The added value of biomarker analysis to the genesis of Plaggic Anthrosols – the identification of stable fillings used for the production of plaggic manure

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Abstract

Plaggic Anthrosols are the result of historical forms of land management in cultural landscapes on chemically poor sandy substrates. Application of plaggic manure was responsible for the development of the plaggic horizons of these agricultural soils.
5 Pollen diagrams reflect aspects of the environmental development but the interpretation of the pollen spectra is complicated due to the mix of the aeolian pollen influx of crop species and species in the surroundings, and of pollen occurring in the used stable fillings. Pollen diagrams and radiocarbon dates of plaggic Anthrosols suggested a development period of more than a millennium. *Calluna* is present in almost all the
10 pollen spectra, indicating the presence of heath in the landscape during the whole period of soil development. Optically stimulated luminescence dating of the plaggic horizon made clear that the deposition of plaggic covers started in the 16th century and accelerated in the 18th century. The stable fillings, used for the production of plaggic manure and responsible for the rise of the soil surface, cannot be identified with
15 pollen diagrams alone. Biomarker analyses provide more evidence about the sources of stable fillings. The oldest biomarker spectra of the plaggic horizons of three typical plaggic Anthrosols examined in this study, were dominated by biomarkers of forests species as *Quercus* and *Betula* while the spectra of middle part of the plaggic horizons were dominated by biomarkers of stem tissue of crop species as *Secale* and *Avena*.
20 Only the youngest spectra of the plaggic horizons were dominated by biomarkers of *Calluna*. This indicates that the use of heath sods as stable filling was most likely introduced very late in the development of the Anthrosols. Before the 19th century the mineral component in plaggic manure cannot be explained by the use of heath sods. We conclude that other sources of materials, containing mineral grains must have been
25 responsible for the raise of the plaggic horizon.

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1   Introduction

Plaggic Anthrosols occur in cultural landscapes, developed on coversands. These chemical poor Late-glacial aeolian sand deposits dominate the surface geology of an extensive area in northwestern Europe. Plaggic Anthrosols are the characteristic soils that developed on ancient arable fields, fertilized with plaggic stable manure. Plaggic Anthrosols have a complex genesis and are valuable records of environmental and agricultural history (van Mourik et al., 2011).

In previous palaeopedological studies of such soil records in The Netherlands (van Mourik et al, 2011, 2012, 2013), information was unlocked by application of pollen analysis, radiocarbon (^{14}C) and Optically Stimulated Luminescence (OSL) dating. Radiocarbon dates of soil organic carbon, extracted from humic horizons from plaggic Anthrosols, suggested the start of sedentary agriculture between 3000 and 2000 BP but are not indicative for the age of the plaggic sediments due to the complexity of soil organic carbon in plaggic sediments (Mook and Streurman, 1983; van Mourik et al., 1995). It was assumed that farmers used organic sods as stable filling, firstly dug on forest soils and later on heaths for the production of stable manure to fertilize the fields. The mineral fraction of the sods was supposed to be responsible for the development of the plaggic horizon and the raise of the land surface. OSL dating applied on quartz grains extracted from plaggic sediments provides more reliable ages of the plaggic sediments. The OSL dates suggested that the rise of the plaggic horizons started in the 16th century and accelerated in the 18th century (Bokhorst et al., 2005). This is rather well in line with historical data, as presented by Spek (2004, p. 965).

The use of ectorganic matter from forest soils in Dutch coversand area, must have been strongly reduced in the 11th-13th century, due to commercial forest clear cuttings as recorded in archived documents (Vera, 2011). These deforestations resulted in the first regional extension of sand drifting and the managers of the heaths had to protect their valuable ecotopes against this historical environmental catastrophe (Vera, 2011).

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Heaths were already present in the Late Paleolithic landscape (Doorenbosch, 2013) and played a ceremonial role in the society of our ancestors. They already had the knowledge to manage the heath as sustainable grazing areas for cattle (Doorenbosch, 2013).

⁵ The use of heath for sheep grazing and other purposes as honey production could continue until the middle of the 18th century (Vera, 2011). In the course of the 18th century, the population growth resulted in an increasing food demand. The deep stable economy was introduced and the booming demand for manure resulted in intensivation of manure production. Farmers started with the use of heath sods as (additional)
¹⁰ stable filling (Spek, 2004). This caused heath degradation and initiated the second extension of sand drifting. The use of sods finished at the end of the 19th century after the introduction of chemical fertilizers (Spek, 2004).

Through the combination of OSL and ^{14}C dating, historical records and the conventional paleoecological proxy of fossil pollen analysis we have a good impression of the
¹⁵ paleoecological environment and the age of such deposits. However, it remains problematic to reconstruct the combination of crop residues and various materials used by farmers as stable filling to produce the stable manure, together responsible for the rise of the surface of Anthrosols. This is also hindering a detailed interpretation of the agricultural practices and shifts therein related to the plaggic agriculture system, and
²⁰ specifically the timing of the onset of the intensive heath sod driven deep stable agriculture with which plaggic Anthrosols are most commonly associated. To address this issue, in the present study we expanded our paleoecological toolset with an adapted application of the recently developed biomarker approach (Jansen et al., 2010). This biomarker approach consists of a combination of analytical chemical analysis and mod-
²⁵ elling with the VERHIB model to unravel concentration patterns of higher chain length (C_{20}-C_{36})*n*-alkanes of higher plant origin preserved in a soil or sedimentary archive into the (groups of) species responsible for their production (Jansen et al., 2010). The approach was originally developed to unravel past local vegetation composition. Upon successful application in a tropical ecosystem setting (Jansen et al., 2013), its ap-

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plicability in palaeopedology was explored (van Mourik and Jansen, 2013). This pilot application concerned a polycyclic soil sequence in driftsand deposits. It showed that the comparison of pollen and biomarker spectra enabled to indicate the plant species, responsible for carbon sequestration in the humic horizons (van Mourik and Jansen,
5 2013). Important conclusion was that biomarker analysis showed promise not only in the reconstruction of past local vegetation composition of a specific site, but also in studies where the emphasis lies not on the vegetation per se, but rather on reconstructing various sources of soil organic matter input (van Mourik and Jansen, 2013).

Goal of the present study was to further explore the applicability of biomarker anal-
10 ysis as part of a multi-proxy reconstruction aimed at unraveling the sources of stable fillings used for the production of plaggic manure in the context of the historic development of the plaggic agriculture ecosystem.

2   Materials and methods

The distribution area of plaggic Anthrososl in NW-Europe is indicated in Fig. 1. Pape
15 (1972) published the first map of the distribution of plaggic agriculture in NW-Europe. Bastiaens and van Mourik (1995) found traces of intensivation and extension of this area in Vlaanderen (Belgium) while van Mourik (1999b) also reported plaggic Anthrosols in Schleswig (Germany). Beside this area with "real" plaggic Anthrosols, Spek (2004, p. 724) summarized information about the occurrence of soils with some evi-
20 dence of application of plaggic manure in the Atlantic coastal zones of Norway, Denmark, France, Galicia, Scotland and Ireland.

We selected three previously investigated plaggic Anthrosols with an undisturbed plaggic Horizon In The Netherlands: Valenakker, Nabbegat and Posteles (Fig. 2). Pollen diagrams, radiocarbon and OSL dates were available. The plaggic horizons of
25 these profiles were resampled for pollen and biomarker analysis as part of the present study. Vertical sampling resolution was: Valenakker 20 cm, Nabbegat and Posteles 10 cm.

Valenakker (van Mourik et al., 2012) is situated southwest of the city Weert (middle Limburg) on the sport fields of a former college; during the 20th century the soil has never been ploughed or subjected to land consolidation. This profile has never been affected by roots of *Zea mays*, introduced in the Netherlands in the middle of the 20th century (van Mourik and Horsten, 1995).

Nabbegat (van Mourik et al., 2013) is situated on the Maashorst (eastern North-Brabant). The plaggic deposits were buried by drift sand around 1800 AD. Consequently, the plaggic deposits have perfectly been protected against damage by land consolidation or pollution afterwards (van Mourik et al., 2013). The site is now vegetated by oak and birch trees. Roots of these trees may have caused input of organic matter by decomposed roots in the upper part of the plaggic horizon.

Posteles (van Mourik et al., 2011) is situated in Twente (eastern Overijssel). The landowner informed us that during the last three generations this land was never subjected to deep ploughing or land consolidation but since 1960 *Zea mays* was regular sowed. In contrast to Valenakker and Nabbegat we can expect biomarkers of this deep rooting cultivated plant.

2.1 Pollen analysis

Pollen diagrams of plaggic Anthrosols provide paleoecological information about plant species, present on site and in the region during the formation of the plaggic horizon. Previous research showed that pollen grains, infiltrated in soils and incorporated in plaggic deposits, are well preserved in the anaerobic and acid microenvironment of excremental aggregates (van Mourik, 1999a, 2001).

Samples for pollen extraction were collected in 10 ml tubes in profile pits. For a correct matching of pollen and biomarker spectra of the plaggic deposits, the same samples were treated for both pollen and biomarker extraction and analysis. The pollen extractions were carried out using the tufa extraction method (Moore et al., 1991, p. 50). For the identification of pollen grains, the pollen key of Moore et al. (1991, 83–166) was applied. Pollen scores were based on the total pollen sum of arboreal and non-

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arboreal plant species. For the estimation of the pollen concentrations of the various soil horizons, the exotic marker grain method was applied (Moore et al., 1991, p. 53).

2.2   [14]C and OSL dating

The determination of the age of plaggic deposits is subjected to various complications (Spek, 2004). Pollen stratification is disturbed by bioturbation and ploughing. Besides, the pollen content is a mix of the regular pollen influx and pollen in stable fillings, used for the production of stable manure (van Mourik et al., 2011). The ages of humic horizons of buried Podzols cannot be determined by ^{14}C dating due to the complex composition of soil organic carbon (van Mourik et al., 1995). During a period of active soil formation, organic carbon can accumulate in the Ah horizon, especially in the humin fraction but also in the humic acid fraction. The age of the humic acids were considered to approach rather well the moment of fossilization of the Ah horizon after burying by driftsand. The difference between humin and humic acids ages was interpreted as a measure for the period of soil activity and humin accumulation. Later, OSL dating confirmed that radiocarbon dates, not only of the humin fraction but also of the humic acids, overestimate the true ages (Bokhorts et al., 2005).

Conventional radiocarbon dating of humin and humic acids showed in presented diagrams, extracted from plaggic deposits, was performed in the CIO (Centre for Isotope Research of the University of Groningen).

OSL dates provide reliable information about the moment of fossilization of plaggic material under the rising furrow because the quartz grain were perfectly bleached during active ploughing (Bokhorts et al., 2005). OSL dating of quartz grains, extracted from plaggic deposits, was performed in the NCL (Netherland Centre for Luminesce Dating, Wageningen University).

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2.3 Biomarker analysis

A detailed description of the biomarker approach using the VERHIB method is presented in our previous publications (Jansen et al., 2010, 2013; Van Mourik and Jansen 2013). Briefly, the basis of the method lies in the unraveling of the preserved concentra-
5 tion patterns of C_{20}–C_{36} n-alkanes, which are exclusive to the epicuticular wax layers on leaves and roots of higher plants (Kolattukudy et al., 1976). While such an application in itself is not new,(e.g. Pancost et al., 2002; Hughen et al., 2004) the novelty of our approach lies in the application of the VERHIB model that we specifically developed to unravel the mixed n-alkane signal encountered in soil or sedimentary archives
10 (Jansen et al., 2010). The VERHIB model consists of a linear regression model that describes how a certain input of plant derived compounds such as n-alkanes over time in a certain archive at a certain location, results in accumulation of these compounds. An inversion of
the forward model is used to reconstruct the accumulation encountered with depth
15 into its most likely vegetation origin (Jansen et al., 2010).

An important matter of debate when using n-alkane patterns to reconstruct past vegetation input is the genotypic plasticity of the n-alkane patterns, in particular in relation to prevailing environmental factors such as climate (e.g. Shepherd and Griffiths, 2006). In a previous study focusing on vegetation of relevance for reconstructions in
20 ecosystems in North-Western Europe where plaggic agriculture occurred, we found that while genotypic plasticity related to climatic factors may influence the signal, such influence does not eradicate the different vegetation origins (Kirkels et al., 2013). To limit external influences as much as possible, relevant vegetation was sampled in close vicinity to the three study sites as much as possible.

25 The first group of selected plant species concerned the main sources of stable fillings, used for the manure production: fermented litter from deciduous forest soils (*Quercus robur*, *Betula pendula*), grass sods from brook valleys (*Molinia caerulea*) and heath sods (*Calluna vulgaris*).

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The second group concerned crop species. Close to the educational Field Study Centre Orvelte (Drenthe) is a traditional plaggic field where they continued with the cultivation of traditional crop species. There we sampled *Fagopyrum esculentum*, *Spergula arvensis*, *Avena sativa*, *Secale cereal, Spergula arvensis*. Modern crop species like *Zea mays* corn and *Solanum tuberosum* were sampled on the Posteles.

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 75 °C and the extraction pressure 17 × 106 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., 2006). The extracts were subsequently fractionated into three fractions containing the *n*-alkanes, the esters and the combination of alcohols and fatty acids respectively. For this, a silica column consisting of extracted cotton wool and silica gel was used, followed by elution with hexane, hexane/DCM (4 : 1) and DCM/Methanol (9 : 1) respectively. Separation of the *n*-alkanes took place by on-column injection of 1.0 μL of the first fraction on a 30 m Rtx-5Sil MS column (Restek) with an internal diameter of 0.25 mm and film thickness of 0.1 μm, using He as a carrier gas. Temperature programming was: 50 °C (hold 2 min); 40 °C min^{-1} to 80 °C (hold 2 min); 20 °C min^{-1} to 130 °C; 4 °C min^{-1} to 350 °C (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 were identified from the total ion current (TIC) signal by their mass spectra (dominant fragment ion represented by $m/z = 57$) and retention times and quantified using a deuterated internal standard (d$_{42}$-*n*-C$_{20}$ alkane (Jansen et al., 2010) as well as a conventional external *n*-alkane standard.

The concentration patterns of the *n*-alkanes with carbon numbers 20-36 in vegetation and soil samples were subsequently used as input for the VERHIB model. In the application of VERHIB, assumptions must be made with respect to rooting depth of the relevant vegetation and the ratio of leaf to root biomass input in the soil (Jansen

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et al., 2010). VERHIB considers the species specific *n*-alkane patterns in plant roots separately from the patterns in plant leaves, and uses this to deal with the input of young root material at depth. With respect to the ratio of input of leaf vs. root biomass as required by the model, no exact information is available for the soil profile under study. Therefore, in line with the exploratory nature of the present study, we applied an assumed leaf/root biomass input ratio of 1.0 and assumed that while input of leaf material always occurred at the top of the soil profile, root input also occurred with depth. In the present study leaf material is represented not by natural leaf influx from standing vegetation as that was harvested, but by leaf material from stable fillings deposited on the soil. Since our pilot study in polycyclic driftsand deposits showed that VERHIB was unable to filter out root input sufficiently (Van Mourik and Jansen, 2013), when interpreting the occurrence of a certain species with depth in the profiles under study as modelled by VERHIB, the possibility of young root input being responsible for the signal was explicitly taken into account.

3 Results

3.1 Profile Valenakker

Profile Valenakker is a plaggic Anthrosol (Aan), overlying a ploughed umbric Podzol (2ABp, 2Bs). The pollen diagram (Fig. 3) and the absolute dates (Table 1) reflects a soil development of ≈ 1400 years.

The post sedimentary pollen spectra in the 2BS show percentages of tree species as *Corylus* and *Quercus* of the Middle Subatlantic. The presence of Poaceae, Cyperaceae, *Rumex* and Ranunculaceae reflects a period of pasture. The high scores of Cerealia in ploughed 2ABp and even the 2B indicate a form of sedentary agriculture before the start of plaggic agriculture. [14]C dating indicate a carbon age of the base (60 cm) of the Aan horizon of ≈ 600 AD. The OSL age of the lower part of the plaggic horizon is 800–900 years younger, ≈ 1560 AD.

Micromorphological observations (Fig. 5a, b) of the plaggic deposits show the complexity of soil organic matter. There are various sources of organic carbon as plants roots, tissue of table fillings and sods. Also the composition of pollen spectra is complex, a mix of the regular pollen influx of plants on the fields and in the surrounding
5 infiltrating into the soil and pollen, and pollen present in various stable fillings.

In previous studies the origin of stable fillings, used in plaggic agriculture, was reconstructed on the base of pollen diagrams (Spek, 2004; van Mourik et al., 2012a, b). The pollen spectra of the Aan horizon show very low scores of arboreal trees but reasonable scores of Ericaceae and Poaceae. Ericaceae pollen may indicate the use
10 of heath sods, Poaceae pollen the use of grassland sods, the combination of sods from degrading heath and the rise of the land surface by plaggic manure is caused by the mineral fraction in such sods. However, the rise of the plaggic horizon of ≈ 60 cm cannot be explained by the use of heath sods if it is true that the use of heath sods (with a mineral fraction) was introduced in the course of the 18th century when better
15 construction materials enabled the farmers to build deep stables (Vera, 2011). In fact, the sources of stable fillings cannot be satisfactorily detected with pollen diagrams.

The biomarker spectrum of the base is dominated by *Quercus.* Despite the low percentages *Quercus* pollen it is very likely that the farmers used forest litter as stable filling. The middle spectrum is dominated by markers of *Avena* and *Secale*. This points to
20 the use of straw from these crop species as stable filling. Pollen of Cerealia is present in the whole diagram. In the upper spectrum biomarkers of *Calluna* are present together with *Avena* and *Secale*. This points to the use of heath sods as additional stable filling during the last phase in the development of the plaggic horizon.

3.2 Profile Nabbegat

25 Profile Nabbegat is a haplic Arenosol (with Mormoder humus form), overlying a plaggic Anthrosol, overlying a ploughed umbric Podzol. The pollen diagram (Fig. 6.) and the absolute dates (Table 2) reflect a soil development of ≈ 3000 year.

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The post sedimentary pollen spectra of the 3ABp reflect the start of agriculture (increase of Cerealia) on a former heath (decrease of *Ericaceae*) in a surrounding with coppice hedges (*Quercus*, *Corylus*). Based on radiocarbon dates, the agricultural activities started before ≈ 1000 BC, the OSL dates point to deposition of plaggic material after ≈ 1500 AD.

The radiocarbon ages indicate that the farmers used organic matter with very few mineral "contamination" for a long time. The OSL ages indicate that the rise of the plaggic horizon started ≈ 1500 AD due to mineral grains as part of the manure. The plaggic horizon developed between 1500 and 1800 AD. Around 1800 AD, short after the introduction of the deep stable economy (Vera, 2011), the plaggic Anthrosol was overblown by driftsand. Apparently, the use of heath sods resulted in heath degradation, sand drifting and acceleration of the rise of the plaggic horizon (van Mourik et al., 2012a). The sand drifting stabilized under planted *Quercus* trees; the roots of these trees reached the buried Anthrosol and may have contributed the scores of biomarkers in the upperpart of the buried plaggic horizon. The composition of the pollen spectra of the plaggic horizon is rather uniform, dominated by Ericaceae and Cerealia.

Figure 7 shows the results of biomarker analysis. Biomarkers of *Quercus* were present in all the spectra, dominant in the lower spectra, regular in the other spectra. This points to the use of forest litter as stable filling during the development of the lower part of the plaggic horizon. The main crop species during this time was *Spergula*. The middle part is dominated by markers of *Avena* and *Secale*, indicating the use of straw. Only in the upper spectrum *Calluna* was found, indicating the use of heath sods during the last phase of the development of the plaggic horizon.

3.3 Profile Posteles

Profile Posteles is a plaggic Anthrosol, overlying a ploughed umbric Podzol. The pollen diagram (Fig. 8) and the absolute dates (Table 3) reflect a soil development of at least 1200 year.

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The pollen content of the buried ploughed Podzol (2Ap, 2B) is post-sedimentary infiltrated in Late-Glacial coversand by bioturbation and agriculture. Characteristic is the sharp decrease of pollen concentrations with depth, shown by the pollen density curve. The spectra of the 2B horizon already reflect evidence of agriculture (Cerealia) in a deforested landscape (low percentages of *Alnus*, *Quercus*, *Fagus*). The spectra of the 2Ap horizon show increasing percentages of Cerealia.

The radiocarbon age of the base of the plaggic deposits (95 cm) is ≈ 850 AD, The OSL age ≈ 1500 AD. The OSL age of the 2Ap (105 cm) is 2035 ± 450 BC, ≈ 3500 year older than sample 95. In this part of the profile we see the effect of bioturbation on the age of the coversand. Grains from the base of the Aan were transported to the 2Ap and reversed, which explains the large standard deviation of the OSL of sample 105 cm.

The actual Ap horizon (the active plough horizon) is palynologically characterized by peak percentages of Cerealia, a slight extension of *Pinus* (planted on the abandoned heath after 1900 AD) and the appearance of *Zea mays* (introduced in Dutch agriculture after 1950 AD). Pollen of Cerealia, Ericaceae and Poaceae were found in all the spectra of the Aan.

The lowest spectrum (80) is dominated by the crop species *Spergula* and the score of *Quercus* indicates the use of forest litter during the development of this part of the Aan.

The spectra 10, 20, 40, 60 are dominated by biomarkers from roots of *Zea mays*. This crop species was introduced around 1950 AD, but the markers of the decomposed *Zea* roots seem to suppress all the others (this was not the case in the profiles Valenakker and Nabbegat). Spectrum 50 is dominated by *Avena* and *Secale*, spectrum 30 by *Zea* and *Secale* and spectrum 0 by *Zea* and *Calluna*. Again the use of heath sods seems restricted to the youngest part of the plaggic horizon.

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4   Discussion

Pollen diagrams of plaggic Anthrosols provide valuable paleoecological information to reconstruct the soil dynamics during the plaggic agriculture. However, interpretation of pollen diagrams is complicated. Pollen grains, extracted from plaggic deposits, may originate from two sources (van Mourik et al., 2011). The first source concerns the regional pollen influx from flowering species and local flowering crop species. Pollen grains precipitate on the soil surface and may infiltrate into the Anthrosols by ploughing and bioturbation. This pollen influx will be mixed with the pollen content of materials, used as stable filling to produce manure.

Pollen will be preserved in plaggic deposits in the anaerobic and acid micro environment of humic aggregates, produced by worms and micro arthropods (van Mourik, 1999b, 2001). In general it is not possible to make a clear separation between pollen grains originating from the regular pollen influx or from materials as sods. Therefore, the identification of the various sources of stall fillings cannot be based on pollen analysis alone. Additional information, acquired by biomarker analysis proved very useful for this purpose.

In the pollen diagrams *Fagopyrum* is found in almost all the spectra of the plaggic deposits and in Valenakker and Nabbegat even in the top spectra of the buried ploughed Podzol, probably as result of pollen infiltration. *Fagopyrum* as crop species on sandy soils was introduced after 1350 AD (Leenders, 1996). Based on this palynological time marker, plaggic deposition started around 1350 AD.

The radiocarbon ages of plaggic deposits are much older. This is caused by (1) older organic carbon, present in the applied stable fillings for the manure production and (2) accumulation of organic carbon during active soil formation. Consequently the radiocarbon dates overestimate the ages of the plaggic sediments, but approach the age of the introduction of agricultural soil management (van Mourik et al., 1995, 2011, 2012a, b). Manuring of infertile soils came already in use in the Bronze Age and also

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the Celtic fields are an example of a prehistorical agricultural system based on manure management (Spek, 2004).

The mineral component of stable manure, applied on the fields, was responsible for the thickening of the plaggic horizon. Ploughing of the furrow will bleach the OSL signal of the mineral grains until the moment that the grains are no longer part of the active soil furrow. For that reason, OSL dating of the plaggic horizon provide reliable ages of the plaggic deposits (Bockhorst et al., 2005). The OSL dates of the profiles Valenakker, Nabbegat and Posteles indicate a start of the thickening ≈ 1550 AD.

It was not possible to determine the sources of stable fillings palynologically. Possible stable fillings were forest litter, sods from moist grass lands and heats sods. But in almost all spectra of the pollen diagrams Ericaceae, Poaceae and arboreal pollen occur. Biomarkers extracted from plaggic deposits, originate from two sources. The first source concerns biomarkers from decomposed roots of crop species, the second source of organic material as straw and sods, used as stable filling for manure production.

In the three diagrams we find *Quercus* as dominant marker in the lowest part of the Aan-horizon, indicating the use of forest litter. In Nabbegat, Quercus markers can also originate from roots of the planted *Quercus* forest after the stabilization of the sand drifting. This is not the case on Valenakker and Posteles. The middle part of the Aan-horizon is dominated by markers of *Avena* and *Secale*, indicating the use of straw as stable filling.

Only in the top of the Aan-horizon markers of Calluna are present, indicating the use of heath sods as stable filling. Based on the results of the biomarker analysis we can conclude that heaths sods were used as stable filling only in the 18th and 19th century. This fits with the observations about the use of heaths in historical archives Vera (2011).

So the question rises about heath management before the introduction of the deep stable economy. Some researchers point to careful heath management before the 19th century. In interviews with farmers, born before 1950, Burny (1999) collected essential

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information about historical heaths management in the Belgian Kempen. Before the 19th century, heath sods were never dug on the dry *Calluna* heath, only on the moist *Erica* heath. These organic sods were not used as stable filling but as fuel for the furnace. Burning of Calluna heaths was the most important management action to
⁵ rejuvenate the heath. Juvenile heath is food for cows. Sods digging was a bad action due to the resistance and incoherence of these dry sods and also the long recovery period. Mowing of older *Calluna* shrubs took place. Twigs were used for roofs, burning and also as stable filling (Burny, 1999). Because of the very low nutrient contribution to the manure of mowed *Calluna*, the farmers preferred the use of twigs of broom
¹⁰ (*Genista).*

An additional factor may be the contribution of biomarkers extracted from sheep droppings. According to Simpon et al. (1999) biomarkers survive the congestion process and stay in the manure. But what do sheep consume? Grazing sheep are very selective in collecting food (Oom et al., 2008; Smits and Noordijk, 2013). They prefer
¹⁵ grasses (*Molinia*, *Festuca* and *Corynephorous*). Only late in the season they eat shoots of Calluna, at that time nourishing with high concentrations Ca, Mg and but no P.

If it is true that *Calluna* heath sods were dug only in the 18th and 19th century, how can we explain the mineral component in the plaggic manure, responsible of the rise of the land surface before that time?
²⁰ According to Smits and Noordijk (2013) there are several sources of minerals. Firstly, an amount of mineral grains will be incorporated in the manure during emptying out the manure of the stable. Secondly, farmers had the knowledge that the addition of sand could improve the fertility of the soil. Not the leached and acid sand from heath sods but not leached sand, dug on sheep walks and in blown out depressions in nearby drift
²⁵ sand landscapes.

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5   Conclusions

The vertical zoning of biomarkers and pollen in plaggic horizons are different. Palynologically, the plaggic horizon is homogenous, the biomarker diagrams show clear differentiation.

We can identify various stable fillings used, based on the vertical distribution of biomarkers.

The biomarker spectra of the base layer of the plaggic horizon are dominated by biomarkers of deciduous trees litter (dominated by *Quercus*), indicating the use of organic matter from the forest floor.

The biomarker spectra of the middle part of the plaggic deposits are dominated by crop species (*Avena, Secale*), indicating the use of straw from these species as stable filling during a relatively long time.

Only the top spectra of the plaggic horizons are dominated *by Calluna,* indicating that heath sods were used as stable filling only during the last phase in the development of the plaggic horizon.

Profile Posteles shows the impact of the contribution of biomarkers of roots of *Zea mays*, introduced around 1950 AD, suppressing the other species.

The negligible percentages of C*alluna* in biomarker spectra of plaggic deposits with exception of the top, suggest an overestimating of the use of heath sods in the traditional interpretation of the genesis of plaggic horizons, the dominance of crop species in biomarker spectra of plaggic deposits suggests underestimating of the use of straw as source material for the production of organic stable manure to fertilize ancient arable fields.

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Table 1. ^{14}C and OSL dates of the plaggic deposits of Valenakker.

Depth (cm)	Calendric ^{14}C ages humin	Calendric ^{14}C ages humic acids	Calendric OSL ages
20			1775 ± 20 AD
40	771 ± 92 AD	1049 ± 78 AD	1635 ± 30 AD
60	595 ± 61 AD	698 ± 54 AD	1565 ± 30 AD

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Table 2. [14]C and OSL dates of the plaggic deposits of Nabbegat.

Depth (cm)	Calendric ^{14}C ages humin	Calendric ^{14}C ages humic acids	Calendric OSL ages
50	428 ± 107 AD	626 ± 45 AD	1775 ± 20 AD
60	37 ± 133 BC	3 ± 101 AD	1635 ± 30 AD
120	1182 ± 139 BC	811 ± 101 BC	1565 ± 30 AD

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Table 3. ^{14}C and OSL dates of the plaggic deposits of Posteles.

Depth (cm)	Calendric ^{14}C ages humin	Calendric ^{14}C ages humic acids	Calendric OSL ages
45	–	–	1758 ± 14 AD
59	–	–	1711 ± 20 AD
70	1132 ± 68 AD	1172 ± 51 AD	1651 ± 31 AD
82	–	–	1626 ± 20 AD
95	884 ± 82 AD	861 ± 85 AD	1517 ± 31 AD
105	–	–	2035 ± 450 BC

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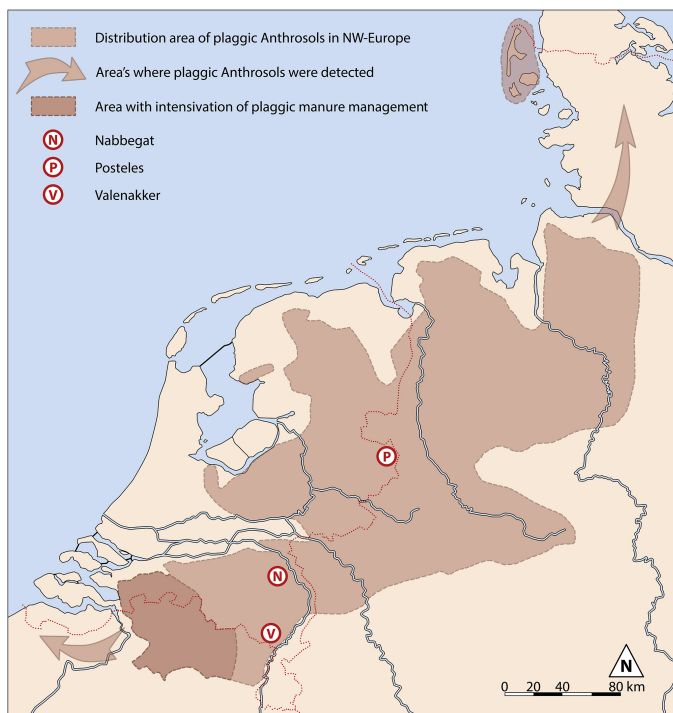
Figure 1. The location of the sampled profiles Valenakker, Nabbegat and Posteles in the distribution area of plaggic agriculture.

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(a) **(b)** **(c)**

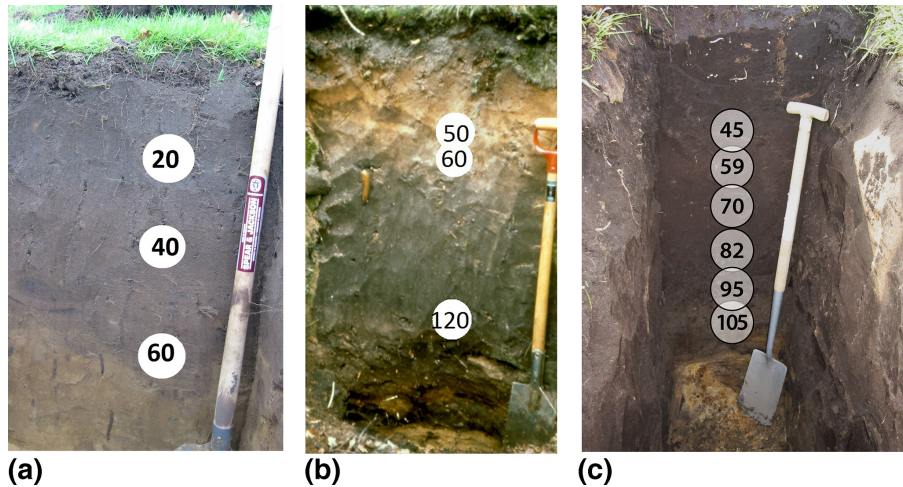



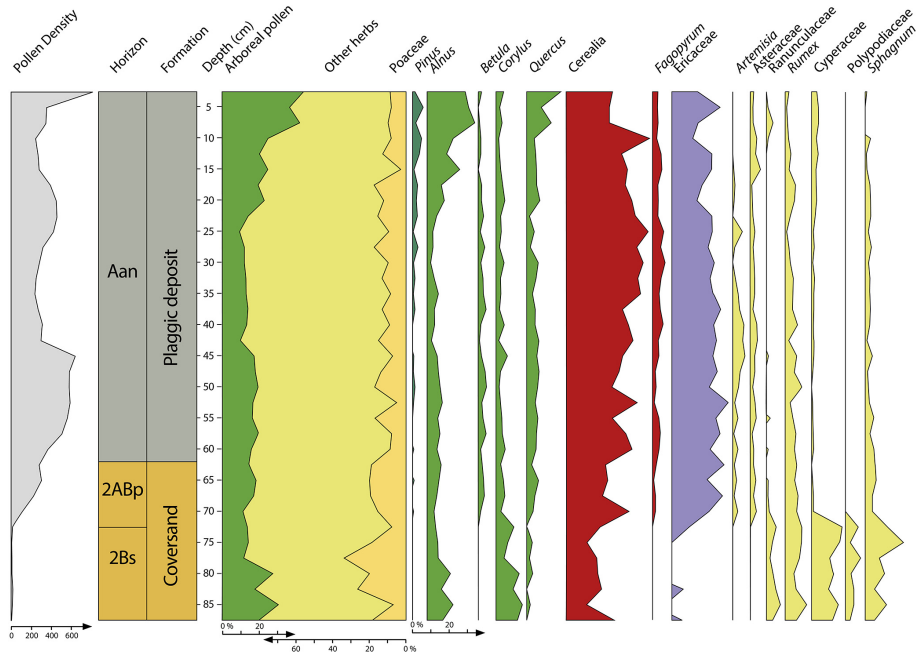
Figure 2. Pictures of the plaggic Anthrosols, selected for this pilot study. The depths (cm) of the OSL samples are indicated in the white circles; the profile locations are indicated in Fig. 1.

Pollen diagram Valenakker

Figure 3. Pollen diagram Valenakker. Pollen density in k grain mL^{-1}.

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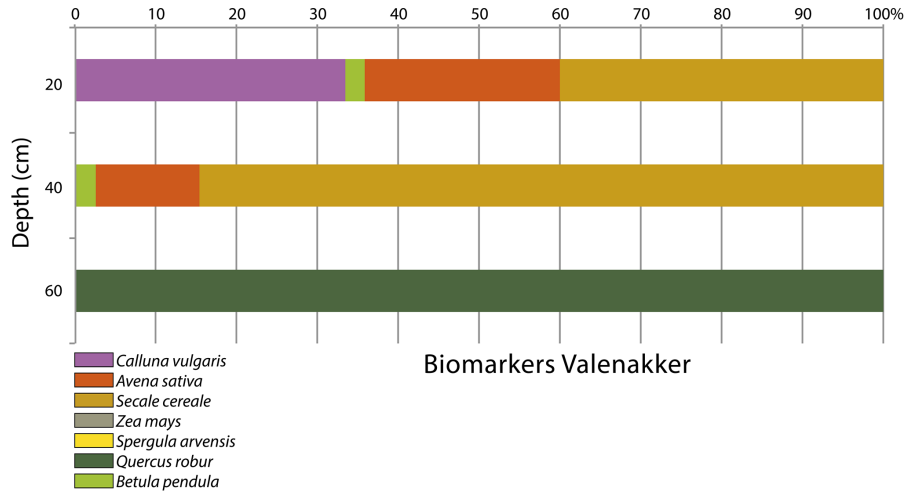
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Figure 4. Biomarker diagram Valenakker.

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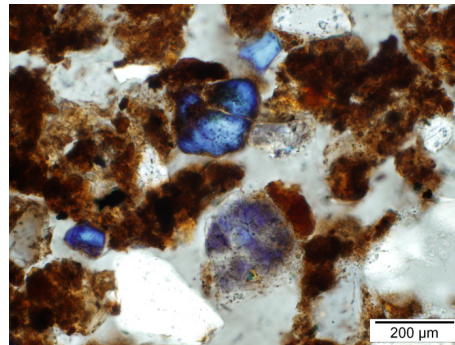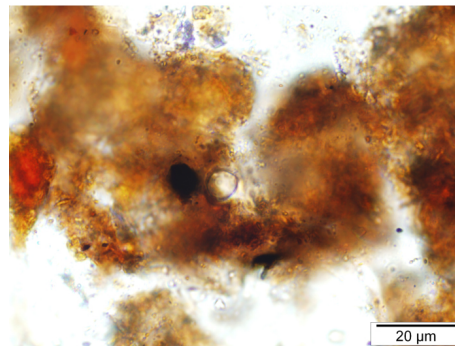
Figure 5. (a) Soil skeleton (plaggic horizon Valenakker) showing a partly intertextic, partly cutanic distribution of ageing organic aggregates. **(b)** Intern fabric of ageing organic aggregate with charcoal fragments and pollen grain (plaggic horizon Valenakker); the acid microenvironment of excremental aggregates explains the pollen preservation under well drained soil conditions.

Pollen diagram Nabbegat
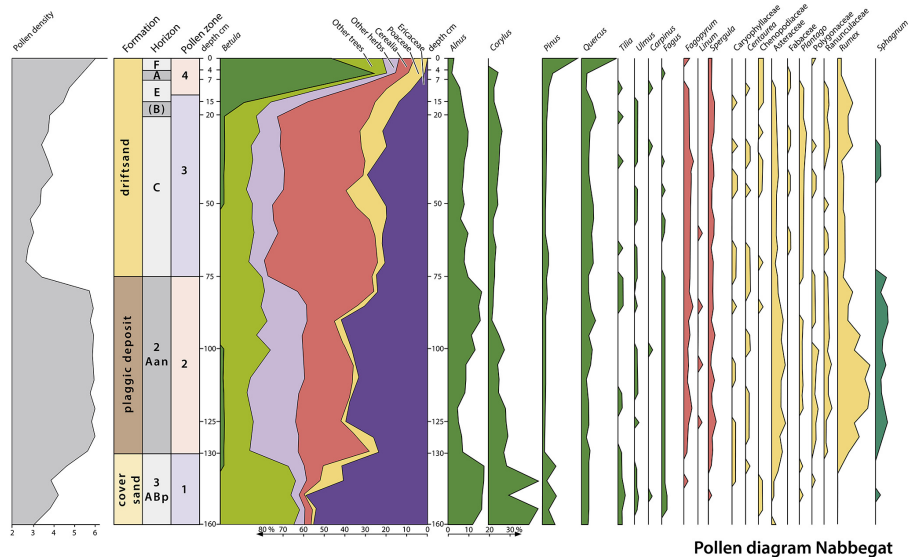
Figure 6. Pollen diagram Nabbegat. Pollen density in $\log k$ grain mL^{-1}.

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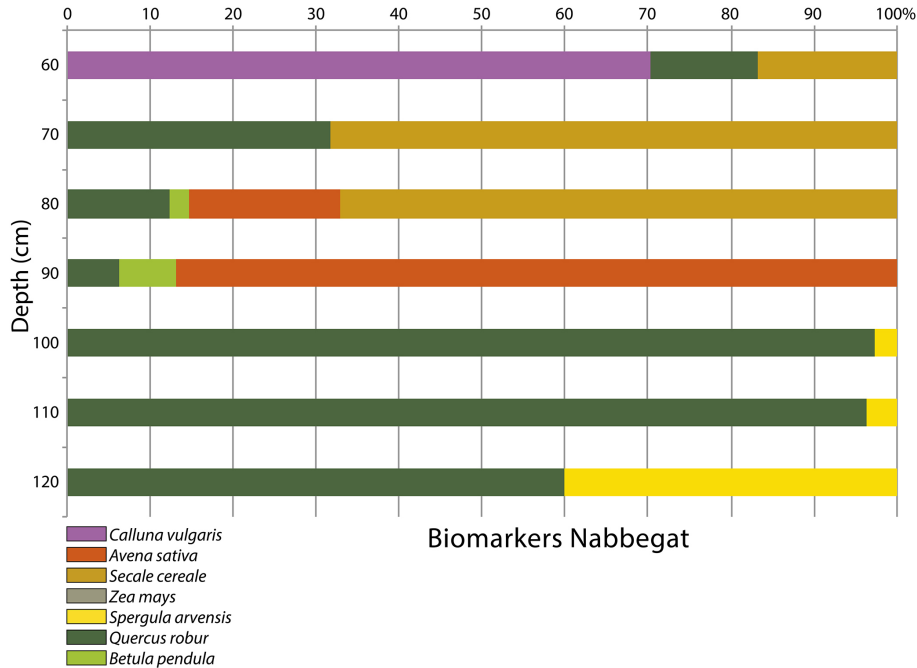
Figure 7. Biomarker diagram Nabbegat.
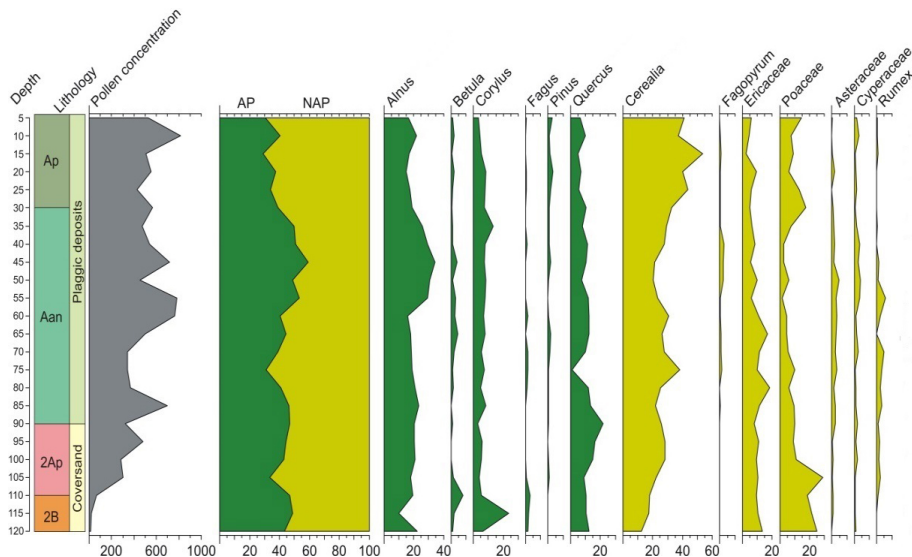
Figure 8. Pollen diagram Posteles; Pollen density in k grain mL^{-1}.

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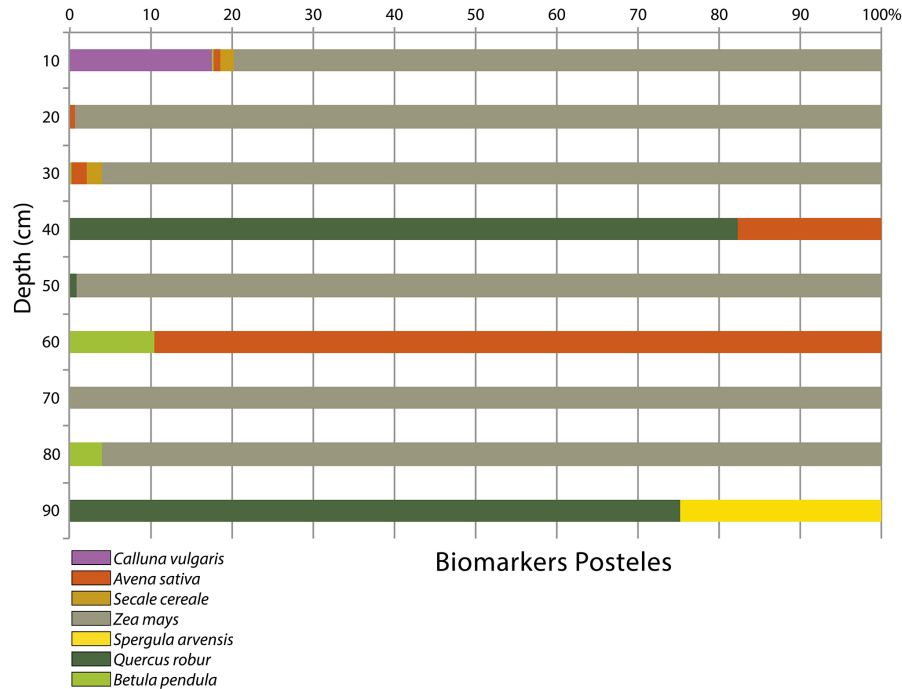
Figure 9. Biomarker diagram Posteles.

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