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Geochronology of Soils and Landforms in Cultural Landscapes on Aeolian Sandy Substrates, Based on Radiocarbon and Optically Stimulated Luminescence Dating (Weert, SE-Netherlands)

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1. Introduction

The landscape of the study area (fig. 1,2) is underlain by coversand, deposited during the Late Glacial of the Weichselian. In the Preboreal, aeolian processes reduced soil formation (Stichting voor Bodemkaratering, 1972) and from the Preboreal to the Atlantic a deciduous climax forest developed (Janssen, 1974). The geomorphology was a coversand landscape, composed of ridges (umbric podzols), coversand plains (gleyic podzols), coversand depressions (histic podzols) and small valleys (gleysols). The area was used by hunting people during the Late Paleolithic and Mesolithic (Nies, 1999). Analysis of the urnfield 'Boshoverheide', indicated that the population increased during the Bronze Age between 1000 and 400 BC to a community of several hundreds of people, living from forest grazing, shifting cultivation and trade (Bloemers, 1988). The natural deciduous forests gradually degraded into heath land. The deforestation accelerated soil acidification and affected the hydrology, which is reflected in drying out of ridges and wetting of depressions, promoting the development of histosols and histic podzols. Sustainable productivity on chemically poor sandy substrates required application of organic fertilizers, composed of a mixture of organic litter with animal manure with a very low mineral compound (Van Mourik et al., 2011a), produced in shallow stables (Vera, 2011). The unit plaggic anthrosol on the soil map of 1950 AD identifies the land surface, which was used for plaggen agriculture. At least since 1000 AD, heath management was regulated by a series of rules that aimed to protect the valuable heat lands against degradation (Vera, 2011). During the 11th, 12th and 13th centuries there was an increasing demand for wood and clear cutting transformed the majority of the forests in driftsand landscapes (Vera, 2011). The exposed landscape was subjected to wind erosion and accumulation which endangered heath, arable land and even farmhouses. As a consequence, umbric podzols, the natural climax soil under deciduous forests on coversand, degraded into larger scale driftsand landscapes, characterized by deflation plains (gleyic arenosols) and complexes of inland dunes (haplic arenosols) (Van Mourik et al., 2011b). In such driftsand landscapes, the majority of the podzolic soils in coversand has been truncated by aeolian erosion. Only on scattered sheltered sites in the landscape, palaeopodzols were buried under mono or polycyclic driftsand deposits. They are now the valuable soil archives for palaeoecological research.

The city of Weert was founded at the end of the 13th century on a deforested topographic ridge of dry sandy soils, surrounded by swampy heath lands (Nies, 1999). Around 1300 AD the citizens ensured the supply of fresh water for the city moat by the creation of the 'Weerter Beek', a canal to connect the moat with a wetland area near the present Belgium border (Salmans and Tillemans, 1994). The topographical map of 1550 AD (fig.1) shows a deforested landscape surrounding the city, with distinct zones of arable land and heath; the natural forest had already completely been transferred into a cultural landscape.

During the 18th century, the population growth and regional economical activity stimulated the agricultural productivity. Farmers introduced the innovative 'deep stable' technique to increase the production of fertilizers (Vera, 2011). Additional to mowed biomass, farmers collected heath sods, including the top of the Ah horizon of the humus forms. This consequently promoted heath degradation and sand drifting, resulting in the extension of driftsand landscapes. During the 19th century, farmers tried to find alternative fertilizers and authorities initiated reforestation projects. The invention of chemical fertilizers at the end of the 19th century marked the end of the period of heath management and plaggen agriculture (Spek, 2004; Van Mourik at al., 2011b; Vera, 2011). The heath was not longer used for the harvesting of plaggic matter and new land management practices were introduced. Heath was reclaimed to new arable land or reforested with Scotch pine. During the 20th century the landscape dramatically changed again through a shift towards industrialization and bio-industry. Geomorphological features belonging to the historical sand drifting and plaggen agriculture survived in the landscape and are now included in the geological inheritance.

During recent decades the interest and need for restoration ecology and geoconservation has increased on global and regional scale (Bal et al., 2001). In the Netherlands, a national ecological master structure was designed to recover the ecological quality and biodiversity and in this context attention was paid to the preservation and restoration of driftsand habitats and landscapes (Koster, 2009, 2010).

Soil maps often serve as abiotical archives for ecosystem restoration management. However, soil classifications are normally based on actual diagnostic properties and therefore neglect relicts of former phases in soil and landscape development. Consequently, soil maps only show the distribution of recent soil types and are thus useless to fully understand the interaction of natural and human processes in time and space. To overcome this gap in knowledge of long term impact of human land use on the development of landforms and soils, the results of three innovative methods, applied to a selection of formerly investigated palaeosols, are presented in this paper. Firstly, the application of OSL dating on formerly investigated and ^{14}C dated palaeosols, to improve the geochronology of the phases in landscape evolution. Secondly the application of biomarker analysis to select the plant species, responsible for the production of organic carbon, stored in humic soil horizons. Finally it is shown how the complete package of palaeoecological information can be processed into soil maps of paleo-landscapes using a geographical information system.

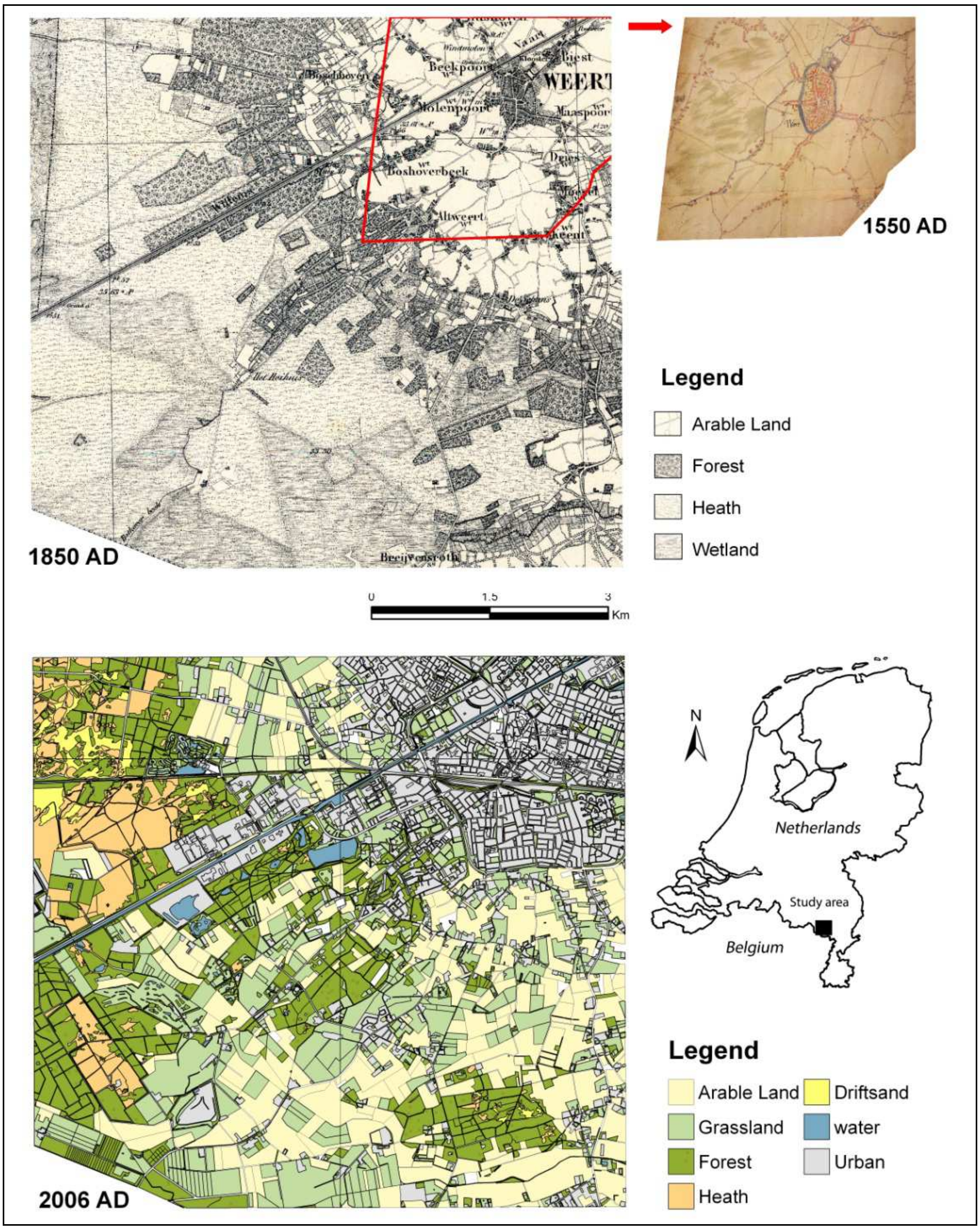

Fig. 1. Land use in the surroundings of Weert around 1550 AD (map of the City of Weert, surveyed between 1550 and 1570 by Jacob van Deventer), in 1850 AD (fragment of the topographical map scale 1:50,000, surveyed in 1837, published in 1863 by the Ministry of War) and 2006 AD (fragment of digital topographical map (Top10 vector), surveyed in 2006 AD).

2. Materials and methods

2.1 Profile selection

Since 1988 several pilot studies have been dedicated to the analysis of histosols, buried podzols and plaggic anthrosols around the city of Weert). Palynology, soil micromorphology and radiocarbon dating were the analytical tools to unlock the palaeoecological information from these valuable soil archives. For the reconstruction of the Late Holocene landscape evolution around the City of Weert, we selected several previously investigated key profiles. This selection comprises a histosol (Kruispeel), 3 buried histic podzols (IJzerenman, Tungelerwallen, Weerter Bergen), 3 buried (polycyclic) podzols (profiles Defensiedijk-1 and -2, Boshoverheide) and 3 plaggic anthrosols (profiles Tungelerakker, Dijkerakker and Valenakker).

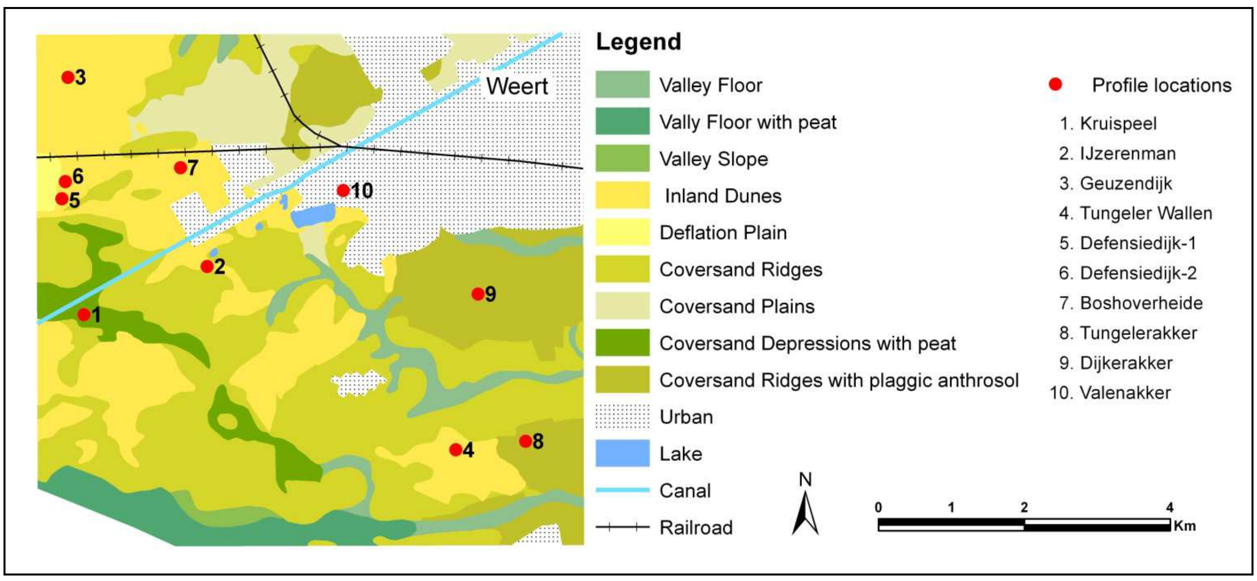

Fig. 2. Fragment of the geomorphological map, scale 1:50.000 with the profile locations.

2.2 Pollen analysis

Peat deposits are considered to contain syn-sedimentary pollen records and the diagrams reflect the characteristics of the local and regional vegetation development. Palaeosols are considered to contain a post-sedimentary pollen content as a result of bio-infiltration of pollen and the diagrams reflect ecological fingerprints of the soil ecological evolution (Van Mourik, 1999-b, 2001). Palynological reference of the Holocene vegetation development of SE-Netherlands, based on pollen analysis of extensive peat bogs in the Peel region have been published by Eshuis (1946) and Janssen (1974). The pollen zoning of the reference diagram is based on the zones of Firbas (1949). To understand the human impact on soils and landforms, local palaeoecological data was collected from a selection of palaeosols. From the profiles Kruispeel, IJzerenman and Weerter Bergen, samples were collected with an auger, vertical sampling distance 2.5 cm. From the other profiles, samples were collected in 10 ml tubes in profile pits, vertical sampling distance 2.5 cm. Pollen extractions were carried out using the tufa extraction method (Moore et al., 1991, p. 50). The exotic marker grain method was applied (Moore et al., 1991, p. 53) for estimation of the pollen densities in the mineral soils. For the identification of pollen grains the pollen key of Moore et al. (1991, p. 83-166) was applied. Pollen scores were based on the total pollen sum of arboreal and non arboreal plant species with the exception the aquatic species in pollen diagram Kruispeel. The pollen extractions were performed in the palynological laboratory IBED, University of Amsterdam. Pollen densities are represented in kilo grains / ml, or in the logarithmic value (log D)of the total amount of pollen grains / ml.

2.3 Soil micromorphology

Micromorphological observations are needed to assess the validity of soil ecological fingerprints, based on pollen spectra of drained soils. (Van Mourik, 2001). In thin sections of soil horizons, pollen grains are detectable but not determinable. The quality of the micro environment of pollen grains provide evidence of infiltration and preservation processes. Micromorphological observations are also relevant to understand the presence and distribution of soil organic carbon. Secondary soil processes can affect the quality of the original soil organic matrix and alter the organic chemistry composition and consequently the results of radiocarbon dating (Van Mourik et al., 2010). Undisturbed soil samples were collected in Kubiena boxes.

Undisturbed soil samples of buried humic horizons were collected in Kubiena boxes. Thin sections of undisturbed soil samples were produced, using the method of Jongerius and Heintzberger (1976) in the soil laboratory of IBED, University of Amsterdam. Thin sections were used to study the occurrence and preservation.

2.4 ^{14}C-dating

In traditional palynological research, radiocarbon dating was applied for absolute dating of pollen zones, as found in peat and limnic deposits. In palaeopedology, radiocarbon datings also have been used for dating purposes. The interpretation of radiocarbon datings of extracted soil organic carbon from soil samples is complicated. Due to the complexity of the provenance of soil organic carbon in humic soil horizons, conventional radiocarbon ages of bulk samples (BULK) are not very reliable. It is preferable to apply radiocarbon dating on extractions of fulvic acids (FUL), humic acids (HAC) and humin (HUM) (Goh and Molloy, 1978; Van Mourik et al., 1995, 2010). These fractions are based on extractability behavior. Fulvic acids are soluble in acid and in lye, the humic acids are insoluble in acid and soluble in lye and the humin fraction is insoluble in acid and in lye. The biological decomposition rate of FUL is relatively high; they migrate easily through weak acid soil profiles or leach completely. Therefore, they are unreliable for any dating purposes. The biological decomposition rate of HAC is medium high. Compared with FUL, they are immobile in the soil profiles and more reliable for dating purposes. The ^{14}C age of HAC is therefore expected to reflect the moment of burying of the soil. HUM (including pollen grains and charcoal) will accumulate in humic topsoil during an active period of soil development; therefore, ^{14}C ages of this fraction will definitely overestimate the age of burial. From these characteristics, we infer that the radiocarbon age difference between the HUM and HAC fractions of the same level will be greater during longer periods of active soil formation. To create a ^{14}C based geochronology, conventional ^{14}C

dating was firstly applied on bulk samples of soil organic matter extracted from soil samples of the profiles Tungeler Wallen, Defensiedijk 1,2 and Boshoverheide; additional on FUL, HAC and HUM fractions of soil organic matter, extracted from samples of the profiles Defensiedijk 1 and 2 and Boshoverheide, and finally on HAC and HUM fractions of soil organic matter, extracted from samples of the profiles Kruispeel, Tungelruy, Dijkerakker,Weerter Bergen and IJzerenman. Radiocarbon datings have been performed in the *Centrum voor Isotopen Onderzoek* (CIO) of the University of Groningen, Netherlands (table 1). For calibration of the radiocarbon ages to calendar years, the program OxCal 4.1 (1 sigma confidence interval) was used.

2.5 Luminescence dating

For a general description of the OSL dating method is referred to Wintle (2008). Applications of OSL dating to plaggic deposits have been discussed earlier by Bokhorst et al. (2005) and Van Mourik et al. (2011b), while applications to polycyclic driftsand sequences were publishe in Van Mourik et al. (2010). The OSL samples were collected in standard pF-rings. Luminescence measurements used an automated Risø TL/OSL reader (DA 15) equipped with an internal Sr/Y beta source, and blue and IR diodes (Bøtter-Jensen et al., 2000). A single-aliquot regenerative dose (SAR) procedure was used for equivalent dose estimation (Murray and Wintle, 2003). OSL ages were calculated by dividing the sample burial dose by the dose rate and can be expressed in years relative to the year of sampling as well as in AD / BC. Quoted uncertainties contain all random and systematic errors in both the dose rate and burial dose assessment, and reflect the 1-sigma confidence interval. Luminescence dating of profile Defensiedijk 1 was performed at the Department of Geology and Soil Science, Laboratory of Mineralogy and Petrology (Luminescence Research Group), Ghent University (UG); of profile Dijkerakker at the Institute of Geography and Earth Sciences, University of Wales, Aberystwyth (UW); of profile Valenakker and Boshoverheide at the Netherlands Centre of Luminescence dating of the Delft University of Technology (NCL).

2.6 Biomarker analysis

Two pilots were chosen for the application of biomarker analysis. The first pilot was a polycyclic driftsand sequence. The research question was: Does the combination of pollen and biomarker analysis allow for a selection of the responsible plant species for the production of biomass and sequestration of soil organic carbon in buried humic horizons? We selected *n*-alkanes and *n*-alcohols with carbon numbers 20 - 36, which are exclusive to the epicuticular wax layers on leaves and roots of higher plants (Kolattukudy et al., 1976), as biomarkers of past vegetation. Recently, analysis of n-alkane and *n*-alcohol patterns preserved in Ecuadorian soils enabled a reconstruction of past vegetation dynamics in the area (Jansen et al., 2008). To explore the applicability of biomarker analysis for vegetation reconstructions in a wider range of soils we applied it as an additional proxy in a selected profile in the Weert setting: Defensiedijk-1. To this end the same A horizon samples were used as for the analysis of fossil pollen in the profile. In addition, leaves and roots from species expected to have been responsible for the dominant biomass input in the profile were sampled from the present day vegetation. These consisted of *Polytrichum piliferum*, *Cladonia rangiferina, Calluna vulgaris*, *Molinia caerulea*, *Corynephorus canescens*, *Deschampsia flexuosa*, *Pinus sylvestris*, *Betula pendula* and *Quercus robur.* Approximately 0.1 g of each of the freeze-dried and ground vegetation and soil samples was extracted by Accelerated Solvent Extraction (ASE) using a Dionex 200 ASE extractor. The extraction temperature was 75ºC and the extraction pressure 17×10^6 Pa, employing a heating phase of 5 min and a static extraction time of 20 min. Dichloromethane/methanol (DCM/MeOH) (93:7 v/v) was used as the extractant (Jansen et al., 2006a). The extracts were pre-treated and derivatized with BSTFA (*N,O*-bis(trimethylsilyl) trifluoroacetamide) containing 1% TMCS (trimethylchlorosilane) following a previously described protocol (Jansen et al., 2006b). Sample analysis took place on a ThermoQuest Trace GC 2000 gas chromatograph connected to a Finnigan Trace quadrupole mass spectrometer (MS), Separation took place by on-column injection of 1.0 l of the derivatized extracts on a 30 m Rtx-5Sil MS column (Restek) with an internal diameter of 0.25 mm and film thickness of 0.1 m, using He as a carrier gas. Temperature programming was: 50ºC (hold 2 min); 40ºC/min to 80ºC (hold 2 min); 20ºC/min to 130ºC; 4ºC/min to 350ºC (hold 10 min). Subsequent MS detection in full scan mode used a mass-to-charge ratio (*m/z*) of 50-650 with a cycle time of 0.65 s and followed electron impact ionization (70 eV). The *n*-alkanes and *n*-alcohols were identified by their mass spectra and retention times and quantified using a deuterated internal standard (d_{42}-*n*-C_{20} alkane and d_{41}-*n*-C_{20} alcohol) (Jansen et al., 2006b). The concentrations of *n*-alkanes and *n*-alcohols with carbon numbers 20-36 in vegetation and soil samples were subsequently used as input for the VERHIB model that was specifically designed to translate such biomarker patterns into the most likely past vegetations patterns (Jansen et al. 2010). As required boundary conditions for the model we assumed a leaf biomarker vs. root biomarker input ratio in the soil of 1:10. For the tree species we assumed the root input to be equally distributed with depth, while for the grass and heath species we assumed all root input to have taken place within the first 36 cm, with 75% of that within the first 2 cm. The lichen and moss species were assumed to have given input only at the surface. The second pilot was a plaggic anthrosol. The research question was: Does the combination of pollen and biomarker analysis enable to detect the origin of the collected biomass for the preparation of plaggic manure? Three samples were analyzed from the plaggic horizons of profile Valenakker. Because of the limited number of horizons and the number of samples was too small to apply the VERHIB model.

2.7 Processing in ArcGIS

Three soil maps for the Weert area have been prepared in a digital environment in ArcGIS 10.0 (http://www.esri.com), following the method described by van Mourik et al. (2011) for a nearby area in the Netherlands. First, the soil map that represents the situation around 1950 and two historical maps, one of 1500 AD and one of 2000 BC. The 1950 soil unit boundaries are based on the scanned and digitized paper soil maps of the Netherlands (BKN50), whereas the two interpretative soil map boundaries are based on the results of the palaeoecological profile studies in this chapter and on available historical information of the vicinity of Weert. The digital 1:50.000 scale soil map of the Netherlands (BKN50 2006) is based on the analogue soil map of 1976 (Stichting voor Bodemkartering, 1976), which was mapped around 1968.

Soil code 1980	Soil name 1950 AD	Soil name 1500 AD	Soil name 2000 BC
Hd	Carbic podzol	Carbic podzol	Umbric podzol
Hn	Gleyic podzol	Gleyic podzol	Gleyic podzol
zEZ, EZg	Plaggic anthrosol	Plaggic podzols	Umbric podzols
pZg, pZn	Umbric arenic gleysol	Umbric arenic gleysol	Umbric arenic gleysol
aVz, zVz, Vz, Vp	Histosol	Histosols	Histic arenic gleysol
zWp	Histic podzol	Histic podzol	Gleyic podzol
zWz, vWz	Histic arenic gleysol	Histic arenic gleysol	Umbric arenic gleysol
Zd	Haplic arenosol	Umbric podzol	Umbric podzol
Zn	Gleyic arenosol	Gleyic podzol	Gleyic podzol
Ln	Siltic gleysol	Siltic gleysol	Siltic gleysol
Bebouwd	Urban	Urban	-

Table 1. Reclassification scheme used in GIS for the preparation of interpretive historical soil maps.

The translation of local (Dutch) soil type names in international labels is based on the World Reference Base (ISRIC/FAO, 2006). The vector-based soil map was clipped to the extent of the Weert study area by using a rectangular mask. The approximately 300 original legend categories were thus reduced to 17 legend units. These were further aggregated, based on similarities in soil texture properties, to 10 categories (table 1).

For the reconstruction of the soil maps of 1500AD and 2000 BC, detailed information on time development was used, which was obtained from the 10 key soil profiles described in detail in this chapter. This refers both to the age and to the palaeoecological information of buried soil horizons, which is indicative for renewed landscape dynamics, that is driven by either natural processes or man-induced interference. Crucial in this step is to define soil sequences for a time-span of approximately 4000 years, which is based on properties of the parent material, position in the landscape, local groundwater conditions over time and historical land cover and land use changes and, to a lesser extent, climate change. In the attribute table of the clipped digital soil geodatabase three additional columns were added for the 1950 AD, 1500 AD and the 2000 BC situations. Detailed, 5m resolution topographical information was used from the digital '*Algemeen Hoogtemodel Nederland*' (AHN5) which contains heights information expressed in cm. Land cover and land use data has been extracted from historical maps around 1550 AD, which shows an almost total deforested landscape with 'islands' of sand around the initial settlement of Weert and locations of former swampy areas. Visualization of the newly generated soil attributes leads to so-called 'interpretative historical soil maps' for the 1500 AC and 2000 BC situations. It was supposed that boundaries between the soil units did not significantly change over this time span. The soil boundaries that underlie the currently urbanized areas were reconstructed according to their likely fit with neighboring soil boundaries of the digital soil map of 2006, and by using historical map information.

3. Results and discussion

3.1 Palaeoecological information from a histosol and buried histic podzols

^{14}C Datings of (buried) histic horizons indicate the start of peat accumulation in coversand depressions around Weert between 1000 and 500 BC, due to wetting of depressions caused by deforestation of the surrounding higher coversand ridges. Similar datings were found in the study area Maashorst, 55 km north of Weert (Van Mourik et al., 2011b). In the more extensive depression of Kruispeel, the accumulation of peat continued during the Late Subboreal and Subatlantic; in small scale depressions gleyic podzols just transferred in histic podzols before they got buried under driftsand deposits around 1000 AD.

3.1.1 Profile Kruispeel, terric histosol (fig. 3-4; table 2;); pollen diagram first published in Van Mourik (1988)

Kruispeel used to be a shallow peat bog, situated in a depression in the coversand landscape (fig. 2). The formation of the histosols started in the Early Preboreal (*Pinus, Cyperaceae*e) with the deposition of humus gyttja, representing a shallow lake bottom soil, followed by a phase of terrestrialization with peat accumulation (*Betula, Salix, Artemisia, Helianthemum, Juniperus*). Compared with the Firbas pollen zoning of the Peel references (Janssen 1974), the composition of the pollen spectra is indicative for pollen zone IV. In the Boreal (zone V) the peat accumulation slowed down. The Atlantic (zones VI, VII) is absent. The accumulation of peat accelerated in the Late Subboreal (zone VIII) around 3300 BC (table 2) and continued in the Subatlantic (zones IX, X). The pollen spectra reflect a mix of species from the disappearing forest (*Corylus, Alnus, Quercus, Fagus*) and the emerging cultural landscape (*Ericaceae, Cerealia, Fagopyrum, Plantago*). *Cerealia* pollen is present in pollen spectra since the Bronze Age, *Fagopyrum* was introduced around 1350 AD (Leenders, 1987).

Diagram Kruispeel shows a clear expression of the impact of the vegetation development of the topographic higher surroundings on the hydrology of the depression. Deforestation on ridges (lower evapotranspiration, higher soil water infiltration) resulted in accumulation of gyttja or peat in the depression. Forested ridges (higher evapotranspiration and lower soil water infiltration) as a contrast resulted in a reduction of the accumulation rate or even in erosion by bio-oxidaten. The youngest spectra reflect the start of the period of reforestation (*Pinus*) since 1850 AD. The combination of reforestation and improve of the drainage by digging the Tungelroysche Beek at the end of the 19th century is responsible for stagnation of peat accumulation. Recently, wetland conditions and ‘peel’ponds have been restored.

number	horizon	depth (cm)	fraction	^{14}C year BP	calibrated ^{14}C age
GrN 25419	2H	45-50	HUM	3440 ± 40	1738 – 1522 BC
GrN 25420	2H	45-50	HAC	3250 ± 40	1617 – 1437 BC

Table 2. ^{14}C datings of profile Kruispeel

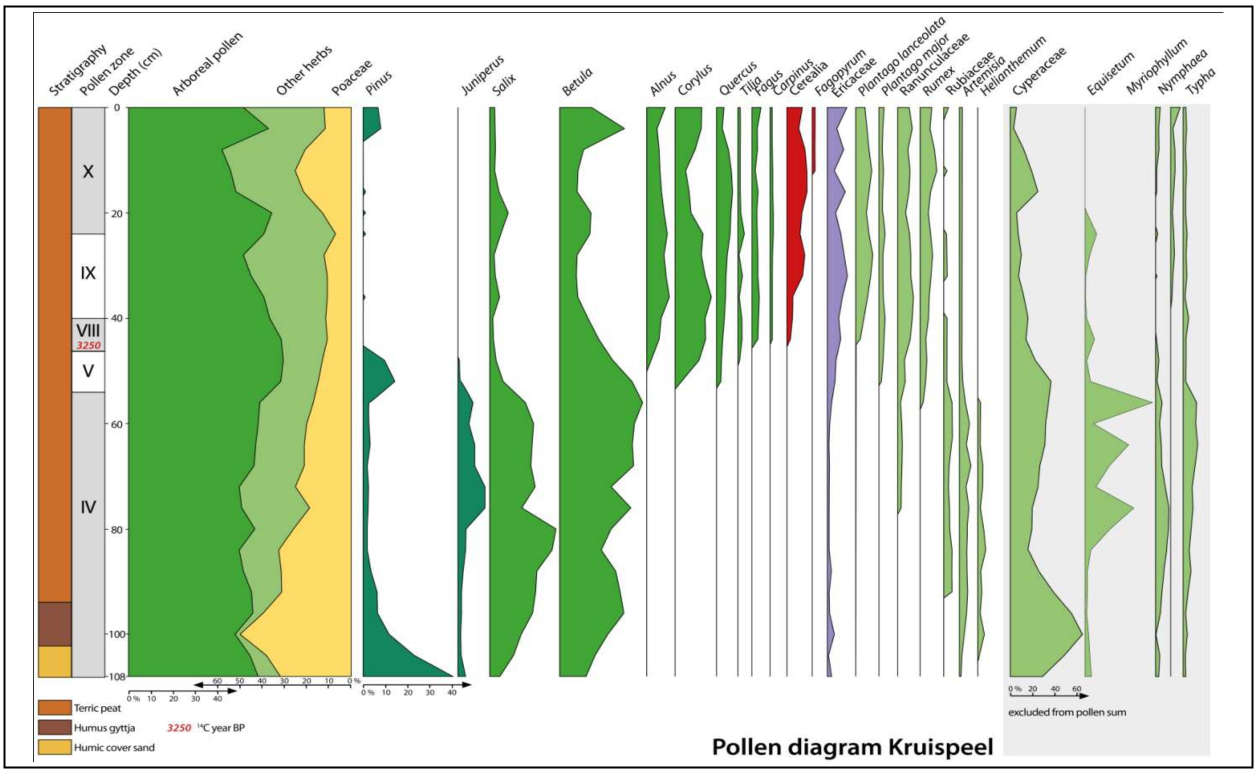

Fig. 3. Pollen diagram Kruispeel.

Fig. 4. Photo of the former peat bog Kruispeel, 2000 AD. The canal 'Tungelroysche Beek' was dug in the 19th century to improve drainage and land reclamation; the pond was created at the end of the 20th century as part of a nature development project to improve landscape quality and biodiversity.

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3.1.2 Profile IJzeren Man, bi-cyclic haplic arenosol, overlying a histic podzol (fig. 5; table 3); pollen diagram first published in Van Mourik, 2000

Based on radiocarbon ages, the histic horizon of the palaeopodzol in coversand developed between 500 BC and 1000 AD. The post-sedimentary pollen spectra in the mineral horizon reflect decreasing scores of deciduous trees (*Corylus, Tilia, Quercus*), indicative for deforestation and high scores of *Ericaceae*, marking the extension of heath. Moist conditions during the development of the 3H or reflected by the scores of *Sphagnum*. Shortly after 1000

AD the histic podzol was buried by driftsand deposits. This age correlates with the period of forest clear cutting (Vera, 2011). The syn-sedimentary pollen spectra of the 2C are dominated by *Ericaceae*, reflecting heath dominance. After stabilization, a micropodzol (2AE) developed. It is difficult to establish an age, based on ^{14}C datings. The date of the HUM fraction probably overestimates the age and the date of the HAC fraction just indicates 'post Mediaeval'. The pollen spectra of the C are dominated by *Ericaceae* and *Poaceae*, reflecting a more degraded heath. After stabilization and reforestation *Larix* and *Pinus* pollen infiltrated, dominating the spectra of the actual micropodzol (3S).

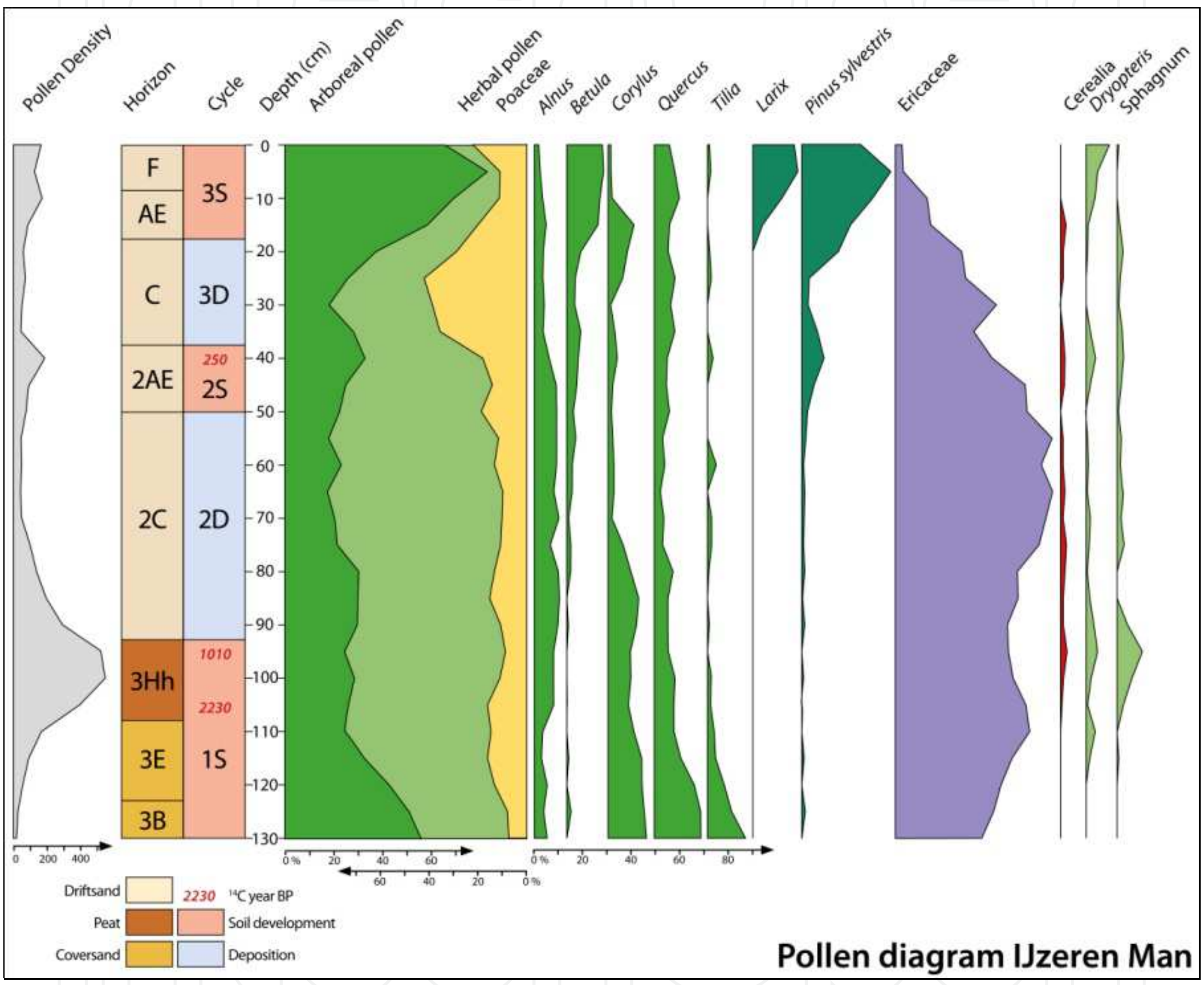

Fig. 5. Pollen diagram IJzeren man

Number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C ages
GrN 21245	2AE	40-24	HUM	1810 ± 90	18-417 AD
GrN 21245	2AE	40-42	HAC	250 ± 50	1482-1955 AD
GrN 23442	3AHh	90-91	HUM	1010 ±30	973-1152 AD
GrN 23443	3Hh	90-91	HAC	900 ± 40	1034-1215 AD
GrN 23444	3Hh	106-107	HUM	2230 ± 90	511-43 BC
GrN 23445	3Hh	106-107	HAC	2140 ± 35	358-56 BC

Table 3. ^{14}C datings of profile IJzerenman

3.1.3 Profile Tungeler Wallen, bi-cyclic haplic arenosol, overlying a histic podzol (fig. 6-7; Table 4); Pollen diagram first published in Van Mourik, 1988

Based on ^{14}C datings, the histic horizon developed between 300 BC and 1000 AD. It is unlikely that these ^{14}C datings are seriously affected by pollution by younger decomposition derivates from roots, considered the thickness of the driftsand deposits.

Number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C ages
GrN 14346	3Hh	135-140	BULK	945 ± 25	1027-1155 AD
GrN 24347	3Ah	160-165	BULK	2140 ± 30	353-56 BC

Table 4. ^{14}C datings of profile Tungeler Wallen

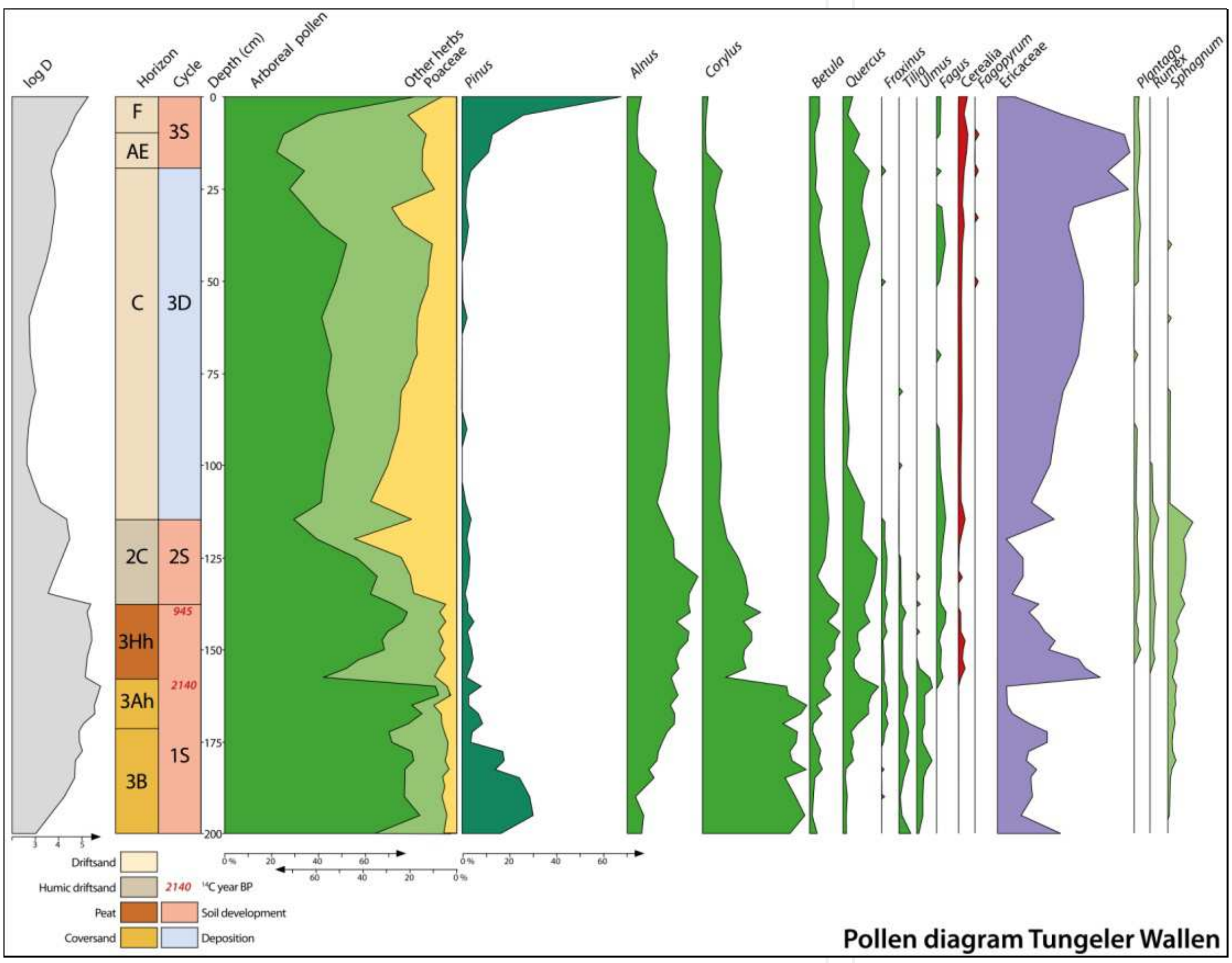

Fig. 6. Pollen diagram Tungeler Wallen.

The post-sedimentary pollen spectra of the palaeopodzol contain a mix of species from the Boreal forest (dominant in the 4B; *Corylus* and *Pinus*) and the Atlantic forest (dominant in the 3Ah; *Alnus*, *Quercus*,*Tilia*, *Ulmus*). The sharp fall of *Corylus* and rise of *Ericaceae* from the 3Ah to the 3Hh indicate a palynological hiatus in the record or even an erosion phase. Moist conditions during the development of the 3Hh are reflected by *Sphagnum*. During the field description two driftsand beds were distinguished. Based on the pollen density curve (log D), the lower bed was considered to represent the soil formation phase of the second cycle. Most probably, the 2AE horizon, expected above the 2C, has been eroded before the start of the third cycle. After stabilization and reforestation with Scotch pine, *Pinus* pollen could infiltrate and dominates the spectra the actual micropodzol (3D).

Fig. 7. Tungeler Wallen

3.1.4 Profile Weerter Bergen, tri-cyclic record; bi-cyclic haplic arenosol, overlying a histic podzol (fig.8-9; Table 5). Pollen diagram first published in Van Mourik, 1999a

Based on ^{14}C datings, the histic horizon developed between 400 BC and 600 AD. The pollen spectra of the palaeopodzol show, just as Tungeler Wallen and IJzerenman, high scores of elements of the former deciduous forest (*Corylus, Quercus, Tilia*), but also *Ericacea* show high scores, indicating heath in the surroundings. The development of the 3Hh took place between ± 200 BC and ± 700 AD. Special attention was paid in this profile on the determination of *Ericacae*, using the special pollen key of Moore et al. (1992) to distinguish *Erica tetralix*. The wetland vegetation is expressed by *Sphagnum, Myrica gale* and *Erica tetralix*. The pollen spectra of the 2C show a decrease of *Corylus* and an increase of *Ericacea*, indicating continuous extension of the heath. The ^{14}C datings of the 2 AE indicates a stable period around 800 AD under heath land conditions. After 800 AD, the micropodzol was buried under younger driftsand deposits. The pollen spectra of the C show very low percentages arboreal pollen and an increase of *Poaceae*, pointing to heath degradation. After stabilization and Pine plantation, *Pinus* pollen could infiltrate and dominate the spectra of the actual micropodzol.

Number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C ages
GrN 23436	2A	35-37	HUM	1150 ± 80	688-1020 AD
GrN 23437	2A	35-37	HAC	1165 ± 45	722-983 AD
GrN 23438	3Hh	67-68	HUM	1325 ± 50	610-809 AD
GrN 23439	3Hh	67-68	HAC	1380 ± 30	606-681 AD
GrN 23440	3Ah	78-80	HUM	2095 ± 80	361 BC-56 AD
GrN 23441	3Ah	78-80	HAC	2290 ±40	407-208 BC

Table 5. ^{14}C datings of profile Weerter Bergen

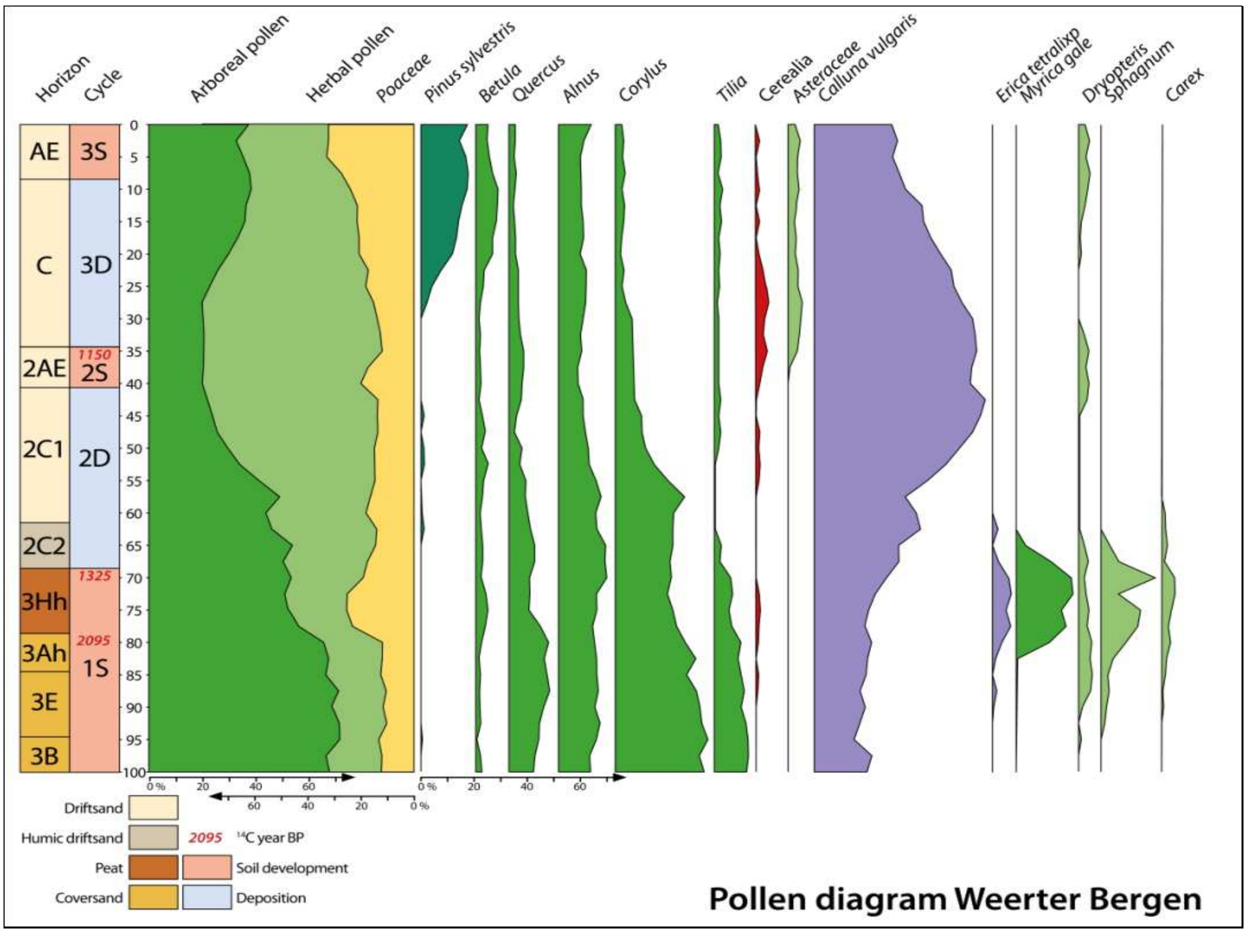

Fig. 8. Pollen diagram Weerter Bergen.

Fig. 9. Profile Weerter Bergen

3.2 Palaeoecological information from buried carbic podzols

Especially in well drained sandy landscapes, polycyclic sequences with buried podzols are unique parts of the soil archives. Pollen spectra provide information about the vegetation during stable and instable period. Application of biomarker analysis allow the selection of species, rooting during stable periods and responsible for the sequestration of soil organic carbon. The combination of ^{14}C and OSL datings indicates that the oldest palaeopodzols have been buried by Pre-Mediaeval small scale driftsand deposits, probably related to natural causes as hurricanes and forest fires or early shifting cultivation. Around 1000 AD a more extensive land surface with podzols got buried by larger scale driftsand deposits, probably related to the period of forest clear cutting. A generation of micropodzols, developed in stabilized driftsands, was buried by younger driftsand deposits after the 17th century, probably related to heath degradation due to the application of deep stable management.

3.2.1 Profile Defensiedijk 1, bi-cyclic haplic arenosol, overlying a bi-cyclic carbic podzol, pollen diagram first published in Van Mourik, 1988

3.2.1.1 Defensiedijk 1, sampled in 1986 (fig.10-15; table 6)

Application of radiocarbon dating in paleopedology is supposed to provide information for the establishment of the geochronology of the landscape evolution, but the interpretation of radiocarbon datings from paleosols is more complicated than in surveys of peat bogs and limnic deposits. This is caused by differential biological decomposition of soil organic litter, resulting in various fractions with different chemical compositions and turnover rates. For that reason, fractionated radiocarbon dating was introduced in paleopedology. Goh and Molloy (1978) investigated the suitability of radiocarbon datings of soil organic matter in quaternary geology and demonstrated the important role of the methods of extraction of organic matter. Ellis and Matthews (1984) established the differences in radiocarbon datings of FUL and HAC in palaeopodzols. The interpretations of the results of fractionated ^{14}C dating are heterogeneous. Mattheuws and Quentin (1983) selected the HAC fraction of the HF horizon for dating of a buried podzol in Norway. Hammond et al. (1991) established the importance of fractionated ^{14}C dating. In their research of peats and organic silts, FUL and HAC were considered as contaminates, leaching from podzolic environments. Dansgaard and Odgaard (2001) interpreted in their research of a buried podzol in Jutland the age of HUM, extracted from the B horizon as indicative for the start of podzolisation, the age of extracted FUL as indicative for the age of burial. Van Mourik et al. (1995) selected the HUM fraction of buried A horizons as indicative for the moment of burial, the differences in age between HUM and HAC fraction as indicative for a period of active soil formation and HUM accumulation and the FUL fraction as contaminated.

Profile Defensiedijk 1 is a palaeoecological record of four geomorphological cycles. Every cycle consist of an instable (D = aeolian deposition) and a stable (S = soil formation) period. During instable periods, syn-sedimentary pollen grains were incorporated in the sediment (low pollen densities), during stable periods, post-sedimentary pollen grains could infiltrate in the soil (high pollen densities). The pollen diagram (fig.10) provides information of the vegetation during instable (syn-sedimentary pollen) and stable (post-sedimentary pollen) periods (Van Mourik, 2001). The development of carbic podzol of the oldest cycle could continue from the Preboreal till the Late Subboreal. The post-sedimentary pollen spectra from the coversand deposit (cycle 1S) seems to reflect the presence of heath (*Ericaceae*) in a deforesting environment (*Corylus, Quercus*).

The post sedimentary pollen spectra from the oldest driftsand deposit (cycle 2D) show the maximal *Ericaceae* scores and the fall of *Corylus*, heath in a deforested cultural landscape. Podzolisation in this deposit could continue from ± 100 BC till 1000 AD. The syn-sedimentary scores of cycle 3D show an increase of *Poaceae* and a decrease of *Ericaceae*, reflecting heath degradation and sand drifting, the post sedimentary spectra of cycle 3S high scores of *Pinus*, reflecting soil formation under Pine forest. The syn-sedimentary spectra of the youngest cycle (4D) are characterized by dominance of *Poaceae* and a drop of *Pinus*, reflecting again degradation and sand drifting.

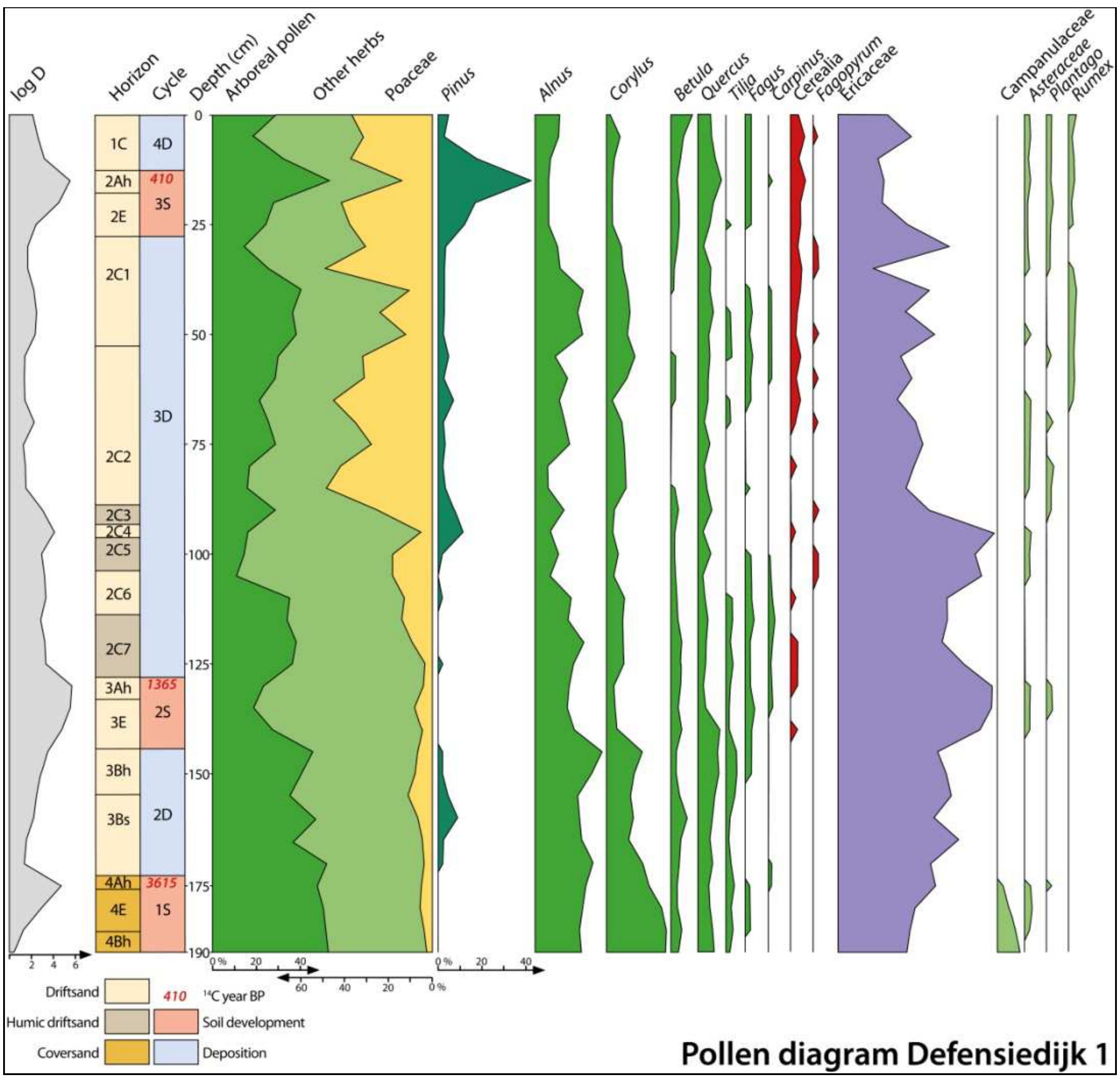

Fig. 10. Profile Defensiedijk 1.

Fig. 11. Defensiedijk 1, 1986

To establish the geochronology of the polycyclic sequence, ^{14}C dating was applied (table 6). The ^{14}C datings of BULK fractions were not satisfactorily for interpretation; especially the age of the 2A horizon was 'too old'. Soil micromorphological observations show the presence of transported organic aggregates and charcoal fragments in this horizon. That explains the 'old' age of the HUM fraction. The dataset sustains the conclusions (Van Mourik et al., 1995) that (1) ^{14}C ages of buried A horizons, based on HAC, are close to the moment of burial; (2) ^{14}C ages, based on HUM fractions are older than the moment of burial; (3) ^{14}C ages, based on FUL fractions are less reliable for understanding the geochronology. The ages, included in the pollen diagram, are the ^{14}C ages of the HAC fractions of the top of the buried A horizons.

number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C age
GrN - 14833	2Ah	025-027	HUM	3230 ± 110	1863-1219 BC
GrN - 14458	2Ah	025-027	HAC	410 ± 45	1423-1633 AD
GrN - 14759	2Ah	025-027	FUL	110 ± 120	1685-1928 AD
GrN - 12804	2Ah	025-027	BULK	1130 ± 45	778-999 AD
GrN - 14837	3Ah	127-129	HUM	1350 ± 50	602-775 AD
GrN - 14459	3Ah	127-129	HAC	1365 ± 25	520-687 AD
GrN - 14760	3Ah	127-129	FUL	850 ± 100	990-1380 AD
GrN - 14838	3Ah	129-131	HUM	1900 ± 110	166 BC-382 AD
GrN - 14694	3Ah	129-131	HAC	1675 ± 30	258-427 AD
GrN - 14774	3Ah	129-131	FUL	1200 ± 130	598-1149 AD
GrN - 12805	3Ah	127-131	BULK	1365 ± 25	620-687 AD
GrN - 14836	4Ah	173-174	HUM	4110 ± 90	2889-2475 BC
GrN - 14460	4Ah	173-174	HAC	3615 ± 35	2123-1887 BC
GrN - 14761	4Ah	173-174	FUL	2200 ± 170	736-123 BC
GrN – 14840	4Ah	175-176	HUM	4430 ± 165	3628-2638 BC
GrN - 14698	4Ah	175-176	HAC	3965 ± 40	2577-2344 BC
GrN - 14775	4Ah	175-176	FUL	3010 ± 140	1605-851 BC
GrN - 12808	4Ah	173-176	BULK	3615 ± 35	2123-1887 BC

Table 6. ^{14}C datings profile Defensiedijk 1 (1986)

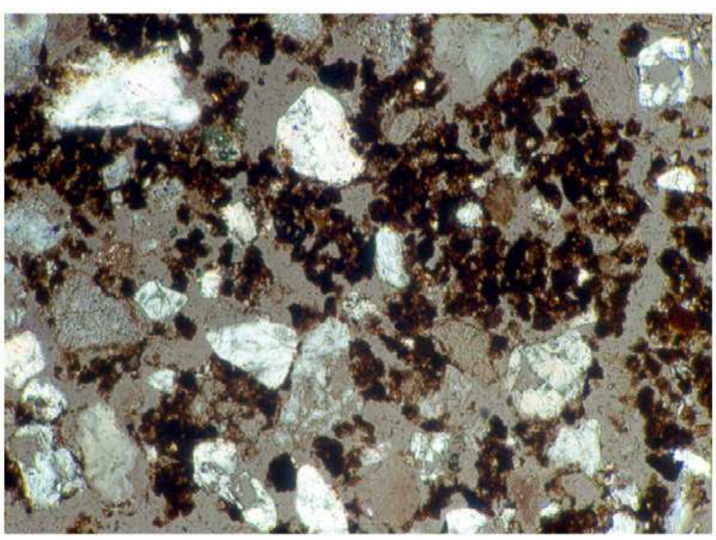

Fig. 12. Profile Defensiedijk 1. 2A horizon. Intertextic distributed organic aggregates with the intern fabric of fecal pallets; soil formation as result of litter decomposition by fungi and micro arthropods.

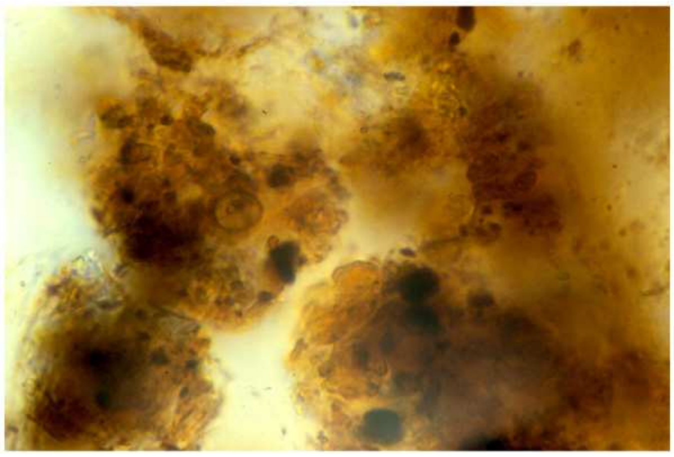

Fig. 13. Profile Defensiedijk 1. 2A horizon. Intern fabric of organic aggregates, showing the incorporation of small charcoal fragments and pollen grains.

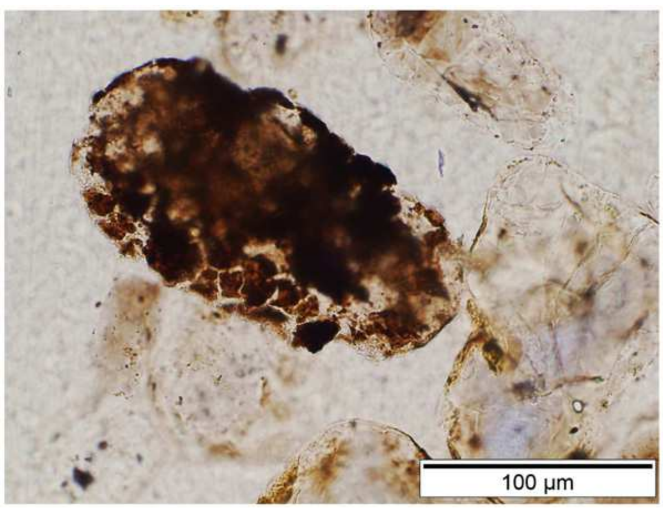

Fig. 14. profile Defensiedijk 1. 2C horizon. Rounded, transported organic aggregate, indicating sin-sedimentary contamination by older organic matter.

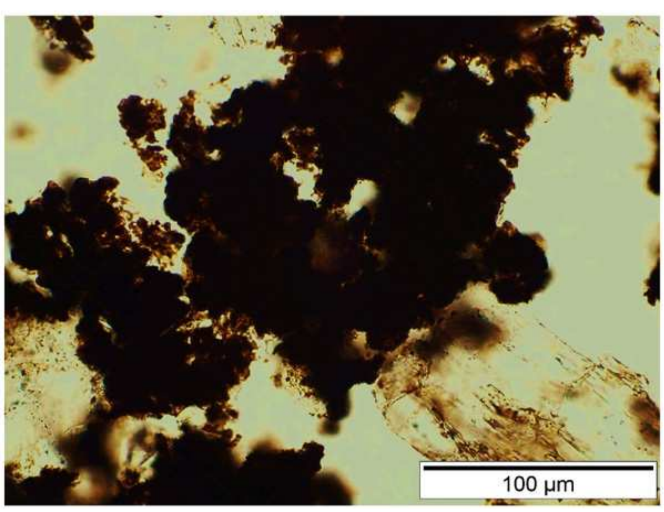

Fig. 15. Profile Defensiedijk 1. 4A horizon. Post-sedimentary, ageing intertextic distributed organic aggregates, indicating undisturbed soil structure.

3.2.1.2 Defensiedijk 1, sampled in 2002 (fig.16-17; table 7)

The geochronology, only based on ^{14}C dating, does not allow temporal separation during one cycle for sand drifting and soil development. Application of OSL dating can solve this problem. Due to aeolian erosion, it was impossible to resample on exactly the same site profile Defensiedijk 1. The horizontal distance between the profiles 1986 and 2002 was 8 meter. The thickness of the oldest driftsand formation was reduced to 15 cm. Defensiedijk 1 has been resampled in 2002 for OSL dating. Control samples were taken for ^{14}C dating (HAC fraction) of the 2AE, 3A and 4A horizons.

The geochronology can be improved (table 7) if ^{14}C and OSL datings are combined. The OSL age of cycle 1 is in line with the age of the coversand formation (Late Dryas). The ^{14}C control dating of the 4A is 'too young' in relation with the OSL age of the 3E horizon. Soil micromorphological observations indicate undisturbed patterns of intertextic modexi, but biomarker analysis points to significant rejuvenation of the organic matrix. The ^{14}C ages of the HUM fractions (table 3) of profile 1986 seem to fit better. The OSL age of the oldest driftsand formation is Neolithic. Maybe sand drifting was related with very early shifting cultivation or with a natural cause (hurricane, forest fire), resulting in aeolian erosion and deposition of small scale low inland dunes. The ^{14}C HAC ages of the 3Ah and 2AE fit rather good with the OSL age of the sequence of burying driftsand deposits.

number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C age	OSL age
W 49	1C1	45	Quartz			1920 AD ± 8
W 54	1C2	55	Quartz			1902 AD ± 10
W 48	1C3	70	Quartz			1912 AD ± 10
GrA 35143	2AE	105	HAC	0410 ± 35	1429-1627 AD	
W 44	2AE	105	Quartz			1652AD ± 30
W 3	2C1	110	Quartz			1412 AD ± 50
W 46	2C1	125	Quartz			1332AD ±100
W 14	2C2	137	Quartz			670 AD ± 60
GrA 35145	3Ah	145	HAC	1230 ± 35	687-885 AD	
W 21	3E	152	Quartz			2698 BC ± 400
GrA 35161	4Ah	158	HAC	2645 ± 40	897-778 BC	
W 24	4Bh	163	Quartz			7198 BC ± 800

Table 7. ^{14}C and OSL datings Defensiedijk 1 (2002)

The composition of pollen, precipitating on and infiltrating in a soil, is a mixture of pollen, dispersed by species rooting on the site and by species, present on distance. Consequently it is impossible to select the species, responsible for soil formation and humus sequestration from pollen spectra alone. Plant leaves are dispersed over much shorter distances by wind than pollen whereas plant root material normally enters a soil record in-situ, except for such cases where a large scale human induced deposition takes place e.g. through plaggen agriculture. As a result, in contrast to pollen records, biomarker records are expected to reflect better the local plant species responsible for soil formation and humus sequestration. For this purpose, Defensiedijk 1 was resampled again in 2008. Samples were taken from the mineral humic 1(A), 2Ae, 3Ah and 4Ah horizons and the humic driftsand layers 1C3, 1C5, 2C3 to compare pollen and biomarker spectra. Also a reference base was created for biomarkers of species, possibly involved in the carbon sequestration during soil formation (*Pinus, Betula, Quercus, Calluna, Molinia, Corynephorus, Polytrichum, Cladonia*)

Fig.16 summarizes the combined results of pollen and biomarker analyses from profile Defensiedijk 1, 2008. Micromorphologically, the intertextic modexal organic aggregates in buried Ah and Ah horizons seem undisturbed, but biomarkers indicate that the original tissue derived compounds can be overruled by younger root derived compounds. This observation is confirmed by a comparison of the pollen and biomarker results.

Fig. 16. Defensiedijk 1, 2002

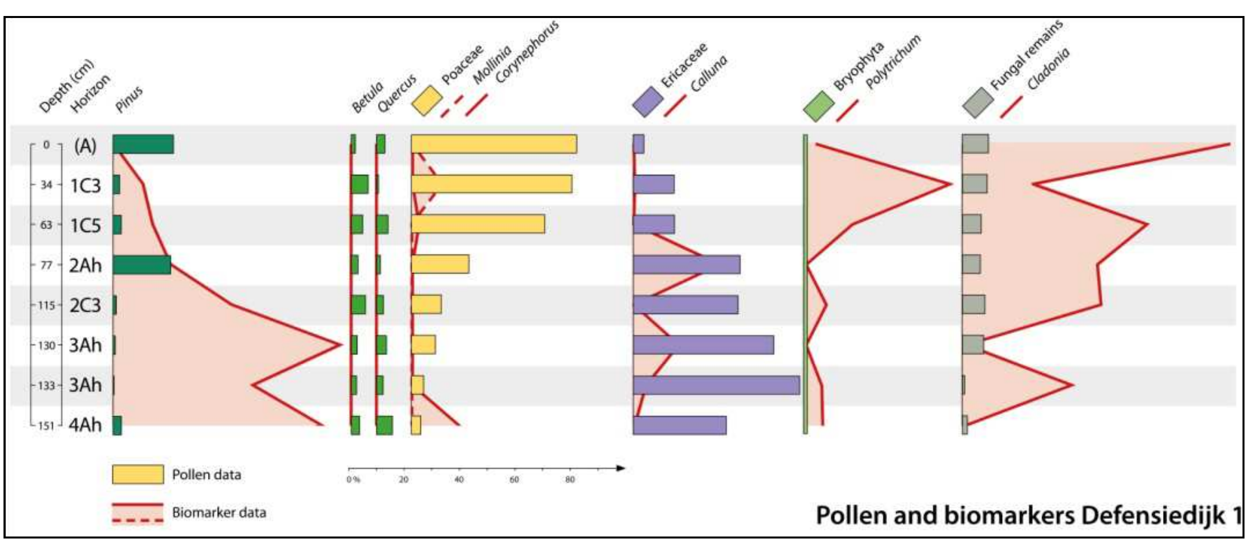

Fig. 17. Pollen and biomarkers profile Defensiedijk 1, 2008.

Fig. 18. Defensiedijk 1, 2008

The pollen spectrum of the 4Ah horizon is dominated by *Ericaceae, Corylus* and *Alnus* and micromorphological observations indicate an undisturbed soil matrix. Pollen grains can be extracted from organic aggregates with a modexal intern fabric and an intertextic distribution pattern. However, no biomarkers derived from *Ericaceae* or *Corylus* are present. Instead in the biomarker based reconstruction, *Pinus* and *Poaceae* are dominant. Pine trees were not introduced in the area until the 19^{th} century and therefore are unlikely to represent the onsite vegetation at the time that the 4Ah horizon was at the surface, given the results of the dating of the horizon (Table 7). Instead, the dominance of Pinus biomarkers most likely represents 'contamination' of the soil organic carbon in this horizon with younger decomposition products of the roots of this deep rooting species. At the same time, the low abundance of *Ericaceae* in the biomarker based reconstruction most likely indicates that this species was absent at the site in significant numbers. Its abundance in the pollen records has been caused by windblown dispersal of pollen from surrounding areas. A cover dominated by grass and moss species as inferred by the biomarker reconstruction seems more likely.

The pollen spectrum of the 3A horizon is dominated by *Ericaceae*. The micromorphological structure is similar to the 4Ah, while the biomarker spectrum is now dominated by *Ericaceae* and *Pinus*. Assuming the abundance of Pinus once more to represent younger root input, heath would appear to have been the dominant vegetation at the site at the time that the 3Ah horizon was at the surface. Most likely the *Ericaceae* that were already present in the vicinity of the site earlier, as indicated by their presence in the pollen spectra of the 4Ah horizon, by now had reached the sampling site, making them show up in the more local biomarker based reconstruction .When the 2Ah horizon was at the surface, the site was most likely covered by heath and lichens, the former being present in the pollen spectra as well as the biomarker reconstruction, the latter showing up only in the biomarker reconstruction since it does not produce pollen. Only some fungal spores are present in the pollen extractions but they do not allow the identification of the fungi, associated with lichens that occur on driftsand and heath (*Cladena* and *Cladonia*)(Domsch and Gams, 1970; Aptroot and Van Herk,1994).

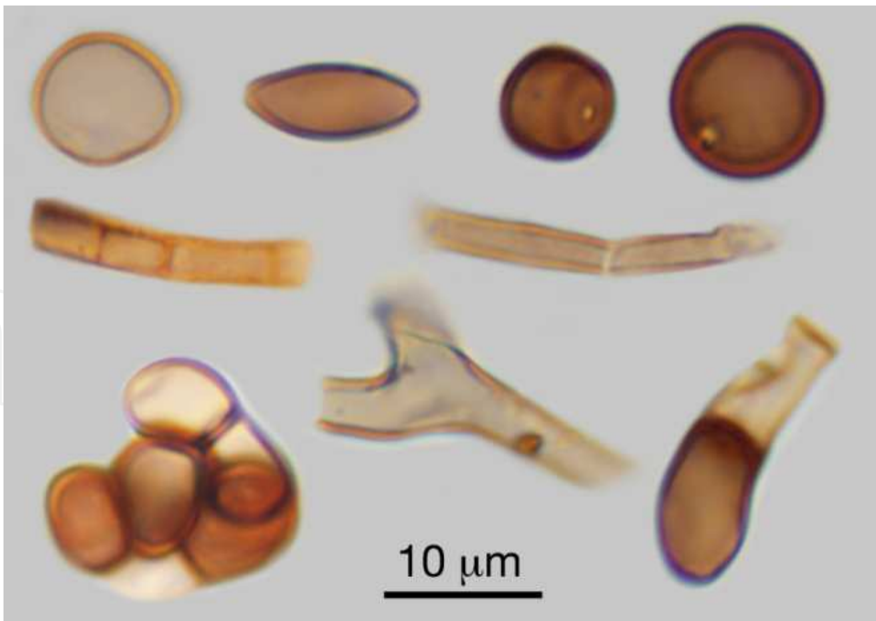

Fig. 19. Fungal remains in pollen spectra of the (A) horizon of profile Defensiedijk 1 (2008). These remains are also present in the other and humic horions

The ochric (A) horizon forms the present surface. The pollen spectrum is dominated by *Poacae*, the biomarker spectrum by lychens. The actual vegetation is dominated by *Cladonia* and *Polytrichum*. *Poaceae* are present in the surroundings, *Corynephorus* on dry inland dunes, *Molinia* in moist depressions. The biomarkers from grasses, specific for dry soil conditions (*Corynephorus canescens*, *Deschampsia flexuosa*) and for moist soil conditions (*Molinia caerulea*) are distinctive, in contrast to the pollen grains of these species. Palynologically, all driftsand layers of the youngest cycle are dominated by *Poaceae* and *Ericaceae*. Based on biomarkers, we can discriminate that the humus in the 1C5 stems from an eroded soil under a vegetation of lichens and dry grasses (probably *Deschamsia*), and in the 1C3 from an eroded site under lichens and Molinia. In both layers, markers of *Calluna* are absent in these spectra.

3.2.2 Profile Boshoverheide, bi-cyclic haplic arenosol, overlying a carbic podzol (fig.18-19; Table 8), pollen diagram first published in Van Mourik, 1988

The set of fractionated ^{14}C datings show similar features as the set of Defensiedijk 1. The ^{14}C ages of the oldest palaeosols (1S) are in line with the composition of the pollen spectra. Dominance of *Alnus* instead of *Corylus*, due to continuous infiltration of younger pollen grains and decay of fossil grains, points to a Middle Subatlantic palynological age; the development of the carbic podzol of the oldest cycle (1S) could continue from the Preboreal till ±1200 AD.

The burial of the palaeopodzol took place after 1200 AD. This is still in line with the period of forest clear cutting. Time, available for the development of the micropodzol (2S), de stable period between the depositions of S2 and S3, was (based on OSL datings) maximal 130. The radiocarbon ages of the carbon fractions, extracted from the 2Ah (with the exception of FUL) look ‘too old’, but the OSL age of the burial of the micropodzol is fits with the heat degradation after the introduction of deep stable management.

number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C age	OSL age
NCL 5106010	1C	027- 032	Quartz			1960 AD ± 2
GrN - 14834	2A	033-035	HUM	1710 ± 35	248-410 AD	
GrN - 14461	2A	033-035	HAC	390 ± 25	1414-1625 AD	
GrN - 14762	2A	033-035	FUL	240 ± 80	1470-1954 AD	
GrN - 12869	2A	033-035	BULK	265 ± 30	1516-1953 AD	
NCL 5106011	2C	035-040	Quartz			1830 AD ± 4
GrN - 14835	3A	125-127	HUM	830 ± 60	1042-1280 AD	
GrN - 14462	3A	125-127	HAC	615 ± 45	1286-1410 AD	
GrN - 14763	3A	125-127	FUL	490 ± 70	1297-1626 AD	
GrN - 14839	3A	127-129	HUM	1460 ± 90	403-768 AD	
GrN - 14702	3A	127-129	HAC	840 ± 45	1046-1274 AD	
GrN - 14773	3A	127-129	FUL	835 ± 55	1044-1277 AD	
GrN - 12870	3A	125-129	BULK	1190 ± 30	720-944 AD	

Table 8. ^{14}C and OSL datings of profile Boshoverheide

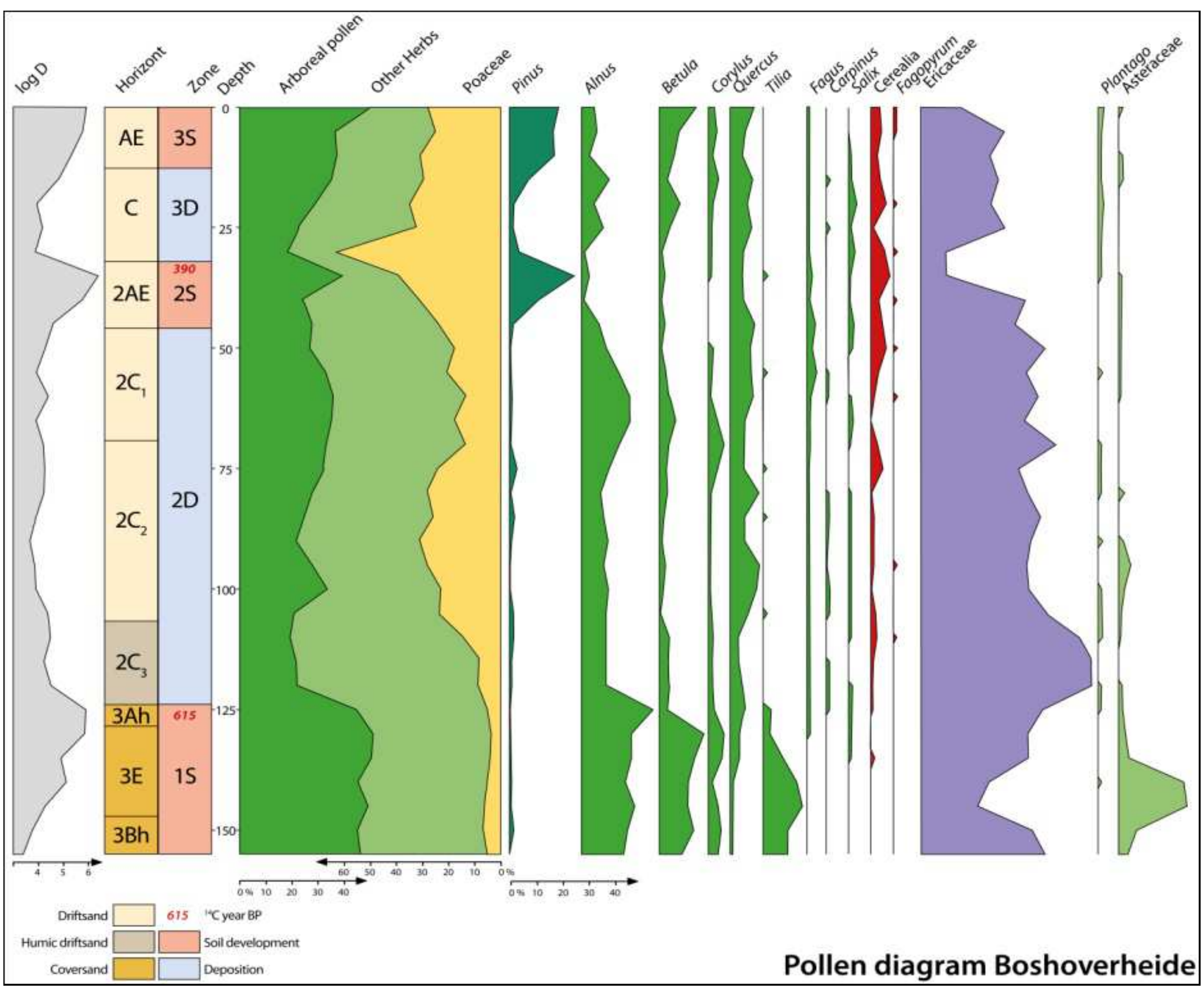

Fig. 20. Pollen diagram Boshoverheide.

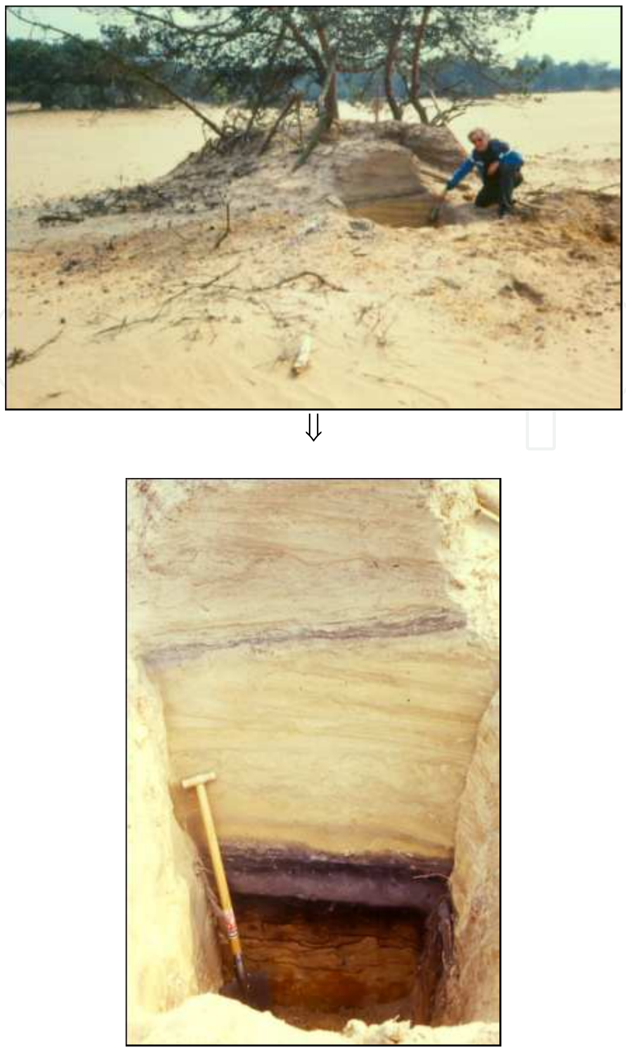

Fig. 21. Profile site Boshoverheide.

3.2.3 Profile Defensiedijk 2, mono-cyclic haplic arenosol, overlying a bi-cyclic carbic podzol (fig.20-21, table 9), pollen diagram first published in Van Mourik, 1988

Profile Defensiedijk 2 is located 300 m NNE of Defensiedijk 1 near the border of a deflation plane and inland dunes. The palynological ages (post sedimentary pollen spectra with relatively high scores of *Corylus* in the oldest buried podzol, the decreasing scores of *Corylus* and the increasing scores of *Alnus* in the youngest buried podzol) and the ^{14}C ages (Bronze Age and Middle Ages) of the burial of the carbic podzols are comparable to Profile Defensiedijk 1. 3D is expressed by a 20 cm thick driftsand layer. The well preserved ^{14}C age of the 2S indicates that the driftsand deposits have been truncated. It is therefore impossible to distinguish between a mono or polycyclic driftsand package

number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C ages
GrN 13511	2A	35-37	BULK	1399 ± 35	582-675 AD
GrN 13512	3A	35-37	BULK	3140 ± 35	1498-1316 BC

Table 9. ^{14}C datings Profile Defensiedijk-2

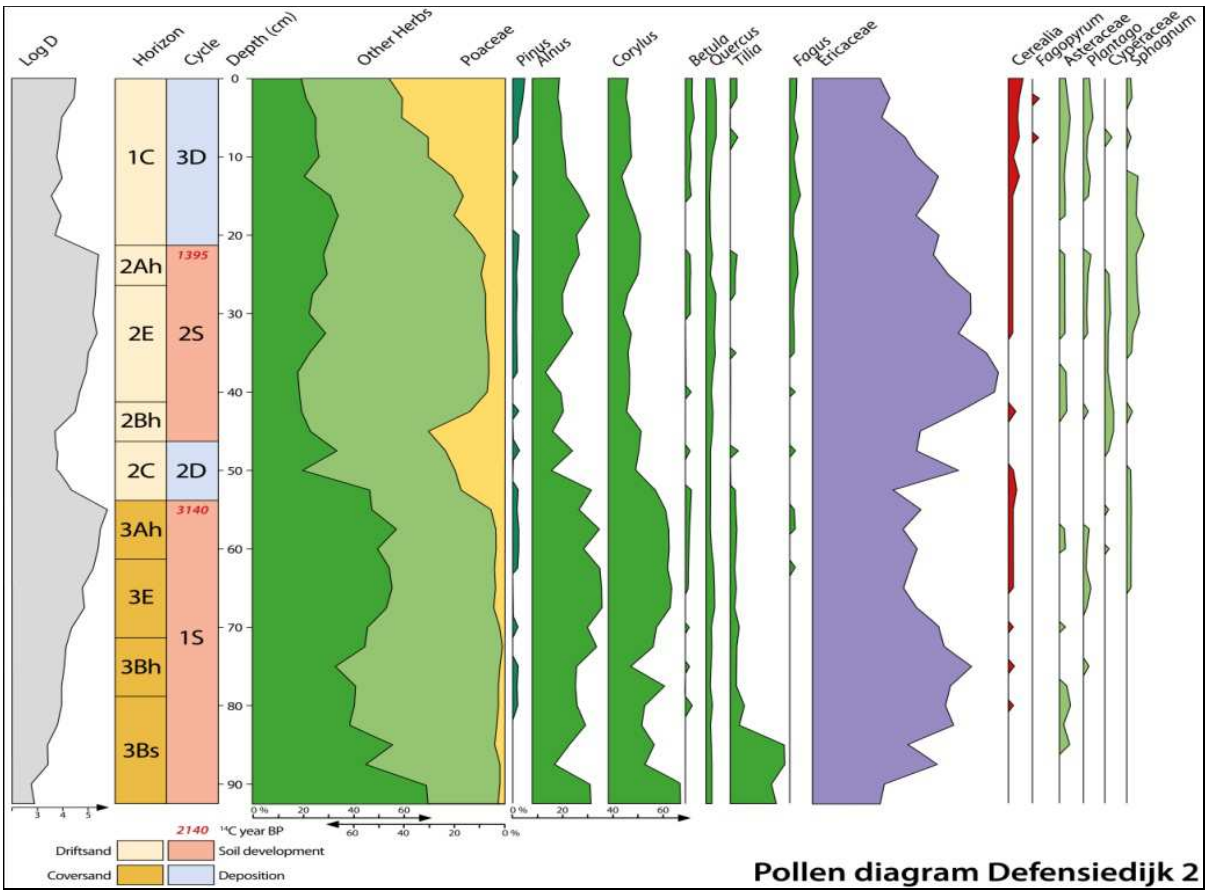

Fig. 22. Pollen diagram Defensiedijk 2.

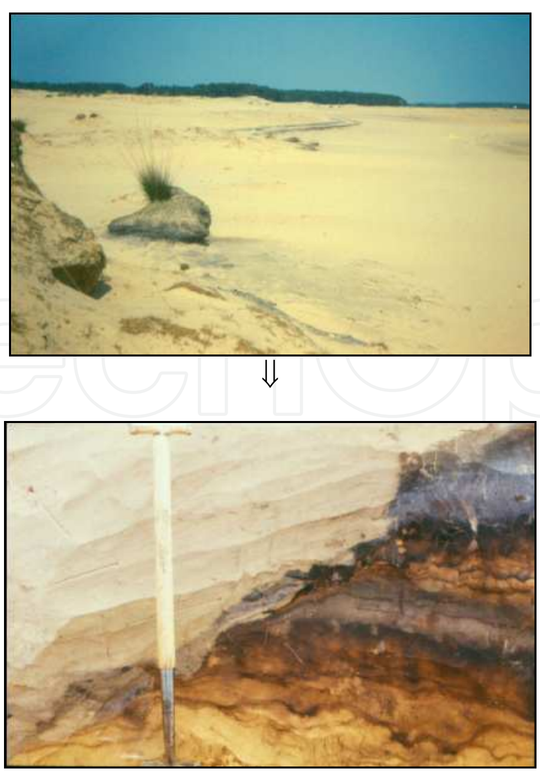

Fig. 23. Profile site Defensiedijk 2.

3.3 Palaeoecological information from the ^{14}C and OSL dated plaggic anthrosols

The introduction and extension of plaggen agriculture on chemical poor sandy soils has long been controversial in historical geography and soil science (Spek, 2004; Van Mourik and Horsten, 1994, 1995). A complication was the interpretation of the validity of radiocarbon ^{14}C datings of organic extractions of plaggic deposits, due to the complexity of the composition of the soil organic matter (Van Mourik et al., 1995, 2010). This contradiction is very well illustrated by the observation that *Fagopyrum* pollen is already present in the lowest samples of plaggic deposits with radiocarbon age over 1000 year. Recently, the application of OSL dating in palaeopedology could clarify the genesis of plaggic anthrosols (Bokhorst et al., 2005, Van Mourik 2007; Van Mourik et al., 2011a). Based on radiocarbon datings agricultural land use is registered from approximately 1000 BC but OSL datings show that the accumulation of true plaggic deposits did not start before approximately 1500 AC. An older organic matrix is suspended in the younger mineral skeleton of plaggic deposits (Van Mourik et al., 2011a,b). The organic matrix consists of aggregates with an internal fabric, related to the internal fabric of modeled excrements of humus inhabiting soil fauna, consisting of organic plasma and micro particles, charcoal and pollen grains (fig.24-25, Van Mourik, 1999b, 2001). Consequently, palynological information and radiocarbon datings from plaggic anthrosols may contribute to the reconstruction of the evolution of vegetation and land use, but not to the absolute dating of plaggic deposits.

3.3.1 Profile Tungelerakker, plaggic anthrosol, overlying a ploughed (plaggic) podzol (fig. 22-23; table 10), Pollen diagram first published in Van Mourik, 1992

The first investigated plaggic anthrosol near Weert was profile Tungelerakker, situated 1050 m east of the Tungeler Wallen site, offering an optimal possibility to compare the pollen zoning in the buried histic podzol and the zoning in a plaggic anthrosol. The scores of arboreal pollen in the post-sedimentary pollen spectra from the ploughed palaeopodzol (S2) are low, the scores of *Ericaceae* are maximal and pollen of *Cerealia* is present. Based on the ^{14}C HUM and HAC ages, this indicates agricultural activity on the site in the period ± 230-770 AD. This fits with the ^{14}C BULK ages of the buried histic horizon in profile Tungeler Wallen, ± 300 BC-1100 AD.

number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C ages
GrN 17364	Aan	65	HAC	995 ± 60	896-1180 AD
GrN 17365	Aan	65	HUM	1390 ±120	405-936 AD
GrN 17366	Aan	105	HAC	1275 ± 75	639-948 AD
GrN 17367	Aan	105	HUM	1640 ± 80	234-595 AD
GrN 17368	2ABp	115	HAC	1370 ± 50	579-771 AD
GrN 17369	2ABp	115	HUM	1580 ± 110	230-660 AD

Table 10. ^{14}C datings of profile Tungelerakker

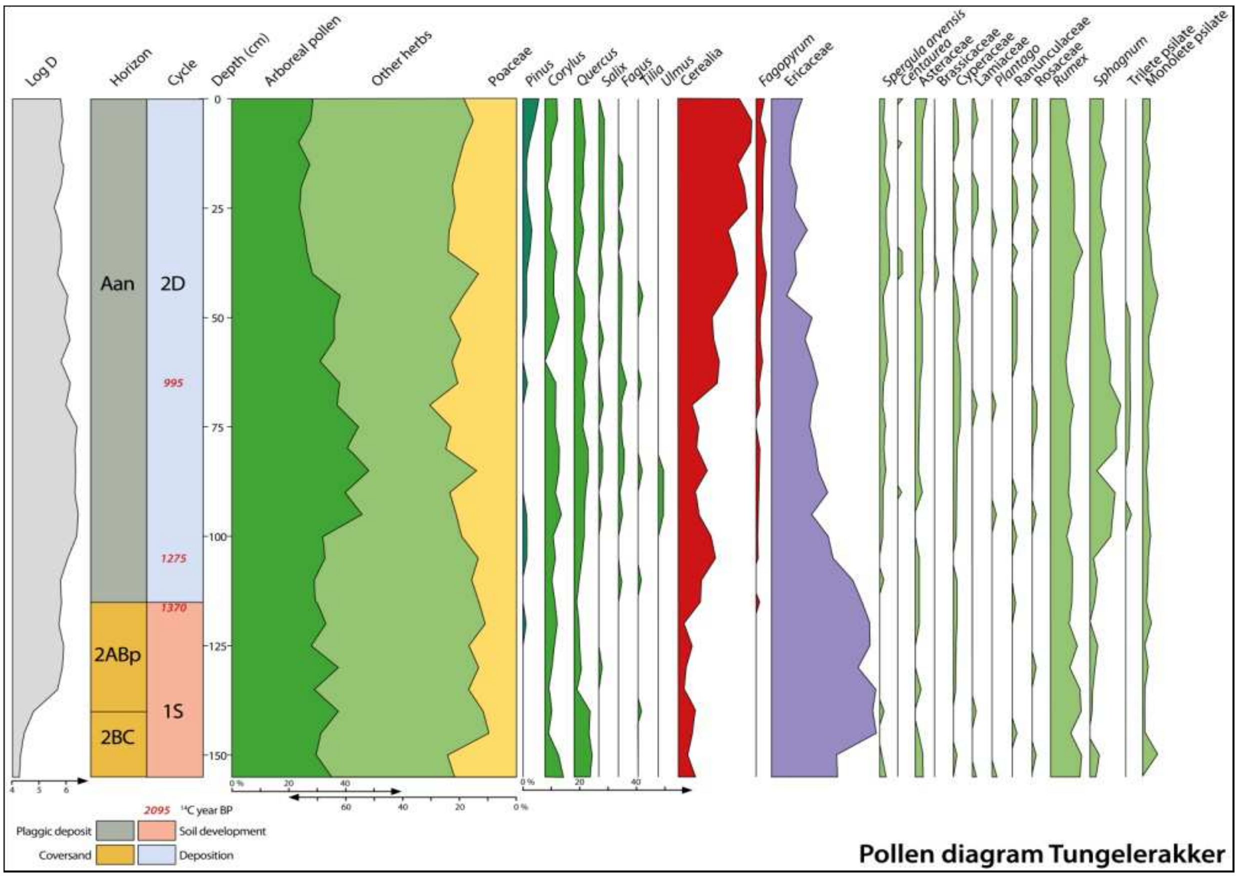

Fig. 24. Pollen diagram Tungelerakker.

Fig. 25. Profile Tungelerakker.

The ^{14}C ages of the plaggic deposits (2D) suggest plaggic deposition from ± 250-1400 AD. Application of OSL dating in more recently investigated plaggic deposits (Dijkerakker and Valenakker) indicate a contradiction between ^{14}C and OSL ages. It is proven that ^{14}C datings are valuable for the reconstruction of the agricultural development. Accurate dating of the plaggic deposits must be based on OLS ages. Palynologically, the Aan can be divided in two zones (2D1 and 2D2). 2D1 is characterized by high pollen densities, decreasing medium scores of *Ericaceae* and medium scores of *Cerealia*. The 2D2 is characterized by lower pollen densities, lower scores of *Ericaceae* and higher scores of *Cerealia*. This reflects probably the increasing crop production and the increasing content of mineral grains of the plaggic manure, related to the introduction of deep stable economy (Vera, 2011).

3.3.2 Profile Dijkerakker, plaggic anthrosol, overlying a (ploughed) carbic podzol (fig. 24-26, table 11), pollen diagram first published in Van Mourik and Horsten, 1994

The post sedimentary pollen spectra in the palaeopodzol (1S) show high scores of arboreal pollen (*Corylus, Quercus, Tilia*) and reflect a period of deforestation. Based on the ^{14}C datings of the 3Ah, the burial under driftsand (2D) took place around 3000 BP, rather similar to the oldest podzols in Defensiedijk-I and -2. The scores of *Cerealia* in the spectra of 1S and 2D point to agricultural activity and probably this (local) sand drifting was related to shifting cultivation. Farmers continued with agriculture on the 20 cm thick driftsand layer. Based on ^{14}C datings, the 2ABp fossilized around 1000 BP (839-1206 AD), close to the OSL age of the 2ABp of around 978 AD. No ^{14}C datings are available of the Aan, but the OSL age of the level 41-46 cm is 1607 AD. The set of datings supports the conclusion that agricultural land management was introduced before 1000 BC; The deposition of plaggic deposits started slow (30 cm between 1000 and 1600 AD) and accelerated during the last centuries of plaggen agriculture (45 cm between 1600 and 1900 Ad), probably related to the introduction of the deep stable agriculture in the 18th century.

OSL palaeodose measurements are based on 48 aliquots. The standard deviation but especially the distribution pattern of the values offers an excellent control on the validity of the dating (fig.31).

number	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C ages	OSL age
A 74/1	Aan	46	Quartz			1607 AD ± 40
A 47/2	2ABp	76	Quartz			978 AD ± 208
GrN19488	2ABp	76	HAC	1000 ± 70	893-1206 AD	
GrN 19487	2ABp	76	HUM	1510 ± 40	433-637 AD	
GrN 19490	3Ap	90	HAC	3040 ± 80	1490-1049 BC	
GrN19489	3Ap	90	HUM	2830 ± 130	1385-794 BC	

Table 11. ^{14}C and OSL datings of profile Dijkerakker

The skewness of the histogram of sample 47/2 indicates that the calculated age is too high, caused by palaeodose overestimation. The true palaeodose cannot be accurately deducted because it is not known whether the skewness is caused by a large amount of partly bleached grains, by a smaller amount of much older unbleached grains or by a combination of these two factors. The aliquot measurements can be a mix of the age of mineral (2D) grains, never again bleached after sedimentation and grains, bleached at the surface after ploughing. Additional, bioturbation can be responsible for vertical transport of 'older' grains from below and younger grains from above.

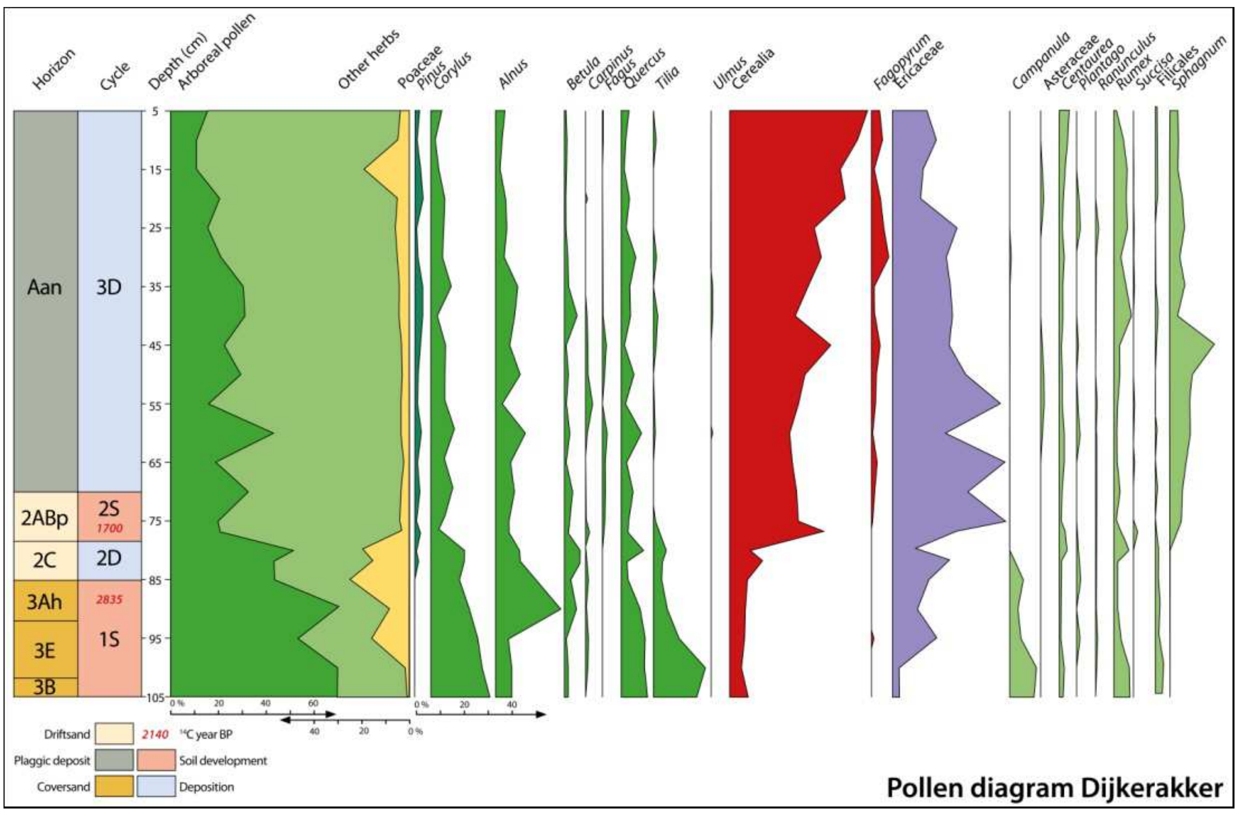

Fig. 26. pollendiagram Dijkerakker.

Fig. 27. Profile Dijkerakker.

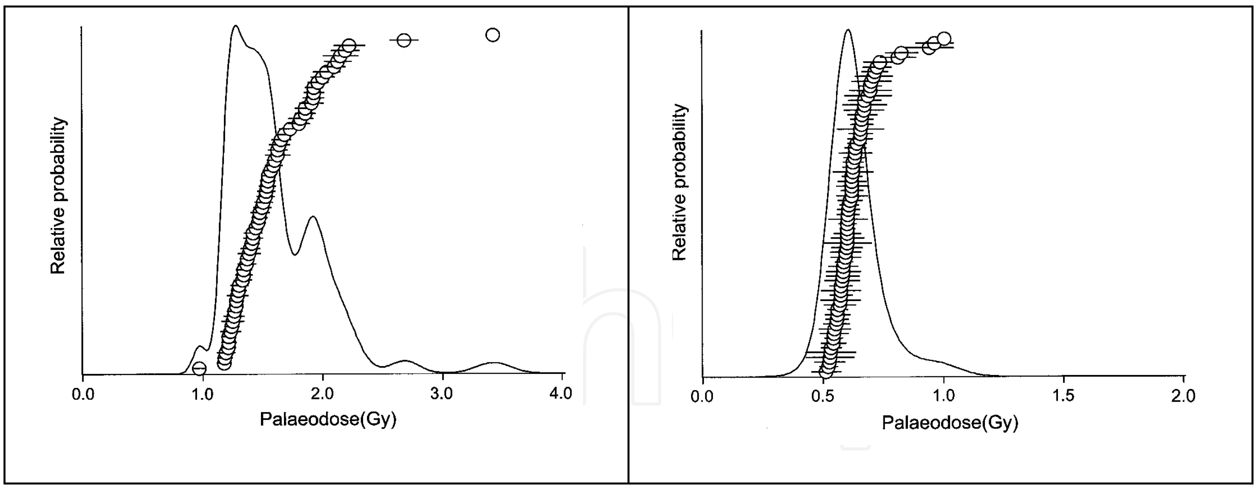

Fig. 28. Distribution of palaeodose values of the OSL datings of profile Dijkerakker. Left sample 47/2 (Dijkerakker 76 cm; 48 aliquots), right sample 47/1 (Dijkerakker 46 cm; 48 aliquots).

The histogram of sample 47/2 in fig. 5b indicates a reliable age, 394 ± 40 before 2001 (343 ± 40 BP). The majority of the mineral grains was completely bleached, promoted by the improvement of plough techniques, the increase of the mineral fraction of the plaggic manure and consequently the increase of the sedimentation rate.

3.3.3 Profile Valenakker, plaggic anthrosol, overlying a ploughed (plaggic) podzol (fig.27-31; table 12), pollen diagram first published in Van Mourik and Horsten, 1995

Profile Valenakker is well preserved in the urban environment of Weert on the sport field of a college and for more than 100 years never been ploughed. The post sedimentary pollen spectra in the BS show the low percentages of tree species as *Corylus* and *Quercus* of the Middle Subatlantic. The presence of *Cyperaceae* and *Sphagnum* indicates former most conditions of a gleysol or a gleyic podzol. Plough traces, together with the high scores of *Cerealia* in the 2Abp and even the 2B indicate a form of sedentary agriculture before the start of plaggen agriculture. Based on ^{14}C datings, plaggic deposition started around 500 AD. Based on OSL datings after 1500 AD.

GrN-nr	horizon	depth (cm)	fraction	^{14}C year BP	Calibrated ^{14}C ages	OSL age
NCL 5104001	Aan	20	Quartz			1755-1796 AD
NCL 5104002	Aan	40	Quartz			1605-1665 AD
GrN 21233	Aan	40	HAC	1000 ± 70	893-1206 AD	
GrN 21234	Aan	40	HUM	1270 ± 90	615-970 AD	
NCL 5104003	Aan	60	Quartz			1535-1595 AD
GrN 21235	Aan	60	HAC	1430 ± 80	429-768 AD	
GrN 21236	Aan	60	HUM	1340 ± 60	538-859 AD	

Table 12. ^{14}C and OSL datings of profile Valenakker

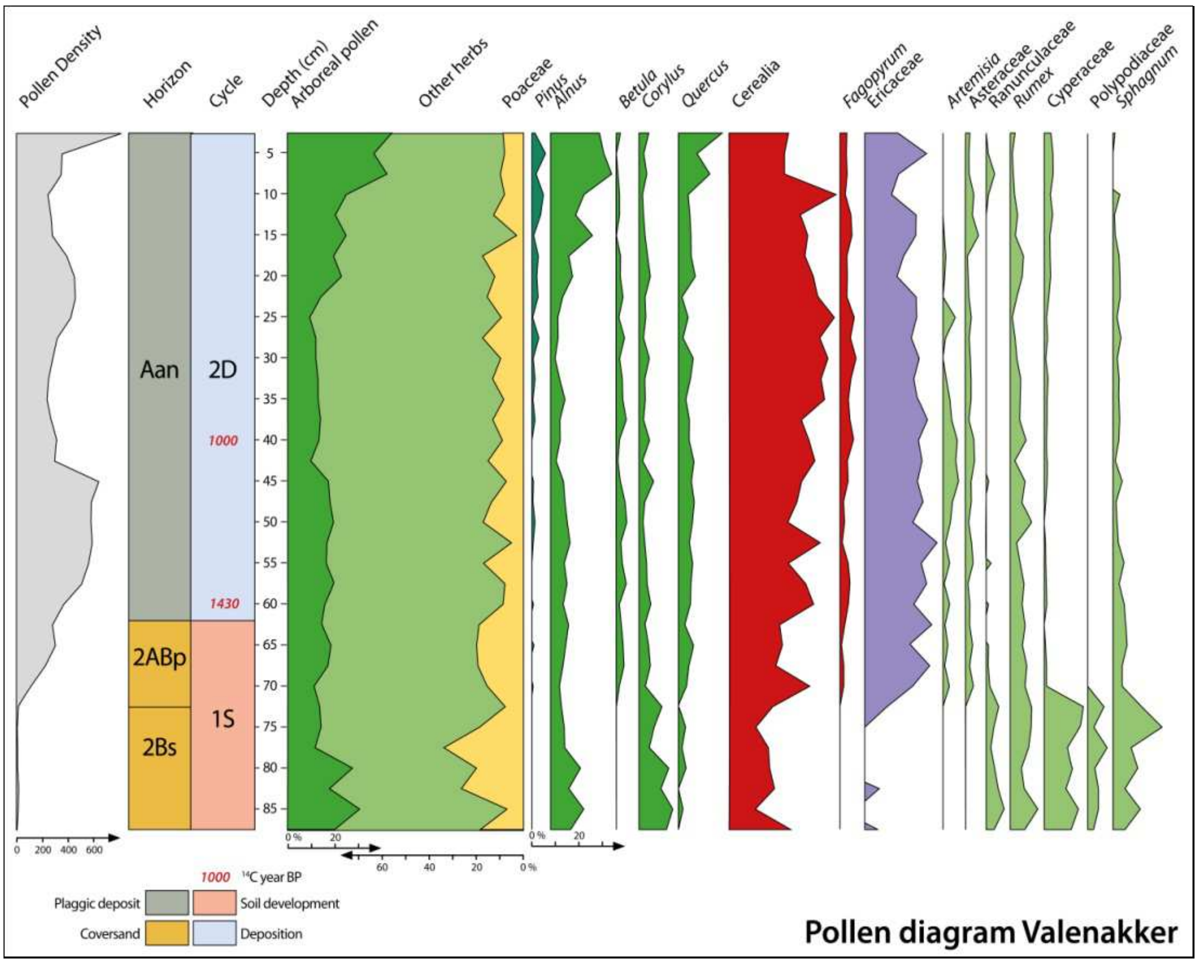

Fig. 29. Pollendiagram Valenakker.

Fig. 30. Profile Valenakker

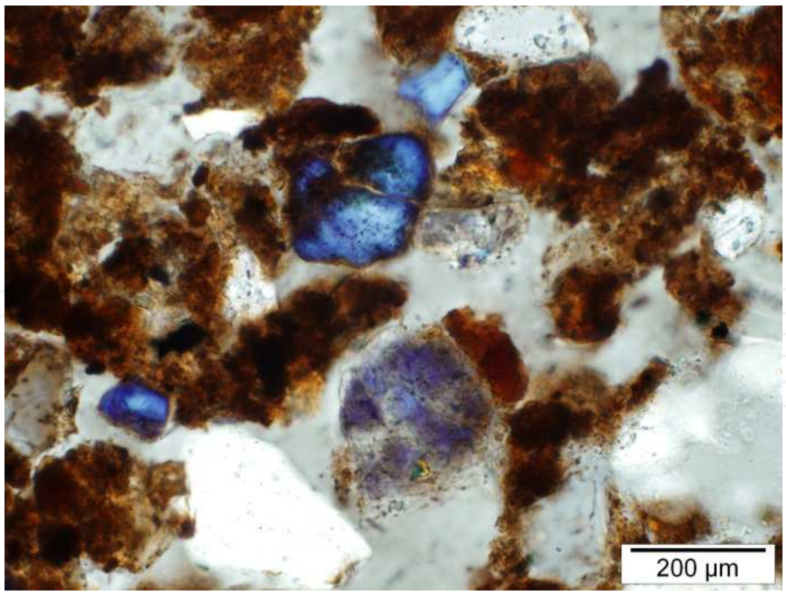

Fig. 31. Profile Valenakker Aan; soil skeleton of the Aan horizon, showing a partly intertextic, partly cutanic distribution of ageing organic aggregates.

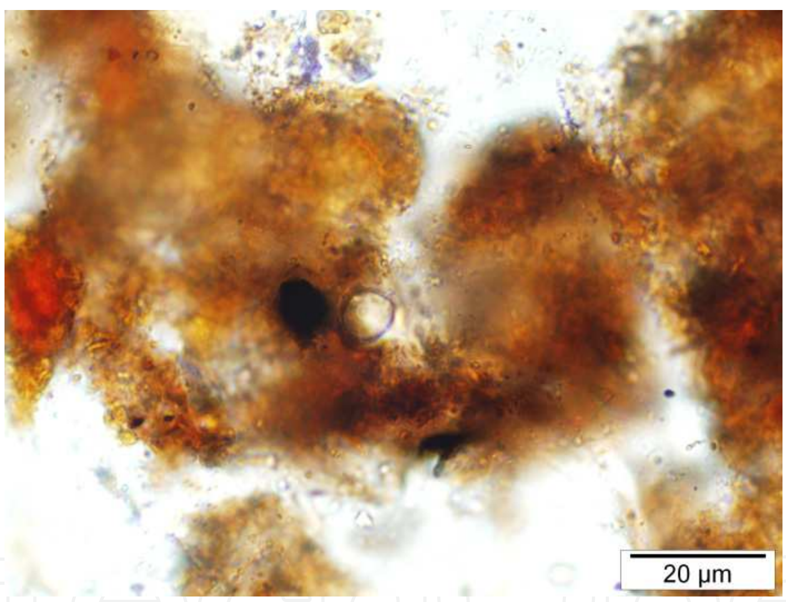

Fig. 32. Profile Valenakker Aan; intern fabric of ageing organic aggregate with charcoal fragments and pollen grain; the acid and micro-environment of excremental aggregates explains the pollen preservation under well drained soil conditions (Van Mourik, 2001).

Micromorphological observations show the complexity of soil organic matter in plaggic deposits. There are various sources of organic carbon as decomposing tissues of rooting plants, sods. The same is true for pollen spectra, a mix of the regular aeolian pollen influx and pollen, released from sods. The result is a plaggic deposit consisting of an older soil organic matrix, suspended in a younger mineral skeleton.

Traditionally, the origin of sods, used in plaggen agriculture, was reconstructed on the base of pollen spectra. The spectra of the Aan and the 2Abp show very low scores of arboreal trees but reasonable scores of *Ericaceae* and *Poaceae*. Ectorganic matter from forest soils is unlikely, *Ericaceae* pollen may indicate heat sods, *Poaceae* pollen on grassland sods, the combination on sods from degrading heath. It is very probably that during the formation of the 2Abp the farmers used mainly mowed heath shallow stables to produce manure for the arable land. During the formation of the Aan the collected sods with a higher mineral fraction to produce plaggic manure in deep stables (Vera, 2011). In fact, the origin of litter or sods cannot be satisfactorily detected with pollen diagrams. For that reason we applied biomarker analysis on two samples of the Aan and one sample of the 2Abp.

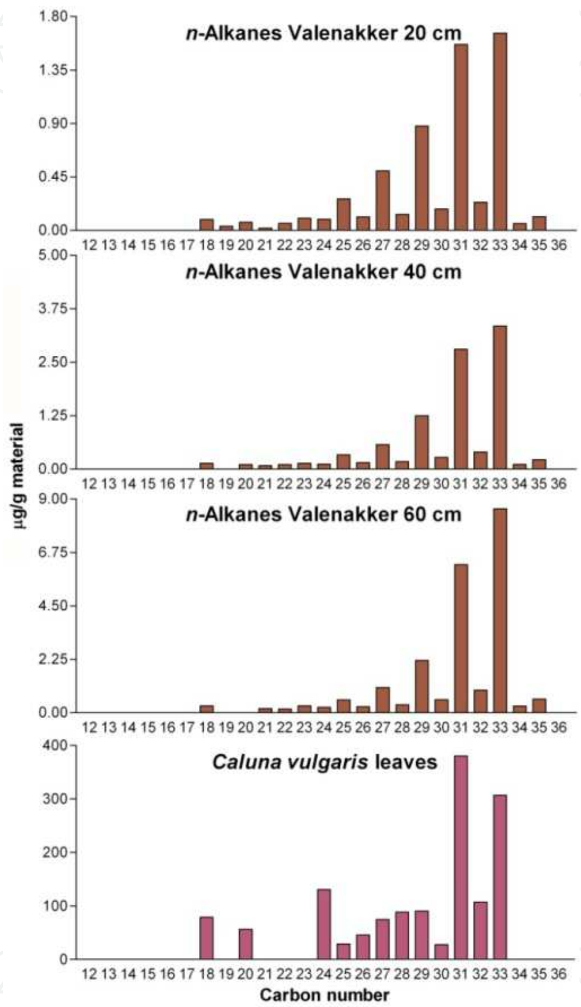

Fig. 33. n-alkane distribution patterns in samples of profile Valenakker and leaves of *Caluna vulgaris*.

In fig. 31 the n-alkane distribution patterns is shown in soil organic matter, extracted from soil samples, as well as in the leaves of *Caluna vulgaris*. While a complete biomarker reconstruction with the VERHIB model was not possible because of the limited samples numbers, a visual comparison of the patterns does yield some interesting information. The C_{31} and C_{33} *n*-alkanes dominated all three soil samples. Of the nine plant species considered (f 2.6) The leaves of *Caluna vulgaris* were the only to also have C_{31} and C_{33} n-alkanes as the dominant *n*-alkanes present. This, together with the uniformity of the *n*-alkane patterns at all depths sampled, is consistent with the history of plaggen agriculture on the profile and points to a dominant use of heath sods therein. It is also consistent with the importance of

Ericaceae in the pollen spectra. At the same time, visual assessment of the n-alcohol patterns (data not shown) does not show a clear link to a single plant species. In this respect the limited number of samples with respect to the soil profile and the plant species considered are a limiting factor in these exploratory analyses. Nevertheless, the results have great potential for the use of biomarkers to help reconstruct organic matter input in plaggen soils in combination with other proxies.

4. Reconstruction of historical soil maps

4.1 Soil map around 2000 BC

The surface parent material exists of coversands which were deposited during Late Glacial and Preboreal time. Initial soil formation started without human interference and continued until Late Subboreal time. As a consequence, the soil map shows an undisturbed pattern of climax soils: umbric and gleyic podzols on coversand ridges, Siltic, umbric and histic gleysols in depressions and valley's. From the Bronze Age on, the effect of human land use on soil forming processes increases. The deciduous forest degraded partially into *Calluna* heath as the result of forest grazing, small scale wood cutting and shifting cultivation. In a further phase, deforestation accelerated and shifting cultivation was replaced by sedentary forms of agriculture during the Iron Age. The soil map reconstructed for 2000 BC therefore shows a soil distribution of only few soil types which is strongly adapted to local coversand topography.

4.2 Soil map around 1500 AC

People learned to collect ectorganic and mowed biomass to produce in the last remains of the forest and on the heath. Plaggen agriculture was probably locally introduced in the Early Middle Ages (Spek, 2004) and became the regular land use system on mineral poor sandy soils in the medieval period. As an effect, the removal of ectorganic matter triggered soil acidification, and replacement of umbric podzols by carbic podzols. Another effect in the landscape was the disturbance of surface and soil water hydrology. Less water was intercepted by forests, which enhanced soil water infiltration. In lower terrain, in-between coversand ridges such as small valleys and local depressions, umbric gleysols developed into histosols. The intense application of plaggic manure on arable land prevented extensive acidification, so that plaggic podzols became a common soil types. The soil map reconstructed for 1500AC shows a much more fragmented pattern as a consequence of this early human interference in the previous natural soil conditions.

4.3 Soil map around 1950 AC

An increasing population demanded intensification of food production. During the 11th, 12th and 13th century clear cutting of the forested areas created an environmental catastrophe: extensive sand drifting (Vera, 2011). Deflation plains with gleyic arenosols and inland dune complexes with haplic arenosols were the results. After the introduction of the deep stable economy in the 18th century, farmers collected additional to mowed biomass more and more heath sod, including the endorganic humic mineral horizon. The mineral fraction of the plaggic manure increased. Sod digging resulted in a first local degradation of the Calluna heath, and over time regional effects were noticeable, that even prevented the regeneration

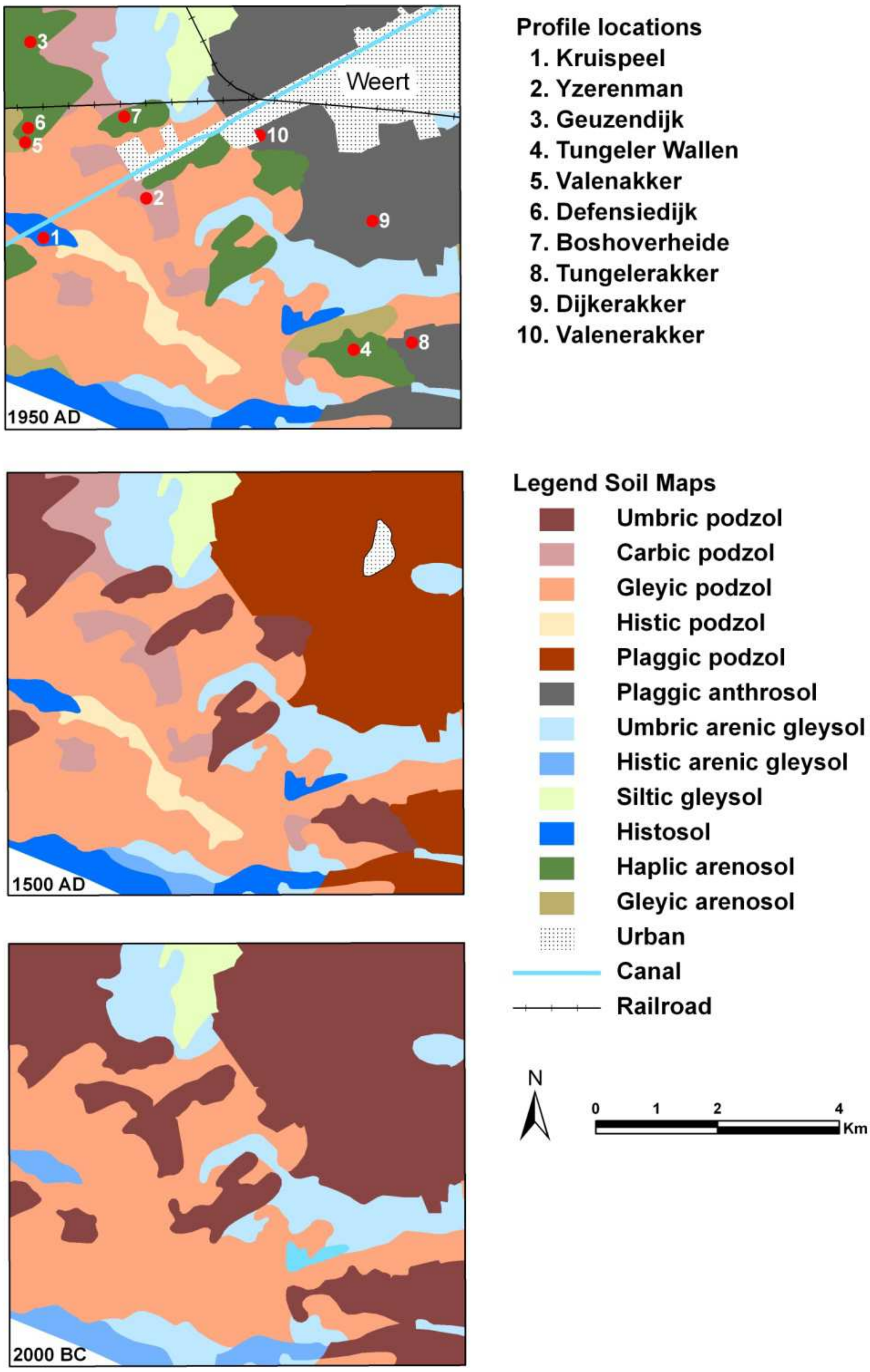

Fig. 34. The evolution of the soil geography

of the vegetation cover. In parts of the Late Glacial coversand landscape this triggered the extension of the typical Late Holocene driftsands. The consequence for soil formation was that plaggic podzols were replaced by plaggic anthrosols, mainly as the result of accumulation of the mineral compound of the plaggic manure. Degradation of the Calluna heath initiated the degradation of carbic podzols to xeromorphic and hydromorphic arenosols. The invention of chemical fertilizers around 1900 AD took away the need to collect sod manure for crop production. The information which is nowadays preserved in many polygenetic soil profiles proves that the resulting soil patterns are strongly controlled by human interference. The legend of the soil map of 1950 AD is based on the Dutch Soil Map, sheet 57-Escale 1:50,000 (Stichting voor Bodemkartering, 1972). The Dutch soil units are translated to the system of the World Reference Base (ISRIC/FAO, 2006).

4.4 Recent developments

Recent land management is further affecting soil development, which will continue to control the transformation of existing soil patterns. The former Calluna heath is partly reclaimed for arable land and partly turned into forest (dominated by Scotch pine). There is also a trend towards stabilization of driftsand areas by invasion and succession of vegetation. The reclamation of the Calluna Heath into arable land changed carbic podzols into anthric podzols. Under Scotch pine, mormoder humus forms developed (Sevink and De Waal, 2010) and haplic arenosols develop to albic arenosols. Peat accumulation was interrupted in the depressions, because soil water infiltration in the forest stands decreased and due to bio oxidation, histosols shift towards umbric gleysol.

5. Conclusions

Paleosols can be considered as important geo-ecological records, but due to the complexity of soil organic carbon, extracted from buried humic soil horizons, an accurate geochronology of such records cannot be based only on ^{14}C datings. The combination of OSL and radiocarbon datings enables the correlation of paleo-ecological data derived from histosols and mineral paleosols and improves the geochronology of the evolution of polycyclic soils and landforms in aeolian sands and plaggic deposits.

In palaeopodzols contradictions appear between OSL and ^{14}C ages. Soil micromorphological observations and the results of biomarker analysis show that the composition of soil organic carbon in buried humic horizons can be affected by secondary soil formation (buried podzols) and sedimentation (micropodzols).

In plaggic deposits radiocarbon datings reflect the development of an older organic matrix, suspended in a younger mineral skeleton. ^{14}C datings of the organic matrix are relevant for the reconstruction of the agricultural history, OSL datings of the mineral skeleton are relevant for the destination of the age of plaggic deposits.

Multi method analyses of polycyclic soil profiles provide the detailed knowledge which is necessary to fully understand time development of soil patterns in areas which are strongly affected by human land use. The combination of traditional soil survey techniques (soil classification, soil mapping), pollen analyses, micromorphology and soil dating techniques (^{14}C, OSL) makes it possible to date major changes in geo-ecological evolution.

Spatial reconstruction of former soils geographical patterns is possible in GIS through a back analysis of soil patterns based on reclassification of current soil types and soil boundaries.

Exploratory application of biomarker analysis in the form of preserved concentration patterns of C_{20} – C_{36} *n*-alkanes and *n*-alcohols showed to be a valuable additional method for the analysis of polycyclic soil profiles. In combination with fossil pollen analysis, it can help to distinguish former regional vegetation patterns from past local vegetation cover at a study site. It also has potential to yield information about the origin of plant derived organic matter in plaggen agriculture systems. However, application in this field of study is still in its infancy and further development of this technique is needed to uncover the full potential of the method.

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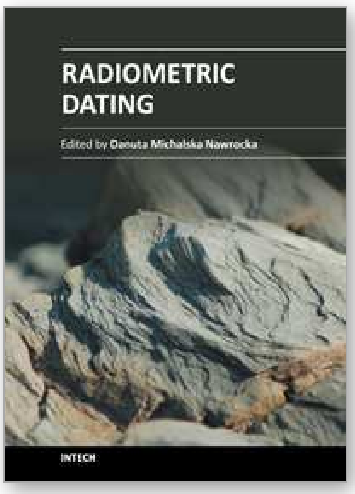

Radiometric Dating

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This book explores a diversity of topics related to radiometric dating, with particular emphasis on the method of radiocarbon dating and a cross-check of its results with luminescence measurements. Starting from the chapter on Methodology the book includes, among other topics, the description of the problem of preparation of samples for 14C measurement, a wide application of the radiocarbon method and a comparison of results obtained by various methods, including the radiocarbon method, the method of OSL, TL and palynology. The issue of radiocarbon dating of mortars and plasters is thoroughly discussed in the book. Chapter Two, Applications, and Three, Luminescence and Radiocarbon Measurements, provide examples of the application of the radiocarbon method in the study of archaeological, geological sites, from the analysis of soils, loesses, to the study of organic deposits filling the depressions in the Morasko Meteorite Nature Reserve. A wide range of studies reveals the great potential of the radiocarbon method, and the presented papers reflect interdisciplinary research.

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