Appendix A1 Reconstruction population density

Estimates of population density (PD in p/km^2) are shown in Table A.1 and Figures 3-6 of the main text. These were based on (i) published population numbers and densities inferred from archaeological settlement data. Benchmark for pre- AD 1000 periods were the Roman period (AD 200) population reconstructions based on detailed micro-regional studies (Van Beek and Groenewoudt, 2011). (ii) Published population numbers and densities based on written sources (only after AD 1500).

For the less-known periods: 1000 BC, 100 BC, AD 500 and AD 800, population density estimates (PD) were based on the number of known archaeological settlements (Zoetbrood et al., 2006), relative to the number of Roman-period settlements. We corrected for differences in the duration of the different archaeological periods and took the period-specific differences in discovery potential of settlements (Groenewoudt, 1994; Deeben et al., 2005) into account.

Estimated numbers were validated and (if necessary) adjusted by comparing them to long-term demographic trends published by Roymans and Gerritsen (2002), Louwe Kooijmans et al. (2011) and Van Munster (2012), and for the Late and post-Medieval periods Faber (1965); McEvedy and Jones (1978); Paping (2009). In the case of (published) settlement density *ranges*, we choose the mean value, unless long-term demographic trends (Louwe Kooijmans et al., 2011; Van Munster, 2012) make higher or lower numbers more likely. This reconstruction gives a relative trend of PD through time, more detailed micro-regional studies that estimate the number of people from the archaeological record would further improve these reconstructions. Below the estimates are further outlined per period:

Early Iron Age (ca. 800 BC)

Population density for the Early Iron Age was estimated to be 50% of the Late Iron Age population on a national level based on (Louwe Kooijmans et al., 2011).

Late Iron Age (ca. 200 BC)

The number of Iron Age settlements is 37% less relative to the number of roman settlements (341 Iron Age and 452 in the Roman age on a national scale) (Zoetbrood et al., 2006), because Iron Age sites are less well recognisable, which negatively influences the discovery rate (Groenewoudt, 1994; Deeben et al., 2005; Verhagen and Borsboom, 2009) we estimate PD to be 50% relative to the Roman Age.

Roman Period (ca. AD 200)

During this period population density (PD) was relatively high, especially in the river area. In the sandy area, population numbers were lower but also increased. For these areas Van Beek and Groenewoudt (2011) reconstructed a mean PD of 4.9 p/km^2

Early Post-Roman period (ca. AD 500)

After the Roman period a strong depopulation occurred, however some major differences can be seen between the study regions (Van Munster, 2012). Based on the number of settlements from the

Early Post-Roman period relative to the number of settlements known from Roman period (Zoetbrood et al., 2006; Van Munster, 2012) we reconstructed a population decline of around 90% in the southern and middle sand areas and of 50 % in northern and eastern sand areas.

Early Middle Ages: Carolingian period (ca. AD 800)

After the population decline around AD 500, population numbers increased towards AD 800, but did not reach the level of the Roman period. The strongest increase is found in the southern and middle sand areas. Based on the number of settlements (Zoetbrood et al., 2006) (corrected for differential settlement discovery rate) it was estimated that – on a national scale - 80% of the Roman-period population is present around AD 800. Assuming an equal distribution over the different sand areas, we projected this percentage on the population in the sand area as well.

Early Middle Ages: Ottonian period (ca. AD 1000)

Numbers based on interpolation between numbers AD 500 and 1500, taking into account the long-term demographic trend (Louwe Kooijmans et al., 2011; Van Munster, 2012).

Late Middle Ages AD (AD 1500)

Numbers AD 1600, minus 10% (see below). Strong population growth from AD 1500 to 1600 of ca. 50 % has been reported for mainly for the large towns in the Netherlands (Faber, 1965; McEvedy and Jones, 1978). These towns are however not situated in sandy areas, therefore the AD 1500 to 1600 population growth much lower here, estimated at 10%. The sharp rise in population numbers in the southern sand area can be explained by the rise of nearby Flemish towns (Theuws, 1989; Spek, 2004: 981-983; Vangheluwe and Spek, 2008; Van Bavel, 1999).

Late Middle Ages AD (AD 1600)

Population densities mentioned by Spek (2004: p966) derived from historical sources (Slicher van Bath, 1957; Bielemans, 1987; Arts, 1993; 1999; Kossmann, 1986). Ranges from these sources and their best guesses are indicated.

Table A.1 Reconstructed population density in people per km^2. For explanation, see text.

	800 BC	125 BC	AD 200	AD 500	AD 800	AD 1000	AD 1500	AD 1600
Northern sand area	1.2	2.4	4.9	2.4	3.9	4.6	6.3	6.0-8.0 (7.0)
stern sand area	1.2	2.5	4.9	2.5	3.9	5.9	10.8	12.0
Middle sand area	1.2	2.4	4.9	0.5	3.9	7.6	17.0	15-25 (17.0)
Southern sand area	1.2	2.5	4.9	0.5	3.9	12.3	33.3	25-50 (37.0)
All sand areas	1.2	2.5	4.9	1.3	3.9	7.2	15.3	19.6

Appendix A2: Datings of the pollen diagrams

Assessing the areal extent of deforestation

The degree of deforestation was used as a proxy for human pressure on the vegetation and hence on the landscape. The relative amount of deforested area was derived from the arboreal pollen percentages (AP%-values) in existing well-dated and detailed pollen diagrams from point locations per sand area. Empirical studies demonstrate that the AP%-values of modern vegetation assemblages are related to landscape openness (Doorenbosch, 2013; Frenzel, 1994; Frenzel et al., 1992; Groenman-Van Waateringe, 1986). Because this relation is strongly influenced by the pollen source area and the vegetation type and pattern, the AP%-values were only used as an indication of relative landscape openness rather than as an absolute percentage of forest cover (Broström et al., 1998; Doorenbosch, 2013; Sugita et al., 1999; 2010). Therefore, we did not compare absolute values between areas but assessed the long-term deforestation trends per region by identifying periods with rising and falling AP%-values.

The pollen diagrams were selected using the Dutch Pollen Database (Donders et al., 2010), based on representability of the regional vegetation trend following comparisons with other sites and studies (e.g. Brinkkemper, 2013; Groenewoudt et al., 2007), robustness of the chronology and detail of the analyses. We only selected pollen diagrams from undisturbed peat sequences, to eliminate the influence of fluvial transported pollen and human interference. For the northern sand area we selected the Mekelermeer pollen diagram (Figure 3). The record from this pingo remnant covers the period from ca. 1200 BC to AD 1100 and was originally published by Bohncke (1991). For the eastern sand area a pollen diagram from a raised bog was chosen: the Engbertdijksveen (Figure 4) covering the period 950 BC to AD 950 (Van der Molen and Hoekstra, 1988). The vegetation development for the middle sand area was best reflected in the pollen diagram from the Uddelermeer pingo remnant (Figure 5 - Engels et al., 2016; unpublished data Gouw-Bouman). For the southern sand area we chose a pollen diagram from the peat infill of an abandoned Pleistocene channel without Holocene fluvial influx, Berkenhof which shows the vegetation trend from BC 1500 to AD 1850 (Figure 6 - Teunissen, 1990). The chronology of all pollen records is supported by radiocarbon dates reported in Appendix (Table B5). Although pollen percentage values can vary strongly between sites, the trends in AP%-values are reasonably similar to pollen records from other natural and relatively undisturbed sequences (Berendsen and Zagwijn, 1984; De Jong, 1982; Engels et al., 2016; Teunissen, 1990). This indicates that the selected sites represent the regional trends well.

The arboreal pollen percentages of the different studies were digitised and recalculated using a uniform pollen sum to enable comparison. To capture regional vegetation trends, we chose a pollen sum comprising upland types only (i.e. vegetation from dry areas), excluding wetland pollen types such as Alder to minimise the effects of local vegetation dynamics. The original chronology of the record was updated using linear interpolation between the sequence calibrated original radiocarbon dates (Bronk Ramsey, 2009; Niu et al., 2013; Reimer et al., 2013).

Table B.5. Datings used for the age-depth model of the pollen records from which the openness is inferred. For Uddelermeer the age-depth model of Engels et al. (2016) was used.

SampleID	depth mid	^{14}C Age	Age error 1σ	Modelled cal age 2σ (min)	Modelled cal age 2σ (max)
Berkenhof (Teunissen, 1990)					

8876	70	650	70	701	528
8877	95	1130	55	1178	936
8878	120,5	1750	55	1815	1554
8879	160	2175	50	2327	2042
8478	208	4130	50	4826	4526
8282	232	7130	70	8153	7792
Engbertsdijksveen (Van der Molen and Hoekstra, 1988)					
GrN-11174	0.5	1070	70	1173	904
GrN-11173	5.5	1180	45	1239	993
GrN-11172	9.5	1340	50	1334	1180
GrN-11171	25.5	1510	50	1488	1305
GrN-11170	35.5	1550	50	1550	1373
GrN-11169	42.5	1700	50	1716	1525
GrN-11168	51.5	1880	50	1894	1705
GrN-11167	59.5	1920	50	1992	1790
GrN-11166	73.5	2130	50	2305	1990
GrN-11165	83.5	2320	60	2681	2154
GrN-11164	99.5	2790	60	2993	2757
Mekelermeer (Bohncke, 1991)					
GrN-10020	108	1695	45	1715	1524
GrN-10021	151	2190	60	2340	2042
GrN-10022	201	4130	60	4833	4450
GrN-10023	251	5590	60	6490	6287
GrN-10024	300,5	6200	70	7266	6932