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Anthropogenic drivers for exceptionally large meander formation during the Late Holocene

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ABSTRACT

Large-amplitude meanders may form in low-energy rivers despite generally limited mobility in theses systems. Exceptionally large meanders which even extend beyond the valley sides have developed in the Overijsselse Vecht river (the Netherlands) between ca. 1400 CE (Common Era) and the early 1900s, when channelization occurred. Previous studies have attributed the enhanced lateral dynamics of this river to changes in river regime due to increased discharges, reflecting climate and/or land-use alterations in the catchment. This paper focuses on local aspects that may explain why exceptionally large meanders developed at specific sites. Through an integrated analysis based on archaeological, historical, and geomorphological data along with optically stimulated luminescence dating, we investigated the relative impact of three direct and indirect anthropogenic causes for the local morphological change and enhanced lateral migration rates: (1) lack of strategies to manage fluvial erosion; (2) a strong increase in the number of farmsteads and related intensified local land use from the High Middle Ages onwards; and (3) (human-induced) drift-sand activity directly adjacent to the river bends, causing a change in bank stability. Combined, these factors led locally to meander amplitudes well beyond the valley sides. Lessons learned at this site are relevant for management and restoration of meandering rivers in similar settings elsewhere, particularly in meeting the need to estimate spatial demands of (restored) low-energy fluvial systems and manage bank erosion.

1. Time periods as used in this paper

Period	Time frame
Late Palaeolithic	12,500 – 8800 BCE
Mesolithic period	8800 – 4900 BCE
Neolithic period	4900 – 2000 BCE
Bronze age	2000 – 800 BCE
Iron age	800 – 12 BCE
Roman period	12 BCE – 450 CE
Early Middle ages	450 – 1000 CE
High Middle ages	1000 – 1250 CE
Late Middle ages	1250 – 1500 CE
Early Modern period	1500 – 1800 CE
Late Modern period	1800 – 1900 CE

2. Introduction

Low-energy meandering rivers often show relatively little lateral migration (Kuenen, 1944; Eekhout, 2014; Makaske et al., 2016; Candel, 2020) because of their low specific stream power ($< 10\,W\,m^{-2}$) (Nanson and Croke, 1992). Nevertheless, meanders with high amplitude may occur in low-energy rivers, with relatively high lateral migration rates compared to other reaches of the same river (e.g. Hooke, 2007). Generally, the lateral migration rates of rivers strongly depend on local bank strength (Schumm, 1960; Hickin and Nanson, 1984; Ferguson, 1987; Nicoll and Hickin, 2010). For example, Hudson and Kesel (2000) compared sections of the Mississippi river and showed that the lowest lateral migration rates occurred in sections where erosion-resistant deposits were present (e.g. clay plugs).

Additionally, anthropogenic effects on river morphodynamics specifically deserve attention, as their influences are much more varied and intense than previously thought (Gibling, 2018). Many

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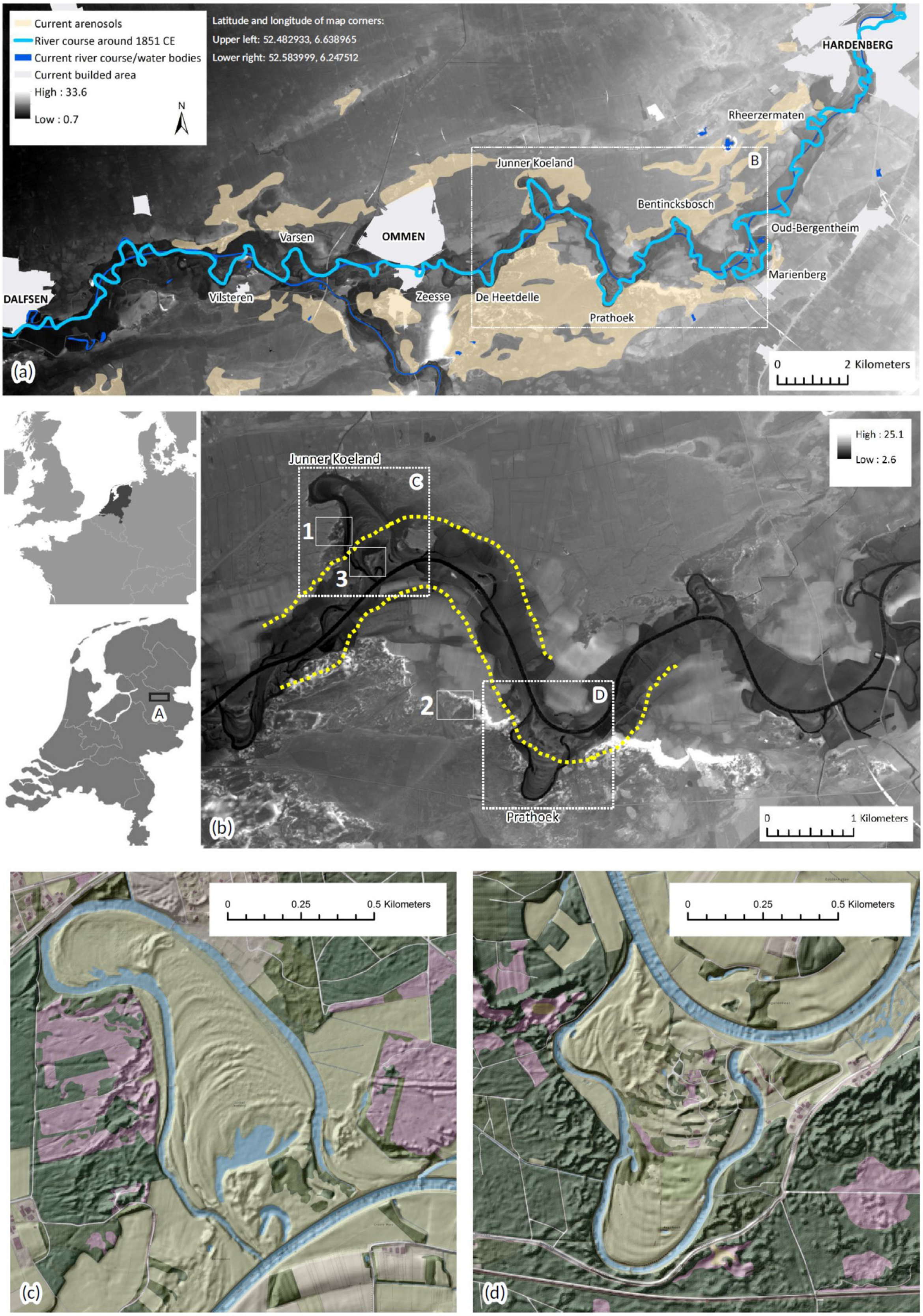

Fig. 1. The Overijsselse Vecht river in the Netherlands. Capitals A—D indicate position of subfigures (a)-(d). (a) Digital elevation model (DEM) of the river reach from Dalfsen to Hardenberg, showing present-day spatial distribution of arenosols (former drift-sand areas, most are currently forested). Meander names are indicated, city names are written in capitals. (b) DEM of the study area showing the two meander bends (Junner Koeland and Prathoek) and the three drift-sand locations (1, 2, 3). Elevation is in meters relative to Dutch Ordinance Datum (roughly mean sea level). The dashed yellow line indicates the valley side, reconstructed at places where large

rivers worldwide have been subject to significant anthropogenic pressure during the Late Holocene by land use changes, partly explaining increased fluvial activity on the entire river-scale (Kondolf et al., 2002; Macklin et al., 2010; Notebaert and Verstraeten, 2010; Brown et al., 2018; Candel et al., 2018; Gibling, 2018; Notebaert et al., 2018). More locally, humans have stabilized many river channels by bank protection, groynes, dikes and other engineering works (Hudson et al., 2008; Dépret et al., 2017). The potential direct and indirect role of humans in destabilising river banks locally has received little attention in literature, and is the main topic of this paper.

Formation of exceptionally large meanders extending beyond valley sides has previously been linked to major climate changes in temperate regions (Alford and Holmes, 1985; Vandenberghe, 1995). At the transition from the Pleniglacial to the Late Glacial, the climate became warmer and wetter and vegetation re-established. Consequently, sediment availability decreased and river discharge increased, resulting in large incising meandering rivers (Vandenberghe and Bohncke, 1985; Vandenberghe and Van Huissteden, 1988; Vandenberghe, 1995). Large meanders from this period are still visible in many river valleys, such as the Dommel, Roer and Niers valleys in the Netherlands (Kasse et al., 2005, 2017; Candel et al., 2020), Tisza valley in Hungary and Serbia (Vandenberghe et al., 2018) and Murrumbidgee valley in Australia (Schumm, 1968).

Exceptionally large meander bends locally also occur in the Dutch Overijsselse Vecht river valley, reaching well beyond the valley sides with a maximum amplitude of almost 1.5 km (Fig. 1). This is more than twice as large as would be expected based on empirical estimations for the Overijsselse Vecht given by Hobo (2006), whose calculations are based on discharge regime and sediment characteristics. Recent geochronological research revealed that these remarkably large meanders formed between ca. 1400–1900 CE (Quik and Wallinga, 2018a,b). During this period meander amplitudes increased at a relatively steady rate of 1–3 m y^{-1}. After ca. 1900 CE, meander migration was halted as the river course was straightened and channelized. Factors that might explain the exceptional meander growth between 1400 and 1900 CE include regime shifts, bedload changes, high-discharge events, varying erodibility of bank sediments, or (indirect) human interference with the river system.

Candel et al. (2018) demonstrated that the Overijsselse Vecht river experienced a discharge regime change around the 15th century, resulting in a shift from a laterally stable to a meandering channel pattern and marking the onset of meander formation. The change in palaeodischarge, characterized by increased peak discharges, may have resulted from climatic fluctuations during the Little Ice Age and large-scale land use change in the catchment (i.e. peat reclamation). This catchment-scale change does however not explain the exceptional meander expansion observed locally, and the historical changes of bankfull discharges and bedload reconstructed by Candel et al. (2018) could not account for the ongoing lateral migration of the large meanders during the 19th and early 20th century.

The Overijsselse Vecht river valley predominantly consists of aeolian coversand deposited during the Late-Pleniglacial, overlying older fluvial deposits (Huisink, 2000). Several meanders of the river seem to have been confined in their expansion (Fig. 1a, Wolfert and Maas, 2007) by the sides of the river's Late-Pleistocene valley, whereas locally some meanders have expanded beyond the valley sides. It has been suggested that (human-induced) drift-sand complexes that developed on river banks may have enhanced bank erodibility locally (Wolfert et al., 1996; Wolfert and Maas, 2007). Alternatively, large meander formation may be linked to increased settlement density and anthropogenic pressure since the High Middle Ages. Additionally, river management may have played a role in local prevention and/or acceleration of bank erosion.

Due to excellent preservation of some cut-off meanders, the availability of detailed geochronological information for the development of two meander bends (Quik and Wallinga, 2018a,b) and a previous palaeohydrological reconstruction (Candel et al., 2018), we consider the Overijsselse Vecht river an ideal case to study local factors influencing lateral meander migration. To gain insight in these factors and their degree of influence we address the following research questions:

(1) What is the character of historical river management during the period of meander expansion (i.e. Modern period), and does this indicate direct human interferences with the river system that resulted in exceptional meander formation observed locally?
(2) How did habitation density in the direct vicinity of the floodplain change through time (i.e. prior to and during meander expansion), and could related land use changes from the Modern period onwards cause enhanced local meander growth?
(3) What was the timing and spatial distribution of (human-induced) drift-sand activity in the study region during the period of meander expansion, and is there evidence for interaction of aeolian and fluvial dynamics resulting in the local formation of exceptional meanders?

To answer these research questions we performed an integrated analysis of archaeological, historical and geomorphological information and optically stimulated luminescence (OSL) dating.

3. Study area

The Overijsselse Vecht (Fig. 1) is a low-energy sand-bed river originating west of Münster in North Rhine-Westphalia (Germany) and entering the Netherlands south of the city of Coevorden. It is a rain-fed river with a catchment of 3785 km^2. The river has its outlet in the Zwarte Water near the city of Zwolle, which debouches into the IJsselmeer (Lake IJssel). Before 1932, the IJsselmeer was still an inland sea (Zuiderzee), with a small tidal range of about 0.2 m (Dirkx et al., 1996; Makaske et al., 2003). Characterizations of the water levels in 1850 demonstrate that the Overijsselse Vecht did not experience tidal influences before closure of the Zuiderzee (Middelkoop et al., 2003; their figures 4 and 5 shows no tidal stroke at Kampen and Katerveer). In the Dutch part the valley gradient is fairly uniform at $1.4 * 10^{-4}$ (Wolfert and Maas, 2007). According to measurements in the period 1995–2015 from a discharge station in the investigated section of the river, the average discharge and mean annual flood discharge are 22.8 and 160 $m^3 s^{-1}$ respectively. The area is characterized by an average annual rainfall of 800–875 mm and an average maximum temperature of 4.9–5.4 °C in January and 24.3–24.7 °C in July (KNMI, 2019a, 2019b). Through large-scale engineering works between 1896 and the 1930s, the original river length of 90 km in the Netherlands has

meander bends occur. A detailed view of the meanders is provided in (c) and (d), showing the topographical map overlying the hillshade DEM with scroll bars and swales relief. Main topographical elements are heathland (purple), forest (dark green) and meadows (light green). Digital elevation model (AHN2; horizontal resolution 0.5 m, vertical resolution 0.2 m): AHN, 2018; Van Heerd et al., 2000; river course 1851 CE derived from: Kadaster, 2018; OpenTopo: Van Aalst (2016) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

been reduced to 60 km by cutting off 69 meanders (Wolfert and Maas, 2007). Revetments fix the position of river banks and the water level is controlled by weirs.

The Dutch part of the Overijsselse Vecht was subdivided into three river reaches by Wolfert and Maas (2007) based on fluvial style. The central reach, stretching from the city of Hardenberg (east) to the city of Dalfsen (west), is characterized by several conspicuous meanders (Fig. 1a). For this study we focus on two presently cut-off meander bends with exceptional amplitudes reaching outside the valley sides named 'Junner Koeland' and 'Prathoek' (Fig. 1b), (cf. Quik and Wallinga, 2018a,b; and Candel et al., 2018), and their wider environment (area of circa 4 × 4 km). These meanders were not cut-off naturally, but through channelization in the early 1900s.

The river banks consist of aeolian coversand on top of fluvioperiglacial deposits. Near the studied bends, the river channel had a width of about 40 m in 1848 CE, and the elevation difference between the river banks and deepest part of the channel was approximately 2.3 m (Staring and Stieltjes, 1848). In the vicinity of the floodplain between Hardenberg and Ommen drift-sand complexes developed that consist of eroded and re-deposited coversand. Nearly all these drift-sand areas are now stabilized by forests that were planted since the mid-nineteenth century. Currently several parts of the floodplain and former drift-sand areas are protected nature reserves.

4. Methods

To identify potential factors for the formation of large meanders in the Overijsselse Vecht we used a combination of data from different disciplines, drawing methods from archaeology, historical geography, geomorphology and geochronology. The methodology is divided in three parts, consisting of analyses of (1) historical river management, to understand the type and level of direct interference with the river system, (2) habitation history and land use change, to detect changing pressures on the landscape, and (3) occurrence and activity period of (human-induced) drift-sands near the two investigated meander bends, which may change stability of river banks. All parts are described below, further details are available in the Supplementary Material. For methods regarding reconstruction of meander formation (lateral migration rates), palaeodischarge and meander cross sections we refer to earlier publications (Quik and Wallinga, 2018a,b; Candel et al., 2018).

4.1. Historical river management

Following a general literature review (Wieringa and Schelhaas, 1983; Coster, 1999; Neefjes et al., 2011) several governmental levels were selected for closer study: the higher authorities being the Dutch government and the province of Overijssel, followed by dike districts (after 1879 continuing as water boards) and marks (local commons (Dutch: *'marken'*), i.e. Late Medieval and Early Modern farmer collectives). To reconstruct the character and intensity of historical river management two subsequent methods were applied. First, we studied general trends in river management for the Dutch part of the Overijsselse Vecht catchment by analysing activities at different governmental levels. Information was obtained from the archives of the various governmental institutions. Second, we focused on river management activities in one of the marks in the study area (i.e. the mark of Arriën), to gain detailed insights in local management. Arriën was chosen because the archives of the mark of Junne are lost, whereas those from the mark of Stegeren are obscured by low readability.

4.2. Habitation history and land use development

To identify possible land use related drivers for increased meander expansion we reviewed various archaeological and historical geographical sources. Late prehistoric, Roman and Medieval archaeological sites from the study area were inventoried using the national Dutch archaeological database (Archis III) and published literature. Historical sources provide information on habitation development from the Middle Ages onwards (see Supplementary Materials for further details).

Within the scope of the present study, highly detailed archival research on the age of individual farmsteads and the numbers of farm animals per unit surface area was not feasible. Instead, we used (1) number of farmsteads as proxy for land use intensity, and (2) a generic retrospective method to date the farmsteads (see Supplementary Materials), based on the historical layering of Medieval property rights (Spek et al., 2010; Neefjes et al., 2011). We are aware that the relation between habitation density and increasing land use intensity is not necessarily linear, but assume a positive correlation as corroborated by e.g. Bieleman (2008).

Additional information on collective land use was obtained from the archives kept by the marks. Toponymical and etymological publications were used to explain and date field name types from the scroll-bar complexes in the Dutch part of the river valley, to interpret former local land use (e.g. Schönfeld, 1955, 1950; Van Berkel and Samplonius, 1989; Malinckrodt, 1974).

4.3. Drift-sand activity

Recent integrative analyses by Pierik et al. (2018) indicated that human pressure on the landscape was the predominant facilitating condition for Late-Holocene drift-sand activity in the Netherlands. Analyses of drift-sands near the Overijsselse Vecht could therefore be considered as part of investigations on habitation and land use development (section 4.2). However, as the geomorphological and geochronological methods that we applied to analyse drift-sand activity diverge from the methods applied in section 4.2, we present them separately here (similarly in the Results and Discussion). To investigate whether a chronological overlap between drift-sand activity and meander expansion exists and to what extent drift-sand deposition may have destabilized river banks we: (1) analysed subsequent historical maps to determine the size of the area covered by active drift-sands through time; (2) conducted a lithological survey of two distinct drift-sand dunes near the two meander bends (location in Fig. 1a, detailed view in Fig. 3a and 3b) and (3) performed optically stimulated luminescence (OSL) dates on selected drift-sand samples to determine the onset of local drift-sand deposition. These steps are described below.

4.3.1. Use of historical maps to estimate drift-sand extent

We analysed the area covered by active drift-sand based on five historical maps dating from 1720 to 1884 CE that were used in the geochronology developed by Quik and Wallinga (2018a). More details on these maps are available in the Supplementary Materials. We used the area currently classified as arenosols (Dutch: '*duinvaaggronden*' and '*vlakvaaggronden*') in the Dutch soil classification system (Alterra, 2014) as validation to compare with the historically indicated drift-sand surface, as these young soils predominantly formed in stabilized drift-sand areas (Jongmans et al., 2013). Further details on the historical maps and procedure are provided in the Supplementary Materials.

4.3.2. Lithological survey drift-sand areas

A lithogenetic survey of two former drift-sand areas adjacent to the two meander bends was performed based on corings covering

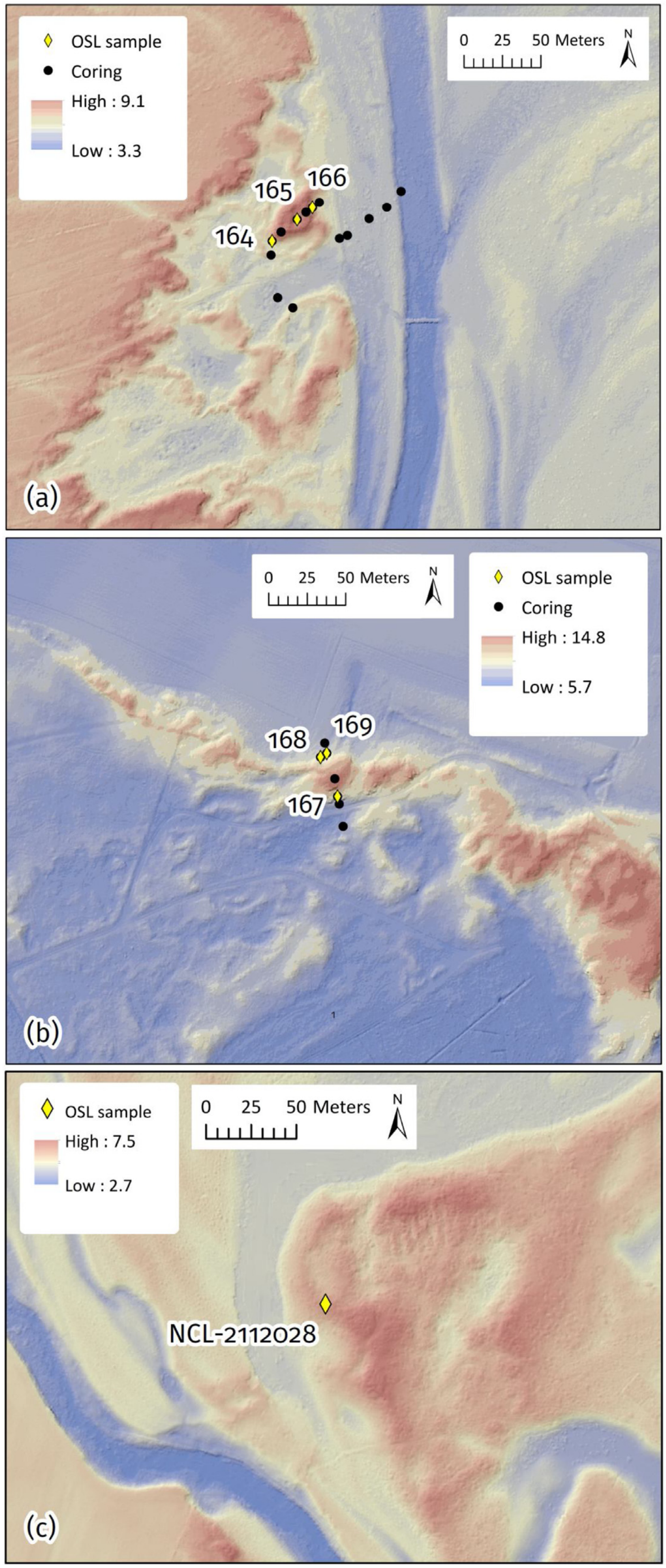

Fig. 2. Drift-sand location 1 (a) and 2 (b), showing locations of corings and optically stimulated luminescence samples of this study; drift-sand location 3 (c) shows the location of a sample from earlier work (Reimann et al., 2016; Rotthier and Sýkora, 2016). For location of (a-c) in the wider study area see Fig. 1. Numbers in (a) and (b) indicate abbreviated sample codes (all should be preceded by NCL-2415). Elevation is in meters relative to Dutch Ordinance Datum (roughly mean sea level). Digital elevation model (AHN2; horizontal resolution 0.5 m, vertical resolution 0.2 m): AHN, 2018; Van Heerd et al., 2000.

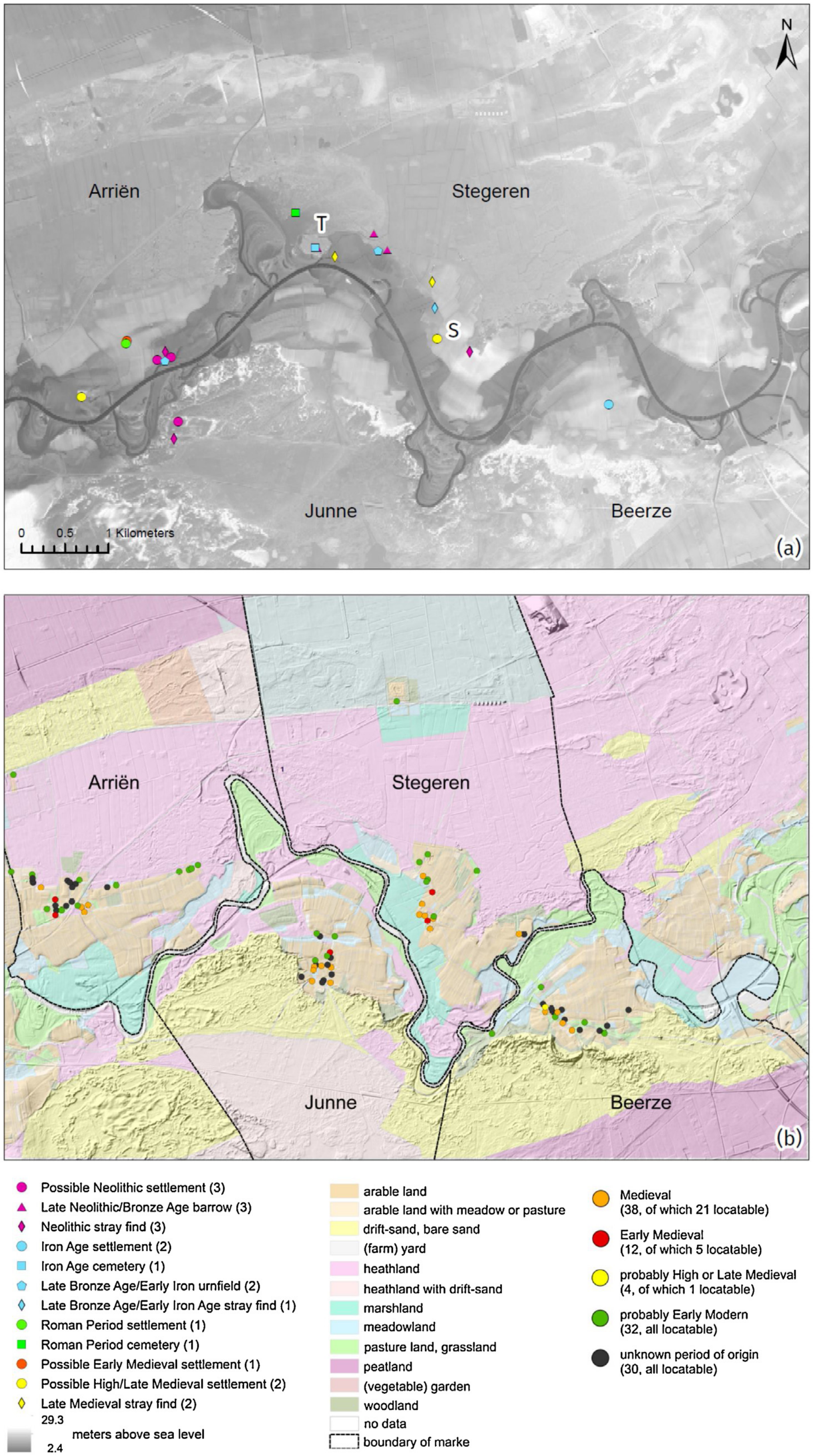

Fig. 3. Settlement and land use pattern in the marks Arriën, Stegeren, Junne and Beerze, showing the settlement and land use patterns in the Neolithic to Roman (a) and Medieval to Early Modern Periods (b). Land use patterns in (b) represent the situation on the 1832 CE cadastral map. The DEM in (a) displays both the present-day channelized river course and cut-off meanders from channelization in the early 1900s, the river course shown in (b) displays the situation of circa 1832. Note that the river course was different in the various periods. The letters S and T are referred to in the text. Sources: cadastral map 1832 (data acquired from the HisGIS programme, https://hisgis.nl/), DEM (AHN2, horizontal resolution 5 m): AHN, 2018; Van Heerd et al., 2000.

the width of a distinct dune. The drift-sand deposits are located on top of coversand deposits. Both sediments are often clearly distinguishable by a palaeo-podzol that formed in the top of the coversand prior to burial by drift-sand. In some places drift-sand is found directly on top of coversand parent material, indicating that the podzol eroded prior to drift-sand deposition. The two dunes (Fig. 1a, 2a and 2b) were selected based on (1) their proximity to the investigated meander bends and position such that drift-sand would have blown towards the river channel under the dominant SW—NE wind direction (Koster, 2010), and (2) presence of a palaeo-podzol in the underlying coversand deposits (at least at the lee side of the dune), to maximize chances that the base of the drift-sand deposit represents the age of first drift-sand activity. Further information on lithogenetic interpretation is available in the Supplementary Materials. Corings were performed using an extended Edelman auger to a depth of 1.2–3.6 m, which was at most points sufficiently deep to reach the in-situ podzol (if present). Five corings were done between the abandoned channel of Junner Koeland and the adjacent drift-sand dune to exclude presence of fluvial deposits underneath the drift-sand covered area (also visible in Fig. 2a). The location and elevation of the corings were determined with a Topcon Global Navigation Satellite System (GNSS) receiver, with a horizontal precision of ~10 mm and vertical precision of ~15 mm.

4.3.3. Optically stimulated luminescence (OSL) dating of drift-sands

To determine the onset of drift-sand deposition near the two river bends, six OSL samples were collected in drift-sand areas 1 and 2 directly above the coversand podzols, aiming to determine the age of first drift-sand deposition and podzol burial (sample locations: see Fig. 2a and b and Supplementary Materials for more details).

After augering to the desired depth, OSL samples were collected in a PVC pipe extension attached to the auger head, which was carefully pressed down the auger hole. At one location (sample NCL-2415164) the pipe was pressed into a vertical exposure. Upon retrieval of the PVC pipe both ends were immediately covered with plastic caps and light-impermeable black tape. For OSL measurements and dose rate determination we followed the procedures described by Quik and Wallinga (2018a). Statistical analysis of the dating results was done using the bootstrapped Minimum Age Model (Galbraith et al., 1999; Cunningham and Wallinga, 2012) with an assumed overdispersion of 0.15 ± 0.03.

5. Results

5.1. Historical river management

Archival study demonstrated that the Overijsselse Vecht was scarcely mentioned in archives of various institutions on multiple governmental levels, indicating that river management was limited and poorly coordinated. This is most evident from reported conversations between the Dutch government and the province of Overijssel, including a request from the government in 1853 CE to the province to investigate which party was concerned with river management. Inevitably, the province of Overijssel concluded that no party was concerned with river management and that land owners locally applied river management practices (e.g. placement of groynes) without governmental coordination (HCO, 2018a). Additionally, willingness of water boards and dike districts to develop regional river management was limited. Archival material of the dyke districts (HCO, 2018b, 2018c, 2018d, 2018e) indicates that these institutions were solely concerned with water safety and related reparation works. The river is also barely mentioned in the constitutions of the local water boards (HCO, 2018f,g). Additionally, the province of Overijssel refused to contribute financially, upon which the government discontinued its financial support for river improvements. Complaints about troublesome water levels downstream of our study area at the municipality of Dalfsen were disregarded by the province, eventually causing the municipality to directly address the king in search for help in 1863 CE (HCO, 2018h).

The mark books of Arriën (1549–1826 and 1765–1835 CE) also indicate scarce attention for river management. Some erosion problems and prevention discussions were recorded, which were solely directed at protection of the mark's greenlands (see 4.2.2). Interestingly, the expansion of the Junner Koeland meander, which migrated northward eroding land in the Arriën territory, was not discussed in the Arriën mark books (HCO, 2018i,j).

5.2. Habitation history and land use development

5.2.1. Spatiotemporal patterns in habitation

The study area includes four rural villages and their territories named Arriën, Junne, Stegeren and Beerze (Fig. 3). These were first mentioned in Late Medieval written sources. However, the frequent occurrence of manorial property rights indicates that all four villages already existed since at least the Early Middle Ages (Neefjes et al., 2011). They are situated at the lower slopes of coversand ridges nearby the Overijsselse Vecht (Fig. 3b) and may well be the successors of earlier settlements that were situated on the higher parts of the coversand ridges. These areas were inhabited since late prehistory. This is corroborated by the distribution pattern of the approximately 20 archaeological sites in the area, including late prehistoric, Roman period and Early Medieval finds (Fig. 3a). A Pleistocene terrace remnant directly east of the Junner Koeland meander was inhabited from late prehistoric to Roman times as well, but has been deserted since then (compare Fig. 3a, letter T, with Fig. 3b). The cultural landscape patterns of the four village territories are rather similar. However, some local differences occur. For example, the oldest nucleus of Stegeren is situated close to the river floodplain on the valley margin (Fig. 3a, letter S), whereas Arriën, Junne and Beerze are slightly further away from the river.

Fig. 4 shows the estimated number of farmsteads at four dates between the end of the Early Middle Ages and 1832 CE. Starting from a very low number of farms around 1000 CE, there is a clear increase until 1300 CE, after which the growth reduces or stagnates until 1500 CE. The Early Modern period shows again a marked

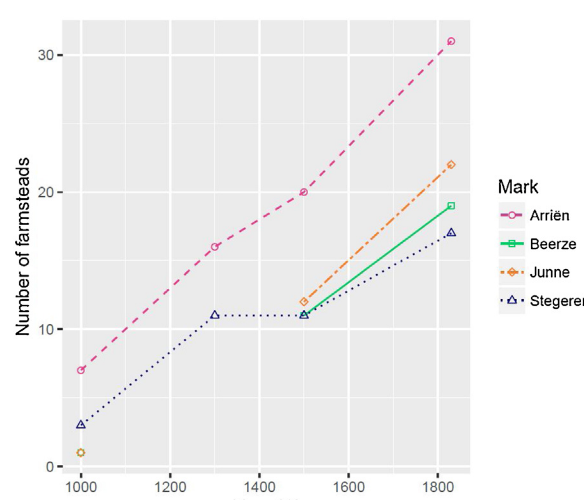

Fig. 4. The temporal development of the estimated number of farmsteads in the four marks of the study area. For two marks (Junne, Beerze) data for 1300 CE were not available.

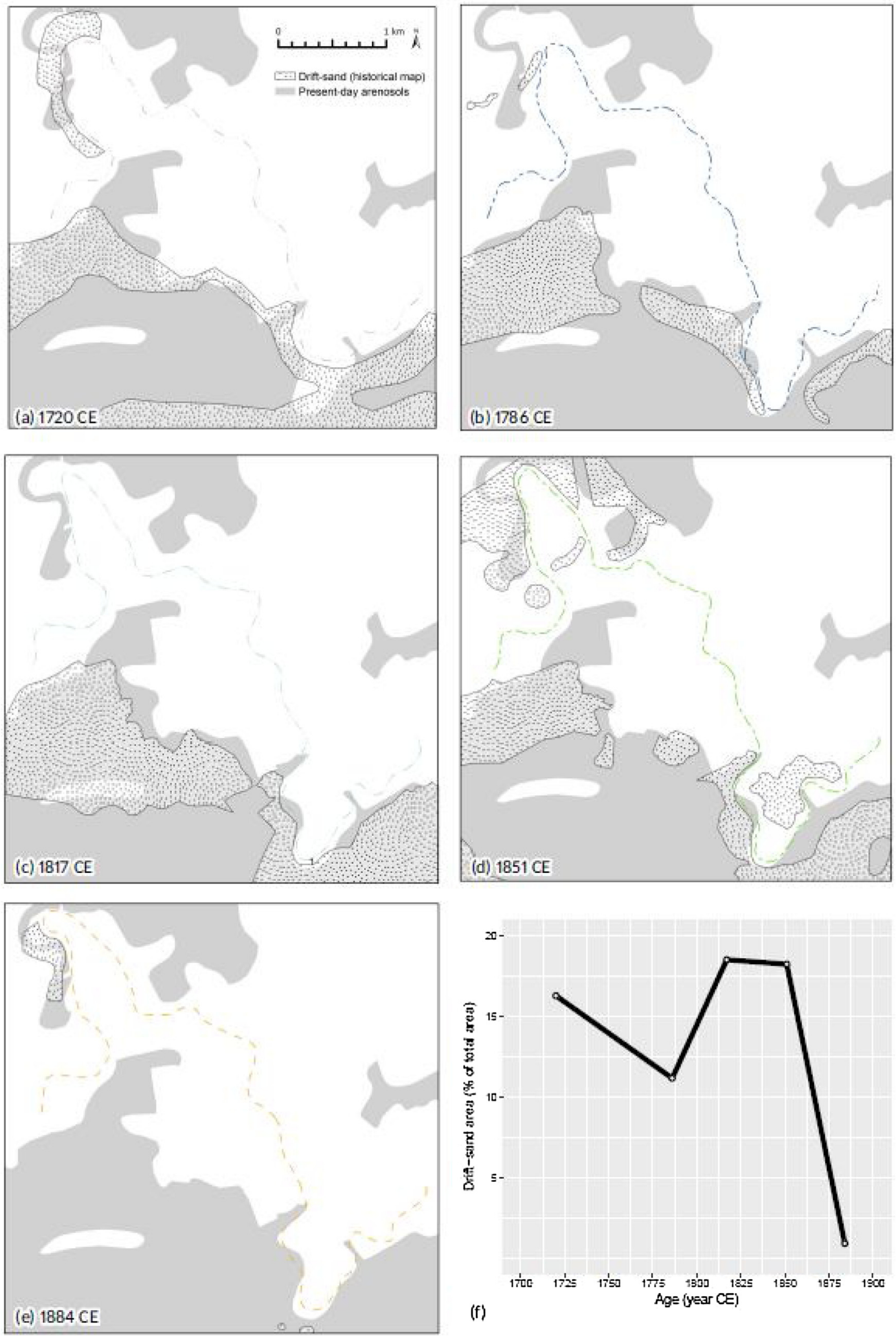

Fig. 5. Development of river planform and drift-sand areas as derived from five historical maps. The dates mentioned are based on the revision date or, if none is given, on the survey date (see Table 2). For the map sheet of the Hottinger atlas the survey covered 3 years; we indicated the middle year in (b). Low-water channel centrelines were derived from the analysis by Quik and Wallinga (2018a). Dotted areas in (a-e) indicate the area covered by drift-sand as displayed on historical maps. Grey shading indicates the area currently classified as arenosols in the Dutch soil classification ('*duinvaaggronden*' and '*vlakvaaggronden*' combined). The graph in (f) shows the relative area covered by drift-sand through time. Source Dutch soil map: Alterra (2014).

increase in the number of farmsteads. The foundation of various new farmsteads in (especially) the High and Late Middle Ages resulted in a more compact settlement pattern, as new farms were built nearby older ones and in similar landscape settings (Fig. 3b). In the Early Modern period this densification process accelerated. Additionally, new groups of farmsteads were built at some distance from the older settlement nuclei, most prominently at the edge of the heathland zone (Fig. 3b).

5.2.2. Spatiotemporal patterns in land use

In late prehistory and the Roman period, the arable fields were situated nearby the settlements. Both were located on the higher parts of the large coversand ridges alongside the river valley (Van Beek, 2009; Van Beek and Groenewoudt, 2011). The position of the arable fields did not change much through time; in the High Medieval period the tops of the coversand ridges were reclaimed into open field complexes (arable land; Dutch: '*essen*'), which stayed in use for agriculture until the present day (Neefjes et al., 2011; Van Beek and Groenewoudt, 2011). The settlements had gradually moved to their present-day position, at the lower slopes of the coversand ridges, from the Medieval period onwards. This important change of settlement location led to a larger fixation or place continuity of different landscape elements, most notably the hamlets and their open field complexes.

Not much is known about the appearance and exploitation of the river floodplain in late prehistory and the Roman period. High-quality archaeobotanical evidence is lacking. With regard to the High Middle Ages, archaeobotanical data (macro remains and pollen) were collected at the archaeologically investigated settlement site of Dalfsen-Gerner Marke, situated approximately 15 km downstream of our study area in a similar landscape setting (Van Haaster, 2006). It was demonstrated that the investigated coversand ridge along the Overijsselse Vecht had lost most of its original woodland vegetation before the Middle Ages. In the High Middle Ages it was largely in use as arable fields, where rye, flax and probably barley and oats were grown. Two different types of grasslands were present in the nearby river valley: one type related to relatively dry soils, that probably was exploited as pasture, and a type linked to wetter soils that was probably used as hayland (Van Haaster, 2006). After the harvest these areas may temporarily have been used for grazing as well. Heather probably grew on the large coversand plains at some distance from the river and may have been used for sheep grazing (Neefjes et al., 2011).

The evidence obtained at Dalfsen corresponds well with information derived from historical sources, which indicate the Medieval reclamation of floodplains for use as haylands (Bakker, 1989). Grasslands were essential for local communities. In his research on farming in the province of Drenthe in the period 1600–1910 CE, Bieleman (1987) analysed old land-tax registers. These distinguish several types of 'greenland' (Dutch: '*groenland*') occurring in stream and river valleys, which were used as either hayland and/or pasture. Even though the various greenland types were taxed differently, the overall value of greenlands was substantial (1.5–2.5 times higher) compared to the value of arable lands. Hay formed an indispensable crop, providing winter fodder for draught animals that were used to cultivate the arable fields (Franklin, 1953; Dirkx, 1997).

The Overijsselse Vecht formed the administrative boundary between marks north and south of the river (Fig. 3b). The typically large floodplain parcels directly bordering the river were owned by the marks and consisted of high-quality grasslands that were exceptionally suited for grazing by cattle, which have higher demands regarding food quality than sheep. In these common pastures every mark member had rights to graze a specific number of cattle (Van Engelen van der Veen, 1924). These greenlands are often indicated with the terms '*mars*' or '*maat/maten*'. '*Mars*' is a toponym for 'land by the water' (Van Berkel and Samplonius, 1989) or 'marshland' (De Vries and De Tollenaere, 1995). '*Mat*' stems from the word '*dagmaat*' (Schönfeld, 1950), an old land measure indicating the area that could be mown by one man in one day (Bieleman and Brood, 1980). By custom, pastures were named after the livestock type grazing there (Schönfeld, 1950). For instance, '*maat*' also occurs in the eastern Netherlands combined with the Dutch word for cow ('*koe*'), as in '*Koemaat*' (Ter Laak and Groenewoudt, 2005). The two scroll-bar complexes investigated here are situated in the marks of Junne and Stegeren. The name '*Junner Koeland*', literally translates as 'cowland of Junne'. '*Prathoek*' is a combination indicating the shape of the land ('*hoek*' means corner, Schönfeld, 1950) and its vegetation ('*prat*' probably originates from the Latin *pratum*, meaning grassland, Malinckrodt, 1974). Based on the combination of archaeological, historical and toponymical information it is highly likely that both scroll-bar complexes were intensively used for cattle grazing for centuries, and that this practice goes back to at least the High Middle Ages.

5.3. Drift-sand activity

5.3.1. Drift-sand covered area through time

The drift-sand covered area derived from each of the five historical maps is displayed in Fig. 5a to 5e, combined with the position of the river as indicated by each map (following Quik and Wallinga, 2018a). The graph in Fig. 5f shows the relative surface area of the drift-sand through time. The area covered by drift-sand increased over time to approximately 17 % in 1851 CE, subsequent large-scale afforestation led to a quick drop in the drift-sand covered area. The former drift-sand areas largely overlap with present-day arenosols, while at a few locations podzols have developed in the drift-sand deposits after stabilization (Alterra, 2008, 2014). For instance in the southern areas in Fig. 5c, where there is no overlap with arenosols, podzols have developed over time. As the onset of drift-sand activity took place at least at 1500 CE (see below), initial development of the drift-sands could not be derived from the maps. The spatial patterns in Fig. 5 clearly show the development of drift-sands directly adjacent to the meanders of Junner Koeland and Prathoek. The land use pattern in Fig. 3b corresponds well with the indicated drift-sand area in Fig. 5c.

Intruding sands formed a nuisance for the inhabitants of the Overijsselse Vecht valley. The first records of defence measures against the drift-sand in mark books from the Dutch part of the river valley date from the 16th century (Bruins, 1981). Sand-drifting was controlled e.g. by construction of tree girths (visible on the historical map of 1720 CE in Fig. 6) or dykes. Consequently drift-sands could reach the river only locally. For instance, the drift-sand west of Junner Koeland at location 1 probably caused relatively few problems, because the arable fields of Arriën lay upwind of the predominant SW-NE wind direction (Koster, 2010). As human-induced barriers were absent, the drift-sand could influence the meander at Junner Koeland. A large part of the drift-sand coming from south of the river was probably caught in the tree girths and dykes surrounding the arable fields of Junne. Drift-sand blowing towards the apex of Prathoek was probably not limited in this way, because no arable fields were present directly south of this meander.

5.3.2. Lithological survey drift-sand areas

The drift-sand dune at location 1 has a diameter of about 30 m and varies in elevation from circa 6–9 above sea level (a.s.l.). At the coring locations the thickness of the drift-sand layer varies between 10 and 180 cm. At location 2 the drift-sand forms a linear structure bordering the arable fields of Junne (Fig. 2b). This drift-sand ridge has a width of about 60 m and a length of circa 1 km. It varies in elevation from circa 8 m a.s.l. at its borders to

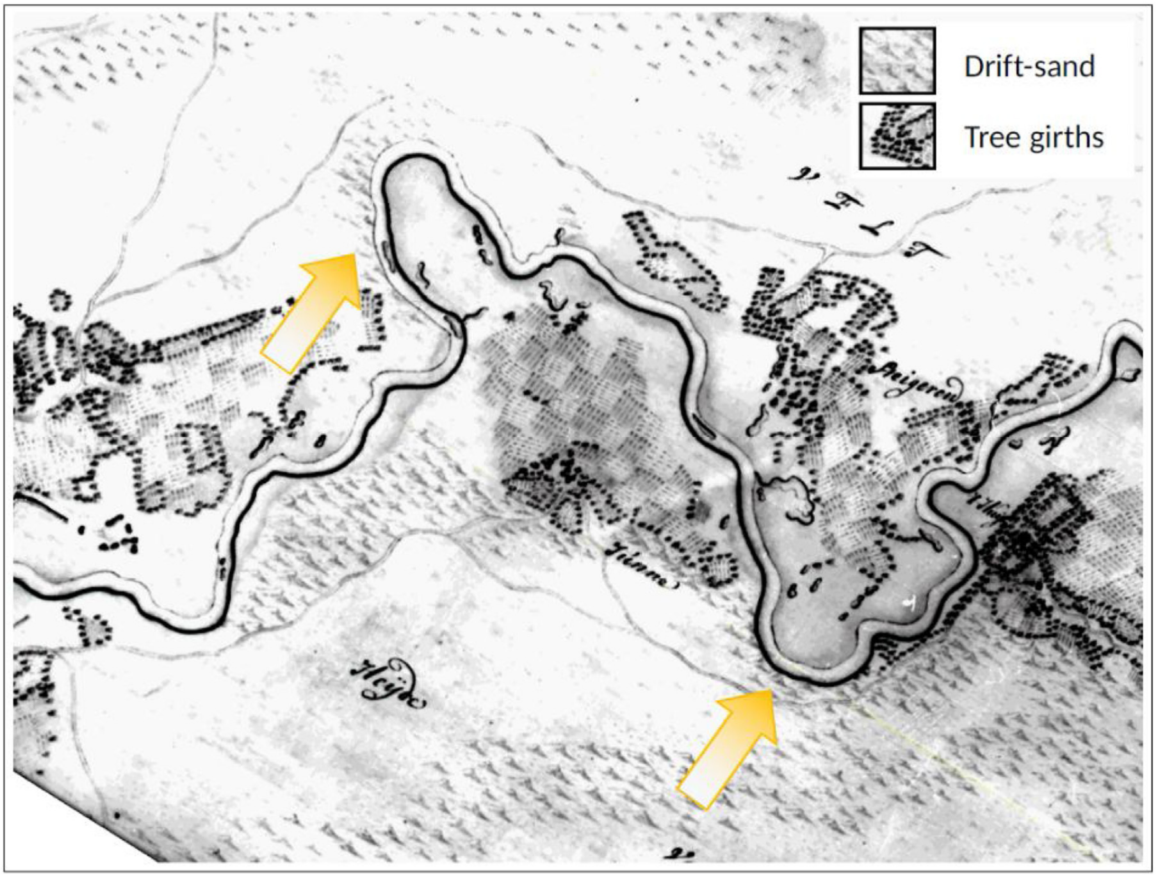

Fig. 6. Section of the map drawn by Pieter de la Rive around 1720 CE. Various areas are characterized by sand dunes. Arable fields are often bordered by tree girths for protection against drift-sand. The dominant wind direction and position where drift-sand could blow towards the river are indicated by arrows. Sources: Algemeen Rijks Archief (1996); Wolfert et al. (1996); Box (2007).

about 16 m a.s.l. at its highest point. Corings showed that thickness of the drift-sand layer varies between 120 and 350 cm (here the maximum thickness of the drift-sand layer is at least 350 cm; augering depth was not sufficient to reach the coversand deposits at the centre of the ridge). The five corings that were placed between the abandoned channel of Junner Koeland and the adjacent drift-sand dune (Fig. 2a) demonstrated that these drift-sands are underlain by coversand, indicating absence of Holocene fluvial deposits underneath the drift-sands. The two corings at the west end of this transect proved that the boundary between fluvial deposits and the drift-sand area is abrupt, which matches geomorphological observations based on the DEM (Fig. 2a) and in the field.

5.3.3. Optically stimulated luminescence (OSL) dating results

The OSL dating results are listed in Table 1. At drift-sand location 1 the OSL results show that the sample taken in the middle of the dune is the oldest (1837 ± 20 CE). The sample from the lee side is somewhat younger (1919 ± 13 CE) and the stoss side sample is youngest (1983 ± 10 CE). A similar pattern was found for location 2, where the sample collected near the middle of the dune is oldest (1500 ± 31 CE), the lee side sample is younger (1620 ± 48 CE) and the stoss side sample is youngest (1820 ± 45 CE). These ages indicate that growth of the dunes was directed against the dominant wind direction, perhaps with some sediment blowing over the dune to the lee side during stormy weather. At location 1, where some bare patches are present today and the dating

Table 1
Optically stimulated luminescence (OSL) dating results for the drift-sand samples. The column 'Podzol' refers to presence or absence of a spodic horizon in the coversand that underlies the drift-sand. RD = Dutch coordinate system, NA = not available. For all samples the palaeodoses and ages are based on the bootstrapped Minimum Age Model (Cunningham and Wallinga, 2012). Source of sample NCL-2112028: Reimann et al. (2016); Rotthier and Sýkora (2016).

Sample		Dune side	Podzol	Location (RD coordinates)		Sample depth below surface (m)		Palaeodose (Gy)		Total dose rate (Gy/ka)		OSL age (ka)		OSL age (year CE)	
Code	Site			x	y	Upper limit	Lower limit	μ	σ	μ	σ	μ	σ	μ	σ
NCL-2415164	1	Stoss	Yes	228798	505,776	0.15	0.2	0.04	0.01	1.18	0.04	0.03	0.01	1983	10
NCL-2415165	1	Middle	Yes	228814	505,790	0.39	0.64	0.19	0.02	1.08	0.04	0.18	0.02	1837	20
NCL-2415166	1	Lee	Yes	228824	505,798	0.15	0.4	0.10	0.01	1.08	0.04	0.10	0.01	1919	13
NCL-2415167	2	Stoss	No	230201	503,787	±3.00	3.19	0.15	0.03	0.76	0.02	0.20	0.05	1820	45
NCL-2415168	2	Lee	Yes	230190	503,813	3.09	3.26	0.42	0.02	0.82	0.03	0.52	0.03	1500	31
NCL-2415169	2	Lee	Yes	230194	503,815	1.24	1.42	0.34	0.04	0.87	0.03	0.40	0.05	1620	48
NCL-2112028	3	NA	NA	229096	505,375	0.28	0.43	0.46	0.06	1.31	0.04	0.35	0.05	1659	51

indicated very recent sedimentation, an increasing importance of NE winds in currently active drift-sands (Jungerius and Riksen, 2010) could also have played a role. According to the cadastral map (Fig. 3b) drift-sand location 1 was covered by heather in 1832 CE, however the OSL dates indicate that the drift-sand remained active until 1983. The largest part of the drift-sand ridge at location 2 had been stabilized by a forest cover in 1851 CE (Fig. 5d). One OSL date was available from earlier work (Reimann et al., 2016; Rotthier and Sýkora, 2016) and denoted as drift-sand location 3 (Fig. 1b, Fig. 2c, listed at the bottom of Table 1). This sample was collected at a depth of 0.28−0.43 meters below the surface in aeolian deposits found on top of a Pleistocene terrace remnant in Junner Koeland. It was dated at 1463 ± 28 CE (Reimann et al., 2016), matching with the ages found at drift-sand location 2, where the oldest sample was dated at 1500 ± 31 CE.

6. Discussion

6.1. River management

The consulted archival material demonstrated that there was no specific authority concerned with regional coordination of river management of the Overijsselse Vecht. Locally, farmers and land owners concerned with protection of their property applied small-scale practices such as placement of groynes. However, this happened only to a limited degree as appears from the low number of records. The aloofness of higher authorities and resulting lack of regional management strategies provided free rein for local land use and drift-sand activity to affect meander development.

6.2. Settlement pattern and land use

The chronological development of the estimated number of farmsteads (Fig. 4, Fig. 7) follows the common trend in Northwest Europe (Bieleman, 2008; Persson and Sharp, 2015). A gradual increase in settlement size during the Early Middle Ages was followed by a strong population growth and reclamation activity between c. 1100 – c. 1350, followed by a stabilization phase or period of reduced growth between c. 1350–1500, and a strong renewed growth after 1500 CE. The farmstead numbers for 1832 are exact as they were derived from the first national Cadastre. The numbers for all other time points should be considered as conservative estimates, since there may have been yeomen and peasants owning farms that were unrecorded in the used Late Medieval sources.

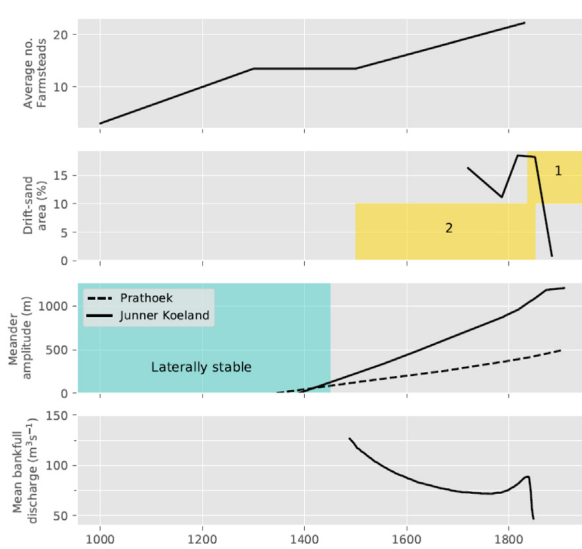

Fig. 7. Multidisciplinary overview of developments in the study area. Top: average number of farmsteads (i.e. averaged for the marks Arriën, Beerze, Junne, Stegeren, see Fig. 4). Upper middle: period of activity of drift-sand areas 1 and 2 as determined with OSL dating and relative drift-sand area as derived from historical maps (see Fig. 5). Lower middle: shift from a laterally stable to a meandering channel pattern (circa 1400 –1500 CE, set to 1450 in the graph, data derived from Candel et al., 2018) and development of meander amplitude of Prathoek and Junner Koeland (data derived from Quik and Wallinga, 2018a). Bottom: reconstructed mean bankfull discharge (data derived from Candel et al., 2018). For the sake of clarity uncertainties are not shown here.

Historical sources indicate that drift-sand became exceedingly problematic near the river valley since at least the 16th century, and that different measures were taken to restrain them (Bruins, 1981). This trend coincides with the strong growth in farmstead numbers from 1500 CE onwards (Fig. 4). It is highly likely that intensified land use led to increased drift-sand activity (Castel et al., 1989; Pierik et al., 2018), as corroborated by the OSL dating results indicating drift-sand deposition from the beginning of the 16th century CE onwards (Table 1). We previously showed that the shift of the Overijsselse Vecht from a laterally stable to a meandering channel pattern took place during the Late Middle Ages, caused by an increase of peak discharges (1400–1500 CE, Fig. 7; Candel et al., 2018). The period of large meander formation locally (roughly 1400–1900 CE, Quik and Wallinga, 2018a,b) overlaps with strong growth in the farmstead numbers and the activity period of drift-sands directly adjacent to the meanders of Junner Koeland and Prathoek (Fig. 7). It seems reasonable to assume that the increase in farmstead numbers resulted in new reclamations, higher land use intensity and indirectly affected activity and expansion of drift-sands.

The grasslands on the scroll-bar complexes (Fig. 3b) were used for grazing (and possibly hay-making) from (at least) the High Middle Ages onwards (cf. Van Haaster, 2006). It remains however difficult to assess whether related land use effects had a significant impact on meander development, as land use on scroll-bar complexes of meanders expanding beyond the Pleistocene valley may have been similar in meanders that remained confined by the valley side. Detecting land use changes at this scale would consequently require archival study at the level of individual farms. We hypothesize that (1) cattle may have enhanced local bank erosion through trampling (Trimble and Mendel, 1995), with shallow water levels in the Overijsselse Vecht (Staring and Stieltjes, 1848) potentially aiding access of cattle to the concave river bank; (2) the high value of the grasslands and the function of the river as administrative border between the marks suggests an economic incentive for deliberate human-induced bank disruption or actions promoting erosion of the concave bend and point-bar development along the convex bend. The mark affected by erosion would lose only drift-sand covered territory of low value. We have, so far, not been able to identify historical sources to test these hypotheses. Highly detailed archival studies may shed light on the relevance of these processes.

6.3. Drift-sand

Our dating results indicate a chronological conformity between lateral meander expansion (ca. 1400–1900 CE, Quik and Wallinga, 2018a,b) and nearby drift-sand activity (Fig. 7). The oldest drift-sand sample was dated at 1500 ± 31 CE. This date indicates the start of the formation of the drift-sand dyke surrounding the arable fields of Junne. Activity of drift-sands must have started even earlier, as construction of this dyke signifies a response to the drift-sands threatening the arable land.

Previous studies suggested that bank stability of outer banks may decrease as they become covered by drift-sand (Wolfert et al., 1996; Wolfert and Maas, 2007). Deposition on the banks may cause riparian vegetation to cease, diminishing the bank erosion-resistance. Additionally, the drift-sand cover itself consists of very non-cohesive material that is prone to fluvial erosion. Historical maps show that the drift-sands were situated directly adjacent to the meanders of Junner Koeland and Prathoek (Fig. 5), and oriented such that sand would blow towards the river under the predominant wind direction (Fig. 6). Protection measures such as the dyke of Junne (drift-sand location 2) locally inhibit drift-sands from reaching the river. Lacking protective structures leave the apex of Prathoek fully exposed. Consequently drift-sand deposition will have affected bank stability of this meander's apex. Additionally, as Prathoek is located directly upstream of Junner Koeland, blown-in sands may have affected Junner Koeland as well prior to drift-sand activity west of this meander (at drift-sand location 1). According to our OSL dates drift-sands were active here from 1837 ± 20 CE onwards. However, historical maps point towards drift-sand activity at this site from as early as 1720 CE (Fig. 5a). Drift-sand activity at location 1 overlaps partly with meander formation at Junner Koeland, and fully with formation of the skewed apex. Drift-sands that were present north of Junner Koeland, as visible on the historical map of 1720 (Fig. 5a), will gradually have been eroded by the river. Drift-sand in this position would not blow towards the river under the predominant wind direction, but the drift-sand cover probably resulted in lower stability of the northern bank and hence was prone to erosion by the expanding Junner Koeland meander. In addition, coring evidence from drift-sand location 1 shows a sharp boundary between fluvial and drift-sand deposits which points towards fluvial erosion of drift-sand-covered terrain (Fig. 2a).

Interactions between fluvial and aeolian geomorphology are widespread but are often not studied in combination, hence the underlying mechanisms are less well understood (Liu and Coulthard, 2015). Our observations support a reduction of bank stability following drift-sand deposition as discussed by Wolfert et al. (1996) and Wolfert and Maas (2007) as active geomorphic process. Additionally, drift-sands can act as an extra sediment supply to the river, altering its morphodynamics by enhancing the rate of scroll bar growth and therefore the rate of bank erosion (Ferguson, 1987; Nanson and Croke, 1992). The collapse of drift-sand covered banks upon fluvial erosion will also lead to additional sediment supply to the river, which may affect river morphodynamics. Cross-sections by Candel et al. (2018) showed that the channel deposits did not incise since 1400/1500 CE, but that the river bed in fact slightly aggraded during the meandering phase. This may point towards high sediment supply due to the drift-sands.

6.4. Reflection on relative importance of drivers

Formation of the Junner Koeland meander started at 1433 ± 92 CE (Quik and Wallinga, 2018a,b). Following the channel pattern change from laterally stable to meandering, the initial formation of meanders was part of the natural regime of the river (Candel et al., 2018). This initial meander formation was not caused or influenced by local allogenic drivers, but by a catchment-scale discharge regime change. However, the continuous growth of meanders like Junner Koeland and Prathoek which migrated beyond the river's valley sides reaching amplitudes over twice their expected size is remarkable. Lack of regional river management strategies led to a situation where the river could meander freely. Rising numbers of farmsteads in the study area created land use pressures that were hitherto unprecedented. A consequence of this high land use intensity was formation of local drift-sands (Castel et al., 1989; Pierik et al., 2018), and drift-sand deposition on river banks will have lowered their resistance to fluvial erosion (Wolfert et al., 1996; Wolfert and Maas, 2007). Our data show that drift-sand influence was present during the entire period of meander growth at Prathoek, and from 1720 CE onwards for Junner Koeland. Based on our multidisciplinary analysis we consider drift-sand activity as the most prominent effect to cause the exceptional meander expansion observed at Junner Koeland and Prathoek. Sand-drifting is in itself a consequence of the high population density and land use pressure. Lacking fluvial management left the boundary conditions for meandering unchanged and allowed drift-sands that locally affected the river to exert their influence on river dynamics.

6.5. Implications

During the Late-Holocene, fluvial activity of rivers generally increased due to catchment-scale land use changes by humans, changing rivers into more actively laterally migrating rivers due to enhanced sediment load and discharges (e.g. Notebaert and Verstraeten, 2010; Brown et al., 2018; Gibling, 2018; Notebaert et al., 2018). Here we show that human influence did not only occur at the catchment-scale, but also contributed to exceptional morphodynamics at the level of individual meander bends.

The lessons learned at this site are relevant for management and restoration of meandering rivers in similar settings elsewhere, particularly considering the need to estimate spatial demands of (restored) low-energy fluvial systems and to adequately manage bank erosion and related hazard risks (e.g. Piégay et al., 2005). In many parts of the world, low-energy rivers are presently being restored from their channelized state to rivers that are allowed to freely erode their banks (Wohl et al., 2005). Restoration goals are often based on the channel planform preceding channelization and aiming to resemble the river course from historical maps. Consequently palaeochannels are reconnected to redesign the river channel (Kondolf, 2006). However, meandering activity strongly relates to stream power (Candel et al., 2018) and local land use, which change over time. Hence, rivers should not be restored to a certain historical reference, as the conditions that allowed this planform to develop may no longer be valid and impossible to return to (Dufour and Piégay, 2009). Instead, priority should be given to characterizing the current and future morphological conditions prior to setting goals for river restoration. We have shown that local changes of morphological conditions may result in exceptional changes of river dynamics. This may lead to unwanted and unexpected erosion of land and infrastructure. Hence a further development of our understanding of small-scale human-landscape interactions in fluvial environments could be of great practical value for the restoration of low-energy rivers and predicting future change.

7. Conclusion

We identified potential direct and indirect anthropogenic drivers for the development of exceptionally large meanders in lowland rivers. Our multidisciplinary and in-depth analysis of the Overijsselse Vecht river:

(1) Indicates lacking regional management of the river system throughout the Early and Late Modern period, which created a situation where local land use and drift-sand deposition could interfere with river dynamics;
(2) Shows a strong increase in the number of farmsteads and related intensification of local land use starting in the High Middle Ages and continuing through the Early and Late Modern period. This increase in habitation density matches with the period of meander growth;
(3) Reveals a chronological conformity between lateral migration of two exceptionally large meanders and (human-induced)

drift-sand deposition on their outer banks. Our results indicate that this interaction may have caused exceptional meander expansion beyond the valley sides.

Data availability

All data from this study are available under CC—BY 4.0 license at the 4TU.Centre for Research Data; see Quik et al. (2020). Details of the OSL dates of the meander bends are available in Quik and Wallinga (2018a, 2018b) and additional information on the palaeohydrological reconstruction can be found in Candel et al. (2018).

Author contributions

BM, GM, JW and CQ proposed the initial outline of the research and selected the field sites. CQ performed the corings in the drift-sand areas followed by OSL sample collection by CQ, JC, and BM. CQ assisted with preparation of the OSL samples in the laboratory, OSL results were analysed by JW. RvB collected and analysed the archaeological data. MP, RvB and TS performed the analyses of Medieval farmsteads. MV analysed historical river management based on archival study under the supervision of RvB, MP and JC. CQ wrote the initial manuscript, with main additions by JC, RvB, and MP. The draft was finalized by all authors.

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2020.100263.

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