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A multi-staged drift sand geo-archive from the Netherlands: New evidence for the impact of prehistoric land use on the geomorphic stability, soils, and vegetation of aeolian sand landscapes

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ABSTRACT

The drift sand area near Hilversum, the Netherlands, holds a geo-archive with multiple drift sand phases and intercalated palaeosols. We studied this area to test earlier theories on the development of podzols in such aeolian sands, the occurrence of sand drifting, and the contemporary vegetation development, and to gain insight into the early human impacts on these fragile ecosystems. Based on OSL and radiocarbon datings, palaeoecological studies, and soil chemical analyses, the age and origin of the drift sand phases and palaeosols were established. Sand drifting started around 6000 BCE (Late Mesolithic), the drift sand covering a distinct podzol in the Younger Cover Sand II. A second Late Mesolithic drift sand phase dated from ca. 4900–4500 BCE. Three later drift sand phases were distinguished of which the last is the classic Late Medieval (and younger) phase, while the first two date from the Neolithic. All intercalated palaeosols exhibited more or less prominent podzolisation. The palaeocological data showed that, prior to the Neolithic, in the forest open patches had developed with non-arboreal vegetation, dominated by Poaceae and Ericaceae. This changed during the Neolithic, most probably linked to the introduction of crop farming, the vegetation gradually acquiring the characteristics of the classic heathland with patches of trees/shrubs. The early sand drifting, podzolisation and opening of the forest are attributed to Mesolithic land use, with intentional burning as major factor. We conclude that the local destruction of the deciduous forests by fire and associated creation of open patches with bare sand were essential for the early sand drifting and podzolisation to occur. The results shed new light on the origin of drift sands, heathlands, and podzols in the Netherlands, and on the environmental impacts of Mesolithic people, and testify to the fundamental instability of these dry inland dune ecosystems.

1. Introduction

The NW-European aeolian sand belt (Fig. 1a) is known for its complex Holocene sediment archives, documenting alternating stable and unstable landscape genetic phases in the form of stacked palaeosols in successive drift sand layers (Koster 2005, 2009). This geomorphic instability is generally attributed to human forcing factors and explained by the easy degradation of heathlands that developed upon early crop farming, which in this sand belt dates to c. 3000 BCE (Louwe Kooijmans 2005; Louwe Kooijmans and Whittle 2007). In the Netherlands, serious degradation and associated sand drifting are assumed to have started in the Late Middle Ages (1300–1500 CE, Pierik et al. 2018) and to result from a combination of such practices as regular burning, sod-cutting, and overgrazing. In later times, it was further fuelled by the increasing

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population density and associated pressure on the degrading heathlands and may have intensified because of the adverse climatic conditions during the colder and stormier 'Little Ice Age' (Koster et al. 1993; Koster 2005, 2009; Pierik 2017; Pierik et al. 2018).

In the Netherlands, the origin of the heathlands, which replaced the forests that had developed upon climate warming in the Early Holocene, was extensively studied by Doorenbosch (2013) and later summarized by Doorenbosch and Van Mourik (2016). Some results from these studies were criticized by Groenman-van Watering and Spek (2016), notably the reliability of pollen data that was used by Doorenbosch as evidence for the early existence of heathlands, i.e., prior to the larger scale introduction of crop farming. However, the overall and since long existing explanation for the massive development of heathlands remained unchallenged. This was that early farmers used a shifting cultivation system through which nutrients in the sandy soils were depleted, inducing the development of short vegetation on the depleted farmland they left behind, which was grazed by their domesticated animals and gradually transformed into heathland (Louwe Kooijmans 2005). The development of the podzols that today mark the NW-European aeolian sand belt is ascribed to the fundamental changes in nutrient cycling brought about by this transformation, notably the strongly reduced rooting depth and the acidifying nature of ericaceous litter (see e.g., Dimbleby 1961; Dalsgaard and Odgaard 2001; Sauer et al. 2007; Doorenbosch and Van Mourik 2016).

According to the FAO World Reference Base for Soil Resources (IUSS Working Group WRB 2015) podzols are defined as soils with a spodic B horizon, which is formed by the illuviation of Al, Fe and organic matter from an overlying eluvial horizon. There are various processes that can lead to podzolization, and often multiple processes occur simultaneously (Buurman and Jongmans 2005). In the quartzitic sands of the European temperate zone, which form the parent material for most heathland soils in the Netherlands and its neighbouring countries, the interaction of dissolved organic matter (DOM) with Al and Fe is seen as the dominant driving force (Buurman and Jongmans 2005). Driven by acidification and the influx of rainwater, DOM is released from the A horizon and subsequently acts as a carrier of Al and Fe released by weathering, leading to eluvation of Al, Fe and DOM (Buurman and Jongmans 2005; Jansen et al. 2004; Jansen et al. 2005). Subsequently, the presence of fresh sorption surfaces on the mineral soil material in the underlying parent material, in combination with a pH gradient and a shift in metal/carbon ratios of the organic Al and/or Fe complexes, leads to (co) precipitation and/or adsorption of Al, Fe and DOM. This results in the genesis of the spodic B horizon (Buurman and Jongmans 2005; Jansen et al. 2004; Jansen et al. 2005). The process can be amplified by direct input and adsorption of DOM originating from roots in the upper spodic B horizon, which may subsequently be redissolved and precipitates in the lower spodic B horizon (Buurman and Jongmans 2005).

Generally, this podzolization in poor substrates of the temperate zone is viewed as a slow process, with centuries to millennia needed for the creation of a well-developed spodic B horizon (Buurman and Jongmans 2005). However, this assumption is based on the dating of only a handful of podzols (Zwanzig et al., 2021) and as such lacks rigorous underpinning. As evidence of the link between agriculture (in the form of significant forest clearance, ploughing and crop farming), heathlands, and podzolization often reference is made to the far less prominent or even absent podzolization underneath burial mounds dating from the period in which such farming was introduced, which in the sandy uplands of the Netherlands is connected with the Middle Neolithic Funnel Beaker culture that started at ca. 3400 BCE (Waterbolk 1964; Casparie and Groenman-van Waateringe 1980; Groenman-van Waateringe 2010; Jongmans et al. 2013; Groenman-van Waateringe and Spek 2016).

In the past decade, it has become ever clearer that the above-described observations and conclusions concern general trends only. Pre-Neolithic heathlands, podzols, and drift sand phases have now been described in several studies on Pleistocene sand landscapes in the Netherlands (Het Gooi: Sevink et al. 2013, 2018; Ossendrecht: Kasse and Aalbersberg 2019; Swifterbant: Hamburg et al. 2012; Veluwe and Brabant: Doorenbos 2013). The study on the drift sands of Het Gooi led

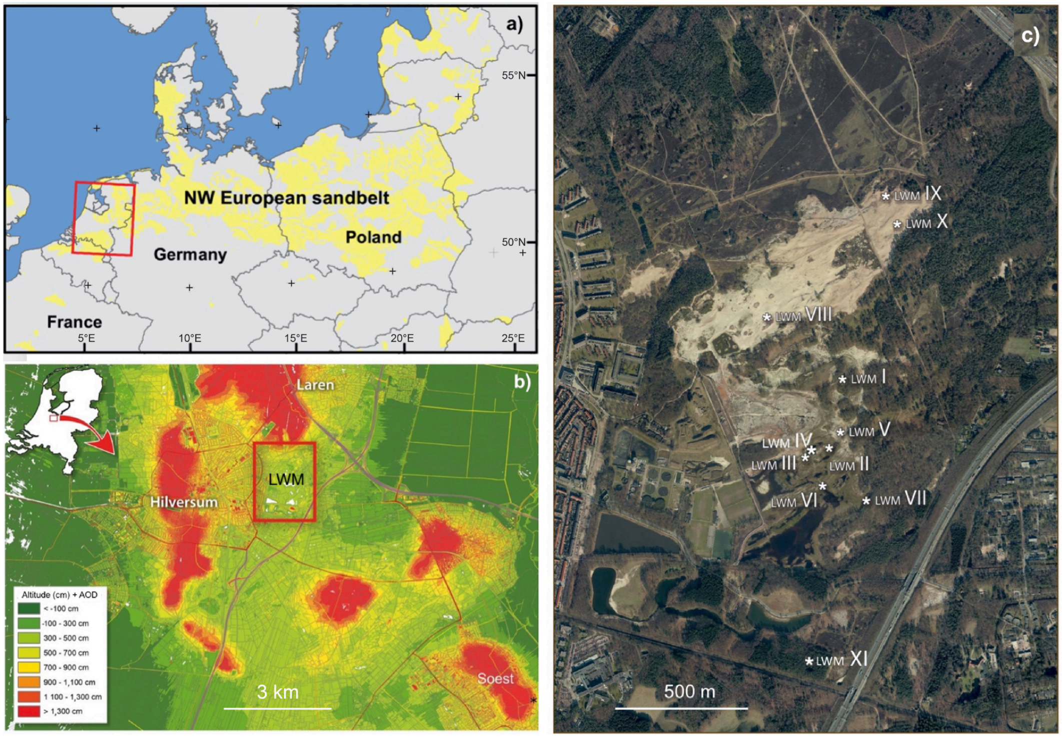

Fig. 1. Location of the area of study and sections, and topography: a) The Netherlands within the NW European sand belt (from Pierik et al. 2018); b) The Laarder Wasmeren area with altitudes derived from the open-source digital Current Dutch Elevation map (AHN3; https://www.ahn.nl), * = location of Mesolithic site at Soest; c) Aerial photograph (Goois Natuurreservaat) with locations of the sections studied. AOD = Amsterdam Ordnance Datum.

Sevink et al. (2018) to conclude that its early heathlands, podzols, and sand drifting likely resulted from the actions of Mesolithic people, with repeated burning as a major factor. An excavation of a large Mesolithic site near Soest (see Fig. 1b for its location) recently produced massive evidence for such quite serious and extended human impact (Woltinge et al. 2019), in line with earlier observations at the Mesolithic Swifterbant site (Hamburg et al. 2012). Early podzols and drift sands are also known from similar areas in adjacent countries such as Belgium, Denmark, and Germany (e.g., Dalsgaard and Odgaard 2001, Tolksdorf and Kaiser 2012; Tolksdorf et al. 2013; Kappler et al. 2019) and attributed to pre-agricultural human impacts.

Our further study of the drift sand landscape in the Laarder Wasmeren area (LWM) in between Hilversum and Laren (Fig. 1b), of which results are reported here, aimed at 1) refining the geochronology of its landscape genetic phases, 2) shedding light on the causes for the early podzolisation and sand drifting, and 3) establishing the extent to which podzolisation occurred in these systems. To that purpose, we studied its palaeosols in more detail, as well as the temporal trends in vegetation development and their link to sand drifting.

In this paper, we first present an overview of the drift sand phases and palaeosols encountered in the LWM area (see Fig. 1c). We then pay attention to their dating and magnitude, with emphasis on the extent of podzolization and weathering. Pollen analyses served to reconstruct the vegetation composition and dynamics during the various phases. Results are integrated into an analysis of the landscape genetic history of the area, with particular attention for the factors involved. We confront our results with those from recent landscape archaeological studies from the NW-European aeolian sand belt, to gain insight into potential human impacts on these fragile systems.

2. Materials and methods

2.1. Study area

The Laarder Wasmeren area has been extensively described in earlier papers by Sevink et al. (2013 and 2018), which were based on observations during a major environmental remediation operation in the years 2003–2010. It is set in a large glacial meltwater valley of Saalian age, cut through an ice-pushed ridge and with a thick Late Pleistocene fill, topped by Late Weichselian cover sands and a thick cover of Holocene aeolian sands with multiple intercalated podzolic palaeosols. In the first paper, soils and drift sand phases were described that were dated using stratigraphic correlations, Optically Stimulated Luminescence (OSL) dates, and some radiocarbon (^{14}C) dates (Sevink et al. 2013). These mostly were of Mid to Late Holocene age. The second paper focused on the occurrence and age of early palaeosols and drift sand phases, notably from the period running from the Allerød to the Middle Holocene (Sevink et al. 2018). It presented a more detailed phasing of

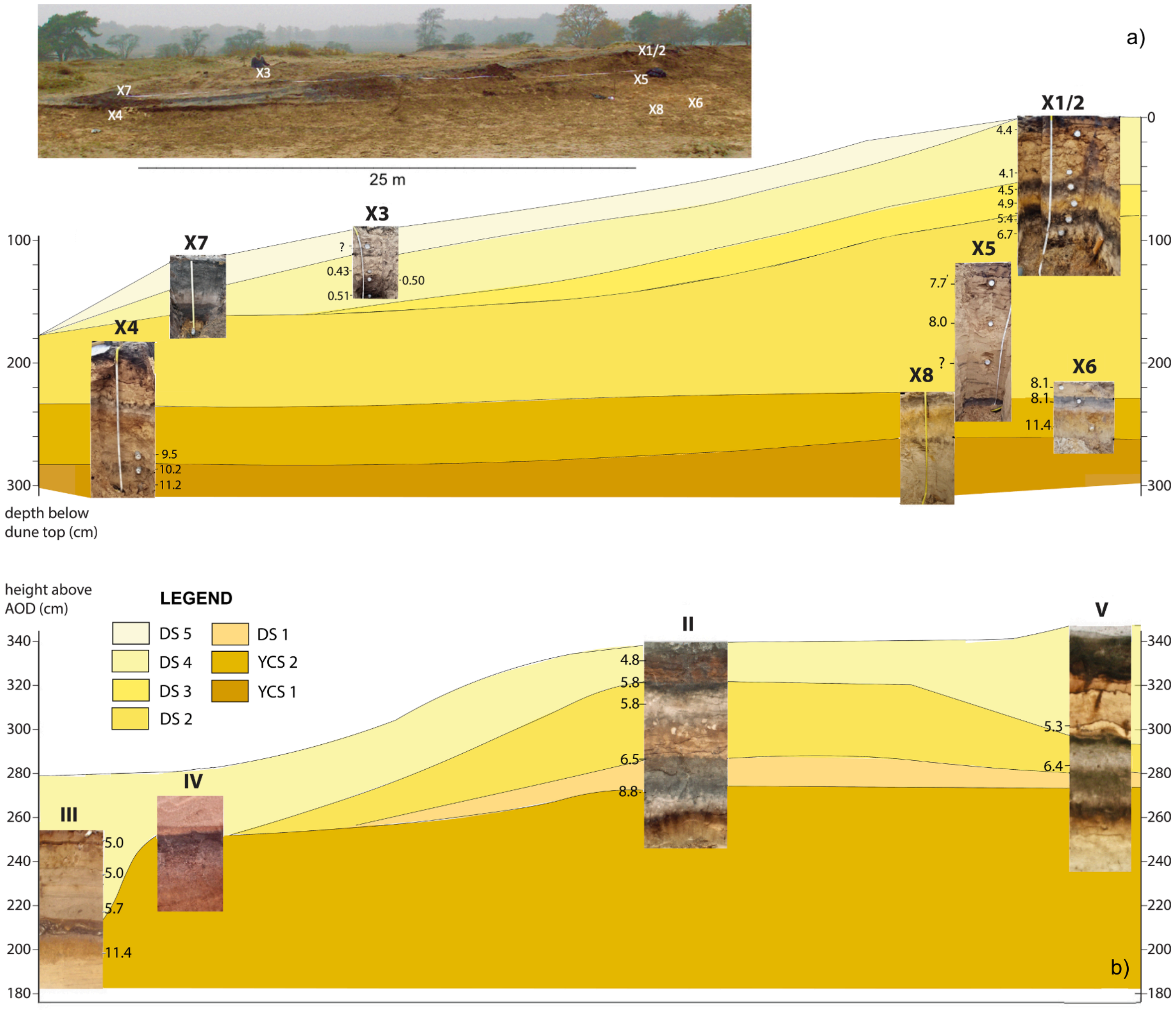

Fig. 2. A) overview of the dune in the bluk (site x) and its sections with locations of the OSL samples and their age (in ka ce;? = Questionable age). Details of OSL ages: see Table 1; details of sections: see Supplement 1. b) Earlier studied sections in the LWM area (after Sevink et al. 2013). For ages (in ka CE) and details for all datings (OSL and ^{14}C): see Supplement 2. DS = Drift sand with numbers indicating their phase (see Table 3); YCS 2 = Younger Cover Sand II; YCS 1 = Younger Cover Sand I. For locations, see Fig. 1c.

this early period for which stratigraphic correlations were less straightforward. The chronology was based on a significant number of absolute ages, including OSL dates and ^{14}C dates on charcoal. Descriptions of the various palaeosols and drift sand phases that were earlier studied and types of analyses performed on these can be found in Supplement 2. Part of these previously obtained OSL dates are also shown in Fig. 2b.

More recently, to the north of the LWM area, in an extension of the drift sand complex called the Bluk, a complex dune was found holding a series of palaeosols and drift sand layers (Fig. 1c, site X). The general stratigraphy and palaeosols encountered were already described in Wallinga et al. (2019). A schematic cross section with locations of the sections studied at this site is given in Fig. 2a. All sections are indicated with a Roman numeral, eventually followed by an Arabic number, referring to the specific section (e.g., site X3).

At site X, the complex basically consists of Younger Cover Sand II dune (Younger Dryas) resting on a classic Usselo soil (Allerød) with a low relief in Younger Cover Sand I (Older Dryas). In the Younger Cover Sand II, a prominent podzolic palaeosol occurs, covered by a complex of four drift sand layers with three intercalated podzolic palaeosols. The drift sand layers follow the morphology of the dune, the layers being thickest near the summit of the earlier dune. Lateral, the various Holocene palaeosols grade into a single Holocene soil through complex intermediary stratigraphies. In Fig. 2b, a similar cross section with earlier found palaeosols in the LWM area is presented. Comparable complex sequences of stacked palaeosols and drift sands were also recently (2022) encountered to the south of the LWM area (Site XI).

Most palaeosols were formed under well drained conditions, lacking evidence for the presence of hydromorphic features, and these palaeosols all exhibited the characteristic macroscopic features of podzols (WBR), being a distinct bleached E horizon and more or less prominent spodic B horizon, generally with distinct iron accumulation in its lower part (see Fig. 2 and supplements 1 and 2). In some sections, more hydromorphic conditions existed, but even here such palaeosols showed distinctly bleaching in their topsoil and illuvial accumulation of organic matter in the form of a Bh horizon (see for example LWM IV).

2.2. *Field, sampling, and analytical methods*

Sections indicated in Fig. 1c were described in the field using the FAO Guidelines for profile descriptions (Jahn et al. 2006). This implies that these descriptions and the horizons distinguished concern individual sections with their specific sequence of horizons. Integration of these field observations and other data resulted in the identification of specific phases of soil formation (palaeosols) and aeolian sand deposition in a local stratigraphic context. Phases may be reflected in the built-up of a certain section, but evidently not all phases that can be distinguished within a certain area have to be present in that section. Thus, distinction is to be made between the profile descriptions (with sections, soil horizons and samples) and the attribution of a certain soil or parent material to one or even several landscape genetic phases in a stratigraphic context (palaeosol and drift sand phases).

At site X, stratigraphic relations between individual drift sand phases and palaeosols were studied and established by observations in many sections. This local stratigraphy and sections sampled are indicated in Fig. 2a, showing the overall build-up of the drift sand – palaeosol complex at this site. The apparent discrepancy between the OSL ages and stratigraphy in section X3 can be readily explained by bioturbation affecting the OSL age of the top of the palaeosol in DS 4 and is discussed in more detail in para 3.1. Stratigraphic relations between earlier studied sections were taken from the earlier publications and are depicted in Fig. 2b (Sevink et al. 2013, 2018).

Sections at site X were continuously sampled (intervals of 3–5 cm) for a range of analyses, including size fractions (>2 mm, 2000–105 μm and < 105 μm), charcoal content of the fraction > 2 mm and chemical composition. Samples were dried at 105° for 24 h and subsequently sieved over a 2 mm mesh sieve. Fractions < 105 μm were obtained by suspending samples < 2 mm in water, heavy stirring for 2 min using a hand-held mixer to breakup aggregates and grain cutans, followed by washing over a 105 μm mesh sieve. Material that passed this sieve was collected by sedimentation and centrifugation of the still suspended material, followed by drying the fractions obtained at 105 °C for 24 h. These were weighed to establish the total fraction < 105 μm, whereafter a subsample was heated in an oven to 550 °C for 24 h to establish the weight percentages of organic matter and mineral material. Chemical analyses were performed on the fractions < 105 μm using a hand-held X-ray fluorescence (XRF) analyzer (Niton XL3t GOLDD +). Charcoal was handpicked from the dry fractions > 2 mm and weighed. A selected number of these charcoal samples was studied microscopically to establish their origin.

Nineteen OSL samples were taken by horizontally hammering PVC tubes into the various sections at site X (see Fig. 2a), with the primary aim to date the various drift sand phases that were identified in the field. Emphasis was on the time of burial of the palaeosols and, in case of thicker drift sand phases, the period of time over which sand drifting took place. For sections with the exact position of the samples, see Supplement 1. OSL ages were obtained on the sand-sized quartz fraction (212–250 μm), using 2 or 2.5 mm aliquots and otherwise largely identical methods to those used for NCL-7511 project as reported in our earlier study (Sevink et al., 2018). The palaeodose was established based on equivalent dose measurements on at least 16 replicates applying the single-aliquot regenerative dose protocol (Murray and Wintle, 2003) using a preheat and cut-heat combination of 200 and 180 °C, respectively. To calculate the net OSL signal we used the early background subtraction approach (Cunningham and Wallinga, 2010). For palaeodose estimation a unweighted mean of equivalent dose results was used, after iterative removal of individual points deviating more than two standard deviations from the sample mean general background. The dose rate was established based on activity concentration of U, Th, and ^{40}K measured from sample material using high-resolution gamma spectrometry. These activity concentrations were converted to gamma and beta dose rates using the conversion factors of Guérin et al. (2011). The organic matter content was based on the measured organic matter in the sample, whereas the moisture content of the samples was estimated based on the usable field capacity of the sampled material (for details, see Wallinga et al. 2019). The contribution of the cosmic dose rate to the total dose rate was determined based on geographical parameters and the estimated average thickness of the overburden through time (Prescott and Hutton, 1994), considering recent deflation at some sections. To obtain the OSL burial age the sample palaeodose was divided by corresponding total dose rate. OSL ages refer to ka since the time of analysis. Where relevant, they were transformed into BCE or CE calendar years.

Radiocarbon dates were obtained by AMS analysis at CIO (University of Groningen) for handpicked charcoal fragments. Pollen samples were taken in metal boxes and processed at IBED (University of Amsterdam). Methods used in the radiocarbon and pollen analysis were extensively described and can be found in the papers cited (Sevink et al. 2013; Doorenbosch 2013). ^{14}C ages, when calibrated, refer to age relative to the reference age (1950).

To assess the degree and rate of podzolization in the various phases, we selected the three ubiquitous, well developed palaeosols in the area: palaeosol 1 (from profile X5), palaeosol 3 (from profiles X1/2 and IV; indicated as 3a and 3b respectively), and palaeosol 5 (from profile V) (Table 3, Fig. 2, Supplements 1 and 2). The presence of a spodic B horizon as diagnostic horizon is the key criterion of the FAO World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB 2015). To qualify as a spodic B horizon several field descriptive criteria exist such as the Munsell colours of the horizon, as well as process-oriented chemical parameters. The total organic carbon content (TOC) is used as an indication of illuviation of DOM, with a threshold of TOC > 0.5 % in the uppermost layer of the B horizon. The fractions of ammonium oxalate/oxalic acid extractable Al and Fe (Al_o and Fe_o) represent Al and Fe present in interlayered minerals, organic complexes, and non-crystalline hydrous oxides (Jansen et al. 2011), and a value of $Al_o + ½Fe_o \geq 0.5$ % is used as indication of illuvation of Al and Fe. It is important to note that in this classification system not all criteria need to be met for the B horizon to fulfil the criteria for a spodic horizon.

For all selected palaeosols, the values of TOC, Al_o and Fe_o were determined in freeze-dried soil samples to allow assessment of the criteria. TOC was determined using a VarioEL (Elementar) CNS auto-analyser. Total C equalled TOC as the acidic soils were free of carbonates. Al_o and Fe_o were determined by a Perkin Elmer Optima-8000 ICP OES (Perkin Elmer Corporation, Waltham, USA) upon ammonium oxalate/oxalic acid extraction following the procedure described by Jansen et al. (2011).

In addition to the standard analyses as per the WRB description of the spodic horizon, for the palaeosols 1 and 3 as expressed in profiles X1/2 and X5 were selected for further analyses. These two palaeosols were selected given their wide occurrence and strong expression based on field assessment, as well as their age (Fig. 2a, Table 3). Both palaeosols 1 and 3 have an age of several millennia and are linked to earlier, pre-agricultural stages of landscape genesis (Table 3). The additional analyses included total contents of the major elements (Al_t, Fe_t, Ti_t, Ca_t, Mg_t, Mn_t, Na_t and K_t), obtained upon microwave assisted HNO_3/HCl digestion with the addition of HF to remove silicates (USEPA 2004). These served to provide an additional indication of the extent of weathering and eluviation/illuviation (ratios of Fe_o/Fe_t and Al_o/Al_t). Contents of the elements upon extractions were determined using a Perkin Elmer Optima-8000 ICP OES (Perkin Elmer Corporation, Waltham, USA).

Lastly, in Supplement 2 an overview is given of the earlier analyses for sections I-IX, for which methods and results have been published in Sevink et al. 2013, Doorenbosch 2013, Wagner et al. 2018, Sevink et al. 2018, and Wallinga et al. 2019.

3. Results and their discussion

3.1. Landscape genetic phases and their age

In the sections found in the drift sand dune area of the Bluk (site X, see Fig. 2a), a series of phases could be identified based on the very distinct stratigraphy. A similar approach has been used in the earlier studies on the adjacent LWM area (Sevink et al. 2013, 2018), of which the stratigraphy of relevant palaeosols is depicted in Fig. 2b. Correlations between the various phases distinguished in these two areas (see Fig. 1b) are primarily based on the OSL and ^{14}C datings, supported by more subjective criteria such as the morphological characteristics of the various palaeosols and magnitude of the drift sand phase concerned.

OSL and ^{14}C dates for the site X are presented in Tables 1 and 2, respectively. The OSL dates are also presented in Fig. 2a alongside the sections from which the samples were taken. The ^{14}C dates concern charcoal from the upper palaeosols (P3, P4, and P5, see Table 3) and considering the ages clearly are reworked charcoal from lower palaeosols, which are indeed often high in charcoal (see also 3.2). For that reason, we refrained from calibrating the ^{14}C ages. Earlier obtained dates for the sections I to IX and published in Sevink et al. 2013 and 2018, can be found in Supplement 2; some of these (OSL datings) are also given in Fig. 2b.

The OSL ages determine the time of deposition for samples taken from C-horizon material in such drift sands, whereas they are much more likely to indicate the time of burial of the paleosol concerned when taken from genetic soil horizons, particularly A and E horizons. This because the signal that is measured in the OSL technique is very likely to be affected by bioturbation that ended once the paleosol concerned was buried by drift sand (see also Sevink et al. 2013; Wallinga et al. 2019 for an extensive discussion). This phenomenon is particularly evident when comparing results for site X1, where the OSL dates for the podzol B horizon clearly reflect the time of deposition of drift sand of phase 4, and for site X3 where these dates for the upper horizons of the same palaeosol (Ah and E horizons) evidently indicate the time of burial of this palaeosol underneath the drift sands of phase 5.

The integration of the various phases into an overall sequence, based on OSL and ^{14}C dates, as well as stratigraphic correlations, is straightforward and results in identification and dating of the units (sediments) and phases (palaeosols) depicted in Table 3. Archaeological periods mentioned are based on Van den Broeke et al. 2005, while the Mesolithic phases were additionally based on Amkreutz (2013) and Woltinge et al. (2019). Later (post-Roman) phases were based on Pierik et al. (2018). They are depicted in Fig. 3. In Table 3, sections are indicated where the various drift sand units and palaeosols were found. Site X (see Fig. 2) demonstrates that in many sections incomplete sequences are encountered, individual phases often merging into compound phases, covering

Table 1

OSL ages for samples from LWM-X and its sections. For positions in these sections, see Fig. 2a and Supplement 1.

NCL Code	Client Code	Depth (m)	Palaeodose (Gy)	Dose rate (Gy/ka)	Age		Validity	Overdispersion (%)
					(ka)	(CE)		
LWM X-7 (52°13′58.59′’N, 5°13′06.59′’E, no surface correction)								
NCL-1417179	LWM X - 3 - OSL 4	0.18	0.44 ± 0.02	0.94 ± 0.03	0.47 ± 0.02	1,543 ± 24	Questionable	30
NCL-1417178	LWM X - 3 - OSL 3	0.48	0.40 ± 0.02	0.92 ± 0.03	0.43 ± 0.02	1,582 ± 21	Likely OK	18
NCL-1417177	LWM X - 3 - OSL 2	0.62	0.46 ± 0.02	0.92 ± 0.03	0.50 ± 0.03	1,521 ± 29	Likely OK	28
NCL-1417176	LWM X - 3 - OSL 1	0.93	0.40 ± 0.02	0.79 ± 0.03	0.51 ± 0.03	1,507 ± 28	Likely OK	25
LWM X-1,2 (52°13′59.04′’N, 5°13′07.08′’E; no surface correction)								
NCL-1417175	LWM X - 1,2 - OSL 6	0.18	4.4 ± 0.2	1.01 ± 0.03	4.4 ± 0.2	−2,337 ± 218	OK	13
NCL-1417174	LWM X - 1,2 - OSL 5	0.48	4.3 ± 0.1	1.06 ± 0.03	4.1 ± 0.2	−2,077 ± 165	OK	12
NCL-1417173	LWM X - 1,2 - OSL 4	0.61	4.4 ± 0.2	0.99 ± 0.03	4.5 ± 0.2	−2,463 ± 215	OK	15
NCL-1417172	LWM X - 1,2 - OSL 3	0.73	5.0 ± 0.1	1.02 ± 0.03	4.9 ± 0.2	−2,861 ± 205	OK	8
NCL-1417171	LWM X - 1,2 - OSL 2	0.86	4.6 ± 0.2	0.85 ± 0.03	5.4 ± 0.3	−3,409 ± 287	Likely OK	29
NCL-1417170	LWM X - 1,2 - OSL 1	0.96	6.3 ± 0.2	0.94 ± 0.03	6.7 ± 0.3	−4,650 ± 300	OK	22
LWM X-5 (52°13′59.04′’N, 5°13′07.08′’E; 1 m surface correction)								
NCL-1417169	LWM X - 5 - OSL 3	0.18	7.8 ± 0.3	1.00 ± 0.03	7.7 ± 0.4	−5,704 ± 354	OK	10
NCL-1417168	LWM X - 5 - OSL 2	0.66	8.0 ± 0.3	1.01 ± 0.03	8.0 ± 0.4	−5,949 ± 368	OK	14
NCL-1417167	LWM X - 5 - OSL 1	0.93	6.9 ± 0.2	0.93 ± 0.03	7.4 ± 0.3	−5,407 ± 340	Questionable	30
LWM X-6 (52°13′58.91′’N, 5°13′07.37′’E; 3 m surface correction)								
NCL-1417166	LWM X - 6 - OSL 3	0.03	7.9 ± 0.2	0.98 ± 0.03	8.1 ± 0.4	−6,128 ± 352	Likely OK	19
NCL-1417165	LWM X - 6 - OSL 2	0.18	7.7 ± 0.3	0.95 ± 0.03	8.1 ± 0.4	−6,072 ± 390	Likely OK	24
NCL-1417164	LWM X - 6 - OSL 1	0.48	12.9 ± 0.4	1.13 ± 0.04	11.4 ± 0.5	−9,359 ± 502	Likely OK	26
LWM X-3 (52°13′58.75′’N, 5°13′07.08′’E; no surface correction)								
NCL-1417163	LWM X - 4 - OSL 3	0.81	9.4 ± 0.3	0.99 ± 0.04	9.5 ± 0.5	−7,467 ± 474	OK	8
NCL-1417162	LWM X - 4 - OSL 2	0.98	10.2 ± 0.3	1.00 ± 0.04	10.2 ± 0.5	−8,181 ± 524	Likely OK	25
NCL-1417161	LWM X - 4 - OSL 1	1.13	11.8 ± 0.4	1.06 ± 0.04	11.2 ± 0.6	−9,167 ± 594	Likely OK	23

Table 2

^{14}C dates for charcoal fragments from LWM X1 and X2.

Sample name	Dated material	GrM	F^{14}C	±1Û	^{14}C Age (yrBP)	± 1Û	%C	‰^{13}C (‰; IRMS)	± 1Û
LWM X1 34–38 cm (P5)	Charcoal(AAA)	17847	0.3630	0.0015	8140	35	65.7	−25.26	0.15
LWM X1 70–74 cm (*P*4)	Charcoal(A)	17854	0.3456	0.0015	8535	35	65.0	−24.30	0.15
LWM X1/X2 122–127 cm (*P*3)	Charcoal(AAA)	17849	0.3565	0.0016	8285	35	65.1	−26.15	0.15

Table 3

Units/Phases distinguished, their OSL based age and archaeological period, sections at which they were encountered and nature of the palaeosols. () = Potentially present, but not identifiable as individual phase/unit.

Unit/ Phase	Age	Archaeological period	Sections at LWM	Nature of soil
Drift sand 5	Start ca. 1500 CE	Late Middle Ages to Recent	All	–
Paleosol 5 (P5)	Till ca. 1500 CE	Till Late Middle Ages	All	Strongly developed podzol
Drift sand 4	Ca. 2500 till ca. 2000 BCE	Late Neolithic	II/X1/2 + (I)/(V)/(IX)	–
Paleosol 4 (P4)	Till ca. 2500 BCE	Till Late Neolithic	X1/2	Weakly developed podzol
Drift sand 3	Start ca. 3800 BCE	Middle Neolithic	III/X1/2 + (I)/(II)/ (V)/(IX)	–
Paleosol 3 (P3)	Till ca. 3800 BCE	Till Middle Neolithic	II/III/V/ X1/2	Strongly developed podzol
Drift sand 2	Start ca. 4900–4500 BCE	Late Mesolithic	II/V + (I)/ (IX)	–
Paleosol 2 (P2)	Till 4900–4500 BCE	Late Mesolithic	II/V	Weakly developed podzol
Drift sand 1	Start ca. 6000 BCE	Late Mesolithic	II/V/IX/ X5/X6 + (I)	Thin E-type layer
Paleosol 1 (P1)	Till ca. 6000 BCE	Till Late Mesolithic	I/II/V/IX/ X4/X5/X6	Distinct Early Holocene podzol
Younger Cover Sand II	Ca 9500 BCE (end)	Late Palaeolithic	All	–
Allerød			VIII/X4/X6	Usselo layer

larger periods. In Table 3, also those sections are indicated where the various drift sand phases and paleosols were encountered as individual units or phases, whereas sections where these are potentially present are indicated between brackets.

The correlation of phases identified at the Bluk with those described in the earlier papers and found elsewhere in the Laarder Wasmeren area, shows that at the sites II and IV an additional early phase of sand drifting and subsequent soil formation occurs, stratigraphically wedged in between the early Holocene palaeosol and overlying drift sand/palaeosol complex found at site X. Apparently this phase (Palaeosol 2), starting between 4900 and 4500 BCE, is absent at this site. On the other hand, the thin drift sand layer and associated weak podzol found at site X and wedged in between two well-developed podzols (Drift sand 3/Palaeosol 4, see Table 3) was not identified elsewhere.

The Drift sand 1 and Palaeosol 2 that were not observed in the site X sections, can be described as a thin stratum of drift sand, probably composed of deflated topsoil material, with Ah and E horizons typical for a podzolic soil (P2), covering an intact Ah horizon of the underlying palaeosol (P1). At the sites mentioned (II and IV), the OSL ages for the burial of this soil phase indicate an age of about 4700 BCE (estimated age of the burial of the underlying palaeosol by the Drift sand 2). This implies that this Drift sand 2 dates from the end of the Late Mesolithic (Amkreutz 2013; Woltinge et al. 2019). The Drift sand 3/Palaeosol 4 sequence, composed of a thin layer of drift sand with a weakly developed Late Neolithic podzol, was only encountered at site X. At site X the youngest drift sand phase (Drift sand 5) was found to cover the most recent palaeosol (P5) at around 1500 CE, evidencing the Late Medieval and younger age of this latest drift sand phase, sand drifting going on until today.

3.2. *The aeolian sands*

Relatively high contents of mineral fines occur in the B horizons of the various podzols, and in the Usselo soil. Data on these contents are presented in Table 4, together with data on the charcoal content. It should be emphasized that 'mineral fines' includes accumulated Al and Fe compounds that precipitated in the B horizons of the podzols, but this plays a lesser role in the Early Holocene podzol (P1) and the Younger Cover Sand II (YCII) in which the podzol developed, given the far larger contents of such fines. Moreover, as is clear from the data, the composition of this podzol is quite variable, with for example a significant percentage of gravel and much higher fines content in section X5. In the upper palaeosols, organic fines follow a similar trend: higher in Ah and B horizons, while in the lower palaeosols contents are very low.

The cover sands of Het Gooi have already been extensively studied for their chemical and granulometric composition (Sevink et al. 2013 for the LWM area; Sevink et al. 2017). Regarding the latter, the various cover sand and drift sand materials sampled at site X fit in the general pattern of well-sorted drift and cover sands with overall low gravel and 'fines' content, of which the latter is defined as the mineral fraction < 105 μm.

Remarkable is the relatively high content of charcoal (>2 mm) in the lower strata of the sequence. Though weight percentages remain low given the low bulk density of charcoal (c. 300 kg/m^3 for pine charcoal, Gao et al. 2017) these amounts are significant in the lower parts of the site X. For the Usselo soil this can be seen as a normal phenomenon (see Van der Hammen and Van Geel 2008), but also higher up, in the Younger Cover Sand II and the lower part of Drift Sand phase 2, contents are quite significant. Similar high contents of charcoal were found in the sections I, VIII, and IX, but their weight percentages were not established (Sevink et al. 2013, 2018; Wagner *et al.* 2017).

3.3. *The palaeosols*

The palaeosols all exhibit podzolic features in the form of macroscopically identifiable characteristics, such as a distinct bleached E horizon overlying a dense Bh horizon. The general characteristics are briefly described in Table 5 and the palaeosols are tentatively classified according to the Dutch system of soil classification (De Bakker and Schelling 1989). The data presented in Table 4 support the field observations regarding the expressions of the typical podzolic features, notably the accumulation of illuviated organic matter, lesser weathering (%K) in the B and C horizons, as compared to the A and E horizons, and occurrence of charcoal. They also show that their granulometry is quite varied, with higher fines and gravel contents in the older palaeosols.

The results presented in Fig. 4 concern the chemical indications of podzolisation in the earlier palaeosols. These were selected because of their extensive occurrence, prominent development, and early genesis (palaeosols 1 and 3, see Table 3). Earlier studied palaeosols include a hydromorphic palaeosol 3 and a palaeosol 5 (Sevink et al. 2013).

All results for the chemical analyses of the palaeosols 1 (section X6), 3a (3 as expressed in section X1/2), 3b (3 as expressed in section IV), and

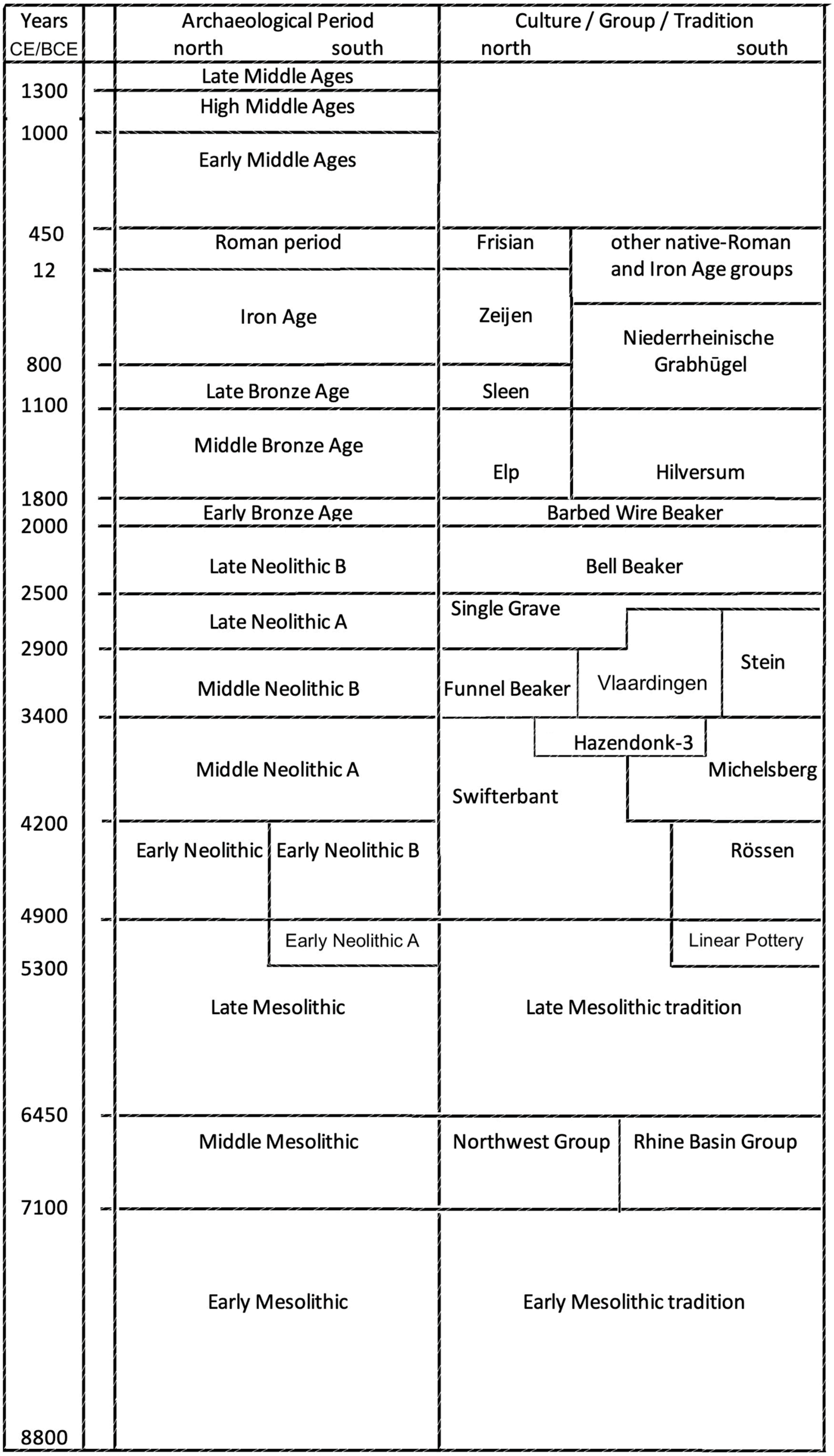

Fig. 3. Schematic chronology of Dutch (pre)history (after: Van den Broeke et al. 2005; Blockmans and Hoppenbrouwers 2017).

Table 4
Data on the composition of sections from site X in weight percentage and mg/kg. Min. fines = mineral fines; Org. fines = organic fines. Section X3 and X1 are at some distance from each other but were stratigraphically linked by sharing the same Bh horizon. YCS = Younger Cover Sand; DS = Drift sand; P = Palaeosol; see also Table 3.

Section	Horizon	Phases	Depth in cm	Gravel	Charcoal	Fines	Min. fines	Org. fines	K (XRF)	Ti (XRF)
				%	%*1000	%	%	%	mg/kg	mg/kg
X3 0–5	Ah	***P5 / DS4***	0–5	0	0	11.63	5.73	5.90	1581	342
X3 5–10	E		5–10	0	0	5.13	2.82	2.31	1405	128
X3 10–15	E		10–15	0	0	3.18	2.17	1.01	1203	71
X3 15–20	Bh		15–20	0	0	3.12	2.22	0.89	954	76
X1 0–5	Bhb1		20–25	0	2.1	2.30	0.85	1.45	148	63
X1 5–11	Bhb1		25–31	0	0	2.68	1.17	1.51	146	40
X1 11–15	Bhb1		31–35	0	0	1.52	0.50	1.02	47	21
X1 15–20	Bh/BCb1		35–40	0	0	0.34	0.15	0.19	24	6
X1 20–25	Bh/BCb1		40–45	0	0	1.22	0.74	0.48	90	23
X1 25–29	Bh/BCb1		45–49	0	0	0.59	0.30	0.29	45	11
X1 29–34	Bh/BCb1		49–34	0	0	0.81	0.39	0.42	62	17
X1 34–38	Bh/BCb1		54–58	0	10.9	0.53	0.28	0.25	46	13
X1 38–43	Bh/BCb1		58–63	0	0	0.35	0.20	0.15	32	8
X1 43–47	Ahb2	***P4 / DS3***	63–67	0	0	0.62	0.40	0.22	71	17
X1 47–52	Ahb2		67–72	0	0	1.25	0.74	0.51	138	32
X1 52–56	Ahb2		72–76	0	0	2.36	1.36	1.00	283	62
X1 56–61	Ahb2		76–81	0	0	2.01	1.18	0.84	321	74
X1 61–65	Eb2		81–85	0	0	0.99	0.72	0.27	187	45
X1 65–70	Bhsb2		85–90	0.05	5.1	0.55	0.41	0.14	83	26
X1 70–74	Bhsb2		90–94	0.03	8.8	0.13	0.08	0.05	15	5
X1 74–78	Bhsb2		94–98	0.01	8	1.29	0.81	0.49	145	41
X1 78–82	Ahb3	***P3 / DS2-1***	98–102	0	0	2.39	1.49	0.91	271	57
X1 82–87	Ahb3		102–107	0	0	2.99	1.96	1.03	756	87
X1 87–92	Eb3		107–112	0	0	2.28	1.96	0.32	766	63
X2 92–97	Eb3		112–117	0	0	2.70	2.36	0.34	658	64
X2 97–102	Bhsb3		117–122	0	0	3.25	2.10	1.15	478	109
X2 102–107	Bhsb3		122–127	0	0	4.50	3.16	1.35	483	106
X2 107–112	Bhsb3		127–132	0	0	4.88	2.70	2.17	725	117
X2 112–117	Bhsb3		132–137	0	0	1.77	1.18	0.59	132	36
X2 117–122	BCb3		137–142	0	0	1.67	1.06	0.61	123	35
X2 122–127	BCb3		142–147	0.17	3.4	1.76	1.29	0.46	161	44
X2 127–132	BCb3		147–152	0	0	0.80	0.51	0.29	66	24
X4	BCb3	***DS2-1***	0–5	0.01	30.5	0.28	0.13	0.15	15	7
X4	BCb3		5–10	0.00	39.1	0.76	0.52	0.24	64	14
X4	BCb3		10–15	0.02	19.6	0.63	0.48	0.14	63	13
X4	Ahb4	***P1 / YCII***	15–20	0.06	27.0	3.29	2.57	0.72	437	80
X4	Eb4		20–25	0.08	59.6	2.92	2.53	0.39	504	90
X4	Bsb4		25–30	0.04	82.8	2.30	2.04	0.25	376	61
X4	Bsb4		30–35	0.03	63.0	1.24	0.95	0.29	161	43
X4	Bsb4		35–40	0.02	20.7	1.84	1.60	0.24	170	35
X4	BCb4		40–45	0.02	23.4	1.32	1.07	0.26	114	24
X4	BCb4		45–50	0.02	13.6	0.72	0.53	0.19	61	18
X4	Cb4	***YCII***	50–55	0.01	13.1	1.03	0.93	0.10	108	15
X4	Cb4		55–60	0.02	20.5	0.46	0.43	0.03	52	17
X4	Cb4		60–65	0.04	18.7	0.68	0.53	0.14	76	23
X4	Cb4		65–70	0.06	16.8	0.66	0.54	0.12	77	21
X4	Cb4		70–75	0.08	33.5	1.61	1.24	0.37	181	46
X4	Ahb5	***Usselo***	75–80	0.08	147.1	1.13	0.87	0.26	113	27
X4	Ahb5		80–85	0.26	222.8	0.44	0.30	0.14	48	17
X4	Eb5		85–90	0.52	21.8	2.62	2.08	0.54	320	98
X5	Drift sand	***DS2-1***	10–5	0.01	164.3	1.33	1.15	0.18	141	23
X5	Drift sand		5–0	0.00	70.3	0.79	0.60	0.19	98	23
X5	Ah1(b4)	***P1 / YCII***	0–5	0.58	46.8	2.53	1.88	0.65	383	82
X5	Ah2 (b4)		5–10	1.06	69.2	3.99	3.51	0.48	668	118
X5	E (b4)		10–15	1.24	86.8	6.78	6.30	0.48	1020	143
X5	Bs1 (b4)		15–20	2.39	99.1	4.91	4.23	0.68	593	147
X5	Bs2(b4) stony		20–25	7.48	43.6	4.61	4.10	0.51	436	114
X5	BC(b4)		25–30	9.97	4.3	3.45	3.27	0.18	347	106
X5	C(b5)	***Usselo***	30–35	2.14	1.5	1.40	0.67	0.73	141	33

5 (section V) are presented in Supplement 3b. These include the results for the TOC, Al_o and Fe_o analyses as well as the derived WRB criterion value of $Al_o + \frac{1}{2}Fe_o$ (IUSS Working Group WRB. 2015) for all palaeosols mentioned, and the total element values for palaeosol 1 and palaeosol 3a that were selected for additional scrutiny of the extent of podzolization (see materials and methods). With respect to the TOC values, all palaeosols meet the criteria of $TOC > 0.5$ % in the top of the first B horizon, indicative of illuviation of DOM. The criterion of $Al_o + \frac{1}{2}Fe_o \geq 0.5$ % was not met in any of the B horizons in the palaeosols.

Selected results from the chemical analyses are presented in Fig. 4 and concern those chemical parameters which are indicative for the extent of podzolisation and weathering. Fig. 4a shows the distribution of oxalate extractable Fe and Al in the palaeosols 1 (section LWM X5), 3 (sections LWM IV and X2), and 5 (section LWM V). These results demonstrate the distinct podzolisation in these palaeosols, except for section IV which indeed exhibited far less prominent macroscopic

Table 5
General description of the sequence of palaeosols encountered in the Laarder Wasmeren area.

- Paleosol 1 (Pl): well-developed podzol, observed in many sections, ranging from hydropodzol (e.g., II, V) in lower positions to xeropodzol (I and X-6). Often with abundant charcoal. Chemical analyses: X-6 (this paper)
- Paleosol 2 (P2): weakly developed podzolic soil, composed of Ah and E horizon in thin layer of drift sand (mostly 10–20 cm), which probably largely consists of deflated£ horizon material. The Bh horizon consists of a slightly transformed Ah horizon of the underlying podzol, with some illuviation of organic material, visible as fibers.
- Paleosol 3 (P3): pronounced xeropodzol, particularly in II and X-1/2. Characteristic mottled Bh horizon. Chemical analyses: X-1/2 (this paper); IV (Sevink et al. 2013, see supplement XX for analytical data)
- Paleosol 4 (P4): weakly expressed xeropodzol, only in X-1/2.
- Paleosol 5 (P5): pronounced xeropodzol with distinct Bh and Bhs horizons, present throughout the area in the top of the aeolian sand complex. Chemical analyses: V (Sevink et al. 2013, see supplement 3 for analytical data).

podzol characteristics and represents a palaeosol (P3) developed under relatively wet conditions (see Sevink et al. 2013). More reliable indicators are the values presented in Fig. 4b, which concern the values for Al_t and Fe_t normalized to Ti_t in the various horizons of Palaeosol 1 and Palaeosol 3a, and the ratios of Al_o/Al_t and Fe_o/Fe_t, respectively. The normalization to Ti_t was performed by correcting the Fe_t and Al_t contents for the relative increase or decrease in Ti_t as compared to the Ti_t content of the uppermost horizon in the soil. The rationale is that Ti_t serves as indicator of weathering in all soil size fractions, with a vertical mobility linked to physical transport of the fine earth fraction rather than chemical eluviation (Sudom and Arnaud 1971). Remaining fluctuations of Al_t and Fe_t contents with depth upon normalization to Ti_t can then be assumed to be caused by processes other than physical translocation of the fine earth fraction, such as pedogenetic dissolution-, complexation- and precipitation-driven eluviation and illuviation that is characteristic of the process of podzolization (Jansen et al. 2004, 2005).

Results presented in Fig. 4 can be summarized as follows: 1) a relative depletion of Al_t and Fe_t from the Ah and E horizons in Palaeosol 1 (section X5), and concurrent relative enrichment of Al_t and Fe_t in the underlying B and C horizons, 2) ratios of Al_o/Al_t and Fe_o/Fe_t show a clear increase in the Bs1 horizon (and for Al also in the E horizon); 3) For Palaeosol 3 (section X2), analogous to Palaeosol 1 (section X5), a relative enrichment of Al_t and Fe_t in the Bhsb horizons. Together, the trends visible in Fig. 4 provide a strong soil chemical indication of podzolization having occurred in both Palaeosol 1 and Palaeosol 3, independent from the visual field observations (Jansen et al. 2004, 2005).

Fig. 4 (D and E) shows a clear increase of the Ca and Mg contents with depth, whether presented as total contents or normalized to Ti, pointing at significant weathering. For K the trend is less clear in section X5 (P1) with the normalized K content declining with depth. This is due to an increasing Ti content with depth, that may well be linked to residual accumulation of heavy minerals in this relatively heterogeneous deposit (see % gravel and fines in Table 4).

Comparing the visual observations on the degree of podzolisation in the various podzols with the analytical data, the overall trend as visible in Table 4 is evident, but a quantification of this degree is clearly problematic. This is due to differences in the nature of the podzolisation and of the parent material. Thus, the palaeosols P3 and P5 can be described as strongly developed podzols with a distinct spodic B differentiated into Bh and Bs horizons, while palaeosols P2 and P4 exhibit far less expressed horizon development, all in aeolian sand that is low in fines (fraction $<$ 105 um). However, these differences cannot be readily expressed in some chemical index given the limited set of data available.

As to the palaeosol P1, the aeolian sand, which is not drift sand, but Younger Cover Sand II, clearly is much higher in fines and has a deviating mineralogy (higher Fe, K and Ti contents). This podzol lacks the distinct Bh horizon and corresponding significant accumulation of illuviated organic matter and has a distinct Bs horizon. It thus differs significantly from the later podzols, but this difference cannot be linked to differences in the degree of podzolisation.

As described in the introduction, the number of studies on early Holocene palaeosols in the western part of the NW European sand belt is increasing, but the information on these palaeosols is generally limited to field descriptions and, in some cases, to data on rather standard parameters, such as granulometry and organic matter content (see e.g., Kasse and Aalbersberg 2019, and Hamburg et al. 2012). This implies that our data on the nature and extent of podzolisation cannot be ranked against those from other studies on similar early Holocene palaeosols. The situation is different for late Holocene podzolic palaeosols and the Lateglacial Usselo soil, where studies with dedicated chemical analyses are much more common (e.g., Gocke et al. 2016 for the late Holocene palaeosols, and Jankowki 2012 for the Usselo soil). In line with the latter studies, our study demonstrates the value of a combination of field observations and dedicated chemical analysis for studies on early podzolisation in aeolian sands.

3.4. *Palaeoecology*

The preservation of pollen grains in podzolic palaeosols can be rather bad (Dimbleby 1961). Pollen in most samples from the X sections in the Bluk indeed was often badly preserved and selective corrosion may have occurred. Nevertheless, based on comparisons with the vegetation history of the Netherlands (dated immigration of tree species and presence/absence of herbaceous human impact indicators; Behre 1981; van Geel et al. 1981; Zagwijn, 1994), these pollen records could be used for approximate dating the top of the podzols which were covered by drift sand. In addition, based on the arboreal/non-arboreal ratio AP/NAP (Broström et al. 1998; Sugita 2007), specific aspects of the local vegetation - from relatively closed forest to an open landscape with ericaceous vegetation - could be distinguished.

Major traits of the local vegetation development in ‘Het Gooi’, in which the LWM area is located, have already been extensively described in the earlier publications by Doorenbosch (2013), Sevink et al. (2013, 2018), Sevink and Van Geel (2017), and Van Geel et al. (2017). We therefore concentrate on the local vegetation and its composition as deduced from the pollen and charcoal remains encountered and pay special attention to these two aspects (dating and openness of the vegetation).

Results for the X sections are presented and discussed below. Information can also be deduced from the charcoal identifications, which are presented in Table 6 and described separately. This is followed by a description of the results for each phase distinguished (see Table 3) in which attention will also be paid to earlier published pollen data for relevant profiles from the LWM area (Doorenbosch 2013: sections II and V; Sevink *et al.* 2014: section IV; Sevink et al. 2018: section I). All data are also presented in Supplement 4.

3.4.1. *Pollen data sections from site X*

In Fig. 5 two of the in total 5 pollen diagrams are presented. These concern the sections X2 and X5. The diagrams for the other sections (X1, X3, X4) can be found in Supplement 4. The results are described starting with the earliest palaeosol.

Section X5 (Palaeosol 1 in Younger Cover Sand II):

In the lower part of the section high percentages of *Corylus* and very low *Alnus* percentages were observed and considering these percentages the lower part of the diagram represents the Boreal period (between ca 9150 and 7900 cal yr BP). The upper two samples of the podzol show increased levels of *Alnus*, indicating that the podzol was covered with drift sand during the transition from the Boreal to the Atlantic period. Human impact indicators like Cerealia and *Plantago* were not recorded, which fits with the age estimation based on arboreal taxa. Local non-arboreal vegetation was dominated by Poaceae and Ericales. The AP/NAP ratio indicates a half open landscape.

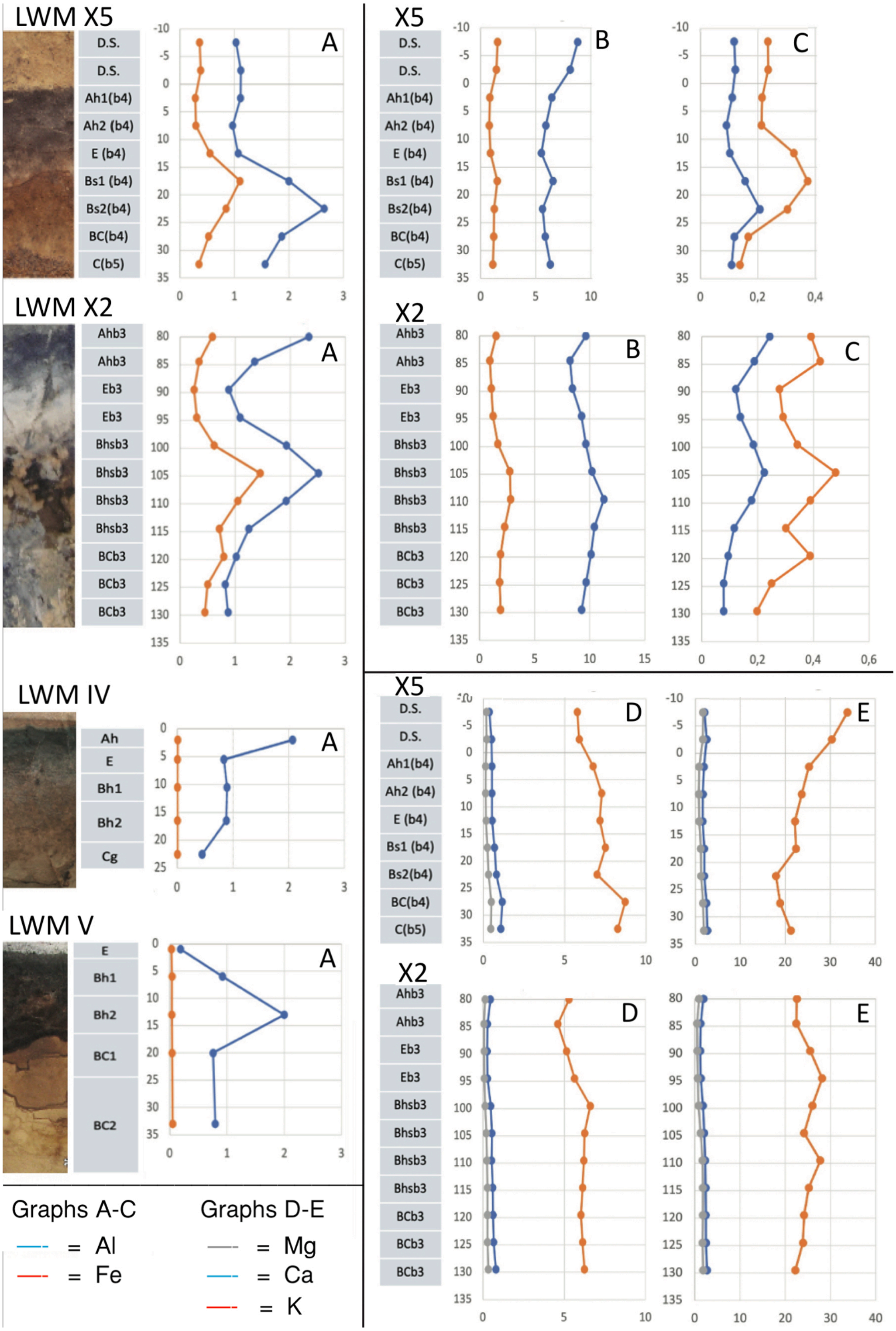

Fig. 4. Data on the chemical composition of the palaeosols P1 (LWM X5), P3 (LWM IV and X2), and P5 (LWM V)., with simplified soil horizons. A)=Oxalate extractable Al and Fe in mg/g soil; B) = Oxalate extractable Al and Fe normalized to Ti in mg/g soil; C = Ratio of oxalate extractable to total Al and Fe; D) Total element contents in mg/g soil (Mg, Ca, K); E) = Total element content in mg/g soil normalized to Ti content (Mg, Ca, K). Y-axis = depth in cm.

Section X4 (Younger Cover Sand II with Palaeosol 1 over Usselo soil – at 75 cm):

Alnus is virtually absent and *Corylus* and Poaceae dominate the local vegetation. Ericales show low percentages only. The pollen record thus points to at least Boreal age (between ca 9150 and 7900 cal yr BP and the AP/NAP ratio indicates an open landscape.

Section X2 (Palaeosol 3 in Drift Sand 2):

The diagram shows high percentages of Poaceae and Ericales (open landscape) but Cerealia, *Plantago* and other human impact indicators were not recorded. In combination with *Corylus* and *Alnus* this may indicate an Atlantic age (between ca 7900 and 5000 cal yr BP). However, considering the occurrence of various herbaceous taxa we cannot

Table 6
Charcoal fragments (>2mm) in the various sections. * = not identifiable at species level.

Section	Paleosol/ Drift Sand	Horizon	Phase	Depth in cm	%*1000	*Ceno-coccum*	*Pinus sylvestris*		Deciduous tree
							wood	cone scale	
X1	P5	Bh/BCb1	DS4	20–25 cm	2.1	2	10	–	–
	P5	Bh/BCb1	DS4	34–38 cm	10.9	3	25	8	–
	P4	Bsb2	DS3	65–70	5.1	4	25	4	3*
	P4	BSb2	DS3	70–74	8.8	3	25	5	1*
	P4	Bsb2	DS3	74–78	8	4	19	2	2*
X2	P3	BCb3	DS2	122–127	3.4	–	17	5	–
X4	P1	Eb4	YCS2	20–25	59.6	–	34	15	–
	P1	Bsb4	YCS2	25–30	82.8	–	25	6	–
	DS2	Cb4	YCS2	65–70	16.8	–	15	30	–
	Usselo	Ahb5	YCS1	75–80	147.1	–	22	> 350	–
	Usselo	Ahb5	YCS1	80–85	223	–	5	140	2
X5	DS2	Cb3	DS2	10–5	164.3	9	85	33	–
	P1	Bsb4	YCS2	15–20	99.1	–	22	c. 75	–

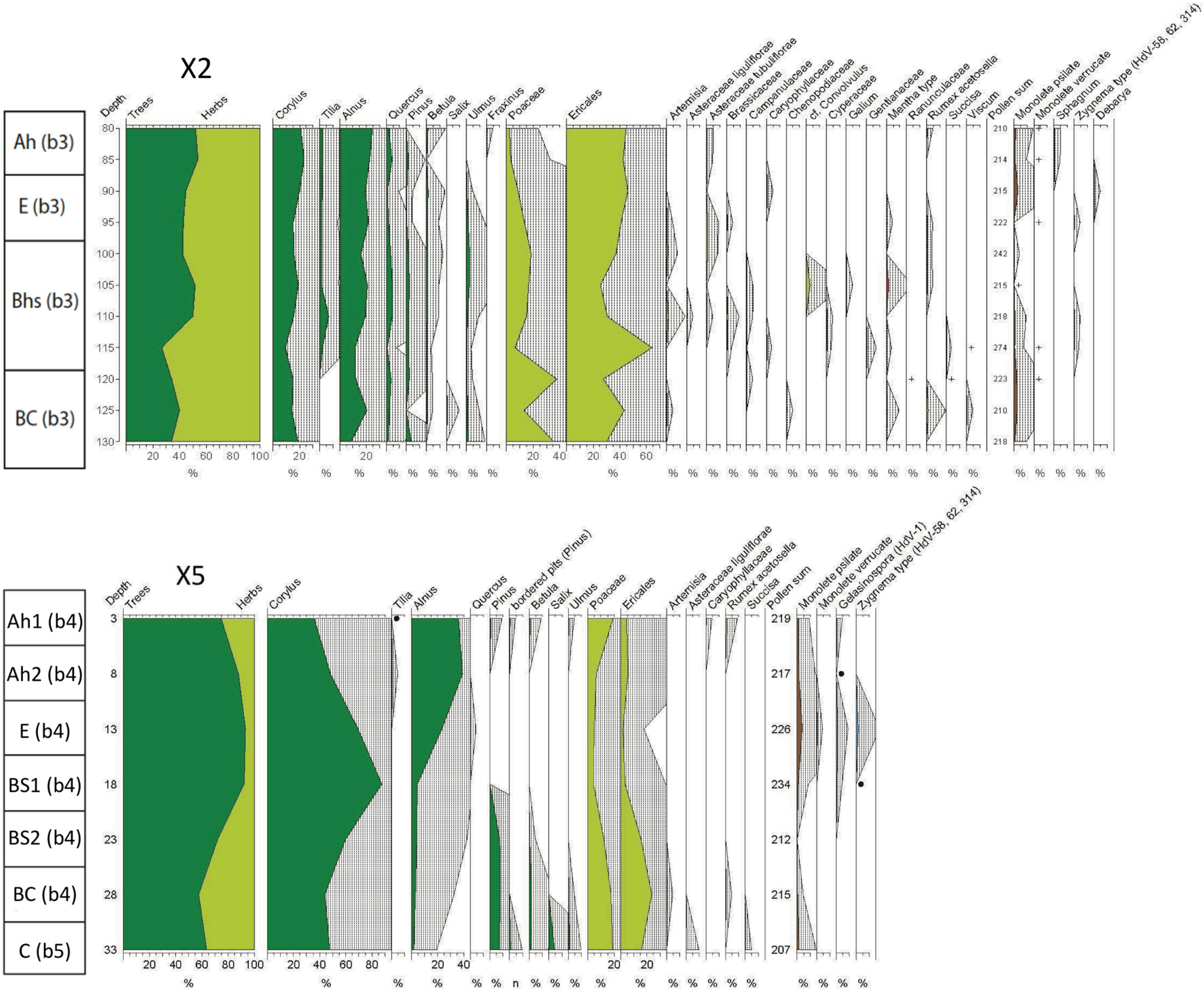

Fig. 5. Pollen diagrams for the sections X2 (Palaeosol 3 in Drift Sand 2) and X5 (Palaeosol 1 in Younger Cover Sand II). Depths indicated relate to the depth indicated in Fig. 4 and Table 4.

exclude a Subboreal age.

Section X1 (Palaeosols 4 in Drift Sand 3 and 5 in Drift Sand 4):

The youngest samples of the upper podzol contain pollen of taxa pointing to a Late Medieval or later age (*Secale, Centaurea cyanus, Fagopyrum*). Spores of coprophilous fungi (*Sordaria, Sporormiella, Podospora*; van Geel and Aptroot 2006) also indicate human impact (relatively dense population of large herbivores). The AP/NAP ratio points to an open landscape.

Section X3 (Top of Palaeosol 5 and Drift Sand 5):

The diagram shows high pollen records of Ericales, together with Cerealia*, Plantago lanceolata, Rumex acetosella* and some other human impact indicators. The presence of *Centaurea cyanus* and *Secale* points to a Late Medieval or younger age, and the AP/NAP ratio indicates an open landscape.

3.4.2. Charcoal

In Table 6 an overview is given of the charcoal content and its origin in the various sections. This table shows that particularly in the Usselo soil and Early Holocene palaeosol (P1) *Pinus sylvestris* cone scales are abundantly present and dominate the charcoal fraction. This is fully in line with the earlier observations: Sections I and IX were also marked by abundant presence of such charcoal (Sevink et al. 2013, 2019; Wagner et al. 2018). In the more recent palaeosols (X1 and X2) only traces of charcoal were found, and these had a high ^{14}C age, demonstrating that this charcoal must be reworked older charcoal. Its composition is indeed very similar to the charcoal in the lower strata. For details, reference is made to the Supplement 3.

3.4.3. Vegetation and phases

For most of the various phases the earlier records (see Supplement 4) and the new records presented above together allow for a well-founded insight into the changes in vegetation over time. The interpretations are primarily based on the data for the Ah horizons and, eventually, the E horizons, since their pollen most likely reflects the vegetation on the soils concerned prior to their coverage. For lower soil horizons from the individual palaeosols it cannot be excluded that a smaller or larger part of their pollen is derived from older pollen reservoirs (i.e., from eroded earlier palaeosols) or is of *syn*-sedimentary age.

Data for *phase 1* (P1) which concerns the early Holocene period of soil formation (>6000 BCE), are available for the following sections: I, II, IV, and X, and for the latter from X4 and X5. Dominant tree species were particularly *Corylus* and *Betula*, and additional *Alnus* and *Pinus*, fully in line with the trends described in the general literature cited before. Pollen of herbaceous taxa is present in variable amounts. Values for Ericaceae are overall low and for Poaceae often more abundant. These results point at an open forest with *Corylus* and *Betula* as important tree species and with patches of short herbaceous vegetation, but no open heathland yet. It is the time of the Mesolithic hunter-gatherers.

The vegetation in *phase 2* (P2) with data from sections II and V, resembles that in phase 1, with *Corylus*, *Betula,* and an increasing representation of *Alnus*, with some *Pinus* and deciduous trees such as *Quercus*, *Tilia,* and *Ulmus*. Here too, herbaceous pollen is relatively scarce, but Ericaceae are more common than in phase 1. During this phase the land was still exploited by Late Mesolithic hunter-gatherers (see section 3.1).

In *phase 3* (P3), with 4 pollen records (sections II, V, IV, and X1/2), the openness of the forest has distinctly increased as indicated by the lower AP/NAP ratio. Ericaceae pollen increased, pointing at a shift towards a more open forest with a distinctly larger heath component. The dominant tree species still are *Alnus*, *Corylus*, and *Betula* while *Pinus* is relatively rare in comparison to the deciduous trees. There are a few taxa indicative for agricultural activities, but their percentages are very low. During this phase a Middle Neolithic population would have been active, but it must be considered that the cereals grown - emmer wheat and barley - do not readily release pollen into the air. Therefore, the impact of farming activities is difficult to assess. Again, the overall pattern is as described in the literature cited.

For *phase* 4 (P4), only 1 pollen record is available (X1/2). The pollen record reveals a rather open landscape comprising a considerable proportion of heath (Ericales). According to its date this vegetation must be placed in the Late Neolithic.

In *phase 5* (P5), with the pollen records for X1 and X3, and the earlier records for sections II and V, the amount of arboreal pollen further declined and Ericaceae increased. The dominant forest species still are *Alnus*, *Corylus,* and *Betula*, with minor contributions of other deciduous trees. However, *Pinus* increased. A marked feature is the trend over time in the NAP pollen composition: initially Poaceae increase and then decline, while Ericaceae show the opposite trend, suggesting a temporal trend in which first grasses expand and then heath takes over, while the forest declines. It is in phase 5 that agriculture also becomes evident in the form of *Secale* and other taxa that are clearly pointing towards a Medieval age (e.g., *Fagopyrum*, *Centaurea cyanus*). The anthropogenic impact is particularly clear in the record from X3, which concerns a drift sand 5 section of Medieval and younger age.

The pollen records thus demonstrate a marked transition in vegetation composition from phase 2, through the somewhat intermediate phase 3, to phases 4 and 5. This is a change from a mixed deciduous forest with open grassy patches to a much more open heath-dominated vegetation with tree patches. The patchy pattern has been described in other studies, such as that by Vera (2000), but with generally little attention for the scale of this pattern and its origin. One of the rare exceptions is the study on the Mesolithic Swifterbant site (Hamburg et al. 2005). Remarkable is that in the early phases forest fires played a distinct role, evidenced by the abundant occurrence of charcoal, while later – phase 3 and later phases – no evidence was found for significant forest fires.

4. General discussion

Confrontation of the results described above with the hypotheses regarding the Holocene genesis of the Dutch sand landscapes described in the introduction immediately leads to questions such as ‘why sand drifting already occurred far before the introduction of Neolithic crop farming?’ (Amkreutz 2013; Woltinga et al. 2019), and ‘how to explain the early significant podzolisation?’. These questions will first be discussed, followed by a discussion on the potential link with Mesolithic land use.

4.1. Sand drifting and its causes

A basic requirement for sandy soils to be eroded by wind is the presence of bare sand at the surface, not covered by vegetation. It may also be protected by ectorganic topsoil horizons such as dense and erosion resistant H horizons encountered in podzolic soils, notably those formed under ericaceous vegetation (see e.g., Emmer 1994; Van Delft et al. 2007; Sevink and De Waal 2010). This is the background for the clear links with crop farming and intensive cart traffic put forward in hypotheses on early (Medieval) sand drifting, which both are thought to initiate ‘open sand’. Pierik et al. (2018), for example, in their extensive study of controls on drift sand dynamics, also mention climate (storminess) as a factor but attribute the initiation of sand drifting to farming and traffic. That open sand is required for sand drifting to be activated in former drift sand areas is in fact one of the basic assumptions in the current nature management of such areas (Riksen and Goossens 2005; Riksen et al. 2008). The question thus is: what led to the existence of such open sand in ‘pre-agricultural’ times, i.e. before the introduction of larger scale crop production with associated destruction of the forest vegetation and ploughing?

The palaeoecological data for the phases 1 and 2 show that in this ‘pre-crop farming’ period open mixed forest with patches of grass-dominated short vegetation existed, with soils that already exhibited clear podzolisation. However, in the sections found in the LWM area preserved topsoils of these buried podzols do not exhibit a mor to moder-like humus form (Green et al. 1993; Van Delft et al. 2007), as can be expected since the type of vegetation that we found is generally associated with mullmoder to moder type humus forms (Baritz 2003; Sevink and De Waal 2010).

An interesting aspect of the charcoal record is that pinecones are an important component, while, based on the pollen records, *Pinus sylvestris* apparently was of minor importance. Combining results from studies on the impact of fires on forest floors (or ectorganic layers; cf. Green et al. 1993; Van Delft et al. 2007) in Scots pine stands and deciduous temperate forests, a potential explanation for the relatively abundant occurrence of pine material, notably from pinecones can be hypothesized. Firstly, studies on humus forms under such pine forests showed that the ectorganic layers have a relatively large pinecone component (scales), these cones being composed of poorly degradable organic matter, which leads to their residual accumulation (Wardenaar and Sevink 1992; Van Wagtendonk and Moore 2010). As to the impact of fire, particularly relevant is the in-depth study of the fire ecology of Scots pine in Northwest Europe by Hille (2006). For deciduous forests fire-risks are low, contrary to Scots pine forests, and in such forests, the ectorganic layer is far less susceptible to fire if moist and low in pinecones, whereas these pinecones were found to strongly promote ground fires (Hille and Den Ouden 2005; Hille and Stephens 2005; Gabrielson et al. 2012). In experiments, under optimal conditions – dry ectorganic layer which contains pinecones - such fires were found to lead to the complete destruction of this layer, exposing the mineral soil. This suggests that the relatively high contents of charred pinecone material might be attributed to their residual accumulation in the ectorganic layer and not to the dominance of Scots pine in the local forest. Moreover, they are the main component that may stay morphologically recognizable as charred remains.

The foregoing observations and data readily lead to the conclusion that forest fires destroyed the protective vegetation cover and ectorganic layer, exposing the mineral soil and thus providing the required conditions for sand drifting. Such fires, to indeed cause a significant exposure of the mineral surface of the soil, which still had a mullmoder to moder type (endorganic) humus form, must have included ground fire, producing the charcoal assemblages that we found.

During the later palaeosol phases (P3, P4, and P5), the vegetation distinctly changed, with a much more restricted presence of forest and with larger open areas with a heath-dominated herbaceous plant community. Indications for nearby agricultural activities are distinct and those for repeated burning in the form of charcoal are absent. The overall situation in these later phases thus is in conformance with the hypotheses described in section 1, though significant sand drifting started relatively early and certainly is not limited to Medieval and more recent times as often postulated by the authors cited.

4.2. Early podzolisation

The earlier theories that exist on the basic causes for the podzolisation observed in the sandy soils of northwestern Europe, which are intrazonal soils (Jansen *et al.* 2005), have already been described in the introduction. In brief: Under natural conditions podzolisation would have been far less expressed, but the changes in vegetation brought about by human interference, notably the transformation of mixed, predominantly broadleaved forest into heathland, is cited as the dominant cause for the pronounced podzolisation observed. Evidence presented concerns the absence of podzols under burial mounds, differences in soil morphology and chemistry between podzols under different types of vegetation (forest versus heath), and lesser pronounced podzolisation in less quartzitic/more loamy sands.

In the literature, considerable attention has been paid to the impact of the species composition of a forest on soil acidification (e.g., Augusto et al. 1998; Van Nevel et al. 2014), confirming the important role of vegetation. The question then arises, whether the impact of forest fires, described in 4.1, would be sufficient to induce a significant podzolisation by interruption of the nutrient cycling typical for mixed broadleaved forest vegetation (characterized by a well-developed root system) by a far more limited cycling as existing in shallow rooting herbaceous vegetation (see e.g., Harrison and Ineson, 1998; Bardgett et al. 2014; Pierret et al. 2016). Destructive fires will also have led to significant nutrient losses by leaching (e.g., Raison et al. 2009), apart from the change in nutrient cycling.

Another, related question is whether the podzolisation that we observed in our earlier palaeosols (phases 1–3) can indeed be fully linked to the specific vegetation at the sites studied, i.e., to shallow rooting herbaceous vegetation, whereas outside these areas, under unaffected forest, soils might be far less advanced towards podzols. Our current results do not allow for a decisive answer to this question: we found no early palaeosols without such distinct podzolisation, which we might correlate with one of the specific early phases and beyond doubt had formed under such forest. The reason that we found no such palaeosols may very simply be that sand drifting in these forests was minimal or absent, and thus any early soil formation was obliterated by later podzolisation, not being buried and ‘fossilized’ under a sufficiently thick drift sand layer. Nevertheless, it remains evident that the assumption that heath vegetation played a decisive role in the early formation of the podzols that we encountered is contradicted by our observations on the composition of the vegetation during the Mesolithic period. Far stronger evidence exists for such role by the change from mixed broadleaved forest to herbaceous vegetation with concurrent decline in nutrient cycling, and the repeated nutrients losses by leaching following upon ground fires.

Evidence for the early existence of prominent podzols in connection with Mesolithic sites is even more common than described in the introduction: they are known from many Dutch studies on Mesolithic sites in (former) sand landscapes. Examples are the Swifterbant site (Hamburg *et al.* 2013), which had a long history of intensive Mesolithic habitation on a cover sand dune. At that site a distinct podzol was found underneath peat, covering the podzol since c. 4500 cal yr BCE. Even older is the podzol at an Early Mesolithic site near Almere, where already by c. 7500 cal yr BCE a prominent podzol had formed in the cover sand ridge on which the site was located, testifying to the sometimes very early age of such podzols (Niekus et al. 2012). These observations are in line with studies on early drift sands elsewhere in the NW-European sand belt, of which the study by Tolksdorf et al. (2013) is a particularly relevant example.

One of the implications of a dominant role of this Mesolithic land use in the genesis of the early podzols is that process rates of this podzolisation are uncertain, being dependent on such factors as the frequency and intensity of ground fires, which may have been highly variable. To this adds the eventual role of drainage (compare X2 and IV) and differences in texture (notably loam content) and mineralogy of the cover and drift sands. In this context it is remarkable that we found periods in the order of ca. 1000 years to be sufficient to lead to the development of podzols, though relatively weakly developed (P2 and P4), while a distinct podzol with well-developed spodic B horizon and marked mineral weathering was formed over a period of about 3500 years during the Early Holocene (P1).

4.3. Impacts of Mesolithic land use

An evident question is whether early forest fires and associated changes in the functioning of the landscape ecosystems in which these fires took place were natural or intentional. Unfortunately, in dry sand landscapes such as the LWM area, environmental archives suited for answering this question are extremely rare (see e.g., Heidgen et al. 2022 for such archive) and we thus have no direct evidence in favour of either natural or anthropogenic causes. Given this situation, answers need to be based on circumstantial evidence. They may be found in ethnographic records (see e.g., Scherjon et al. 2015) and in studies on Mesolithic hunter-gatherers (see e.g., Mason 2000; Heidgen et al. 2022;

Nikulina et al. 2022).

Severe human impacts, including intentional fires, were described for two Dutch Mesolithic sites that were studied in detail for their archaeology: the nearby Soest site (<10 km) and the Swifterbant site at a larger distance from the LWM area (c. 45 km). At Soest, a Mesolithic site on the flank of an ice-pushed ridge overlain by cover sands, in the period between 7120 and 6020 cal yr BCE the vegetation was herbaceous with *Calluna*, *Corylus* shrubs and minor *Quercus*, *Pinus sylvestris*, and *Betula*, rather like the situation in the LWM area. Woltinge et al. (2019) describe that the Mesolithic people intentionally opened the landscape. At Swifterbant, a site on a cover sand dune, from c 8300 cal yr BCE people cut down trees and open areas were created. *Pinus sylvestris* forest dominated (Hamburg et al., 2012). In the Boreal-Early Atlantic period, this forest had been replaced by a relatively open deciduous forest, mostly *Quercus*. The overall characteristics are as described above: a distinct human impact with open patches and indications for the use of fire and promotion of *Corylus*. A similar conclusion was reached by Bos et al. (2006) for sites near Zwolle.

More clues can be found in recent studies on hunter-gatherers in other parts of Mesolithic Western Europe. Bishop et al. (2015) performed an extensive study on the role of Mesolithic people in actively structuring Scotland's woodlands and concluded that this role was important, focussing on systematic exploitation of hazel for food and fuel, and of oak for fuel. This may have created areas of adventitious and/or deliberate coppice. The authors suggest that the structure of native woodlands has always been influenced by anthropogenic activities and describe the potential role of deliberate fires in the structuring of this landscape and its vegetation. In another extensive study on the potential indications for the use of fire by Mesolithic people, Heidgen et al. (2022) concluded that these people probably enlarged open areas in forests and wetlands in the Neckar River area (south-western Germany) using fire. This activity went together with large-scale hazel processing and expansion of hazel woodland. They explicitly state that after 9,5 cal kyr BP frequent low intensity local fires were probably controlled by Mesolithic hunter-gatherers, who used fire as part of their subsistence practices. Remarkably, the fires were also found in wetland vegetation, which is an environment that is certainly not apt to natural fires. However, some studies, such as that by Tolksdorf et al. (2013), though describing a significant impact of Mesolithic communities on the contemporary ecosystems are more reluctant to conclude that intentional fires played a role in the ecosystem degradation.

In an authoritative overview of the disturbances in deciduous temperate forest ecosystems of the northern hemisphere Fischer et al. (2013) explicitly state that 'fire is a natural disturbance event in boreal, subalpine and to a certain degree dry (coniferous) temperate forest ecosystems, but not in deciduous forests of the temperate zone'. This is very much in line with the conclusions by Bobek et al. (2019) on the susceptibility to fire of deciduous forests in central Europe, which was found to be truly low. The increase of broadleaved trees later during the Holocene is assumed to have seriously reduced the fire frequency. Unfortunately, very few studies seem to exist on natural fires in broadleaved temperate forests, most Early Holocene and later fires being explicitly attributed to anthropogenic causes, and their frequency being much lower than in coniferous forests. The studies on the Swifterbant site rather confirm the conclusions described above - temperate broadleaved forests are not susceptible to natural fires - since the evidence found for the use of fire is described as local in nature and restricted to the direct environment of the site.

The LWM pollen records show that broadleaved trees and shrubs dominated the vegetation during the Mesolithic period (phases 1 and 2) with a very minor place for the coniferous tree *Pinus sylvestris*. In such forests, the various studies all agree that natural fires did not regularly occur, whereas the observations point at regular fires, most probably in the form of ground fires. As explained above the charcoal preserved in palaeosols 1 and 2 can be attributed to a selective preservation of pine remains in the form of cone fragments that accumulated in the ectorganic layer. In this context, the absence of contemporary charcoal in the palaeosols 3, 4, and 5, while charcoal abounds in the earlier palaeosols forms another indication against a natural origin of the forest fires and associated charcoal in the LWM area. Remarkable is that the same phenomenon – disappearance of indications for forest fires in the Neolithic - is reported in virtually all other studies mentioned and described as a very strong indication for intentional burning. This leaves scope for the conclusion that Mesolithic hunter-gatherers indeed took an active part in the shaping of the Dutch sand landscape and its vegetation by promoting forest fires.

5. Conclusions

Use of fire by Mesolithic people in the form of local, repeated ground fires would well explain the set of phenomena that we observed in the LWM area being: a) the transition from a dense mixed deciduous forest to an open forest with patches of grass-dominated short vegetation, b) soil degradation and reduced nutrient cycling leading to the development of podzols under this grass-dominated short vegetation in the open patches, c) repeated cycles of sand drifting followed by recovery of the vegetation. Such hypothesis also explains several controversies, notably those about the age and genesis of drift sand and podzols in the Netherlands described in the introduction, and the role of large herbivores in the Holocene development of the vegetation in NW-Europe. The latter discussion started when Vera (2000) published his theory on their role.

Population densities during the Mesolithic are described as having been low, with densities from around 0.1 to a maximum of 1 person/km^2 (Riede et al. 2007). This implies that habitation sites with significant environmental impacts, such as encountered at Swifterbant and Soest (see section 1), must be rare. It is only later, during the Neolithic, that population densities increased. Moreover, for causing the impacts described above, these Mesolithic sites must have been in dry sand landscapes, as indeed was the case at Swifterbant and Soest. Evidently, the spatio-temporal patterns in the Mesolithic habitation of the Netherlands and neighbouring countries are far from well-established and may have varied considerably (see e.g., Crombé et al. 2011; Amkreutz 2013), but it is beyond doubt that chances for finding preserved geo-archives in these dry sand landscapes with records of such Mesolithic activities are low. In other words, the earlier studies on the genesis of podzols and drift sands, and thus hypotheses derived from these studies, may well have been on sites and in areas, where such archives were absent, and the impact of Mesolithic land use by hunter-gatherers was restricted or simply not recognized.

The theory of Vera (Vera 2000; Vera et al. 2006) is largely based on the assumed open nature of the NW-European forests in pre-Neolithic times, deduced from pollen records and ascribed to the impact of grazing by large herbivores. The theory is seriously disputed by many archaeologists (e.g., Louwe Kooijmans 2012), palaeoecologists (e.g., Bos et al. 2006; Sugita 2007) and ecologists (e.g., Newton et al. 2013). Truly remarkable is how little attention is paid in this theory to the role of Mesolithic hunter-gatherers, with their potential significant impact on the vegetation, but also on the herbivore populations. Our results point at a far more important and basic role of Mesolithic people in the transformation of the contemporary forests that Vera ascribed to large herbivores. Moreover, rendering the vegetation more attractive for these animals and facilitation of their hunting is described as one of the main reasons for the intentional use of fire by Mesolithic people (Mason 2000; Innes and Blackford 2003; Davies et al. 2005; Scherjon et al. 2015; Nikulina et al. 2022).

Willemse and Groenewoudt (2012) were among the first to stress the role of prehistoric land use in the reactivation of Late Glacial aeolian landforms in the Netherlands and to emphasize that these landscapes were 'in a state of incipient instability to erosion and desertification'. They concluded that impacts of prehistoric reclamation were associated with localised nuclei, led to sand drifting, and were situated in settlement *infields* that were linked to Neolithic and later agriculture.

Our study provides further evidence for such incipient instability, reflected in repeated phases of sand drifting, but also shows that anthropogenic impacts were more complex than only sand drifting and date back to as early as the Late Mesolithic (i.e., c. 6000 BCE). The impacts of Mesolithic land use that we observed also went far beyond an impact on the vegetation only; an impact often stressed in studies on hunter-gatherer niche construction activities (see e.g., Nikulina et al. 2022). They concerned a significant, but rather local-scale ecosystem degradation, presumably brought about by repeated local ground fires, and included a set of related phenomena: a) a patch wise enhanced soil degradation, resulting in the development of podzols, b) a gradually opening forest with grassy patches, and c) local sand drifting.

In the LWM area, in line with the many other studies on drift sand areas in the Netherlands and adjacent countries, during the Neolithic period ecosystem degradation progressed. This involved a transformation of the open forest into a heath-dominated much more open landscape that was grazed and expanding agriculture with a crop production system that was based on ‘nutrient mining’, whether in the form of shifting cultivation, Celtic fields or use of manure produced by grazing domesticated animals (see e.g., Arnoldussen 2018). Here too, the Laarder Wasmeren geo-archive testifies to the potential complexity of this later period, with three phases of sand drifting of which two date from the Neolithic. In Fig. 6 the trends described above are depicted with emphasis on the landscapes during the Late Mesolithic and the Late Neolithic.

Complex and early geo-archives as we found require the existence of Mesolithic sites that were inhabited over prolonged periods of time and a continued burial of palaeosols under successively accumulating drift sand layers over a major part of the Holocene. Such conditions are rarely fulfilled, rendering the LWM geoarchive rather unique. Nevertheless, there is a fair number of Mesolithic sites in the NW-European sand belt with similar phenomena, supporting the conclusion that earlier hypotheses on the origin and age of the podzols, heath lands and drift sands that link these to only Neolithic and later land use impacts indeed are obsolete.

Lastly, our research demonstrates the strength of a broad multidisciplinary approach in the study of complex drift sand landscapes, and in that approach is innovative. It provides important clues for the still open debate on issues that are related to the inherent fragility of this type of landscape under the impact of early – Mesolithic – land use, notably regarding the degradation of its soil and vegetation, and the occurrence and origin of sand drifting.

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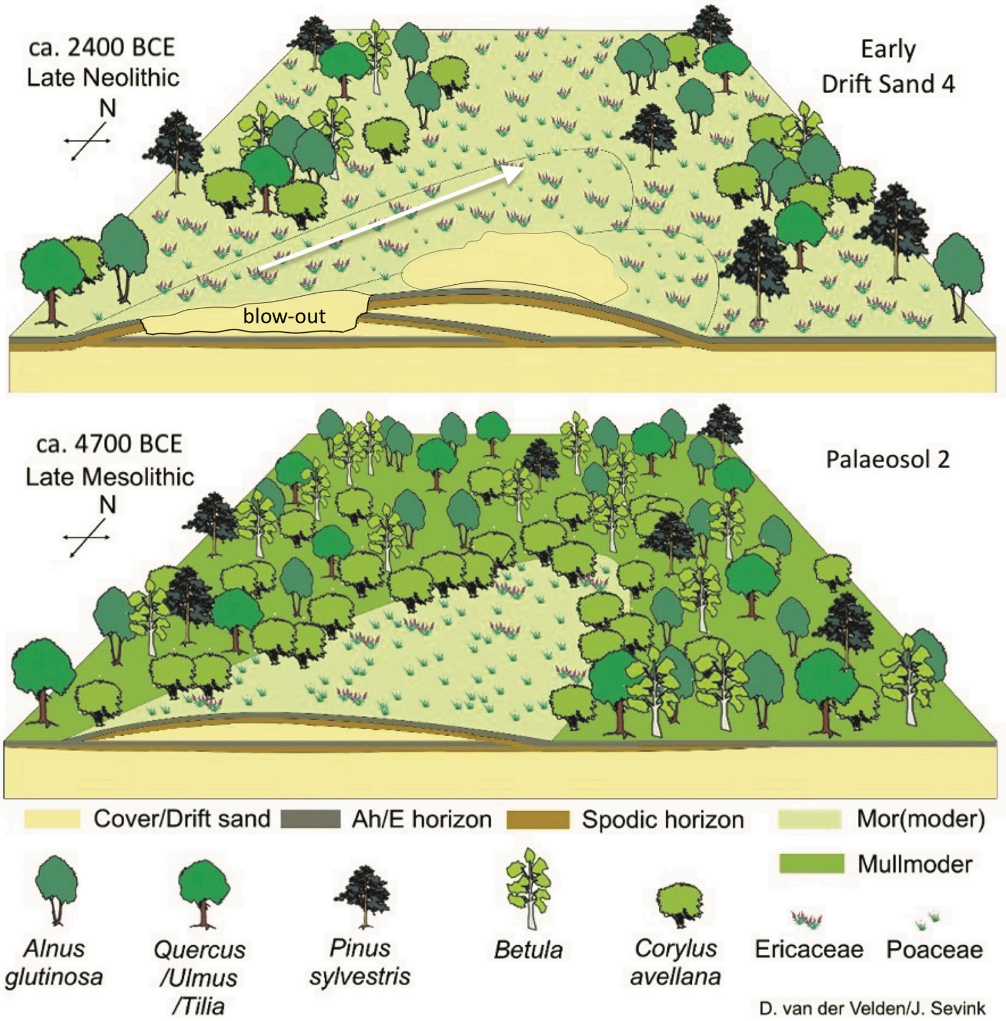

Fig. 6. Schematic representation of the landscape in the LWM area during the Late Mesolithic (Palaeosol 2), with weakly developed podzol in drift sand over Early Holocene palaeosol, and during the Late Neolithic (Early Drift Sand 4 phase). Dominant winds from the SW (arrow).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2023.106969.

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