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Late Holocene landscape instability in the Breckland (England) drift sands.

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Abstract

This research investigates the landscape instability associated with the drift sands, which are widespread across north-western Europe. It focuses on Breckland, UK using new sites along with existing geomorphic, archaeological and historical data. This shows landscape instability of drift sands occurred at 5240±1040 years BCE, 600± 100, 1150±50, 1600 and ~1790 CE. Comparison of these phases to climate records show no clear patterns with drifting occurring during dry/wet as well as cold/warm periods. Additionally, similar climatic shift s lead to diverging reactions of landscapes in different regions throughout Europe. At the regional scale, land usage and population pressures also may not be the direct cause of sand drifting, suggesting that complex responses or different triggers at different times were responsible. Within this, society's unawareness of the inherent landscape instability and the threat posed by the sand hazard may have been important as it affected whether mitigation measures were or could be implemented. In Breckland, initial instability may have been due to the establishment of the open field system on virgin soil. Later changes in land ownership and associated power within the society, led to an inability of communities to implement mitigation measures and large land owners abstaining from tackling the sand hazard. Whilst the widespread coversands and climatic extremes provide the underlying susceptibility to sand drifting, it would appear that drift sands of the last 2000 years may provide less of a sedimentary archive of Late Holocene climatic changes and more a record of land management changes.

1. Introduction

Large parts of Europe are superficially covered with cold-climate, wind-blown sand forming a coversand belt (e.g. Zeeberg, 1998). This coversand landscape has been periodically reworked by wind, forming dunes collectively referred to as drift sands (e.g. Bateman and Godby, 2004; Koster, 2007). The development and application of optically stimulated luminescence (OSL) dating shows that sand mobility and dune formation are often older than first assumed (Verhaert et al., 2001-2002; Derese et al., 2010; Sevink et al., 2013). It also has shown that regional divergences between phases of drift sand activity exist (Bateman and Godby, 2004; Derese et al., 2010).

Two main issues remain regarding the timing and significance of drift sands phases. Firstly, dated layers are often given the same weight and importance when determining drift sand phases (e.g.

Castel, 1991). Whilst helping to understand landscape instability phases, such an approach makes understanding triggers for them difficult (Telfer et al., 2010). Thin dated sediment layers and isolated sand drift patches may reflect only minor movements of sand or slow dune growth. In contrast, thick sediment deposits and newly formed dunes or dune fields may have resulted from a regional trigger(s) and result in a more profound impact on the coversand belt and drift sands within it. Secondly, the location of dunes and places of sand reactivation to settlements and agriculture are often not taken into account when drift sand phases are discussed. In the field of disaster research phases are defined as significant when a trigger creates a disturbance that is of sufficient magnitude to flip a system into another regime of behaviour (Gunderson, 2000). The relocation of parts of a dune within a dune complex is a different type of event than the creation of new dune fields, the enlargement of open sand landscapes and the coverage of productive agricultural land by drifting sand. Only the latter, which cause a fundamental shift, either in societal activities or across the wider landscape, can be considered major events. In the context of drift sands, the easiest phases to identify are those that exceeded the resilience threshold leading to landscape instability but then when the disturbances reduced or became absent, the landscape returned to a stabilised mode.

The causes and extent of the drift sand landscape instability phases are currently not well understood for either European drift sand landscapes nor desertification (e.g. Fanta and Siepel, 2010; Henry et al., 2017). In part, this is because understanding causes and effects through time and space when there are multiple variables, each with their own leads and lags, is a not trivial exercise.

Landscape instability of the drift sands as well as desertification processes have been variously attributed to climate, growing population pressure, agricultural overexploitation, increased mobility and usage of roads during the later Middle Ages (Castel, 1991; Cordova, 2007; Derese et al., 2010; Heidinga, 2010; Koster, 2010; Rosen, 2011; Fan et al., 2016; Henry et al., 2017; Pierik et al., 2018). For the European coversand belt it was originally thought that drift sand phases increased significantly after 1200 AD (Castel, 1991; Koster, 2010; Vera, 2011). However, new OSL research using a combined and weighted scale of drift sand phases and placing them within the context of the wider land use and management has shown that this does not hold for the entire European drift sand belt. While Koster (2010) has showed concentrations of drift sand movement in the central Netherlands from 1400 AD, in other regions, for example the Campine in Belgium, there was only minor but constant re-deposition of sand (De Keyzer, 2016). In contrast, between 900-1000 and again 1700-1800 AD the Campine region underwent large-scale sand inundations, enlarging the drift sand landscape and covering habitation sites, fields and pastures (ibid).

Recent research has proposed a societal cause for periodic sand drifting as communities' perceived vulnerabilities towards the sand hazard fluctuated and, therefore, so did their responses (De Keyzer, 2016; Pierik et al., 2018). In some places, communities installed and maintained windbreaks and wind erosion mitigation measures. For example, in Belguim, the villages of Retie, Kalmthout, Ravels, Geel and Arendonk planted small plantations (called "heibossen", heather forests) in order to prevent or limit drift sands (Verhoeven, 1907; Ernalsteen, 1935; Prims, 1944; Helsen, 1949; Koyen, 1958). Elsewhere or at other times the sand drifting hazard was not seen to warrant this. These changes in perceived hazard risk through space and time are thought to have led to the observed regional differences in sand drifting phases (De Keyzer, 2016; Pierik et al., 2018).

In this present work, a historical and palaeoenvironmental perspective are combined to look into the sand drift phases of the Breckland region of East Anglia, UK. First, the aeolian activity history of Breckland from the mid-Holocene to the present is reconstructed, through a programme of OSL and radiocarbon dating used in combination with a range of archaeological and documentary evidence. From this, major phases of sand drifting are identified and compared to climatic, land-use and societal information to try to understand why drifting occurred when it did.

2. Regional Background

The essential physical character of Breckland is a gently dissected Upper Cretaceous Chalk plateau lying at an altitude of 30-45 m OD that is bounded to the west by the thick peat and silt deposits of the low-lying Fens (Fig. 1; Lee at al., 2015). The underlying coversand (e.g., Chorley et al., 1966; Bristow et al., 1990; Clarke et al., 2001; Booth at al., 2015), the ultimate source of Breckland's drift sands, has been shown to have accumulated within the Last Glacial cycle within periglacial structures in four main phases around 55-60 ka, 31-35 ka, 20-22 ka and 11-12 ka (Bateman et al., 2014). Coversand found with Breckland at the Grimes Graves site was emplaced by ~14.4 ka (Bateman, 1995). Thus, initial sand emplacement was before the Holocene and so Breckland has had the potential for sand drifting throughout the Holocene period. Climatically, Breckland is one of the driest regions in Britain with an average annual precipitation of less than 600 mm (Farrow, 1915; Sheail, 1979; Corbett, 1973). It is particularly dry in spring/early summer months when, on average, less than 50 mm of precipitation is received (Corbett, 1973). The low precipitation, coupled with the free-draining sandy soils and losses through transpiration and evaporation, leads to a significant negative soil moisture budget.

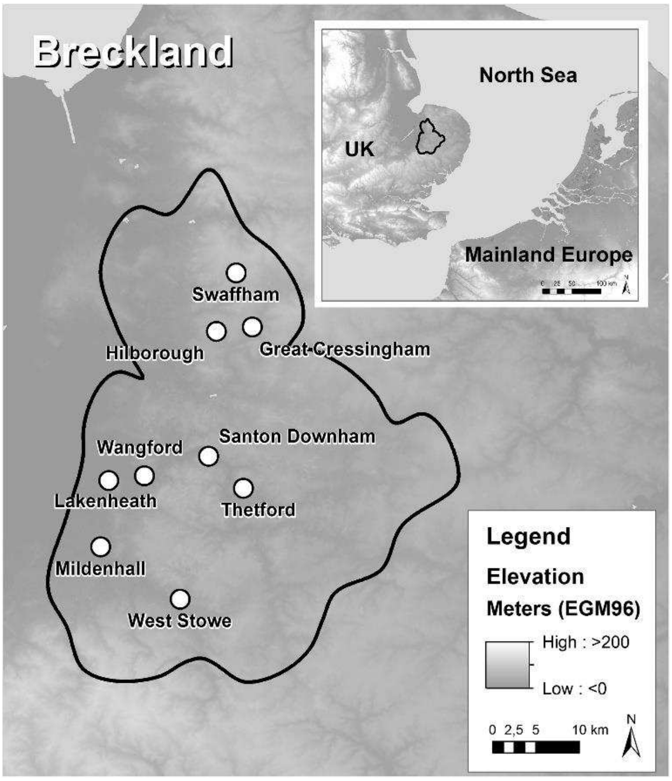

Fig. 1. Delimitation of Breckland region of East Anglia, UK based on that of Postgate (1960)

The climax vegetation of the region was a mixed forest, but by the Neolithic period (4000-2500 BC) the more closed forests were replaced by more open landscapes (Bennett, 1983). The *Calluna*-heath tended to occupy the more central portions of higher ground and was surrounded by stretches of grass-heath and large tracts dominated by bracken (Farrow, 1915; Postgate, 1960; Crompton and Sheail, 1975; Bailey, 1989).

Bateman and Godby (2004) identified sand drift deposition took place from the middle Holocene c. 4500 BC (6500 years ago) at Wangford Warren, with three important drift sand phases around 720 ± 240, 1620 ± 80 and 1830 ± 40 AD (ibid). The latter is supported by seventeenth and eighteenth century observers and travellers. Gilpin (1805, p.28) described the area between Brandon and Mildenhall warrens in 1769 AD as a 'Mere African desert. In some places this sandy waste occupied the whole scope of the eye. The whole country indeed had the appearance of a beaten sea coast'. John Evelyn (1952, p 10 December 1677) had a similar picture in his mind, when he wrote in 1667 AD that 'traveling sands have so damaged the country, rolling from place to place, and like the sands in the deserts of Libya, quite overwhelmed some gentlemens' whole estates'.

Thus, the climate, low relief, open landscape and pre-existing aeolian superficial sediments all provide conditions in Breckland favouring wind erosion and drifting of sand. It is for these reasons we have chosen to focus on this region to understand the underlying causes that led to landscape instability.

3. Methodology

3.1 Geomorphic and sedimentary evidence

To establish a master chronology for Breckland drift sands, the British Geological Survey Dando drilling rig was used to take a core (6.7 m in length) in the most prominent dune within the Wangford Warren (TL756842; 52°25'N, 0°35'E) drift sand dune field and a second core in the inter-dune area (1.9 m in length; Fig. 2, 3). To supplement this and get lower into the stratigraphy, additional exposures in nearby land drains were also examined. Both cores and sections were logged in terms of their sediments and structures and sampled for luminescence and radiocarbon dating.

A single radiocarbon sample was obtained from the organic-rich unit at 0.75 m depth in the inter-dune core. This was sent for Accelerator Mass Spectrometry Radiocarbon dating at the 14Chrono centre, Queens University Belfast. For the OSL dating, all samples were prepared to clean and extract course grained (90-250 µm) quartz at the Sheffield Luminescence laboratory as per the method outlined in Bateman and Catt (1996). All samples were measured as per Bateman and Godby (2004) to make measurements comparable. In brief, measurements were made at the aliquot level with quartz mounted as a monolayer across aliquots 9.6 mm in diameter. All measurements were carried out in in a Risø reader with stimulation via blue-green LED array and measurement through a UV filtered photomultiplier tube. OSL signals were dominated by a fast component, were found to be uncontaminated by a feldspar-derived signal and grew well with laboratory dose. Palaeodoses (D_e) were measured using the SAR protocol (Murray and Wintle, 2003) with a pre-heat of 220°C for 10 seconds experimentally determined via a dose recovery test. Final D_e values for each sample were based on the measurement of multiple aliquots and, as D_e

replicates were normally distributed and the scatter low, were calculated based on the mean De. Dose rates were based on elemental analysis measured by inductively coupled plasma spectroscopy (ICP) analysis for the core samples and *in situ* gamma spectroscopy using an EG&G Micronomad for the samples from sections. Palaeomoisture contents were based on present-day values with ± 5% error to allow for past fluctuations. OSL data, ages and their calculated errors are shown in Table 1. These show good down-core increases with age with large temporal jumps associated with logged stratigraphic changes. There is also good correlation between the lower part of the dune core, the inter-dune core and the upper part of the Drain 1 site (Fig. 1, 2).

The new OSL ages in conjunction with previously published Breckland drift-sand ages (Table 2) were analysed to provide a more complete chronology of the drift sand activity in the core of Breckland (n=29). This was undertaken using cluster analysis using the finite mixture model of Galbraith and Green (1990) with a sigma b value of 0.19 based on the mean age uncertainty of these OSL data.

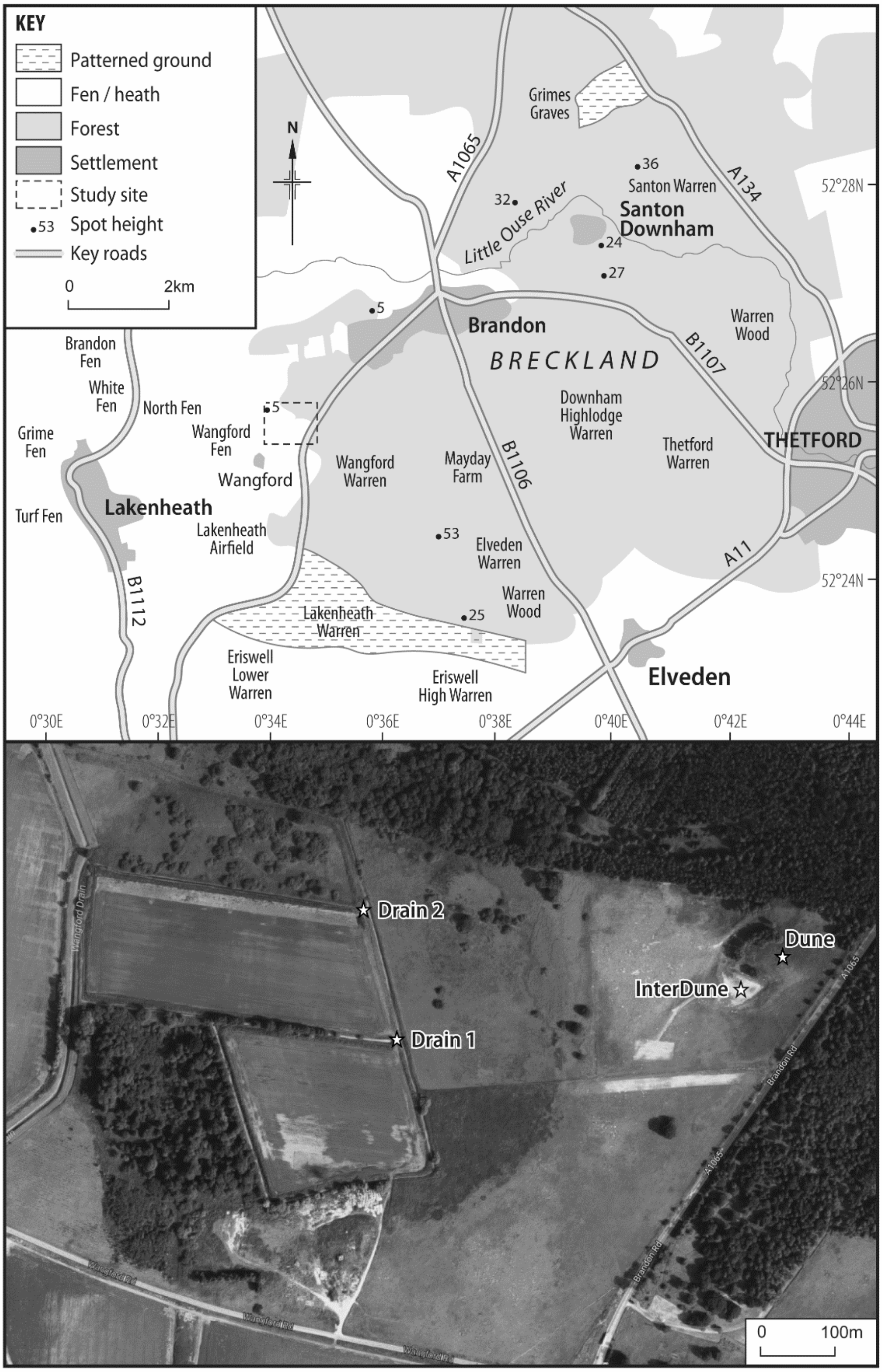

Fig. 2 . Wangford Warren samples sites and other Breckland drift sand sites mentioned in the text.

Table 1
OSL ages and associated information from the drift sands found at Wangford Warren.

Stratigraphic position	Lab code	Depth (m)	Water content (%)	β dose rate (Gy/ka)	γ dose rate (Gy/ka)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	D_e (Gy)	Age (ka)	Age (yrs)
Dune	Shfd08093	0.6	5.8	0.632 ± 0.023	0.271 ± 0.054	0.194 ± 0.010	1.107 ± 0.060	0.07 ± 0.06	0.06 ± 0.06	1948 ± 60 AD
	Shfd08094	1.6	6.3	0.645 ± 0.017	0.206 ± 0.029	0.181 ± 0.009	1.042 ± 0.035	0.25 ± 0.06	0.24 ± 0.06	1768 ± 60 AD
	Shfd08095	2.78	5.2	0.653 ± 0.021	0.347 ± 0.073	0.159 ± 0.008	1.169 ± 0.076	0.27 ± 0.03	0.23 ± 0.03	1778 ± 30 AD
	Shfd08096	3.5	4.3	0.707 ± 0.018	0.365 ± 0.034	0.151 ± 0.008	1.233 ± 0.039	0.28 ± 0.01	0.23 ± 0.01	1778 ± 10 AD
	Shfd08097	4.15	6.6	0.670 ± 0.015	0.360 ± 0.067	0.139 ± 0.008	1.179 ± 0.069	0.26 ± 0.02	0.22 ± 0.02	1788 ± 20 AD
	Shfd08098	4.62	5.4	0.642 ± 0.021	0.226 ± 0.030	0.187 ± 0.009	1.065 ± 0.038	1.53 ± 0.03	1.40 ± 0.06	608 ± 60 AD
	Shfd08099	5.55	3.6	0 600 ± 0.020	0.203 ± 0.025	0.165 ± 0.008	0.978 ± 0.033	1.35 ± 0.02	1.38 ± 0.05	628 ± 50 AD
	Shfd08100	5.75	10.9	0.576 ± 0.016	0.202 ± 0.033	0.168 ± 0.008	0.956 ± 0.038	1.57 ± 0.03	1.64 ± 0.07	368 ± 70 AD
	Shfd08101	6.3	14.6	0.491 ± 0.015	0.261 ± 0.044	0.189 ± 0.009	0.951 ± 0.048	8.70 ± 0.29	9.15 ± 0.55	7140 ± 550 BC
	Shfd08102	6.55	12.6	0.480 ± 0.037	0.235 ± 0.083	0.192± 0.010	0.917 ± 0.092	15.09 ± 0.63	16.5 ± 1.8	14500 ± 1800 BC
	Shfd08103	6.73	13.8	0.516 ± 0.029	0.249 ± 0.70	0.188 ± 0.009	0.963 ± 0.077	15.25 ± 0.48	15.8 ± 1.4	13800 ± 1400 BC
Inter-dune	Shfd08104	0.4	11.6	0.526 ± 0.019	0.290 ± 0.058	0.199 ± 0.010	1.025 ± 0.062	1.27 ± 0.03	1.24 ± 0.08	768 ± 80 AD
	Shfd08105	0.6	19.3	0.473 ± 0.014	0.229 ± 0.056	0.196 ± 0.010	0.908 ± 0.060	1.53 ± 0.02	1.69 ± 0.11	318 ± 110 AD
	Shfd08106	0.9	9.6	0.541 ± 0.016	0.286 ± 0.056	0.200 ± 0.010	1.037 ± 0.059	8.14 ± 0.10	7.86 ± 0.46	5850 ± 460 BC
	Shfd08107	1.3	16.6	0.521 ± 0.013	0.375 ± 0.051	0.193 ± 0.010	1.099 ± 0.054	12.58 ± 0.56	11.44 ± 0.76	9400 ± 760 BC
	Shfd08108	1.6	13.5	0.499 ± 0.023	0.306 ± 0.022	0.189 ± 0.009	1.004 ± 0.033	15.91 ± 0.42	15.85 ± 0.68	13800 ± 680 BC
	Shfd08109	1.85	9.4	0.325 ± 0.011	0.175 ± 0.056	0.178 ± 0.008	0.688 ± 0.058	12.48 ± 0.42	18.1 ± 1.6	16100 ± 1600 BC
Drain 1	Shfd03091	0.65	2.5	0.304 ± 0.026	0.160 ± 0.010	0.193 ± 0.010	0.670 ± 0.029	7.80 ± 0.19	11.64 ± 0.58	9600 ± 580 BC
	Shfd03090	1.5	16.5	0.359 ± 0.030	0.188 ± 0.012	0.182 ± 0.009	0.743 ± 0.029	24.56 ± 0.74	33.0 ± 1.8	31000 ± 1800 BC
Drain 2	Shfd03092	1.5	8.5	0.246 ± 0.020	0.146 ± 0.009	0.172 ± 0.009	0.577 ± 0.024	16.84 ± 0.67	29.2 ± 1.7	27000 ± 1700 BC

3.2 Archaeological and historical evidence.

Breckland has a wide range of archaeological, historical and documentary information about the landscape and the sand drifting in it. A key early source were the reports from the archaeological excavations carried out on the Anglo Saxon village at West Stow since drift sand was shown to have covered it (West, 1985; Crabtree, 1989; 2012). Such archaeological records have been used here to provide *terminus post quem dates* (TPQ) when sand drifting occurred. From 1600 AD onwards, the eyewitness accounts of Wright (1668) and Evelyn (1952) were consulted to give an exact date for when and where these events occurred. The precision of these records is far greater than those obtainable from sedimentological/geomorphic evidence. For example, Thomas Wright's eye witness accounts of the Wangford Warren 'sand flood' allow pin-pointing this event to the single year 349 years ago (1668 AD) where OSL from adjacent dunes date it to ~420± 65 years ago (1520-1650 AD; Bateman and Godby 2004).

Table 2
Previously published OSL ages from Breckland drift sands (taken from Bateman and Godby 2004) and used with new data to establish regional phases of drift-sand.

Site	Lab Code	Depth (m)	OSL Age (ka)	Age (yrs AD/BC)
Wangford Warren Dune	Shfd99103	1.35	0.11 ± 0.04	1889 ± 40 AD
	Shfd99104	0.95	0.13 ± 0.07	1869 ± 70 AD
	Shfd99105	0.50	0.10 ± 0.05	1899 ± 50 AD
	Shfd99106	0.10	0.03 ± 0.03	1969 ± 30 AD
Wangford Warren inter-dune	Shfd99107	0.50	1.56 ± 0.26	1499 ± 260 AD
	Shfd99108	1.15	6.53 ± 0.54	4531 ± 540 BC
Wangford Warren Dune (site3)	Shfd00074	0.35	0.21 ± 0.04	1790 ± 40 AD
	Shfd00075	1.45	1.28 ± 0.17	720 ± 170 AD
	Shfd00076	2.15	1.12 ± 0.17	880 ± 170 AD
Sandton Downham	Shfd02077	2.70	0.34 ± 0.04	1662 ± 40 AD
	Shfd02079	3.30	0.40 ± 0.04	1602 ± 40 AD
	Shfd02078	3.60	0.53 ± 0.04	1472 ± 40 AD

In order to understand the societal context of when drift sands occurred, land exploitation strategies and levels, grazing pressure and landscape management were evaluated. Even though the historical sources are scarce and fragmented, especially for the earliest periods, they provide crucial information allowing societal changes to be correlated with geological events such as drift sand phases and general landscape instability. This research was carried out by compiling and collecting data from historical field books, animal stock accounts, manorial accounts, yield registers and price data found in published sources and at the Norfolk Records Office (NRO Norwich). The 16th, 17th and 18th century field books of Hilborough (NRO Norwich HIL 2/39 A 878 x 4; NRO, HIL 2/41, 882 x 6; NRO, HIL 3/27, 879 x 1.) were analysed for changing property structures. Historical animal possession was traced via two exceptional sources: the Blackbourn tax account of 1283 (Powell, 1910) and the Great Cressingham tithe accounts of 1624-1640 (Norfolk RO, PD 131/ 38.). Price data and indices were obtained from the agricultural series by Thirsk (1967). Population densities were derived from censuses that are available from the seventeenth century onwards and before that from tax registers and manorial accounts (Spufford, 1965; Bailey, 1989; Dyer and Palliser, 2005). The analysis of the historic Breckland economy was done by using price, cost and profit data (Postgate, 1960; Thirsk, 1967; Bailey, 1989). Finally, the state of the historical landscape drew on previous work undertaken by historical geographers and landscape archaeologists (Farrow, 1915; 1917; Watt, 1960; 1981a; 1981b; Williamson, 2007).

4. Establishing Breckland Sand drift phases

4.1 Geomorphic and sedimentological evidence

As shown in Fig. 3, the dune core revealed, under a thin (7 cm) immature podsol soil, an upper unit of 1.25 m of massive, medium to coarse well-sorted yellowish brown sand (10YR 5/6) with occasional flint fragments (Fig. 3). At 1.25-1.7 m, the sand has some laminar fine bedding, finer with increased silt and dark yellow (10YR 3/6). This unit OSL was dated to between 60 ± 60 and 240 ± 60 years old (Shfd08093 – Shfd08094). Below this the sediment comprised of 2.4 m-thick, massive, fine sand yellowish brown (10YR 5/4) to dark yellowish brown (10YR 4/6) in colour all dating to ~230 ± 30 years ago (Shfd08095 to Shfd08097). Within this, at 2.9 m depth and beneath a sharp boundary, there was a 3 cm-thick layer of mottled (10YR 4/2) sand. At 4.1 m depth a 20 cm-thick organic-rich sand was encountered (10YR 3/2 very dark greyish brown). Beneath this a 1.5 m-thick unit of massive well-sorted medium to coarse sand yellowish brown (10YR 5/4) sand with some layers of iron mottling. This had OSL an age of ~1.40 ± 0.06 ka (Shfd08098 and Shfd08099). At 5.6 m, a 10 cm-thick depth dark yellowish brown (10YR 3/4) organic-rich sand was cored with a second 5 cm-thick unit encountered at 5.75 m. Between this was a complex intercalation of fine silty sand with some organic material dating to 1.64 ± 0.07 ka (Shfd08100). From 5.75 m was medium sand with an OSL age of 9.15 ± 0.55 ka (Shfd08101) before two organic-rich units (15 cm and 10 cm) were encountered at 6.1 m and 6.4 m. Beneath 6.4 m the sand became medium to coarse grained brownish yellow in colour (10YR 6/6) and contained some pebbles (possibly ventifacts) and flint clasts. This sand unit was much older at between 15.84 ± 1.36 and 16.45 ± 1.79 ka (Shfd08102-Shfd08103).

The inter-dune core comprised of an upper 45 cm-thick fine to medium sand unit 10YR 5/4 (yellowish brown) in colour (Fig. 3). Locally this exhibited horizontal bedding and was OSL dated to 1.24 ± 0.08 ka (Shfd08104). At 0.5 m, a 10 cm-thick organic-rich sand was encountered beneath which the sand was fine to medium with some mottling. At 0.75 m a second organic unit, 5 cm thick, was found. This unit returned a radiocarbon age of 2380 ± 24 cal. years BP (UBA-12286), similar to that reported by Bateman and Godby (2004) from a nearby test pit of 1980 ± 140 cal. years BP (BETA141015). This is conformably bracketed by OSL ages of 1.69 ± 0.11 ka from the sand above it and 7.86 ± 0.46 ka from the sand below it (Shfd08105 and Shfd08106, respectively). A further sand unit (30 cm thick) terminated in a 20 cm-thick organic-rich sand which overlay a homogenous medium to fine sand (10YR 5/2, grayish brown) containing much coarser and less well-sorted sand with flint and pebbles inclusions. This was much older with OSL ages of 15.85 ± 0.68 ka and 18.14 ± 1.64 ka (Shfd08108 to Shfd08109).

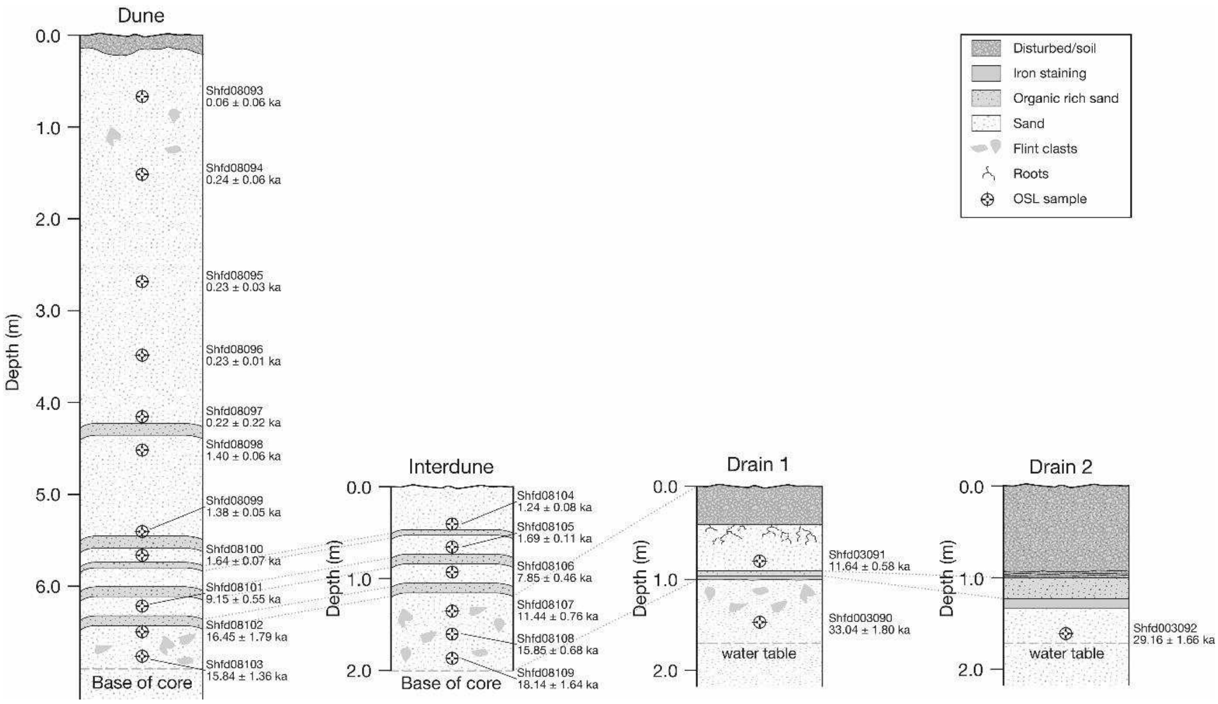

Fig. 3. Stratigraphic logs, OSL sample positions and derived ages for the cores and sections at Wangford Warren.

The uppermost sediment in Drain 1 had been disturbed by ditch clearing (Fig. 3). Under this was revealed an upper unit of medium to coarse sand (10 YR 3/2 light brownish gray) with some small granules. This was dated to 11.64 ± 0.58 ka (Shfd03091). This overlaid a 10 cm-thick organic-rich sand and a 10 cm-thick iron-stained mottled sand. The lowest unit, under a diffuse and irregular boundary to the above, was a medium to coarse brown (7.5YR 4/3) sand with flint clasts up to 5 cm in diameter. This was dated to 33.04 ± 1.80 ka (Shfd03090). The Drain 2 exposure beneath the disturbed sediment also had an organic-rich sand unit overlying a 10 cm-thick iron-mottled sand. The organic unit here was 25 cm thick with some fibrous content. The basal sand unit was a yellowish brown (10 YR 5/8) coarse sand from which an OSL age of 29.2 ± 1.97 ka (Shfd03092) was obtained.

In summary, at Wangford Warren, it would appear that at least two phases of sand drifting took place; the first around ~1400 years ago (600 AD) and the second around 220 years ago (1780 AD). Fen peat encroachment occurred at ~1700 years ago (300 AD) and a number of times between 7.9-9.2 ka. Beneath the organic units would appear to be the Late Pleistocene coversand sheet dating to between 18.5 – 11.4 ka fitting with the coversand ages found elsewhere (Bateman, 1995; Bateman et al., 2014). The lowest sand unit is much less well-sorted and much older (~39-33 ka) and is interpreted to relate the original fluvial sediment from which the coversand (and ultimately drift sand) was derived.

4.2 *Archaeological and historical evidence*

The archaeological excavations of the Anglo Saxon village at West Stow provided evidence of a major drift sand phase, since sand (over 1 m thick in places) covers the entire Anglo Saxon village and the ridge and furrows of surrounding agricultural fields (West, 1985; Crabtree, 1989; 2012). The sand drifting made ploughing or cultivation impossible, forcing the community to abandon the site altogether (*ibid)*. The ridge and furrow structures relate to a late medieval occupation providing a *TPQ* date for sand drifting of 1100-1200 AD (West, 1985; Crabtree, 1989; 2012).

A second sand drift phase was documented by the eyewitness report of Thomas Wright (1668). In this event around 1668 AD, up to 3 m of sand were deposited on the village of Downham, thereby subsequently known as Sandy Downham or Santon Downham. Sand even is reported to have blocked the nearby River Ouse (Wright, 1668). Sand drifting appears to have originated at Wangford Warren but within a decade the sand drifting had become active in other localities as well. Sand drifting in this event is thought to have affected an area of more than 400 hectares (Postgate, 1960).

While a number of sand-drifting phases clearly occurred in Breckland, records of lost settlements, covered fields, the creation of dune complexes in the heath lands, are missing in the period 1300-1600 AD. Whilst it is unlikely that no aeolian activity occurred during this period, this appears to have been a period of overall landscape stability.

4.3 Sand Drifting in the Breckland region

Analysis of the new and the pre-existing Holocene OSL data along with the archaeological and historical data sources find evidence for five regional phases of drift sand activity during the Holocene. The first is dated to 5240 ± 1040 years BC (7240 ± 1040 years ago). After this rapid accumulation of drifting sand, was a period in which deposition alternated between thin aeolian deposits and fen peat encroachment. The second drift sand phase took place at 600 ± 100 AD in which ~1.4 m of sand accumulated at Wangford Warren at around 6 mm/yr on average. This phase of sand drifting, with its creation of a new dune field, constitutes a significant shift of landscape stability with the dune complex remaining a source of future sand drifting. The third and fourth sand drifting phases occurred at 1100-1220 and ~1600 AD respectively, affecting West Stow and Santon Downham. These two phases are also thought to be significant as they are known to have destroyed productive agricultural land and inundating villages. Breckland data do not refer to any invasive drift sand phases between 1300-1600 AD that appears to have been a period of relative landscape stability in which a podzol layer had time to develop at Santon Downham (Bateman and Godby, 2004). Finally, a phase at 1790 ± 25 AD is recognised in which 2.44 m of sand was deposited at Wangford Warren at ~17 mm/yr. Whilst no evidence was found for new dune fields it shows a significant growth of landscape instability.

Table 3

Summary of Breckland Drift-sand phases based on cluster analysis of both new and previously published OSL ages as well as archaeological data.

Event	Timing (years BC/AD)	Source of Evidence	Notes	Ecological resilience
1	5200-6280 BC	OSL -Wangford Warren		
2	500-700 AD	OSL -Wangford Warren	6mm/yr sand accumulation,	Shift of ecological stability domain
3	1100-1200 AD	TPQ from archaeology at West Stow	1 m of sand covering agricultural fields	Shift of societal and ecological stability domain
4	1515-1645 AD	OSL - Wangford Warren and Sandton Downham. Regional historical evidence	3 m of sand covering buildings	Shift of societal and ecological stability domain

5	1765- 1815 AD	OSL - Wangford Warren	17 mm/yr. sand accumulation	Expansion of existing dune site, constant resedimentation afterwards

To sum up, Breckland, experienced distinct phases of heightened landscape instability in between long periods of relative landscape stability (Table 3). As can be seen in Fig. 4, these phases of regional Breckland drift sand activity diverge from other regions within the general European drift sand belt and add to the evidence that conditions conducive to sand drifting in north-west Europe were at the regional scale (Pierik et al., 2018).

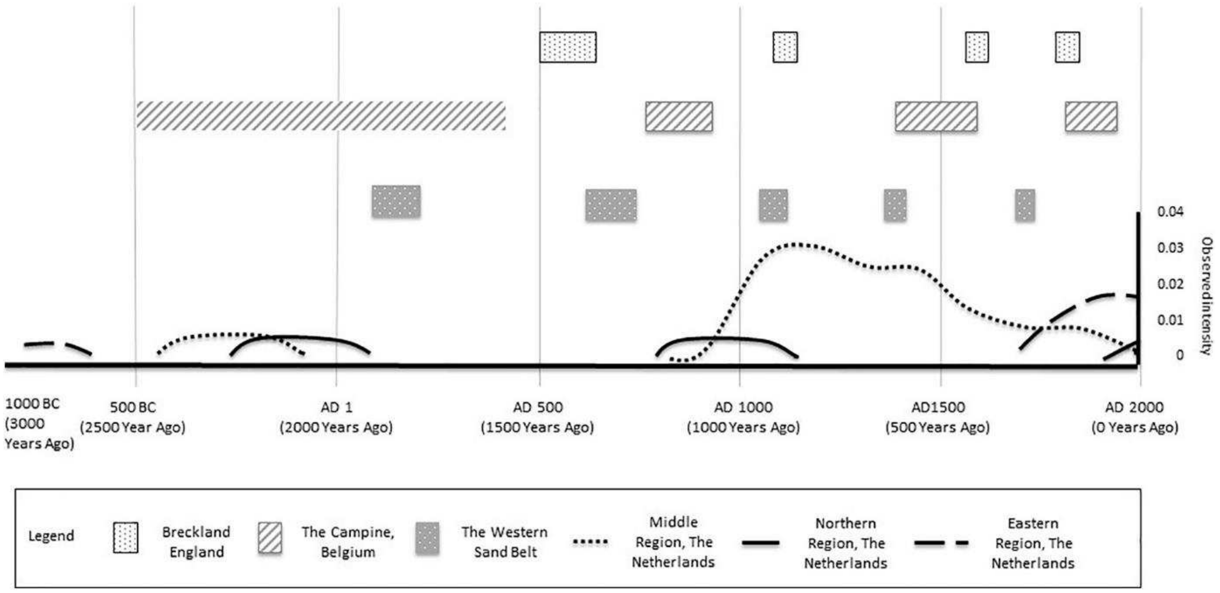

Fig. 4. Drift sand phases in the Western Coversand Belt reconstructed for the last 3000 years. The dotted, striped and full lines represent observed sand activity determined by OSL studies (Source: Pierik et al. (2018). The bars show drift sand phases without any indication of intensity. Data based on this study, Bateman and Godby, (2004); Tolksdorf and Kaiser, (2012); De Keyzer, (2016); Pierik et al. (2018).

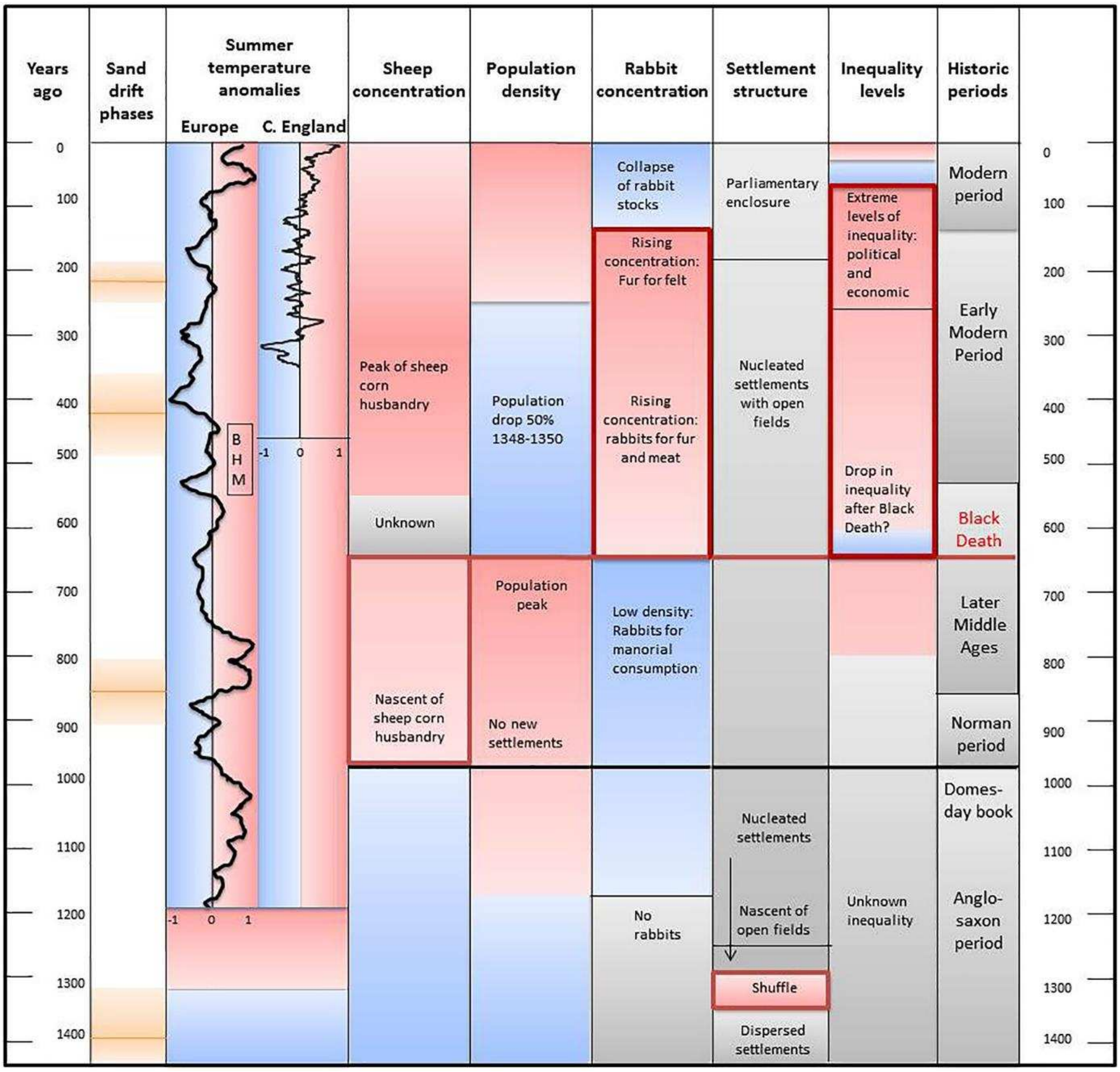

Fig. 5. Scheme showing the Holocene Breckland drift sand phases alongside the climate, agricultural and societal changes through time. Coloured version is available online. Orange fills show the drift sand phases with error margins. The temperature anomalies are based on Luterbacher at al. (2016) and the central England temperature series (Manley, 1974; Parker et al., 1992; Parker and Horton, 2005). Red fills indicate high or rising levels of agricultural or societal variable, blue fills shows low or declining levels. Grey fills refer to a lack of information or the absence of a factor. The red borders around certain fields, indicate strong correlation with sand drifting. The Black Death and date of Domesday Book are indicated as relevant historical dates. The right bar shows the historical periods.

5. Discussion

The new data presented above clearly indicate distinct phases of landscape instability and sand drifting with different regions active at different times. Koomen et al. (2004) proposed that the drift sands of the Veluwe (Netherlands) region arose as a direct result of an autonomous geomorphological process. It is thought that drift sand could only start to move by entrainment when wind velocity was above ~3 m s^{-1} (Warren, 1979), the sediment surface was bare and no wind breakers existed to interrupt wind flow (Koster, 2010). Whilst a wide range of climate related triggers have been debated, such as droughts, warm and cold spells or changing water tables (e.g., Jungerius and Riksen, 2010) the exact relationship of drifting sand and climate is not clear. A comparison was made of the newly determined Breckland drift sand phases with the Central England Temperature record (Manley, 1974; Parker et al., 1992; Parker and Horton, 2005), the England and Wales precipitation record (Wigley and Jones, 1987; Gregory et al., 1991; Jones and Conway, 1997; Alexander and Jones, 2001) and the European temperature anomaly record (Luterbacher et al., 2016). The UK climate data shows dry periods around 1780, 1800, 1850 and 1890 AD (Fig. 6a) , a clear cooling event centred on 1690 AD, small cooling events at around 1740, 1760, 1810, 1840 and 1880 AD and a particularly warm period centred around 1730 AD (Fig. 6b). Fig. 6c shows extreme warm and dry weather around 1895 and 1940 AD, and cool and dry weather around 1800 and 1880 AD. The 1668 AD flood in Santon Downham and sand movement at Wangford appears to have coincided with a cold spell. Likewise, the Wangford Warren drift phase around 1790 AD coincided with a cool period around 1800 AD. The sand inundation at West Stow appears to have coincided with a warmer period measured between 1100-1200 AD (Luterbacher et al., 2016). The drift sand phase of 600 AD is more difficult to link with weather extremes but coincides with the end of the cooling period between 300 and 500 AD (Fig. 5; Luterbacher et al., 2016).

Whilst there appears some coincidence of Breckland sand drifting with climatic extremes, sand drifting appears to have coincided with both dry/wet and cold/warm events. Additionally, similar or extreme climatic events do not appear to have triggered sand mobility in Breckland, e.g. the warm periods around 1740 AD or the dry period around 1780 AD. This is a similar finding to comparative research within the wider European cover sand belt (Pierik et al., 2018). This shows similar climatic shifts, or weather extremes led to diverging reactions in terms of drift sand stability in different regions. In the Belgian Campine, Camenisch (2015) reported extremely cold winters in the 1430's and in 1407/1408 AD but these times were characterised by stabilised sand dunes and decreased sand mobility (De Keyzer, 2016). Similarly, the coldest winters and weather extremes during the seventeenth century Maunder Minimum appear to have had no fundamental effect on the Campine dunes (ibid).

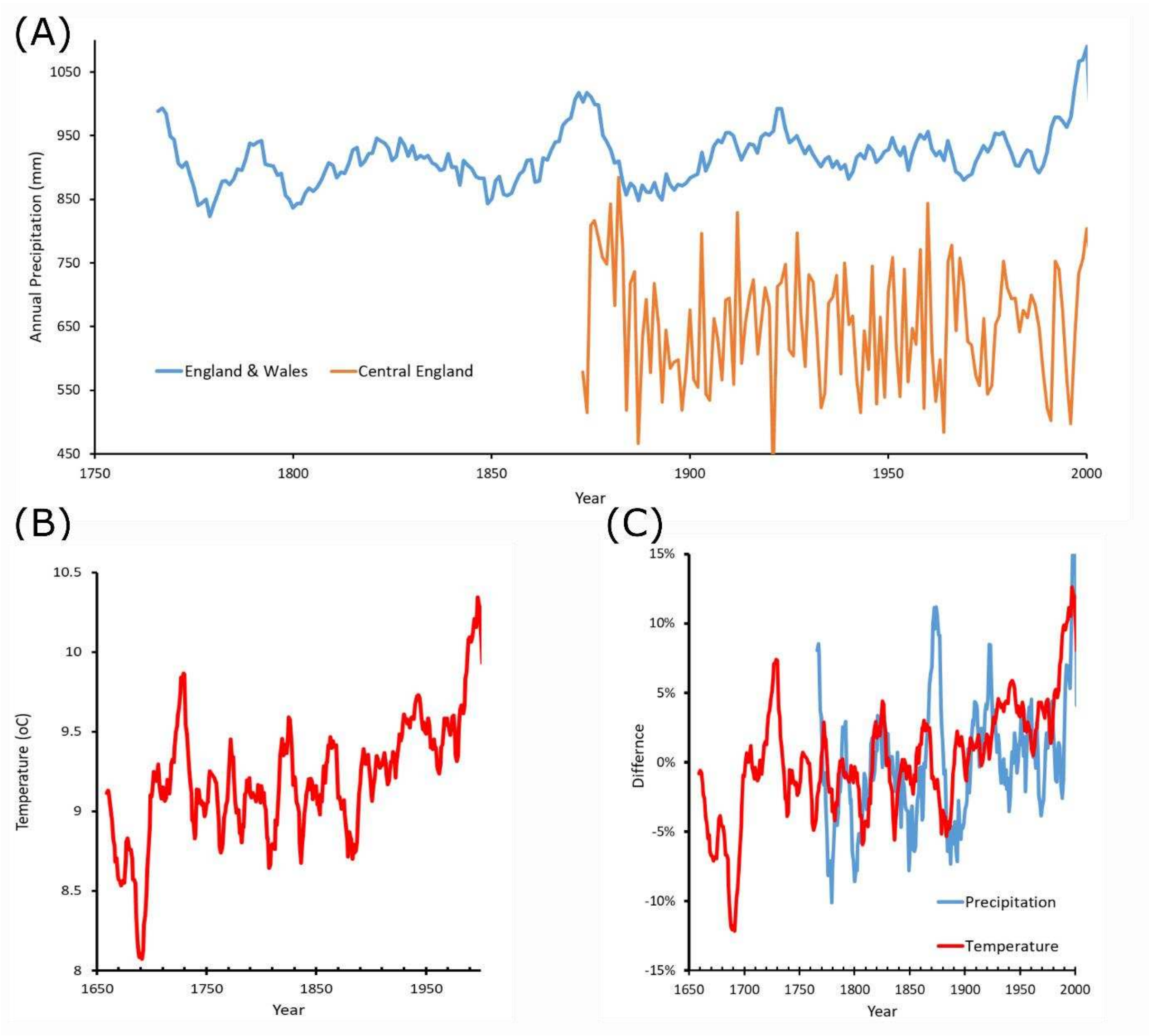

Fig. 6. Historical climatic data (A) both annual precipitation for both England and Wales and Central England (with a 10-year filter); (B) annual average temperature for Central England (with a 10-year filter) (C) deviation of precipitation and temperature from long-term averages.

Late Holocene landscape instability and drift sand phases might also be a regional response to intensification of agricultural exploitation and increased population densities (Castel, 1991; Koster, 2007; Derese et al., 2010; Heidinga, 2010; Tolksdorf and Kaiser, 2012). In the Breckland region, there is a coincidence of the 1100-1200 AD drift-sand phase with rising population and landscape pressures because of an economic boom. For example, in Chippenham (Cambridgeshire) the recorded population soared from 32 recorded tenants in 1061 to 143 tenants in 1279 (Spufford, 1965). At the same time, commercial sheep breeding had become firmly established with >70% of households possessing sheep and an average 760 sheep per village roaming the surrounding open fields and heathlands (Table 4) (Powell, 1910). However, it appears that the sand drift phase of 600 AD occurred just before an intensification process, when population densities were relatively low, and not significantly higher than the preceding centuries (see **Error! Reference source not found.**; Higham, 2010; Rippon, 2010). Likewise, during the sand drift phase ~1580 AD, there was an economic recession, arable land usage was shrinking and population densities were at their lowest point since the later Middle Ages with many deserted villages (**Error! Reference source not found.**Postgate, 1960; Spufford, 1965; Thirsk, 1967). Also the period when the Breckland landscape is thought to have been stable (1300-1600 AD) includes the period 1500-1600 AD when landlords developed huge flocks of sheep and started to enlarge their rabbit warrens (**Error! Reference source not found.**; Allison, 1957; Postgate, 1960; Bailey, 1990; Williamson, 2007). Thus, whilst some drift sand phases coincide with increases in population or intensification of agriculture, not all do. Again, the same can be seen elsewhere in Europe. In The Netherlands during the Roman period (56 years BC – 400 year AD), when pressure on the landscape was high (based on population densities and deforestation levels), sand drift activity was reduced (Pierik et al., 2018). In the Belgian Campine drift sands were most significant before 1300 AD when land exploitation and population levels were low (De Keyzer, 2016).

It would appear that even at the regional level climate, land usage and population levels may not be the direct cause of Late Holocene sand drifting. Complex responses or different triggers were responsible at different times. This having been said, one commonality observed is that changes in Late Holocene landscape stability and instability appear to have coincided with reorganisations of societal structures or when a shift in land management took place. In Breckland, the sand drift phase of 600 AD coincides with a time when two centuries of relative social stability, moderate population levels and dispersed settlements changed. Around 600 AD, the population rose and isolated farms became clustered into nucleated village centres. Additionally, new land was exploited through the implementation of an agricultural open field system while older areas were abandoned (see "settlement shuffle" **Error! Reference source not found.**; Rippon, 2010; Higham, 2010). The drift sand phase of ~1580 AD can also be traced to coinciding with a reorganisation of society and changes in land use management. As exemplified by the Parish data from Hillsborough before 1550 AD, Breckland communities owned diverse range of sizes of land from smallholders (<5 ha) through to large estates (>10 ha; Fig. 7). By 1700 AD this had changed, with small holdings increasing from 27% to 55% and most of the remainder (39%) being large estates (Fig. 7). Additional to this, by 1600 AD advantages of scale had led to the establishment of huge warrens (up to 1000 acres) by landlords. This was due to a rising demand, yet falling price of rabbits relative to the cost of living. Profit levels could only be maintained by scale enlargement (Fig. 8; Postgate, 1960; Sheail, 1978; Williamson, 2007). Landscape stabilisation around 1300-1600 AD in Breckland coincided with the population reduction after 1348 AD caused by Black Death, harvest failures and sheep pestilence (Spufford, 1965; Slavin, 2012) which led to significant agricultural and societal changes. Peasant sheep ownership dwindled and the late Medieval crisis led to more moderate animal stocks which reduced the pressure on the landscape (Spufford, 1965; Bailey, 1989; Slavin, 2012; Campbell, 2016). Such major reorganisation periods have been pinpointed for other NW European drift sand events. For example, the abandonment of Celtic fields or the relocation of settlements coincides with drift sand phases in the Netherlands (Roymans and Gerritsen, 2002; Spek et al., 2003; Pierik et al., 2018).

Table 4

Sheep and cattle numbers in the Blackbourn hundred in 1283 AD based on data from Powell (1910).

Village	Taxed households	Total sheep	Average sheep per household	Sheep owning households in village (%)	Total cattle	Average cattle per household	Bovine owners of taxed households (%)

Troston	33	612	19	42	109	3	97
Livermere Parva	27	649	24	52	54	2	78
Honington	38	197	5	61	97	3	79
Ingham	29	1019	35	62	135	5	79
Weston	40	215	5	68	158	4	98
Fakenham Magna	19	932	49	68	62	3	74
Barningham	55	255	5	69	186	3	93
Wordwell	20	466	23	70	54	3	80
Bardwell	127	1313	10	71	456	4	81
Euston	34	1103	32	76	112	3	97
Knettishall	28	345	12	79	151	5	89
Culford	21	599	29	81	67	3	86
Sapiston	29	650	22	83	110	4	90
Barnham	47	2523	54	92	193	4	83
West Stow	21	1097	52	95	76	4	91
Rushford	10	191	19	100	43	4	100
Average	**36**	**760**	**25**	**73**	**129**	**4**	**87**

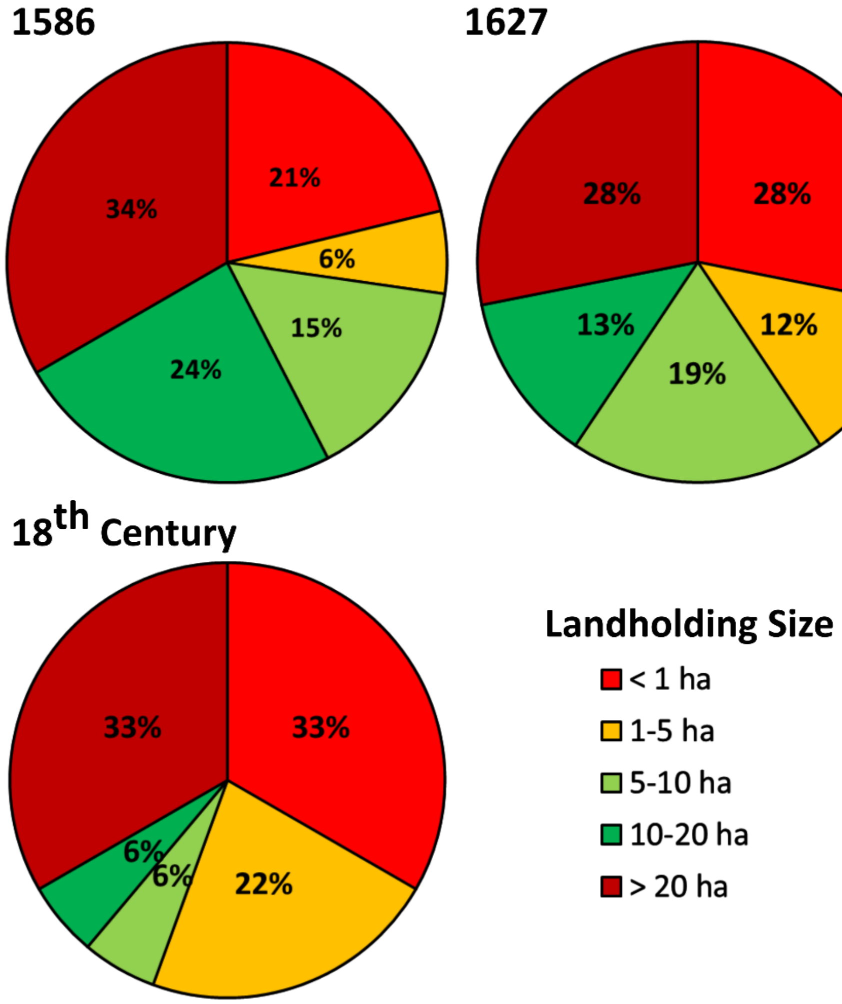

Fig. 7. Changes in Landholding sizes from 1586 to the eighteenth century in Hilborough (Norfolk) showing decrease in landholdings between 5-20 ha. Based on parish record data from Norfolk Record Office (Norwich); HIL 2/39 A 878 x 4; NRO, HIL 2/41, 882 x 6; NRO, HIL 3/27, 879 x 1.

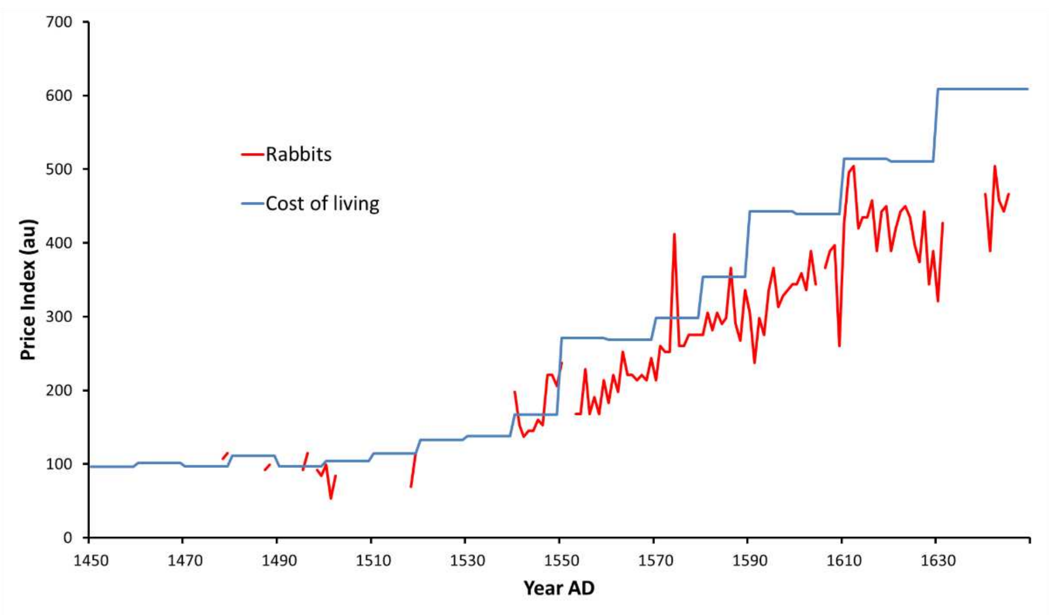

Fig. 8. Price index of rabbits compared to the cost of living based on data from Thirsk (1967). Price index takes 1450 AD as 100.

The impact of societal re-organisation and land use and land management changes could have triggered landscape instability by preventing hazard mitigation. Once drift sands were recognised as a hazard, mitigation strategies to prevent drifting sand required investments in plantations, hedges as wind breaks and in the cultivation of fodder for sheep and rabbits by either large land owners (landlords) or through communal action (De Keyzer, 2016). In Breckland, the implementation of an open field system on virgin lands around 600 AD would have taken away vegetation, uncovering the soil for at least part of the year. Added to this, the Breckland landlords chose to create fields without windbreaks. This was because their animal flocks required free movement to and from arable plots and open common heathlands which the planting of hedges would have restricted (Allison, 1957; Postgate, 1962; Sheail, 1979; Bailey, 1990; Whyte, 2011). Likewise, in the period around 1600 AD, the increased number of poor households (Fig. 7) and increased polarisation of society in terms of wealth (Fig. 5) made it much harder for communities to co-ordinate action to prevent sand drifting. At the same time, as sheep and rabbits could be grazed just as profitably on heathland vegetation and degraded land unfit for arable production, a degraded or unstable landscape did not fundamentally hinder the commercial activities of the landlords who owned rabbit warrens and flocks of sheep. As a result, landlords were less inclined to invest in the landscape and prevent sand drifting and degradation of the soil. Related to this, it has also been attested that a lack of sufficient fodder became common in rabbit warrens around 1600 AD (Postgate, 1960). Therefore, when extreme cold spells occurred, increased numbers of rabbits strayed from their warrens looking for fodder, leading to vegetation stripping and enhanced vulnerability to wind erosion of agricultural fields beyond the warrens (Farrow, 1917; Watt, 1960; 1981; Sheail, 1979; Dolman and Sutherland, 1992). This way, the recurrent drifting of sand occurred until around 1850 AD when windbreaks were finally planted and wealthy landlords invested in woodlands for hunting. Large-scale state reforestation initiatives from 1900 AD onwards finally stabilised most of the Breckland landscape (Postgate, 1960).

6. Conclusions

- New and existing Breckland OSL data clearly show a late Pleistocene coversand sheet, dating to 18.5 – 11.4 ka, underlies the drift sands. Five phases of drift sands were identified at 5240 ± 1040 years BC, 600 ± 100, 1100-1200, 1580 ± 65, and 1790 ± 25 AD. Of these, significant thicknesses of sand accumulated during the latter three phases.
- Differences in the timing of landscape instability exist between different regions within the European drift sand belt.
- Whilst there appears some coincidence of sand drifting with past climatic extremes, no clear pattern or trends are observed with drifting occurring during dry or wet, cold or warm periods. Additionally similar climatic shifts led to diverging reactions of landscapes in different regions throughout Europe.
- It would appear that even at the regional level, land usage and population levels may not be the direct cause of sand drifting, and that complex responses or different triggers at different times were responsible.

- Society's unawareness of the inherent landscape instability and the threat posed by the sand hazard may have been important as it affected whether mitigation measures were or could be implemented. In Breckland, initial instability may have been due to the establishment of the open field system on virgin soil. Later changes in land ownership and associated power within the society along with up-scaling of sheep and rabbit rearing led to the inability of communities to implement mitigation measures and large land owners abstaining from tackling the sand hazard.
- Whilst the widespread coversands and climatic extremes provide the underlying susceptibility to sand drifting, it would appear that drift sands of the last 2000 years provide less of a sedimentary archive of Late Holocene climatic changes and more a record of land management changes.

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