sum (Groenman-van Waateringe & van Wijngaarden-Bakker, 1987). More recently, in 2016, a palynological record of the Uddelermeer was published, from the Late Glacial to the present. The Uddelermeer is located approximately 5 km from the Kootwijkerveen, and could provide valuable information on the vegetation development in the region. In this section, the regional vegetation development from 1-1500 AD will be discussed based on these records.

A detailed reconstruction of the vegetation development in the central Netherlands can be provided based on a regional pollen diagram (Engels et al. 2016). This research was conducted in the Uddelermeer, a pingo remnant from the Last Glacial Maximum. The Uddelermeer is located 5 km north of the Kootwijkerveen. The palynological record from this site shows that a rapid increase in AP percentages occurred during the start of the Holocene (figure 15). During the Preboreal, the development of a birch woodland was quickly followed by the expansion of pine-birch woodland. Corresponding to the general vegetation development in the Netherlands, the presence of hazel increased during the onset of the

Boreal (Engels et al., 2016). During the Atlantic period, a deciduous forest was present in the central Netherlands. A variety of tree pollen was found, including elm, oak and alder. Analogous to the general vegetation development, elm decreased significantly during the start of the Subboreal. During this specific period, the first signs of human impact in the region were found: cereal and ribwort plantain (*Plantago lanceolata*) pollen (Engels et al., 2016). Decreasing AP percentages were found during the Roman period. In approximately the 3rd or 4th century AD (corresponding to c. 1750 cal. yr. BP) a period of forest recovery occurred, continuing until approximately 700 AD (1250 cal. yr. BP) (figure 15). This suggests that in this region reforestation commenced relatively early, since it is generally assumed to begin in 450 AD, corresponding to the Migration Period. Following this period of reforestation, increasing human impact on the environment can be identified in the Uddelermeer (Engels et al., 2016). Heather and cereals increase, while AP percentages decrease. The sudden and strong maximum of *Cannabis/Humulus* type pollen indicates the retting of hemp in the water body. The increasing LOI values starting from 1500 AD (450 cal. yr. BP) suggest an increase of mineral influx in the Uddelermeer after the end of the Middle Ages.

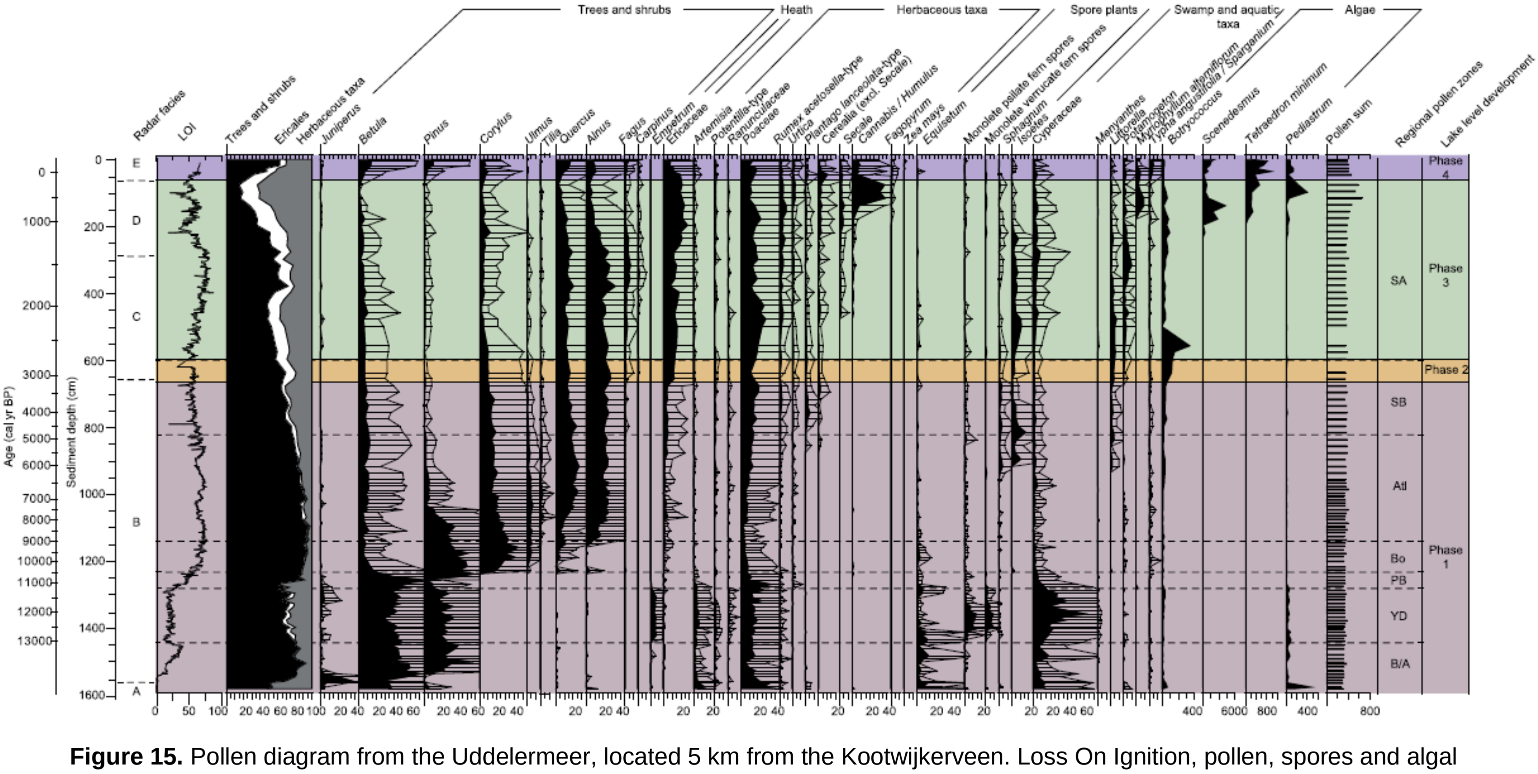

Figure 15. Pollen diagram from the Uddelermeer, located 5 km from the Kootwijkerveen. Loss On Ignition, pollen, spores and algal taxa have been counted. The time scale is plotted in cal. yr BP. 1-1500 AD, the period used in this study on the Kootwijkerveen, corresponds to 1950-450 cal. yr BP. *Retrieved from Engels et al., 2016.*

A local pollen diagram from the Kootwijkerveen itself shows various changes in forest cover from 1-1500 AD, of which decreases of AP percentages in the Late Middle Ages are sometimes attributed to the iron production in the Veluwe area. The pollen diagram from the Kootwijkerveen itself shows that during the Roman period, lime disappears from the vegetation assemblage around the Kootwijkerveen. Simultaneously, hornbeam appears and the first presence of rye is recorded (figure 9) (Koster, 1978). According to Koster (1978) the oak-birch and oak-beech forest surrounding the Kootwijkerveen region expanded greatly during the Migration period in the Early Middle Ages. After the 9th century deforestation increased, and really intensified from the 12th century. This is in accordance with the expansion and intensification of agriculture around the 9th and 12th century, respectively (Groenewoudt et al., 2007). Heidinga (1984) argues that local iron production was especially important in this trend, because of the requirement of wood for the charcoal industry. Early sand drifting phases in the 6th century in Hoog Buurlo and Hoenderloo, two sites close to the main iron production area in the Veluwe, could be an indication of early deforestation as a result of the production of charcoal for the iron industry (Heidinga, 1984). However, this is highly criticized by Joosten (2004) who claims that large scale deforestation in the Veluwe only started after the local iron production was discontinued in the 9th century. Therefore, it is argued, burning wood for the iron production could not have been a cause for sand drifting (Joosten, 2004).

In the Late Middle Ages, agriculture expanded and intensified, leading to a decrease in AP percentages, the expansion of human indicator species and an increase in crop growth. The increase of heather is correlated to the deforestation trend from the 9th century onward. Simultaneously, the pollen percentages of oak and beech are very low and hornbeam is absent. Towards the end of the 11th century grasses (Poaceae), cereals, plantain and buckwheat show an increase. These are species indicating crop cultivation and treading of the surface (Koster, 1978). According to Groenman-van Waateringe & van Wijngaarden-Bakker (1987), the area directly surrounding the settlement, which was most intensively used, must have been largely free of any forest cover. Only few trees were present, deliberately planted in order to protect the arable fields and settlement from wind. Before the final sand drifting phase made crop cultivation impossible in the area, rye, common oat (*Avena sativa*), barley (*Hordeum*) and flax (*Linum*) were cultivated in the region of the Kootwijkerzand (Koster, 1978). Based on the presence of these crops, it is assumed that crop rotation was used (Pals, 1984).

A new vegetation reconstruction will be made in order to complement to the palynological data from this region and to integrate it with archaeological evidence. The vegetation reconstruction in this study will also focus on Non Pollen Palynomorphs (NPP's) and will emphasis on the period of high drift-sand influx around the 11th century.

6. Material and methods

6.1 Fieldwork

6.1.1 Area selection

The focus of this study is on the role of human impact and local environmental change before the onset of aeolian activity. In this respect, The Veluwe area is of specific interest since several drift-sand areas are present here and research has shown that human interference played a role in the onset of this aeolian activity (Koster, 1978; Koster & Favier, 2005). The Kootwijkerveen (52°12'26.48" N 5°47'55.33" O) contains recent peat deposits as well as drift-sand influx. It is located approximately 2,5 km north of the most northern boundary of the Kootwijkerzand (figure 16 and 17). The ombotrophic peat bog started growing when water stagnated on top of an impermeable humus podzol layer (B2h/B22 horizon) in a coversand depression (Koster, 1978).

In The Netherlands, large scale peat reclamation resulted in the near disappearance of peat formations which can be used for late Holocene research (Castel, 1991). In the Kootwijkerveen the drift-sand influx resulted in optimal conditions for this research. Firstly, the influx prevented the excavation of the underlying peat layers for fuel. Secondly, the influx created the opportunity to investigate human impact and environmental change before the onset of aeolian transport.

Figure 16. Location of the Kootwijkerveen on the map. *Source: Google Earth*

Figure 17. Location of the Kootwijkerveen and Kootwijkerzand. *Source: Google Earth*

6.1.2 Site selection

The borders of the Kootwijkerveen were mapped in order to detect its extent. Drilling was done using an Edelman corer with 6 cm gouge attached. Based on the height profile (AHN map), boundaries of the peat could be estimated. Coring was done lateral to this estimated boundary. Adjustments were made to planned coring locations when the boundary of the peat seemed to deviate from what was expected. The presence or absence of peat layers was noted during the on-site core descriptions (Appendix B).

The optimal coring location was identified based on exploratory drillings in a transect from west to east (figure 18). The transect from north to south was not completed, only two of the planned seven drillings were carried out. This was because based on these drillings, it was found that the depth of the bog was relatively uniform throughout the area and there was no need to identify the thickest part. Drilling was done using an Edelman corer with attached gouge (6 cm). Care was taken not to drill through the B horizon. The sediment was placed on the sediment surface and described on site (appendix A).

When choosing the coring location, several preconditions had to be taken into account. Firstly, the peat layer had to be of maximum thickness in order to retrieve the highest resolution and the most complete dataset possible. Secondly, an optimal condition of the peat was required, meaning that humification of the peat layers was as low as possible and that sand was minimally present. Low humification of the peat ensures the most optimal preservation of organic material, since its exposure to oxygen is minimized. Additionally, low humification lowers the risk of finding hiatuses in the core sequence (Castel, 1991). Finally, the coring location preferably had to contain a gradual transition from peat to drift sand, which is described as 'peaty sand' (Koster, 1978). It is expected that especially in these layers the relation between human impact, vegetation development and the onset of aeolian dynamics could be studied optimally.

Figure 18. Locations of the 12 exploratory drilling sites. *Source: Google Earth.*

6.1.3. Coring

In October 2016, two cores were taken at locations where all three previously discussed conditions were met (figure 19). Overall, in both locations the peat was in good condition, was relatively thick and drift sand covered the peat accumulation. An Edelman corer (6 cm gouge), Piston corer and a van der Staaij suction corer were used to retrieve the cores in location B. Location A was cored using the van der Staaij suction corer only, since the Edelman and Piston corer were not able to core through the fibrous material and got stuck. On site, Optically Stimulated Luminescence (OSL) samples were taken in both sampling locations: OSL-KWKV-2 (30-50 cm) in location A and OSL-KWKV-1 (40-60 cm) in location B. Also, in the parabolic dune on the eastern side and in the drift sand accumulation west of the Kootwijkerveen OSL samples were taken: OSL-KWKV-4 (90-110 cm) and OSL-KWKV-3 (70-90 cm). OSL-KWKV-3 was taken in the drift-sand deposit directly on top of a podzol profile in the coversand. These OSL samples were taken in order to date the deposition of aeolian material into the bog and the formation of the parabolic dune (figure 20).

The cores were stored in PVC pipes wrapped in plastic foil. The exact location and depth were written down on the plastic and in our fieldwork notes. At Utrecht University the cores were stored at 4-8 °C before further use in the laboratory, in order to minimize decomposition. Three AMS samples were taken in the lab (figure 19). Unfortunately, the ^{14}C AMS samples were not analyzed in time to be able to use them in this study.

Figure 19. Locations of both cores. *Source: Google Earth*

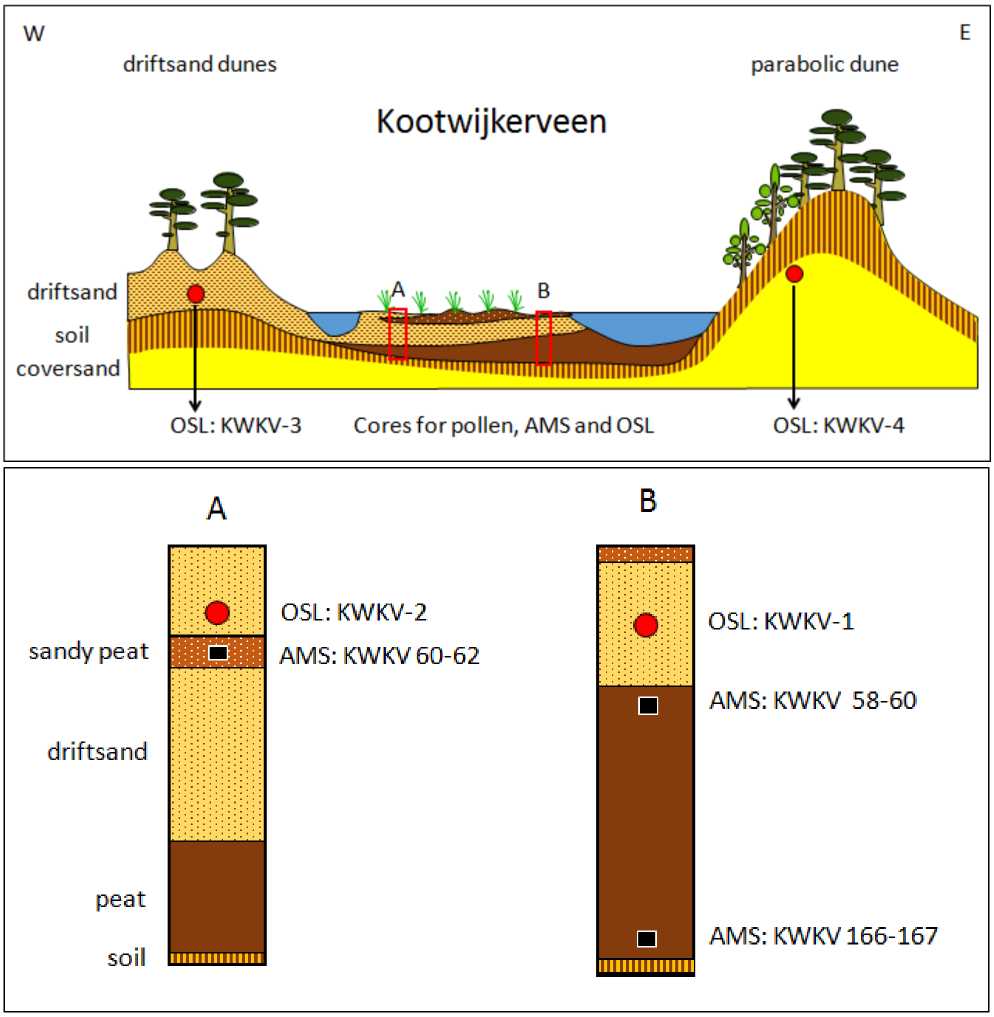

Figure 20. Cross section of the Kootwijkerveen, from west to east. The locations of both cores are indicates, as well as the 4 OSL samples and 3 samples for ^{14}C analysis that were taken. *Retrieved from: Hoek, unpublished.*

6.2 Labwork

6.2.1. Lithology

In the laboratory of Utrecht University, first the plastic wrap and PVC pipes were removed from the cores. The core was cut in half over the whole length in order to expose the clean inner structure. Photos were taken with a measuring rod placed next to the cores, indicating the correct depths (Appendix C).

A detailed description of the lithology was made based on visual interpretation of the sediment. Focus was on the texture, colour and grain size of the deposits.

6.2.2. Sedimentological analysis

To determine the organic content of the sediment, Loss On Ignition (LOI) analysis was carried out (Heiri et al., 2001). Samples of approximately 1 cm^3 were taken every centimeter throughout the cores, starting from the bottom and working towards the top. This was done because contamination in the natural environment usually occurs from bottom to top as well. The samples were weighed and placed in ceramic crucibles with a known weight, and were heated to 105 °C for 12-24 hours. This was done in order to determine the dry weight of the samples. In this respect, the samples were weighed immediately after coming out of the furnace to reduce moisture uptake. The samples were then heated to 550 °C for 4 hours. By doing so, organic matter was oxidised into carbon dioxide and ash (Dean, 1974; Heiri et al., 2001). The samples were weighed again.

The organic matter content of the samples could be determined as the percentage of weight loss after ignition using the following equation:

$$LOI(\%) = (W_g-W_b) / (W_d-W_b) \times 100\%.$$

Where W_g represents the weight of the ceramic crucible containing the sediment after heating to 550 °C, W_b the weight of the empty ceramic crucible and W_d the weight of the crucible containing the dry sediment after heating it to 105 °C. The LOI data was visualized using Microsoft Excel.

6.2.3. Palaeoecological analysis

It was decided to focus this research on location B only, due to limited availability of time for palynological analyses and as a result of the difference in quality of both cores. The peat accumulation in location A was discontinuous and of poorer quality and quantity than in location B. In total 64 samples for palynological analysis were taken from location B. Every 2 centimeter a sample of approximately 1 cm^3 was taken, again working from the bottom of the core towards the top to minimize contamination. Because the peat was very fibrous, it was not possible to take consistent volumetric samples and the recommended sample size of 0.3 cm^3 could not be retrieved. As a result *Lycopodium*-tablets were not added because it is not informative when using volumetrically inconsistent samples. Consequently, pollen concentrations and influx could not be calculated. The samples were processed using the 'Work instructions pollen preparation' of Utrecht University, an instruction manual adapted from standard techniques (Faegri & Iversen, 1989) (Appendix D).

A light microscope with 600 x magnification was used to count pollen, fern spores, fungal spores and other non-pollen palynomorphs. Several keys were used to ensure correct identification of pollen and fern spores (Beug, 2004; Moore et al., 1991). The identification of fungal spores and other non-pollen objects was based on the work of van Geel (1998). Eventually a selection of 23 of the in total 64 samples was chosen for analysis. These 23 samples were equally distributed across the whole core (Appendix E). In some samples the pollen density was relatively low, therefore for a large number of samples more than on slide was prepared. Samples were counted in higher resolution towards the top of the core, where the transition from peat growth to drift sand takes place. Additionally, samples were counted in higher resolution when the pollen diagram showed distinct and unexpected fluctuations.

A pollen diagram was constructed using TILIA (version 2.0.41). The pollen sum (*n*= 300) included trees, upland herbs, heather and cereals. Alder, willow (*Salix*) and grasses were not included in the pollen sum, since in this specific environment they could represent a local rather than a regional signal.

7. Results

7.1 Peat extension

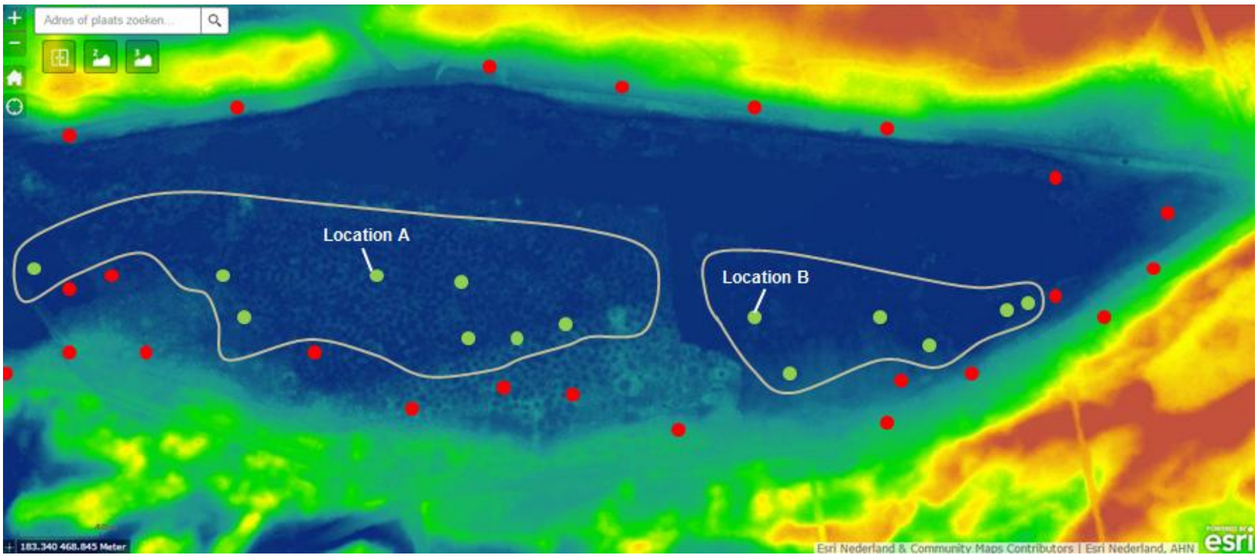

Figure 21. Schematic overview of the current extension of peat deposits in the Kootwijkerveen. The locations were peat was found are indicated with a green circle. A red circle is depicted where no peat was found. The elevation (high-low) is displayed as a transition from red-yellow-green-blue.

In figure 21 a schematic overview of the extension of the peat deposit is shown. Based on the presence of peat and the location of these sites on the AHN map, the extension of the peat bog could be inferred. While in sites with a relatively high elevation almost no peat deposits were found, in lower sites such deposits were found. The peat deposit is divided into two areas, separated by a water body. Since open water was present in the northern region of the bog, there was no ability to investigate the presence of peat more thoroughly in this specific area.

Apart from the extension of the peat, other assumptions can be made based on the AHN map of the region (figure 6, 21). From the AHN map it is visible that dunes are present towards the southwest of the area. This suggests that drift-sand influx started from and was most intense in the southwest of the bog. On the eastern side of the bog a parabolic dune is present (figure 6). Preliminary OSL results indicate that this parabolic dune dates from the Younger Dryas (ca. 12.400 cal. yr. BP). Furthermore, drift-sand dunes surround the bog. Preliminary OSL results indicate that drift-sand dune formation the western region, adjacent to the bog, dates from ca. 1625 AD (figure 6, figure 20). Furthermore, these preliminary results indicate that the drift-sand deposit in the samples from location A and B date from ca. 1775 AD and ca. 1450 AD, respectively.

Several land management activities were carried out in the Kootwijkerveen in order to protect and promote active peat growth in this raised bog. In the 1930's, the groundwater level was lowered as a result of the construction of a ditch in the eastern part of the bog (Londo, 2001). Hereafter, the eastern part was excavated after which it was used as a meadow until 1968. From then on, the area was actively managed by Staatsbosbeheer. Mowing took place every year and fertilization was stopped in order to promote peat growth. Since this did not provide the desired effect, in 1983, 40 cm of nutrient rich topsoil was removed in the eastern part which was formerly used as a meadow (figure 22). Location B is located in this area, indicating that 40 cm of the top of this core was removed 34 years ago.

After the completion of these activities, the drainage ditch was closed, leading to a significant increase in groundwater level. This led to the development of an open water body in the northern part of the excavated area. During the excavation activities in 1983, it was found that the subsurface was highly variable, with peat and sandy sediment alternating on a small scale. This suggests more human interference in the area than previously thought, at least in the eastern part, which was formerly excavated (Londo et al., 1994). In the southwestern part of the bog, an open water body developed due to the removal of a Norway spruces (*Picea abies*) and subsequent excavation of the nutrient rich topsoil in 1990 (figure 18) . Currently, Bulbous rush (*Juncus bulbosus*) is abundantly present in this water body (Londo, 2001).

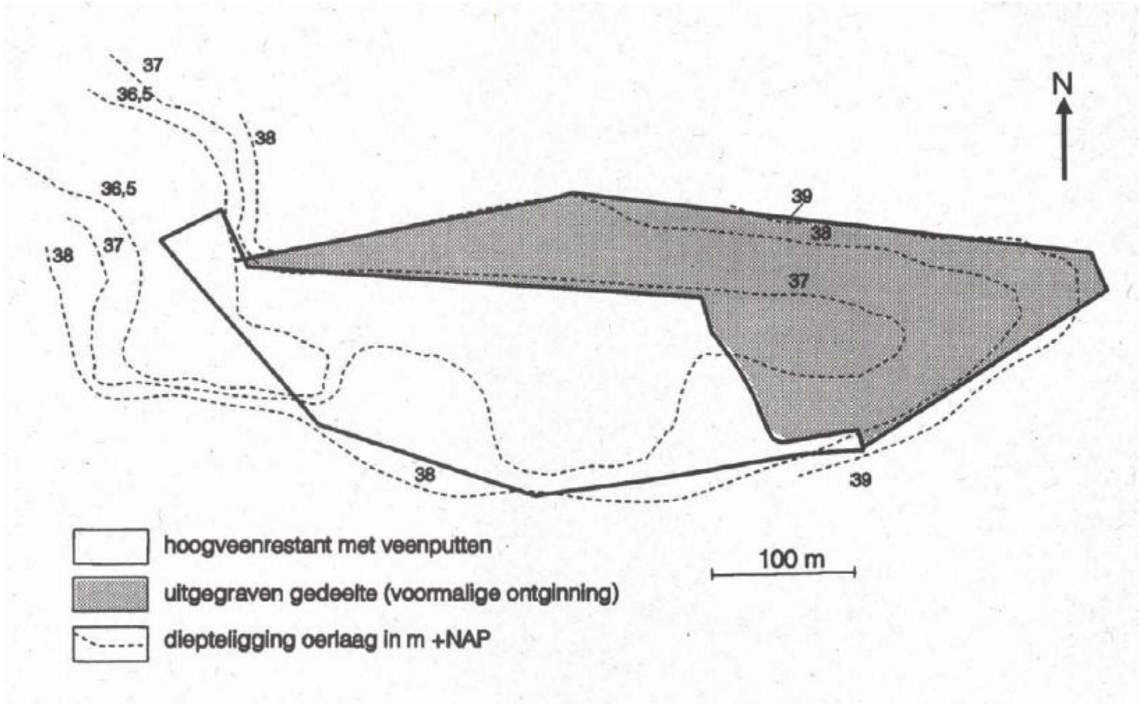

Figure 22. Overview of the Kootwijkerveen. The excavated area is indicated in grey, the former bog with peat hags is indicated in white. The dotted lines indicate the depth of the B horizon. *Retrieved from: Londo et al., 1994.*

The Kootwijkerveen has a surface area of approximately 8,5 hectares. According to Londo (2001), approximately 600 peat hags can be found in the bog. Currently, the Kootwijkerveen is characterized by a heterogenous surface where large sedge and peat moss tussocks are present on top of a recent peat layer (figure 23). These tussocks are very characteristic for this area and can be recognized on the AHN map as a raster-like structure on the surface of the bog (figure 21). In the water bodies, which developed after management activities in 1990 and 1983, species such as bottle sedge (*Carex rostrata*), black sedge (*Carex nigra*), water horsetail (*Equisetum fluviatile*) and bog pondweed (*Potamogeton polygonifolius*) expanded. Since their presence reduced water movement, a favourable environment for peat moss growth was created (Londo, 2001). During fieldwork in October 2016, characteristic species that were found included bog asphodel (*Narthecium ossifragum*), bog cranberry (*Vaccinium oxycoccus*), European bur-reed (*Sparganium emersum*) and spoonleaf sundew (*Drosera intermedia*).

Figure 23. The Kootwijkerveen peat bog, October 2016.

7.2 Lithological analyses

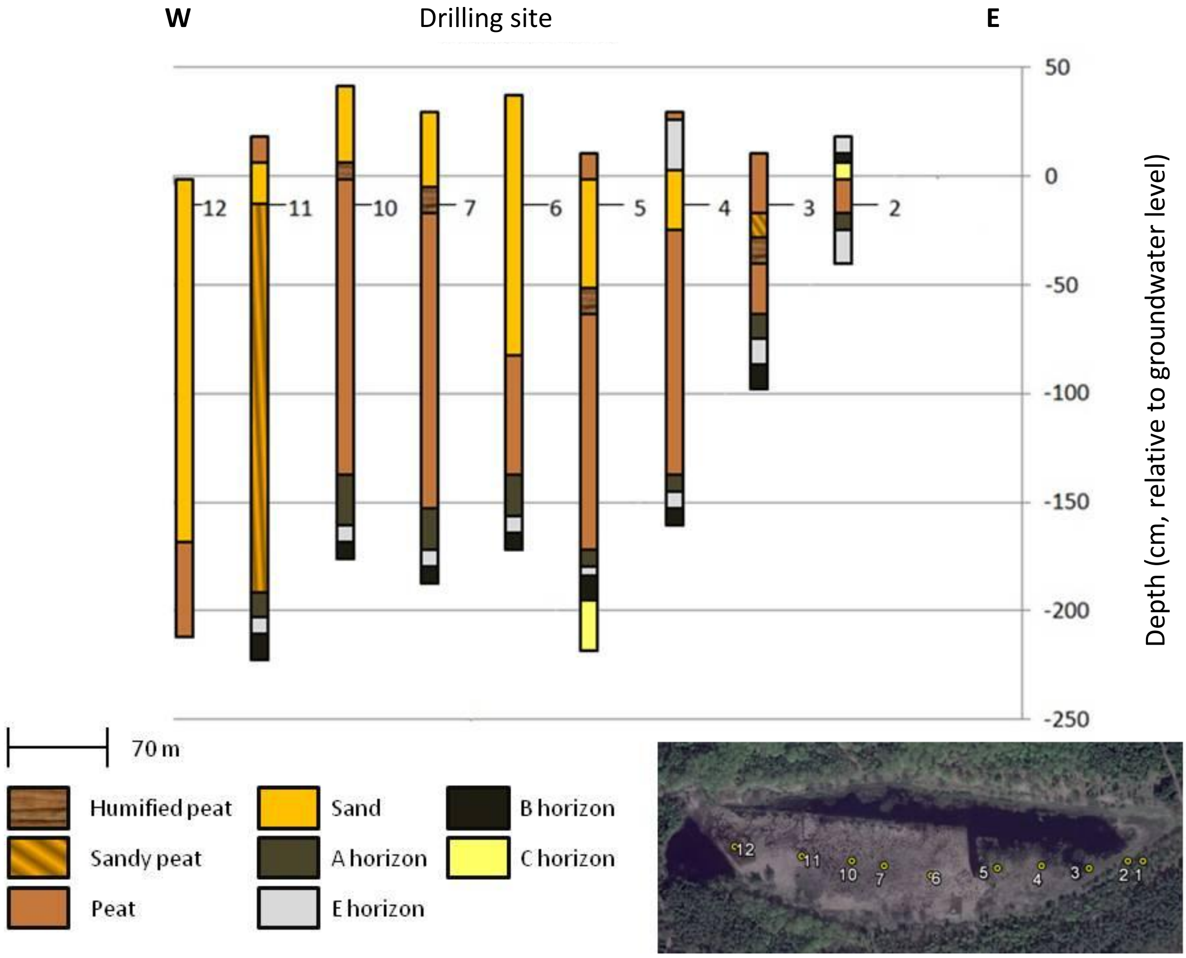

Figure 24. Schematic overview of the lithology of the area. A scale bar and legend are provided in the lower left corner of the figure. An overview of the locations of the exploratory drillings is added.

A total of ten of the twelve exploratory drillings, in a west to east profile, were used to construct a schematic overview of the lithology of the area (figure 24). From this schematic cross-section, it becomes clear that the thickness of the peat deposit is not constant. The quality of the peat is high, with a few exceptions where sandy peat and humified peat was found. In the coversand deposit underlying the peat bog, a similar soil development was found throughout the area. A small part of the B horizon was found several times. In the middle of the west-east transect the peat thickness and quality was highest. Towards the west relatively more influx of sand can be observed. Except for site 3 and 7, a drift-sand layer was found overlaying the peat deposit on every site. In site 10 and 2 a drift-sand layer was found above the current groundwater level, of 44 and 45 cm, respectively. The thickness of the drift-sand layer fluctuates because of the dunes in the drift-sand deposit. The thickness of the drift sand layer increases towards the western edge of the area.

Based on these exploratory drillings it was decided to use location A and B for further research, since in these locations both peat deposits were of high quality. When discussing the actual cores that were taken in site 5 and 10, these will be referred to as location B (52°12'25.91" N   5°48'02.01" O) and A (52°12'26.22" N   5°47'52.10" O), respectively. Next to their high quality, these locations were selected based on the differences between them: in site 10, the peat deposit extends above the groundwater level and growth of recent peat is not present here. In site 5, the top of the peat deposit is placed below the water table and recent peat growth was found. Furthermore, since the main drift-sand influx was from the west, it could be of interest to compare differences in timing and intensity of aeolian influx by choosing a location in the west and east of the bog.

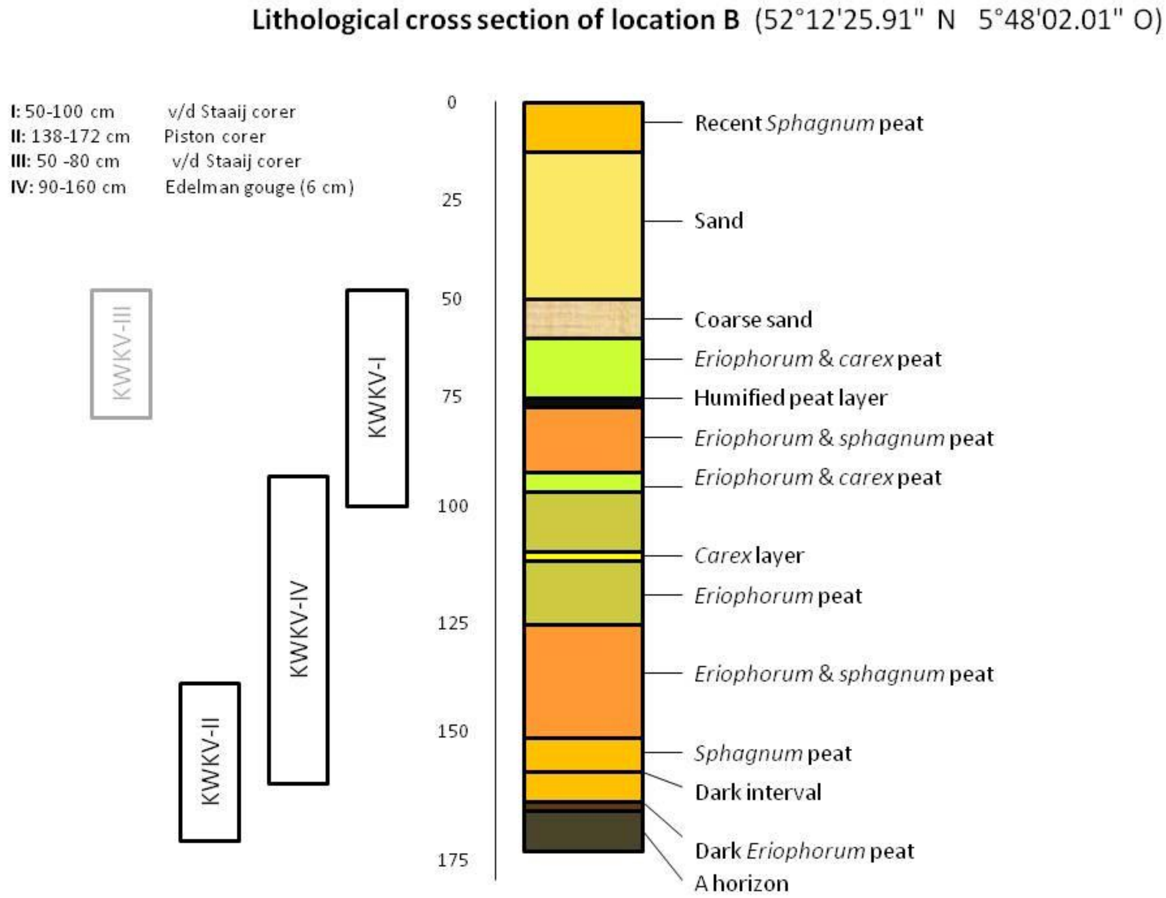

Figure 25. Schematic overview of the lithology on location 1. The different core sections are shown on the left, accompanied by information on the method of coring. KWVK-III was not used for further analysis.

Of the total four core sections in location B, three were used for further analysis (figure 25). Core section III was not used due to overlap with the qualitatively better and longer core section I.

The lower boundary of the peat section is located on top of a dark sandy layer, the A horizon. This is the topmost layer of the coversand deposit on which peat started growing. Overall, the peat deposit of this core is characterized by its high quality. Organic material is preserved very well and almost no mineral input is visible. Humification is minimally present. The peat deposit is dominated by the presence of cotton grass (*Eriophorum*), which was recognized as slightly orange coloured and filamentous organic remains. The lowermost section of the peat (165-152 cm) consists of yellowish peatmoss (*Sphagnum*) peat, with a cirrous structure. A clearly discernible black horizon is present on 153 cm depth. From 120-102 cm a textured peat layer is present, with a layer of *Carex* remains concentrated at 110 cm. Towards the top of the peat deposit an increased presence of *Carex* was observed,

occurring together with cotton grass. While almost the entire peat deposit consisted of fresh and pure peat, a humified layer was found from 72,5 – 74 cm.
On top of the peat deposit a layer of coarse sand is present. The transition from peat to sand is sharp. The grain size of the sand decreases towards the top of the core. Recent *Sphagnum* peat was found growing on top of the drift-sand deposit. During fieldwork the groundwater level was located 10 cm below the top of the soil. Location B is located in the area that was formerly excavated in the 1930's, and of which 40 cm of nutrient rich topsoil was removed in 1983.

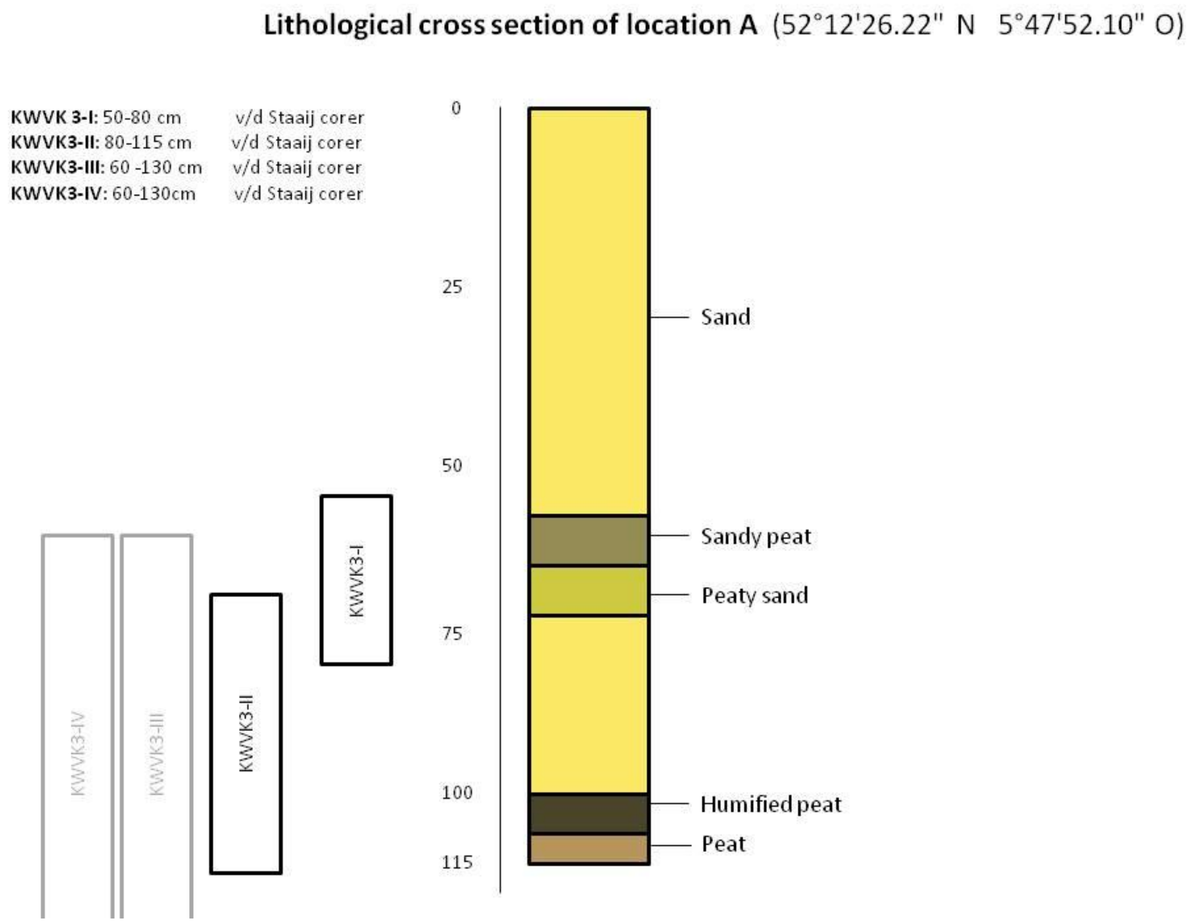

Figure 26. Schematic overview of the lithology on location 2. The different core sections are shown on the left, accompanied by information on the method of coring. The sections in grey were not used for further analysis.

While during the exploratory drilling a relatively thick peat deposit was found, the core which was taken at this location had a different composition (figure 26). In location A the surface was more irregular than that of location B, which could be an indication that perturbation took place here. The core was dominated by sandy material. A peat deposit of only a few centimetres thick was found, of poor quality. Next to this, only peaty sand and sandy peat deposits were found (58,5 – 71 cm). Because the two cores that were taken from 60 – 130 cm were of poor quality, accurate analysis deeper than 115 cm was impossible.

Coring was difficult in this location, because of the wet conditions of the sandy soil. Few coring devices are suitable for drilling in wet sandy soils. Here, the v/d Staaij suction corer was used, but instable and collapsing sandy layers were a problem in retrieving an intact and continuous core.

7.3 LOI analyses

Loss On Ignition analysis provides a quantitative estimate of organic content, and can be used to determine the aeolian influx into the peat. Values exceeding 100% were corrected for and fixed at 100%, since it is not possible for the weight loss to exceed its total weight.

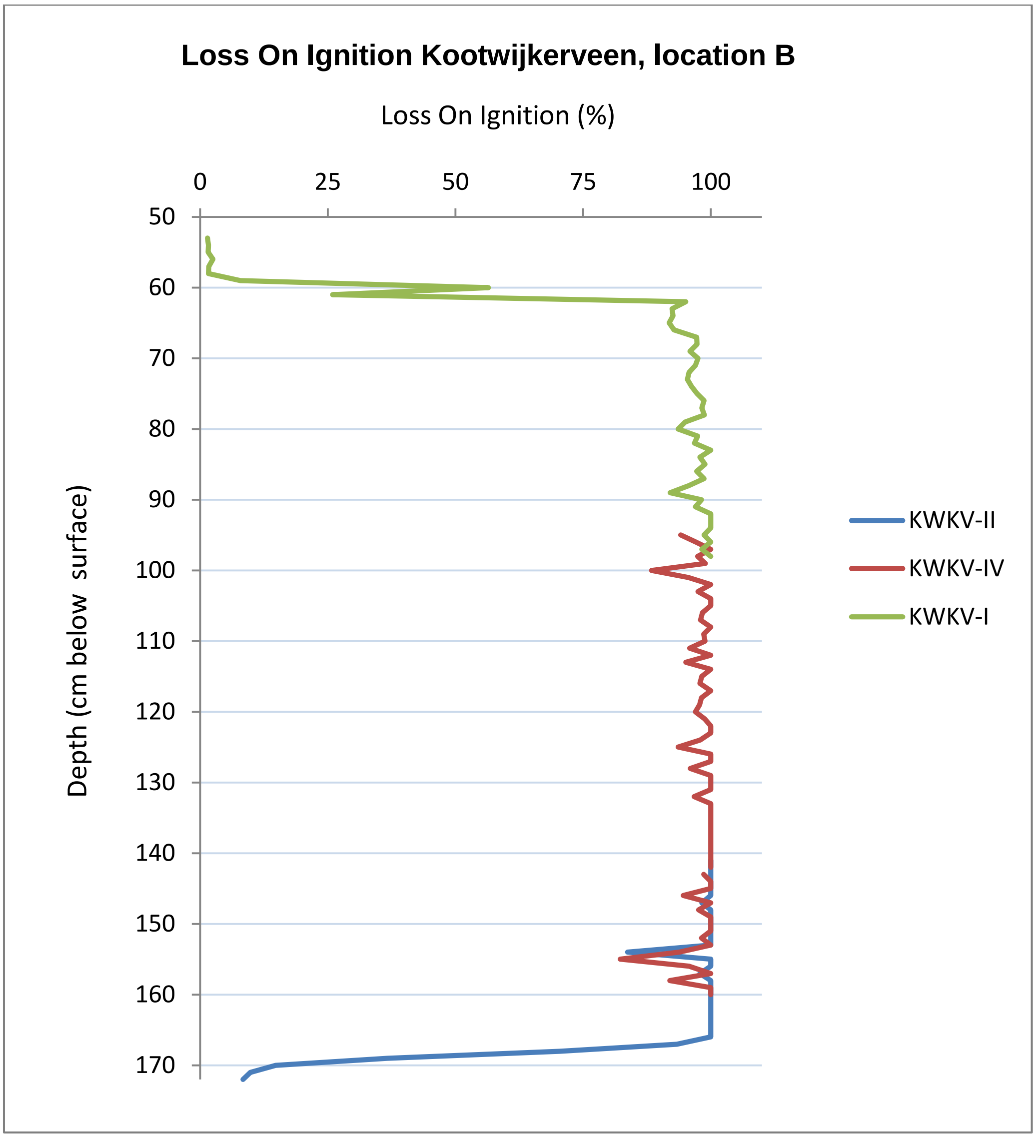

Figure 27. Loss On Ignition values from the Kootwijkerveen, location B.

In general, the LOI values show a similar result to that of the lithology of the core (figure 27, figure 25). Overall the composition of the peat deposit is highly organic with very little mineral input. The LOI values do not display gradual transitions, but are characterized by abrupt changes mainly during the start and end of peat formation.

From 169 – 166 cm the LOI values increase from 36 to 100 %. Peat growth during this first phase is characterized by constant high LOI values. A negative excursion is present in the interval of 153 – 155 cm. This corresponds to the dark interval which was identified in the lithology of the core. Relatively low LOI values of 82%, 83% and 93% interrupt the trend of high organic influx from 166 – 132 cm.

Although from 132 – 76 cm the LOI values still indicate a significant organic influx, more fluctuations are visible than during the first stage of peat growth. At 100 cm and 95 cm two discernible negative excursion are present, with values of 88% and 94%, respectively. However, the latter excursion is not resembled in the LOI curve of KWKV-I.

The uppermost section (95 cm – 76 cm) is still characterized by significantly high LOI values. However, two slightly more negative values are present at 89 and 80 cm, when the LOI values decline towards 93%. The interval from 76 – 62 cm is characterized by a slight but constant decline towards lower values, from 98% to 92%, respectively. This could be indicative of the start of mineral influx. Especially in the interval between 67-62 cm a marked decrease is visible, declining to 91% approximately. After 62 cm the LOI values decrease significantly and abruptly, decreasing from 95% at 62 cm depth to 1,5% at 57 cm depth. This is indicative of a sudden and significant influx of mineral material. A slight increase is discernible between 61 – 60 cm, from 25% to 56%, after which the significant decline in LOI values continues and reaches values as low as 1,5% again.

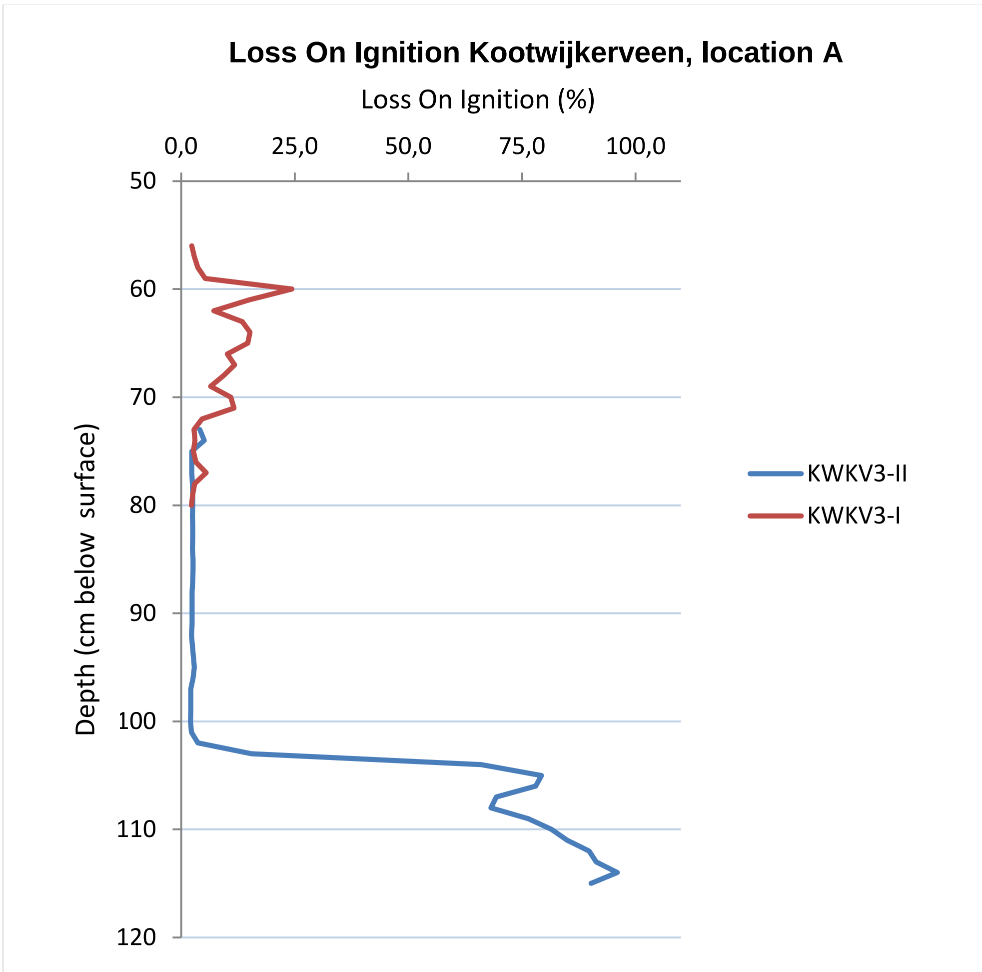

Figure 28. Loss On Ignition values from the Kootwijkerveen, location A.

The results from the LOI analysis are congruent with the lithological analysis (figure 28, figure 26). This core is characterized by its overall low organic matter content. Only in the bottom part of the core (115 – 110 cm) the LOI reaches values of 95% to 100%. In general, values are fluctuating around 2%. In the interval between 73 and 60 cm LOI show a gradual increase towards maximum values at the end.

Based on the results of location A it was decided not to use this core in for further analysis. Therefore, the palaeoecological analysis is based on the core of location B only.

7.4 Palaeoecological analysis

In total, 64 samples were taken from the core taken at location B. A selection of 23 samples were analyzed in order to construct a pollen diagram (figure 29). The samples that were not used in this study will be further analyzed in subproject C of the Dark Ages Project. A detailed overview of the samples that were taken from the core and the selection of 23 samples that were used in this research can be found in appendix E.

In some samples the pollen density was relatively low. Therefore, for the majority of depths more than one sample was prepared and counted in order to reach a pollen sum of 300. In total 81 slides were counted (table 1). A simplified overview of the LOI values and a lithology column were added to the diagram in order to create a complete overview of the data. A more detailed version of the diagram can be found in appendix F. Four different zones were distinguished based on regional trends that were identified in the pollen diagram. The results will be discussed per zone.

Depth (cm)	Number of samples
56	2
62	7
64	1
68	5
70	1
74	1
76	2
86	5
90	1
96	3
103	2
113	2
125	2
129	3
133	3
139	2
143	6
149	6
155	8
152	8
158	7
164	3
169,5	3

Table 1. The number of slides that were counted for each depth.

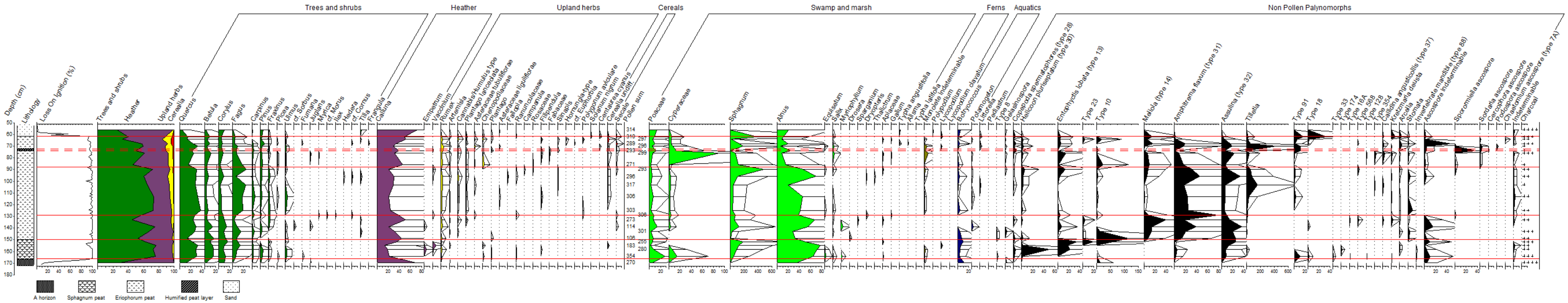

Figure 29. Pollen diagram of the Kootwijkerveen, coring location B. The red lines confine the four zones which are distinguished . The interrupted lines indicate the presence of the humified zone.

7.4.1. Zone 1 (166 – 150 cm)

This zone is characterized by a general increase in Arboreal Pollen (AP) percentages to maximum 75%. A marked decrease in heather species is discernible, especially in common heather (*Calluna*). All tree species (oak, birch, beech, hornbeam, pine, ash and elm) which were present from the start of peat formation increase in percentages throughout this zone. Oak was the most dominant species, with a maximum pollen percentage of 25%. While common heather decreases with approximately 20%, blueberry (*Vaccinium*) and crowberry (*Empetrum*) pollen percentages increased slightly. This is indicative of the presence of a relatively closed woodland with few openings. Upland herb pollen percentages show relatively low values and remain constant throughout zone 1. Pollen of meadow-sweet (*Filipendula*), the buttercup family (Ranunculaceae), goosefoot family, plantain and dock were present in low percentages. After the woodland maximum in zone 1, a decrease in AP percentages was accompanied by an increase in common heather pollen percentages, indicating a relative increase in the openness of the surrounding. Birch and hazel pollen percentages slightly increased while the forest opened up, since these tree species thrive in high light conditions (Iversen, 1973).

In the local environment swamp and marsh vegetation was relatively abundant in the beginning of zone 1, which was the period when peat first started to grow. The plant community consisted of alder, grasses, sedges (Cyperaceae), horsetail (*Equisetum*), willow and watermilfoil (*Myriophyllum*).

A general increase in the diversity and abundance NPP’s towards the end of zone 1 is congruent with the increasing presence of heather, since an increase in heather pollen percentages corresponds to a change towards drier conditions. A dry environment is favourable to fungi spores (van Geel, 1978). Especially type 13, type 10 and *Assulina* show an increase towards the end of the zone. The relative abundance of type 31 increases in the beginning of the zone, after which it decreases. Relatively many charcoal residues were found throughout the entire zone.

7.4.2. Zone 2 (150 – 129 cm)

Zone 2 is characterized by overall high heather percentages interrupted by a peak in AP percentages. Two heather maxima of approximately 45% and 55% are present, at the beginning and at the end of zone 2, respectively. In between these heather maxima, woodland percentages increase (150-140 cm). This increase in tree and shrub percentages is predominantly due to the 20% increase in oak pollen percentages. Although oak, beech, hazel and birch pollen percentages did not increase synchronously, they all showed an increase during the decline in heather pollen percentages. Ash was absent during the first phase of zone 2. Its pollen percentages increased while the rest of the tree and shrub species declined and heather percentages increased. Compared to zone 1, woodland was more diverse. Whitebeam (*Sorbus*), walnut (*Juglans*) and lime were also present. In this zone, a relatively open environment was present, with a peak in reforestation, during which regionally a diverse forest type developed on the dry sandy soils. The diverse vegetation community in this zone could indicate an increase in the landscape diversity and/or fragmentation of the landscape.

The diversity of upland herb species decreased compared to the previous zone. During the increase in woodland and the decline in common heather pollen percentages, crowberry and dock increased slightly. At the same time, the local environment changed: alder, grasses, peat moss (*Sphagnum*), watermilfoil and podweed increased in percentages, while type 10 shows a marked decrease. This could be indicative of wetter conditions. During the second heather peak of 55% the abundance of these swamp and marsh types decrease and *Meliola* (type 14) percentages increase. This could imply that drier conditions were present towards the end of zone 2. Charcoal was relatively less abundant than in other zones.

7.4.3. Zone 3 (129 – 88 cm)

A general increase in AP percentages distinguishes this zone from the other three. The percentages of this woodland remained stable throughout the zone. Heather pollen percentages remained relatively low compared to the rest of the diagram, approximately 20%. The percentages of upland herbs increased towards the end of the zone, from 5 to 10%. Concurrently, the presence of cereals also increase slightly towards the end of the zone.

While oak, beech, hornbeam and elm show a general increase in pollen percentages, birch and hazel showed low values. Towards the end of the zone the woodland diversity increased due to the presence of ivy (*Hedera*), dogwood (*Cornus*) and lime. Birch and hazel pollen percentages increased slightly. At the same time, beech decreased markedly with approximately 15%, from 25% to 10%. After this, its percentages recovered quickly. Throughout the majority of the zone, a closed oak-beech forest was present. The forest started to open up and became more fragmented towards the end of the zone. The diversity of the woodland increased and scattered open places developed.

A large variety of upland herbs were present. New species such as charlock mustard (*Sinapis*), common knotgrass (*Polygonum aviculare*) and the composite family (Asteraceae) were introduced. These are arable weeds and indicate human presence. Dock, ribwort plantain and hemp (*Cannabis/Humulus*-type) pollen percentages increased in presence and indicate an increase in anthropogenic influence in the area. This is supported by the increasing percentages of cereals, mainly caused by the presence of *Cerealia* but later also rye increases.

The increase in aquatic vegetation percentages (alder, peat moss, wood fern (*Dryopteris*), meadow-rue (*Thalictrum*)) is indicative of an increase in the groundwater level towards the end of zone 3. The increase in green algae (*Botryococcus*), *Entophyctis lobata* and *Amphitrema flavum* support this.

7.4.4. Zone 4 (88 – 61,5 cm)

During this last stage of peat growth the anthropogenic influence on the environment increased markedly. This can be inferred from the decrease in trees and shrubs and the relative increase of heather percentages. However, especially the increasing pollen percentages and diversity of upland herbs, the increase in cereals and other anthropogenic indicators support this trend. After a first sharp decrease in AP percentages, a slight recovery takes place. However, AP percentages remain lower than in zone 3. After this, in the top layers of the peat deposit, AP percentages decrease to the lowest values of the entire diagram. During the last stage of peat growth birch and hazel pollen percentages increased slightly. Occasional occurrences of walnut, needle sunrose (*Fumana*), bayberry (*Myrica*), dogwood and buckthorn (*Frangula*) are recorded and indicate increased human presence (Castel, 1991).

In the upland herb community, the percentages of dock, the goosefoot family, hemp and meadow-sweet were relatively high and more or less continuously present compared to other zones. Zone 4 was further characterized by an increasing diversity in the upland herb community in the second half. Arable weeds were introduced, such as *Hornungia*-type, spurge (*Euphorbia*), European black nightshade (*Solanum nigrum*), and cornflower. The presence of cornflower is especially closely linked to human impact, since it was restricted to growing as a weed in agricultural fields (figure 30). While previously only present in very small numbers, plantain was present in higher percentages from the second half of zone 4, when AP percentages decreased. The presence of plantain is indicative of the presence of open areas in the region, where land was ploughed and cultivated. The increase of in both overall diversity and human indicator species in the second half of this zone suggests that the anthropogenic influence increased over time. This is also clearly discernible from the cereal pollen percentages, which increase towards the end of the zone. In general, an open and fragmented forest was present in the region, with crop cultivation and herbs growing in open areas. Towards the end of the zone crop cultivation increased at the expense of woodland. Before sand drifting increased significantly, open areas with herbaceous vegetation and crops dominated the landscape in this region.

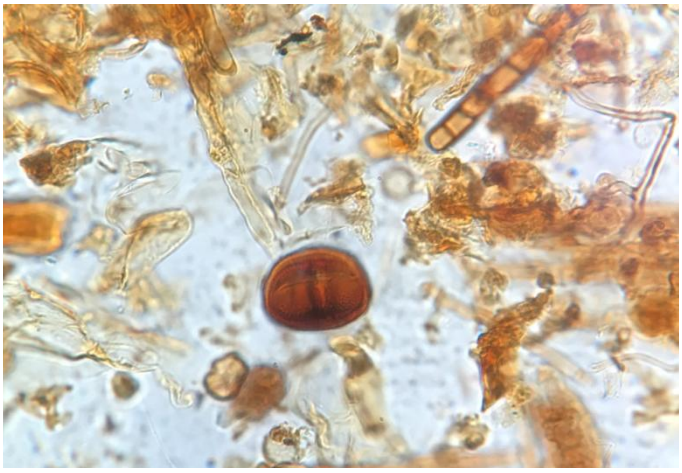

Figure 30. Pollen grain of cornflower (*Centaurea cyanus*), a typical anthropogenic indicator. Magnification: 600 x.

The intensification of anthropogenic influence in zone 4 is apparent from the spores of coprophilous fungi that were found (*Sporormiella, Sordaria, Cercophora, Podospora* and *Chaetomium*). These fungi are absent in the rest of the diagram. The local environment experienced a marked increase towards drier conditions in the first half of zone 4, which can be inferred from the peak in sedges and the presence of a humified peat layer. The peak in sedges percentages preceded the humified layer in the lithology of the core. During this significant increase in the percentage of sedge pollen, grasses and willow pollen percentages also increased. The percentage of unidentified monolete spores from ferns increased as well. Of the NPP's, *Entophyctis lobata*, *Assulina* and *Tilletia* show an increase in percentages, as well as type 354, *Callidina angusticollis* and *Kretzmaria deusta*. According to Van Geel (1978) the overall increase in NPP's could be related to dry conditions.

In the humified peat layer, alder and sporormiella ascospores increased significantly, while peat moss shows a clear decrease. All the NPP types which were abundant during the former peak in sedge percentages now significantly decline. Also the percentage of sedges decline, whereas grasses and alder increase in percentage.

In the layers succeeding this humified layer, during the final phase of peat growth, the local environment was characterized by fluctuations in a large number of pollen and NPP types. *Chaetomium* was the most dominant coprophilous fungi type during this last phase.

The influx of drift sand on top of the peat deposit coincides with a marked increase in heather pollen percentages. Hazel and lime increased, percentages of upland herb species decline significantly and its diversity also decreases. Cereals decrease accordingly. In the local environment, peat moss decreases significantly and *Botryococcus* increases. Nearly all the NPP percentages decline.

8. Discussion

8.1 Peat extension

Apart from a few exceptions, the extension of the peat bog seems to be related to the elevation of the area. In the lower-lying areas peat deposits were found, whereas the soil surface of the sites where no peat was found were slightly more elevated. This is in line with the expectations, since peat starts growing in lower lying areas where water stagnates (Koster, 1978).

However, it should be mentioned that the current elevation of the soil surface is not always predictive of the depth of the palaeo B horizon. Therefore, a scenario could be possible in which peat is present in the more elevated sites, but was buried and subsided under the pressure of a thick layer of sand. Unfortunately, the depth of the cores was restricted and therefore not suitable to infer whether peat was present in the deepest layers. Since mapping of the peat extension in this region was carried out mainly in order to determine the optimal coring location, the presence of peat in the more elevated sites was not investigated in more detail.

The direction of aeolian influx was presumably from the southwest. From the overview of the peat extension in figure 21 a cluster of dune-like, elevated zones can be identified in the southwestern part of the bog. This suggests that the sand blew in predominantly from this direction and formed drift-sand accumulations near the southwestern border zone of the bog. The excavation of the northeastern part of the peat in the 1930's further supports that the main aeolian influx was from the southwest. The drift-sand layer covering the peat was presumably much shallower in the northeastern part, because drift-sand influx was less intense here and started later (Londo, 2001).

The preliminary OSL results indicate that a layer of drift-sand covered the core in location B in ca. 1450 AD. Furthermore, these preliminary results suggest that after a short phase of peat growth in location A, drift-sand deposition intensified again in ca. 1775 AD. In general, these dates of drift-sand deposition confirm that sand drifting started to intensify in the Late Middle Ages. However, the onset of sand drifting in core B (ca. 1450 AD) does not match the results of Koster (1978), who argues that sand drifting started in the 11th or 12th century already. This incongruence could be a result of the extrapolation of the ^{14}C date in the upper peat layer, based on the mean peat growth per year (Koster, 1978).

8.2 Lithology

From the cross section it is apparent that the soil underlying the peat bog has a uniform and distinct soil profile, where the A, E and B horizon are well developed. The thickness of the peat deposit decreases towards the east. Towards the southwestern part of the transect the input of drift sand is more pronounced, as discussed in paragraph 8.1. Correspondingly, the drillings that are located near the drift-sand accumulations in the southwestern region, such as sites 12, 11 and 6, are characterized by a high input of mineral material. Therefore, it could be assumed that mineral influx first started in the southwestern region of the area, and was most intense here (Koster, 1978).

In the core which was taken at location B, corresponding to site 5 in the west-east transect, an uninterrupted peat sequence was present covered by a layer of drift-sand. Mineral influx in the peat deposit itself was minimal or absent. The peat deposit consist of different types of peat. The lithological analysis of this core suggests an uninterrupted peat growth at this specific location, after which a coarse layer of sand was deposited on top of the peat. Layers of well-sorted, fine grained sand continued to be deposited during the ongoing instability in the regional environment. The recent peat that was found in the top 10 cm of this core presumably started growing after the excavation in 1983, after which the groundwater level was elevated (Londo et al., 1994).

Contrary to what was expected based on the drilling at site 10, the core at location A is characterized by a very high mineral influx. Although peat is present in the lowermost part of this core, most of this layer is strongly humified due to exposure to oxygen. This core suggests that after initial deposition of drift sand peat started forming again when sand drifting was less intense. This resulted in peaty sand and sandy peat layers. However, this peat growth did not last, since sand drifting became too intense again. Preliminary OSL results indicate that this increased sand drifting, after the a short phase of peat formation, increased again in ca. 1775 AD.

It should be taken into account that the results of the drillings and the cores are not a perfect reflection of the lithology of the area. While drilling was carried out in a east-west transect, site selection was biased. Locations were selected based on the possibility to enter the area, which led to selecting sites particularly close to sandy deposits or dry vegetation on top of the peat bog. Besides, the lithology was found to be relatively diverse on a local scale, particularly the drift-sand layer on top of the peat deposit. This could be inferred from the results of this study, when comparing the drilling from site 10 and the corresponding core at location A. Also, during the excavation activities in the northeastern part in 1983, the subsurface was found to be relatively diverse on a local scale (Londo et al., 1994). Therefore, it should be taken into account that the lithology of the transect could deviate somewhat from the schematic overview in 24.

8.3 LOI analyses

The LOI curve of location B shows that overall, the aeolian influx was minimal or absent during peat formation. High organic values suggest uninterrupted peat growth. This is different from the analysis of Koster (1978), who describes the occurrence of five drift-sand phases in the area (figure 10). While a distinct phase of increased aeolian activity was expected to be found towards the top of the peat deposit, the mineral influx increases only slightly here (67-62 cm). The vegetation development of this particular interval will be discussed in section 8.4. A transition to an environment dominated by mineral influx occurred abruptly and rapidly. This could indicate that either the vegetation around the peat bog blocked the aeolian influx during earlier drift-sand phases, or that these phases were not yet intense enough to reach the Kootwijkerveen. A negative excursion in LOI values occurs simultaneously to a dark interval which was described during the lithological analysis (153-155 cm). This indicates that this layer was strongly oxidized as a result of fire activity. Therefore, a relative decrease in organic components can be indentified in the LOI analysis. The other negative excursion occurring at the top of core KWKV-IV (95 cm) is considered to be a result from mineral pollution during coring, since it is not reflected in the curve of KWKV-I and is located in the top of the core section.

In location A, only 15 cm of peat was found, with lower LOI values than in location B. The composition of the core was very different than was expected based on the exploratory drilling, in which a peat deposit was found of approximately 1,5 m thickness. The exploratory drilling and core were taken in very close proximity, suggesting a local disturbance of the environment, either due to natural causes or due to anthropogenic influence. This disturbance could possibly have been caused by small scale peat excavation in the area. According to Londo et al. (1994), 600 peat-hags were found in throughout the Kootwijkerveen.

8.4 Pollen diagram

In this section, a reconstruction of the vegetation and other environmental parameters will be made based on the results of the pollen diagram (figure 29). It should be taken into account that the percentages of the pollen types cannot directly be related to their abundance in the environment, since pollen production and distribution is highly variable. Entomophilous (insect pollinated) plants, such as the buttercup and goosefoot family, produce relatively less pollen than anemophilous (wind pollinated) types such as sedges, grasses and most trees. In the upland herb assemblage, dock and meadow-sweet are likely to be overrepresented. Although they are entomophilous, they produce relatively many pollen compared to the other upland herb species (Janssen, 1974). Furthermore, it should also be taken into account that this is a relative pollen diagram, which could provide a somewhat distorted image of the actual changes in pollen deposition. As one type of pollen increases markedly, the other types automatically decrease because the diagram is based on relative abundances (Janssen, 1974).

The changes in the samples from the A horizon underlying the peat deposit (<166 cm) are not discussed in detail. This is because of the bad pollen preservation of sandy soils in comparison to peat deposits, making a comparison of the samples from the peat to those from sandy deposits unreliable. AP percentages are low and heather percentages are high, which does not necessarily display a regional signal. It is rather expected to be a result of local heather growth on top of the coversand deposit, before the onset of peat growth.

8.4.1. Zone 1

In this first phase of peat growth in the Kootwijkerveen, the regional environment was characterized by a the presence of a closed woodland with AP percentages ranging between 70-75%. A diverse forest type, dominated by oak, was present. Human impact was very low and open spaces in the woodland were sparse. The increase of plantain relative to other pollen types can be indicative of a local environmental disturbance. A transition towards more humid conditions in the regional environment can be inferred from the presence of the buttercup family and meadow-sweet (Castel, 1991). The small cereal peak could have been indicative of small-scale agriculture in the region. However, this peak is based on only one pollen count. Simultaneously to the increase of heather at the end of zone 1, birch and hazel expanded. Both species thrive in open areas in the landscape. While normally present in the undergrowth of the forest, in open areas hazel is a pioneer species, where it grows as shrub vegetation on open areas and next to forest edges (Bos & Zuidhoff, 2015).

During the start of peat growth, water stagnated on the impermeable horizon in the coversand depression. Locally, this created a favourable environment for species that occur in moist environments, as can be inferred from the abundance of swamp and marsh species in the pollen diagram. Horsetail, watermilfoil, willow and grasses show an overall increase. These swamp and marsh plants thrive in partly submerged or humid environments. The pollen diagram indicates the local presence of alder carr. This local humidity increase is in accordance with the regional diagram as discussed before.

The local environment shows a transition towards more arid conditions at the end of the zone. In general, the species abundance and diversity of the swamp and marsh assemblage declined and that of the NPP's increased. These trends can all be related to a decrease in humidity, since the growth of heather is related to dry conditions and in turn, heather growth is positively related to presence of fungal spores (Van Geel, 1978).

Simultaneously, towards the end of zone 1 the increased abundance of charcoal matches the increase in heather, the negative excursion in LOI values and the dark interval which was described during the lithological analysis. This could have been a short phase of increased natural fire activity in the area possibly caused by drought, because human indicator species were not yet abundant.

8.4.2. Zone 2

This part of the diagram is characterized by an overall decline in forest cover. For this part of the diagram relatively many slides had to be counted. After doing so, the pollen sum still remained low. The lower pollen density could indicate a more rapid deposition compared to other zones, from which it could be assumed that zone 2 includes a shorter period of time. Alternatively, it could also indicate that the size of the bog expanded so much that the pollen influx was relatively lower.

Overall a drier and more open environment was present compared to the previous and following zones. Heather was abundantly present. The deforestation trend in this period could have been related to a natural cause, to a period of increased human influence, or both. Furthermore the heather peaks in the beginning and end of this part of the diagram could also have been related to variation in the size of the bog. When the bog decreased in extent, locally a zone rich in heather could have developed.

The generally open environment with a high abundance of heather was interrupted by short phase of woodland regeneration. In general, the woodland which was present throughout this zone was relatively diverse compared to the rest of the diagram. This could have been related to the transition towards a more open landscape, leading to forest fragmentation and therefore an expansion of the forest edge area. This could have provided a chance for the increase in tree diversity. However, the pioneer herb species did not show an equal increase in abundance and diversity you would expect when open areas increased and led to forest fragmentation. During the peak in reforestation, regionally on dry sandy soils mainly oak-beech forest developed while locally in humid areas alder carr regenerated.

Anthropogenic indicators such as dock, hemp and ribwort plantain are indicative of active human interference in the regional environment. Especially ribwort plantain suggests active human interference, since this species is associated with open vegetation that was heavily trampled or grazed upon. Its presence is generally associated to open areas since it needs full sunlight to grow (Faegri & Iversen, 1989; van Beek et al., 2015).

In the local environment, alder carr declined in the first part of zone 2. Locally, nutrient poor conditions were present, as can be inferred from the presence of sundew (*Drosera*). The pollen dispersal of sundew is poor and it has a competitive advance in nutrient poor situations since it is a carnivorous plant. During the small forest regeneration phase in this period the local vegetation and NPP's show a trend towards wetter conditions. Swamp and marsh species such as watermilfoil and pondweed increased close to the peat bog and in the undergrowth of the alder carr in the immediate vicinity of the area. Following this forest regeneration, the regional environment showed a transition towards drier conditions with an increase in heather growth. The local environment showed a consistent trend with a decrease in swamp and marsh vegetation and a decrease in NPP dry indicators (*Meliola, type 10*).

8.4.3. Zone 3

Overall, this zone was characterized by the presence of a dense and diverse forest cover. The low abundance of heather and the photophilous trees birch and hazel suggests that open places were not abundantly present and the forest fragmentation was limited. Hazel was present in small percentages, a sign that it was located in the undergrowth of the forest where its pollen production was poor and had a limited dispersal. Only when the dense shading forest disappears hazel starts to increase and disperse its pollen more effectively. This could have occurred towards the end of the zone, when a sharp decrease in beech was accompanied by an increase in hazel (Iversen, 1973). This increase in hazel was accompanied by an increase common dogwood, and ivy climbing the trees in the undergrowth of the forest. The increase in woodland diversity towards the end of the zone is an indication for a more fragmented environment.

Although open areas were less abundantly present than in the other zones, the diversity of herb species increases significantly compared to zone 2 and the abundance of upland herbs increases throughout the zone. A continuous presence of ribwort plantain could indicate that open grasslands were present in the region which were trampled by people or grazed by animals. The presence of open places scattered throughout the woodland is further supported by the presence of mugwort, dock, the composite family and charlock mustard. Furthermore, since cereals and arable weeds were found, it can be assumed that agriculture was present in the region. Apart from rye species, pollen dispersal of cereal species is usually very limited (Behre, 1981). Therefore, it could be assumed that crop cultivation was already important, although on a small scale, since in general a dense forest cover was present.

Surrounding the peat deposit, alder carr was abundantly present during the whole zone, indicating moist conditions. Since this type of vegetation requires relatively high nutrient levels, it is assumed that the alder carr did not grow close to the bog but in residual channels or valleys that were locally present. The first and last phase of zone 3 are characterized by an increase of the groundwater table. During these phases, alder carr expanded, while willow and horsetail occupied the edges of the peat area and the undergrowth of the alder carr. During the last moist phase also wood fern and meadow-rue grew alongside the edges of the peat area. The continuous presence of fern spores, green algae and pondweed further support a relative increase in moist conditions during this zone.

8.4.4. Zone 4

In general, this zone was characterized by an increase of human influence on its environment. The end of the zone is placed based on the LOI values, when the peat formation stopped and the aeolian influx increased abruptly. Deforestation occurred on a wide scale, especially in the last phase of this zone (70-61,5 cm) when a steady decline is discernible. This is clearly visible from both the general vegetation composition and the individual tree species declining in percentages. A steady increase in the upland herb pollen indicates that the environment became more open. Crop cultivation was expanded. Crop cultivation increased even more towards the end of the zone, as can be inferred from the steady increase in rye and cereal pollen and the occurrence of cornflower. Regionally, forest was actively removed in order to make the environment suitable for crop cultivation, which can also be inferred from the relative abundance of charcoal. A general increase in *Gelasinospora* also indicates that people actively used fire to clear the forest. This fungi type is often found in relation to charcoal, either because it is attracted by dry conditions or because it is carbonicolous (van Geel et al., 2003). Although from the pollen diagram one could assume that the cultivation of rye was more important than all the other cereal crops in total, rye was probably subsidiary. Rye is wind-pollinated and produces a lot of pollen and is therefore overrepresented with respect to the cereals. Although it would have been interesting to do so, for example to infer whether crop rotation was used, no additional distinction in different cereal types was made during pollen analysis.

Since deforestation led to an increase in light penetration, hazel could have been dominant in open areas. However, the relatively low values of hazel in combination with the abundance in upland herb pollen and the local increase of grass pollen percentages indicate that fallow land and grass pastures were abundantly present. They were actively accessed by people and grazed upon by animals, as can be inferred from the ribwort plantain, plantain and knotgrass curves. This is supported by the increase in coprophilous fungi in the local environment.

In the local environment, in the middle of this zone a transition towards dry conditions occurred. The abundance of sedges greatly increased. Generally, sedges are indicative of moist areas and can be found near water edges or moist valleys. However, this sudden and significant increase suggests the presence of sedges in the peat bog itself. When sedges significantly increase in the peat bog itself it is indicative of a transition towards more nutrient rich and drier conditions, creating sedge tussocks on the surface of the peat bog. During this phase, willow advanced to the edges of the bog because of local dry conditions. Valleys became drier as can be inferred from the decrease in presence of alder carr. The increase in *Entophyctis lobata* (type 13) suggests that locally, the nutrient increase was relatively restricted, as this fungi type is associated with ombotrophic peat bogs (Van Geel, 1978).

After the decrease in sedges and willow, the dry phase continued. This can be inferred from the humified peat layer and the increase in *Sporormiella*, *Sordaria* and *Cercophora* ascospores. Near the bog however, valleys became moister, as can be inferred from the increase in alder carr abundance and the expansion of grasses. The humified peat layer was a result of a lowering of the water table, exposing the top peat layers of the deposit to oxygen, leading to decay of organic matter. *Cercophora* ascospores can be related to this decaying plant material in the humified peat layer, such as wood, leaves and herbaceous stems. However, their presence is also related to increasing population densities of herbivores, since the co-occurrence of these ascospores and especially the presence of *Sporormiella* and *Sordaria* indicates the presence of dung of large herbivores (van Geel et al., 2003). While in general these coprophilous fungi spores can be indicative of human impact, in raised bogs located relatively distant from settlements they are not. This is because of the less efficient dispersal ability of these spores in comparison to pollen, since the fungal fruit bodies are present near the ground where wind-dispersal is not effective. Therefore, in raised bogs relatively distant from settlement sites, the presence of coprophilous fungi can only be used as an indication of the local presence of animals (van Geel et al., 2003). The local environment was arid enough for herbivores to occupy the local environment. The presence of plantain and ribwort plantain and the increase in heather in the regional pollen diagram support this.

Especially during the last phase of zone 4 (67-62 cm) when the LOI values decreased, cereals increased strongly and cornflower was found. Woodland abruptly decreased towards the lowest values of the entire diagram and crop cultivation was intensified significantly. The diversity of the upland herb community increased and an open herbaceous vegetation was present with knotgrass, plantain, charlock mustard, *Hornungia*-type, the goosefoot family and dock, matching the increase of mineral influx in the peat layers. Anthropogenic indicators such as hemp, cornflower and *Chaetomium* were present in this last phase. The vegetation development indicates a marked increase of the anthropogenic influence on its environment, together with an increase in aeolian influx. The local environment was relatively dry with little alder carr, peat moss, willow and other swamp and marsh species.

After zone 4, the aeolian influx abruptly increases and peat growth is stopped. In general, all the vegetation types decline, except for heather, hazel, lime, grasses and alder. Hazel could have grown as a pioneer species on open places overblown with drift sand. However, overrepresentation of heather pollen could have occurred due to its local presence on the sandy layers, and could therefore have biased the results. Since the topmost sandy layers have a much poorer pollen preservation, this phase is not studied in detail.

8.5 Combining the results

In this section, the results from the literature review, lithological, LOI and paleoecological analysis will be combined and discussed.

In general, all the results indicate that the regional environment was relatively undisturbed until eventually human impact increased markedly and an open environment replaced the closed forest. This corresponds to the LOI analysis of the core, showing high organic values even when the literature and the palaeoecological analysis indicate a decrease in woodland and a marked increase in human impact. However, both archaeological and local LOI data indicate that in the Kootwijkerveen, four minor drift-sand phases preceded the final drift-sand episode that stopped peat growth around the 11th century AD (figure 10) (Heidinga, 1984; Koster, 1978). Evidence of such minor phases of aeolian influx have not been found in this study. This suggests that there are local differences in aeolian influx in the area itself. The location of the core used by Koster (1978) to determine the aeolian influx could have been more towards the southwestern region of the peat bog, where a higher influx of drift sand was found during this study. This could have led to the large difference in aeolian influx compared to the location that was used in this study. Since Koster (1978) did not provide information on the exact location of the core, a more detailed comparison between different areas cannot be provided.

According to Koster (1978), based on ^{14}C dating, peat started growing after 300 AD. However, since the location of the core used in his research is not clear and the area has proven to be very diverse, the start of peat growth in the core used in this study could deviate. ^{14}C analyses are currently being processed. Since minor drift-sand phases are absent in this location, dating of the different zones can be done only based on archaeological evidence and regional vegetation development.

One scenario could be that peat started growing before 300 AD. Then, the decrease in AP percentages in zone 2 would correspond to the occupation of the area starting in the 2nd century AD, of which archaeological evidence was found (Heidinga, 1984). After this decrease in AP percentages, a period of reforestation started. Data from a pollen diagram in the Uddelermeer shows that reforestation started relatively early in this region, in the 3rd or 4th century AD (Engels et al., 2016). This is in agreement with this scenario, arguing a relatively early onset of peat growth. While a larger settlement (Kootwijk 3) was present from the 2nd century onward, it is not likely that the deforestation in zone 2 occurred solely because of the increase in human influence. While the area was occupied during the Late Roman Period, only evidence for small settlements with a few houses was found. The extent of deforestation was approximately equal to that of zone 4. If this zone of the pollen diagram does correspond to the Late Roman Period, other environmental factors such as drought must have been an extra factor in the deforestation trend. Evidence for local fire activity was found towards the end of zone 1, and the local pollen diagram does show a trend towards dry conditions in zone 2. This is in accordance to the period of precipitation decrease in the 3rd century AD in Western Europe (Buntgen et al., 2011). However, this scenario does not match the start of peat growth in the 3rd century, which was found by Koster (1978). This would imply that the start of peat growth was variable throughout the area.

In the other scenario, peat growth started around or later than 300 AD, equal to the age that Koster (1978) found. The beginning of zone 1 would correspond to the period after the abandonment of the Late Roman settlement in the area and during the beginning of the Migration Period. The area was scarcely inhabited, allowing woodland to expand. Only towards the middle of zone 3 the human impact increases again. The short interval in zone 2 is a disruption of the general reforestation trend, which in this scenario could have been caused solely by natural influences such as drought. This drought is supported by the local pollen diagram and evidence of fire in the end of zone 1, although it remains unclear whether this deforestation could have been caused by natural conditions only. Furthermore, it is supported by the evidence of a distinct dry period in the first half of the 6th century (figure 13) (Buntgen et al., 2011). Since C-14 dates of this study are not available yet, there is no indication which scenario occurred. This scenario is, however, closest to the starting date of peat growth as determined by Koster (1978).

From zone 3 onward dating of the vegetation development is less debatable. It is assumed that the changes in the regional vegetation from zone 3 onward can mainly be related to human impact, since the Medieval Warm Period (800 – 1300 AD) was relatively constant, both in temperature and precipitation. In zone 3, the presence of scattered open areas in a generally dense woodland could correspond to a slight increase in human influence in the area around the 6th and 7th century (Heidinga, 1984). This matches the increased availability of rye at the end of zone 3, which was found in The Netherlands from the Middle Ages onward (Bos & Zuidhoff, 2015). The increase of human impact on the environment from the beginning of zone 4 could be related to the establishment of a larger settlement (Kootwijk 2) in 750 AD, marking the increase of human influence in this region. The dry period between 950 and 1000 AD which has been described by Heidinga (1984) could possibly correspond to the humified peat layer and the increase of sedges and willow. Since this dry period is not reflected in the pollen diagram from the Uddelermeer or in the climate reconstruction from Europe (figures 15 and 13, respectively), it is assumed to be a local event (Engels et al., 2016). This period marked the end of the larger settlement. After the end of Kootwijk 2, different smaller settlements were dispersed throughout the area. The date of this dry period is supported by the occurrence of cornflower pollen in the peat layer directly above the humified layer. According to Bos & Zuidhoff (2015), cornflower was found in The Netherlands from the 10th or 11th century, approximately. Simultaneously, the forest continued to decline and open herbaceous vegetation was present. Therefore, it could be assumed that after the dry period people living in several smaller settlements continued to cultivate crops and use plaggen practice, until finally the absence of vegetation caused a significant increase in sand drifting, marking the end of peat growth. According to the preliminary OSL results, the onset of sand drifting marked the end of peat growth in ca. 1450 AD. Following this, settlement was concentrated in Kootwijk 6, located adjacent to the area where sand-drifting was most intense.

9. Conclusions

This study aimed to reconstruct the vegetation development and aeolian influx in the Kootwijkerveen from 1-1500 AD. The second aim was to assess the role of anthropogenic as well as climatic influences on the vegetation development of this region. To accomplish this, a literature research was conducted to reconstruct the anthropogenic influence, climatic variability and drift-sand patterns in the region. Then, LOI analyses were conducted and a detailed vegetation reconstruction was made from a core which was taken in the Kootwijkerveen. Correlations were made between the vegetation development and drift-sand phases from the core itself, and these trends were placed in regional context using literature.

- *How was the vegetation development in the Kootwijkerveen region between 1-1500 AD?*

From the pollen diagram it can be inferred that a relatively closed forest cover was present from the beginning of peat growth, which presumably started in the Mid- or Late-Roman Period. After a short period of deforestation in which an open vegetation with heather was present, the forest cover increased again. This resulted in scattered open areas with herbaceous vegetation and small-scale cereal growth in a wooded area. After this, forest cover started to decrease significantly and heather and herbaceous vegetation replaced patches of closed forest. Crop cultivation became increasingly important and indicators of human presence, grazing and disturbance of the environment increased. These were especially widespread in the very last phase of peat growth, when open areas with heather and crop growth increased rapidly. Peat growth stopped approximately in the 15th century as a result of a significant aeolian influx. Therefore, after approximately 1450 AD the vegetation development could not be reconstructed using pollen analysis. However, from the literature study it became clear that the region continued to be dominated by drift-sand influx until active reforestation took place in the 18th and 19th century.

- *What was the influence of human settlement in Kootwijkerveen region on the vegetation development between 1-1500 AD?*

In the beginning of peat growth, population density in the area was limited. Therefore, the impact of human occupation on the environment was expected to be small. The short increase in openness of the vegetation after the start of peat growth could be related to human settlement in the area in the Late Roman Period (2nd – 3rd century). However, the small scale of this settlement and the magnitude of this vegetation change suggests that this was a combination with a period of drought.

The scattered open places in the reforested region could have been related to the small scale settlements after the Migration Period, in the 6th and 7th century AD. From 750 AD a larger settlement was founded in the region, which could have led to the rapid increase of deforestation in the area. Whether this deforestation was related to the iron industry could not be inferred from the results of this study. From the literature study it became clear that after the local dry period in the 10th century, smaller settlements were established scattered throughout the area. In spite of this, the human impact on its environment remained significant, as a result of deforestation and using plaggen practice for agriculture. In the pollen diagram this human influence during the very last phase is indicated by the presence of cornflower, plantain, charlock mustard and the goosefoot family.

- *What was the influence of the vegetation development in the Kootwijkerveen region on the drift-sand dynamics between 1-1500 AD?*

Based on the archaeological evidence and the LOI results of a study conducted in the Kootwijkerveen, it was expected to find four drift-sand phases before the final influx that stopped peat growth (Koster, 1978). However, these phases were not present in the core used in this study. Aeolian influx was found only during the very last phase of peat growth, when significant deforestation took place and open areas with heather, herbaceous vegetation and crop cultivation were present. In this last phase, aeolian influx increased abruptly and significantly. The differences between this study and the literature study of the Kootwijkerveen suggest that aeolian influx was locally variable.

- *What was the influence of climate fluctuations on vegetation development in the Kootwijkerveen region between 1-1500 AD?*

The distinct deforestation in zone 2 could have been caused by a combination of human settlement as found in archaeological evidence and a dry period that was described in the 3rd century AD in Western Europe. Although this scenario seems plausible, it would mean that peat growth in this specific location started before the 3rd century. This is earlier than described by Koster (1978), who based his conclusions on the extrapolation of a C-14 analysis in close proximity to the core used in this study. Alternatively, the deforestation could have been caused by a significant decrease in precipitation in the first half of the 6th century. Currently no decisive conclusions can be provided, since the C-14 samples have not been analyzed yet. However, it is evident that a decrease in precipitation was of influence on the deforestation phase in zone 2.

In general, the climatic influence is assumed to be of minor importance compared to the anthropogenic influence in the region. Apart from the reduced precipitation in zone 2, only the dry period in 1000 AD which was evident from archaeological evidence, could have been related to the dry period which was found this study from 72,5-74 cm. During the Medieval Warm Period (800-1300 AD), the temperature and precipitation remained relatively constant. Conversely, archaeological and palynological data indicate that human influence on the environment continued to increase. Therefore, it is assumed that after the period of deforestation in zone 2, the changes in the regional vegetation were mainly related to human impact.

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Appendix A

In this appendix the descriptions of the exploratory drillings in Kootwijkerveen can be found. The coordinates are provided in the 'Rijksdriehoeksstelsel' (RD) notation.

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
1	183440	468879	. <125

Depth (cm)	Description
0-65	Drift-sand layer, material badly sorted at top and well sorted at bottom
85-94	Eluviation zone (E horizon), light grey
94-100	B horizon, black
100-125	B horizon, brownish

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
2	183422	468878	45

Depth (cm)	Description
30-38	Subsoil and eluviation zonn (B and E horizon)
38-45	C horizon
45-55	Peat
55-60	A horizon
60-76	E horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
3	183372	468870	10

Depth (cm)	Description
0-20	Recent peat accumulation, *Sphagnum cuspidatum*
35-40	Sandy peat
44-49	Oxidised peat
49-54	*Sphagnum* peat
55	Layer of gravel / coarse sand
56-70	Sphagnum peat
70-80	*Sphagnum* peat
80-90	A horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
4	183310	468870	25

Depth (cm)	Description
0-3	Recent *Sphagnum* peat
3-23	E horizon, eluviation zone
23-45	Coarse sand
55-165	*Sphagnum* peat
165-169	A horizon
169-175	E horizon, eluviated
175-180	B horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
5	183253	468869	10

Depth (cm)	Description
0-10	Recent *Sphagnum* peat
15-50	Sand
50-60	Coarse sand
60-65	Black peat, oxidised
65-180	Peat
180-188	A horizon
188-191	E horizon
191-197	B horizon
200-220	C horizon,orange from leached iron

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
6	183168	468860	40

Depth (cm)	Description
0-120	Sand
120-122	Layer of *Carex* roots
122-180	Peat
180-195	A horizon
195-205	E horizon, eluviated material
205-210	B horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
7	183108	468872	30

Depth (cm)	Description
0-36	Sand
36-44	Compact peat
44-180	Peat, loose
180-200	A horizon
200-207	E horizon
207-210	B horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
8	183114	468882	No data

Depth (cm)	Description
0-70	Sand
210	B horizon

Site was very difficult to access

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
9	183123	468855	20

Depth (cm)	Description
0-50	Sand
50-173	Peat
173-180	A horizon
180-191	E horizon
191-200	B horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
10	183065	468876	50

Depth (cm)	Description
0-44	Sand
44-50	Oxidised peat
50-193	Peat
193-208	A horizon
208-215	E horizon
215-220	B horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
11	183001	468883	20

Depth (cm)	Description
0-15	Recent peat formation
15-30	Light coloured sand
45-60	Sandy peat. Layers of coarse sand between 50-60 cm
60-210	Peat with mixed coasrse sand
210-220	A horizon
220-230	E horizon
230-240	B horizon

No.	X coordinate	Y coordinate	Groundwater level (cm beneath sediment surface)
12	182915	468895	0

Depth (cm)	Description
160-210	Peat

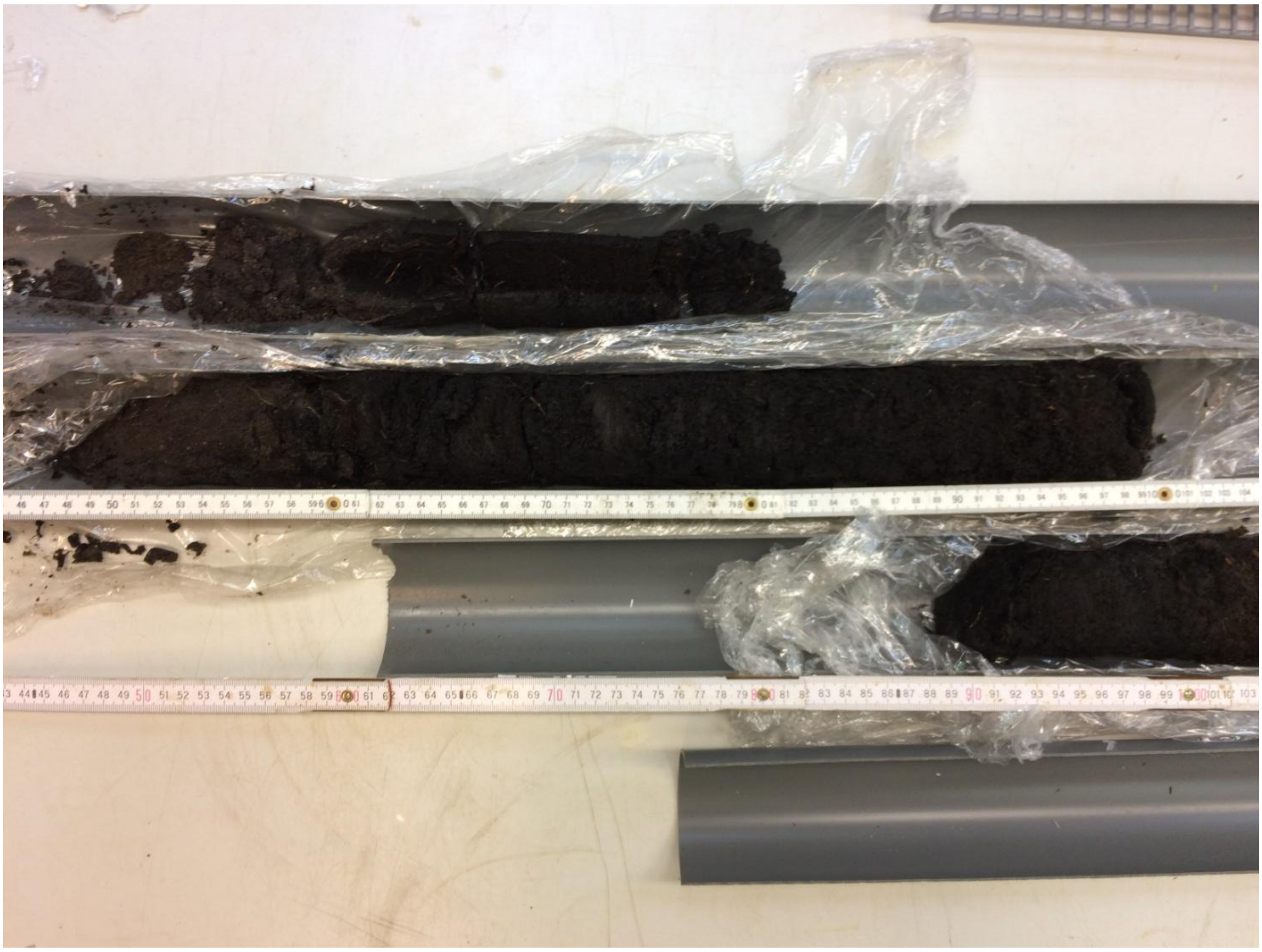
Appendix B

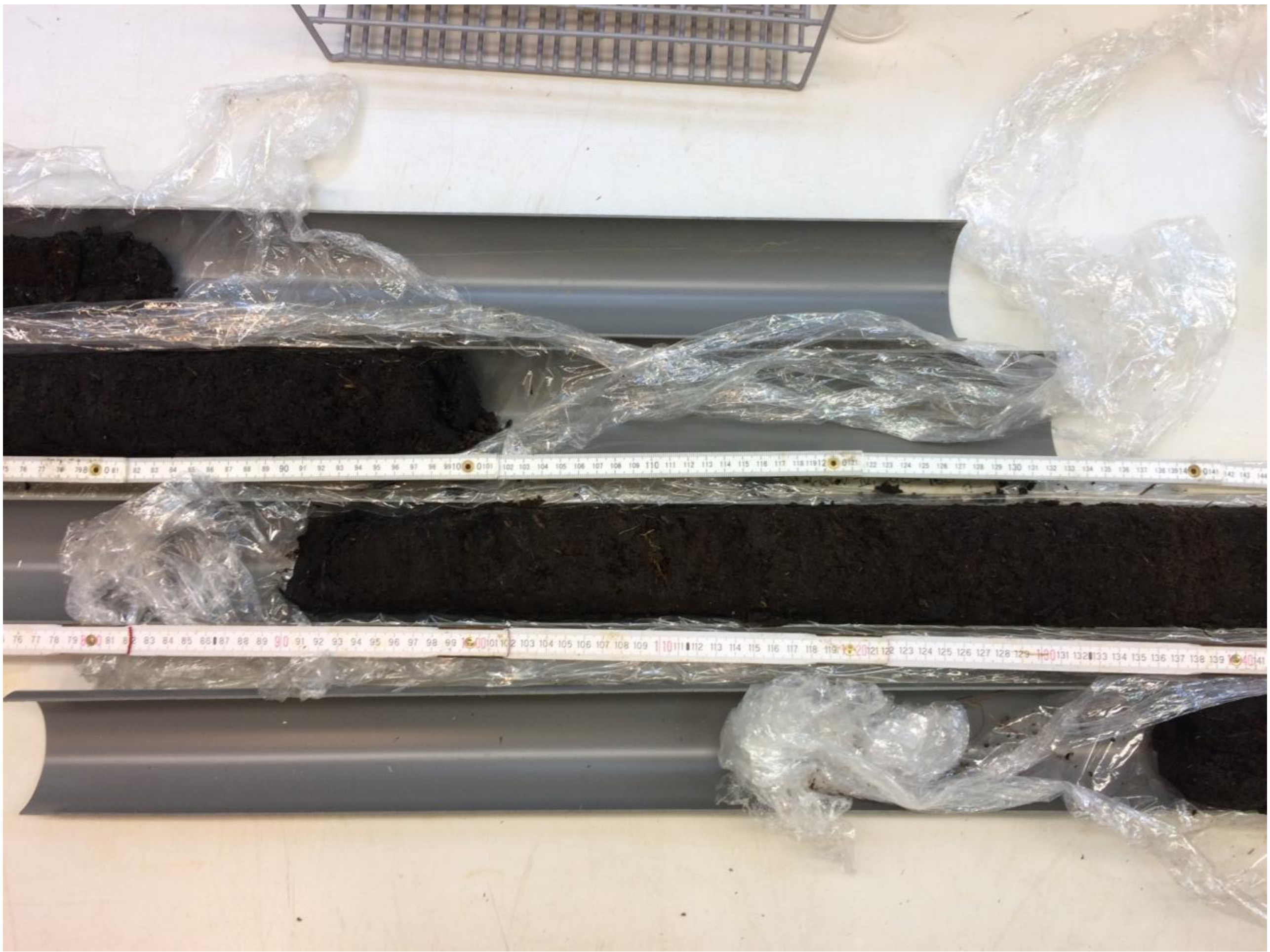
In this appendix an overview is presented of the 29 coring locations and whether peat was found or not.

Boring	RD X	RD Y	
1	183451	468911	-
2	183432	468872	-
3	183397	468874	-
4	183379	468874	Veen op 80 cm
5	183360	468836	-
6	183302	468833	-
7	183270	468840	Veen op 1 m (overgang zand-veen)
8	183218	468812	-
9	183173	468829	-
10	183147	468850	Veen
11	183138	468836	-
12	183090	468819	-
13	183034	468847	-
14	183009	468867	Veen
15	182952	468852	-
16	182927	468881	-
17	182943	468889	-
18	182928	468867	Veen
19	182928	468854	-
20	182900	468849	-
21	182934	468952	Veen
22	183011	468968	-
23	183130	468979	-
24	183193	468966	-
25	183252	468962	-
26	183318	468951	-
27	183409	468930	-
28	183338	468856	Veen
29	183280	468851	-

Appendix C

Here, pictures of all the core sections from location B are provided. The core consists of four sections: KWVK-III (50-80 cm), KWVK-I (50-100 cm), KWVK-IV (90-160 cm), KWVK-II (138-172 cm).





Appendix D

A description of the laboratory manual for pollen preparation is presented below (in dutch). The steps are divided in four steps which can each be completed in one day.

Werkvoorschrift Pollenpreparatie UU-FG

In met name stap 2 worden sterke zuren gebruikt, raadpleeg vooraf de fact-sheets over de te gebruiken chemicaliën. Raadpleeg bij onzekerheid altijd Wim Hoek.

1. Ontkalken en uitlogen

- Ca 0.3 cm^3 materiaal in 15 ml centrifugebuis, aanvullen met aqua dest. tegen oxidatie
- Bij kalkhoudend materiaal: uitzuren met 5% azijnzuur, daarna 2 maal wassen met aqua dest. Om zuur te verwijderen (aanvullen, centrifugeren 1 minuut bij 1700 r.p.m. en decanteren)
- Eventueel *Lycopodium* toevoegen, tbv absolute pollendiagrammen). 5 ml KOH 5% toevoegen om humusverbingingen te verwijderen, zo kan later het organische materiaal makkelijk verwijderd worden.
- 60 minuten verwarmen in stoof bij 70 °C om reactie te stimuleren. Dit specifieke sediment uit het Kootwijkerveen wordt slechts 30 minuten verwarmd in de stoof, omdat het organisch materiaal al zo los is.
- Zeven over 200 µm, humusverbindingen en grote plantendelen blijven achter en pollen en andere verbindingen worden doorgelaten. Hierna overgieten in 15 ml centrifugebuis en centrifugeren, 5 minuten op 1700 r.p.m.
- Twee maal uitwassen om de KOH te verwijderen uit de oplossing (2 keer vloeistof decanteren, aanvullen met aqua dest, vortexen en 5 minuten centrifugeren op 1700 r.p.m.)

2. Acetolyse

<u>NB. zuren altijd decanteren in speciaal zuurvat</u>

- Twee maal uitwassen met ijsazijn om water te verwijderen (2 keer vloeistof decanteren, 5 ml ijsazijn toevoegen, vortexen en 5 minuten centrifugeren op 1700 r.p.m.).
- Acetolyse mengsel maken: 9 delen Azijnzuurhydride + 1 deel H_2SO_4 (bij 48 samples is dit 180 ml + 20 ml).
- Na decanteren ca. 4 ml acetolyse toevoegen en vortexen. 5-10 min verwarmen bij 100 °C in warmtebad. Tussendoor (na het bereiken van 100 °C) éénmaal vortexen. Door de acetolyse worden de humusverbindingen opgelost en verdwijnen ze uit het monster.
- Centrifugeren, acetolyse mengsel decanteren.
- Tweemaal uitwassen met aqua dest. om zuur te verwijderen (2 keer vloeistof decanteren, aanvullen met 10 ml aqua dest., vortexen en 5 minuten centrifugeren op 1700 r.p.m.).
- Monsters die volgens LOI analyse geen minerale delen bevatten slaan stap 3 (zware vloeistof scheiding) over worden pas behandeld als aan stap 4 wordt begonnen.

3. Zware vloeistof scheiding

<u>NB. Resten zware vloeistof altijd decanteren in plastic wasfles voor zware vloeistof.</u>

- Monsters vortexen en decanteren.
- 4 ml zware vloeistof (natrium-polywolframaat met d=2.0) toevoegen. Vortexen om goed te mengen.

- 15 minuten bij 1700 r.p.m. centrifugeren om te scheiden op soortelijk gewicht. Pollen zijn lichter dan de zware vloeistof en zullen boven komen drijven. Er wordt hier een langere centrifugetijd aangehouden omdat de vloeistof visceuzer is.
- Kraag decanteren in (nieuw genummerde) conische centrifugebuis. Aanvullen met aqua dest. tot 10 ml. Goed vortexen en 5 minuten centrifugeren bij 1700 r.p.m., restant zware vloeistof decanteren.
- De zware vloeistof die overbleef in de 'oude' buis opnieuw aanvullen met 4 ml zware vloeistof, nogmaals 15 minuten op 1700 r.p.m. centrifugeren. Door de tweede keer zware vloeistof toe te voegen komt het soortelijk gewicht uit op 2.0, terwijl als men slechts 1 keer aanvult met zware vloeistof het soortelijk gewicht lager uitkomt door vermenging met aqua dest.
- Kraag decanteren in de nieuw genummerde conische buis, waar al pollen van de eerste keer met zware vloeistof centrifugeren in zitten.
- Alle overgebleven zware vloeistof door filteren mb.v. koffiefilter zodat zware vloeistof kan worden hergebruikt.
- Twee maal wassen met aqua dest. (aanvullen met aqua dest., vortexen, 5 minuten centrifugeren op 1700 r.p.m. en decanteren).

4. Afwerken

- Twee à drie maal uitwassen met aqua dest. (monsters decanteren, aanvullen met aqua dest., vortexen en 5 minuten centrifugeren op 1700 r.p.m.)
- 1.5 ml alcohol toevoegen de laatste keer decanteren. Vortexen.
- Overbrengen in Eppendorf cup.
- Eppendorf cup uitcentrifugeren, 1 minuut op 1700 r.p.m.
- Decanteren en glycerine toevoegen (evenveel glycerine als monster).
- Residu een nacht drogen bij maximaal 70 °C. Zo verdampen alle vloeistoffen en houdt men alleen pollen en glycerine over in Eppendorf cups.
- Preparaat maken met glycerine (op warmteplaat 100 °C).

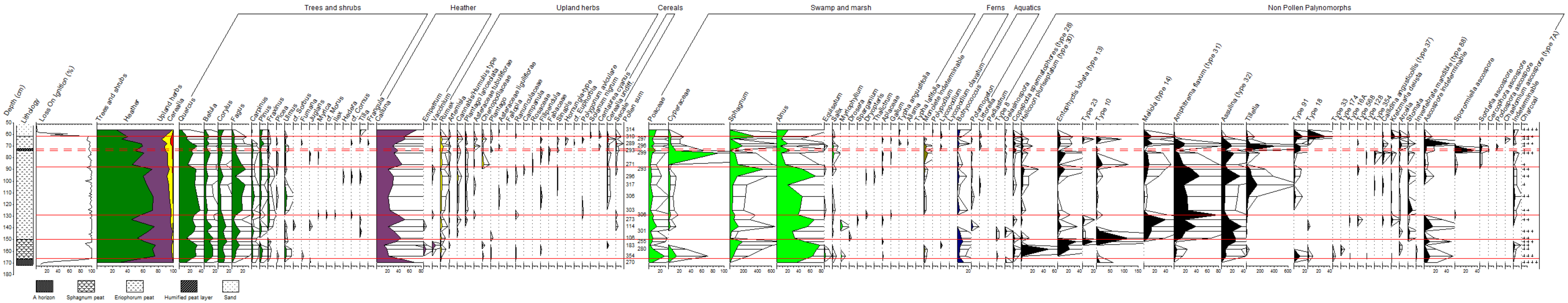
Appendix E

In this appendix, and overview of the samples of core B that were prepared is provided. The samples that were analyzed in this study are shown in green.

Sample nr	Depth (cm) from:	to:	Core name
1	169	170	KWKV II
2	167	168	KWKV II
3	165,5	166,5	KWKV II
4	163,5	164,5	KWKV II
5	161,5	162,5	KWKV II
6	159,5	160,5	KWKV II
7	157,5	158,5	KWKV II
8	155,5	156,5	KWKV II
9	153,5	154,5	KWKV II
10	151,5	152,5	KWKV II
11	149,5	150,5	KWKV II
12	156,5	157,5	KWKV IV
13	154,5	155,5	KWKV IV
14	152,5	153,5	KWKV IV
15	150,5	151,5	KWKV IV
16	148,5	149,5	KWKV IV
17	146,5	147,5	KWKV IV
18	144,5	145,5	KWKV IV
19	142,5	143,5	KWKV IV
20	140,5	141,5	KWKV IV
21	138,5	139,5	KWKV IV
22	136,5	137,5	KWKV IV
23	134,5	135,5	KWKV IV
24	132,5	133,5	KWKV IV
25	130,5	131,5	KWKV IV
26	128,5	129,5	KWKV IV
27	126,5	127,5	KWKV IV
28	124,5	125,5	KWKV IV
29	122,5	123,5	KWKV IV
30	120,5	121,5	KWKV IV
31	118,5	119,5	KWKV IV
32	116,5	117,5	KWKV IV
33	114,5	115,5	KWKV IV
34	112,5	113,5	KWKV IV
35	110,5	111,5	KWKV IV
36	108,5	109,5	KWKV IV
37	106,5	107,5	KWKV IV
38	104,5	105,5	KWKV IV
39	102,5	103,5	KWKV IV
40	100,5	101,5	KWKV IV
41	98,5	99,5	KWKV IV

42	96,5	97,5	KWKV IV
43	94,5	95,5	KWKV IV
44	95,5	96,5	KWVK I
45	93,5	94,5	KWVK I
46	91,5	92,5	KWVK I
47	89,5	90,5	KWVK I
48	87,5	88,5	KWVK I
49	85,5	86,5	KWVK I
50	83,5	84,5	KWVK I
51	81,5	82,5	KWVK I
52	79,5	80,5	KWVK I
53	77,5	78,5	KWVK I
54	75,5	76,5	KWVK I
55	73,5	74,5	KWVK I
56	71,5	72,5	KWVK I
57	69,5	70,5	KWVK I
58	67,5	68,5	KWVK I
59	65,5	66,5	KWVK I
60	63,5	64,5	KWVK I
61	61,5	62,5	KWVK I
62	59,5	60,5	KWVK I
63	57,5	58,5	KWVK I
64	55,5	56,5	KWVK I

Appendix F



Trees and shrubs
Heather
Upland herbs
Cereals
Swamp and marsh
Ferns
Aquatics
Non Pollen Palynomorphs
A horizon
Sphagnum peat
Eriophorum peat
Humified peat layer
Sand