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Late-Holocene Inland Dune Activity in the UK: A case study from Breckland East Anglia.

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Abstract

Inland dune fields found in Breckland, East Anglia, UK have previously been correlated with the widespread Late-Devensian coversands of the region and a seventeenth century 'sandflood' which is known to have inundated the village of Santon Downham. A programme of optically stimulated luminescence and radiocarbon dating undertaken on the dunes at Wangford Warren and Santon Downham, reveals that episodic aeolian activity has taken place during the last 7000 years. Five sand depositional phases on Breckland dunes are identified: *c.* 6500, *c.* 1600-1100, *c.* 500, *c.* 400-335 and from *c.* 200–30 years before present. Between *c.* 2120-1840 years ago and within the period 1100-300 years ago quiescent periods allowed the development of Fen peat and soils. Local controlling factors on aeolian activity in Breckland appear to be related to anthropogenic activities and livestock (sheep and rabbits) reducing vegetation cover, and decreased precipitation and sea-levels which led to lowering of water-tables. Breckland aeolian activity, when compared to the national and sub-continental Holocene aeolian activity record, shows a high level of concordance. The underlying forcing factor for Late Holocene dune activity in the UK and elsewhere in Europe appears to be climatic instability in the North Atlantic, associated with both the 'Little Ice Age' and previous similar events which led to increased storminess, climatic variability and lower temperatures.

Keywords: Inland aeolian dunes, coversand, luminescence dating, Breckland.

Introduction

Perrin *et al.* (1974) and Catt (1977) revealed that the UK has an extensive (if somewhat fragmented) and varied range of aeolian derived sediments and geomorphic features including loess (e.g. Parks and Rendell 1992), coversands (e.g. Bateman 1995), mountain top sand sheets (Ballantyne 1998) and both coastal and inland dune systems (e.g. Matthews 1970; Bailey et al 2001; Wilson et al 2001). In addition, ventifacts and associated desert pavements have also been reported (e.g. Edwards 1936; Hoare *et al.* 2002). The UK is by no means unique in having such a relict aeolian record, as in large parts of eastern France, Germany, Poland and the Baltic states coversands are prevalent (e.g. Högbom 1923; Koster 1988; Zeeberg 1998) whilst loess is found in France, Belgium, Germany and widely throughout eastern European countries (e.g. Rousseau *et al.* 1998; Frechen *et al.* 1997; Frechen 1999). Similarly, there are numerous inland and coastal dune systems in France (e.g. Clarke *et al.* 2002), The Netherlands (e.g. Castel 1991), Poland (e.g. Kozarski and Nowaczyk 1991), Denmark (e.g. Clemmensen *et al.* 2001) and Finland (e.g. Käyhko *et al.* 1999). Many of these contain important information concerning former wind and circulation patterns as well as more general palaeoenvironmental information. As the controlling factors responsible for the different aeolian features vary, the latter offer the potential to differentiate between deposit/site specific factors and more pervasive factors affecting aeolian deposits at the regional or sub-continental scale.

This paper focuses on the UK inland dune record, specifically from Breckland, East Anglia (Fig 1). Through a programme of optically stimulated luminescence (OSL) and radiocarbon dating used in combination with a range of other evidence the aeolian activity history of Breckland from mid-Holocene to present is reconstructed. The causal factors for this regional activity are then discussed in the context of aeolian records both at a national and sub-continental scale.

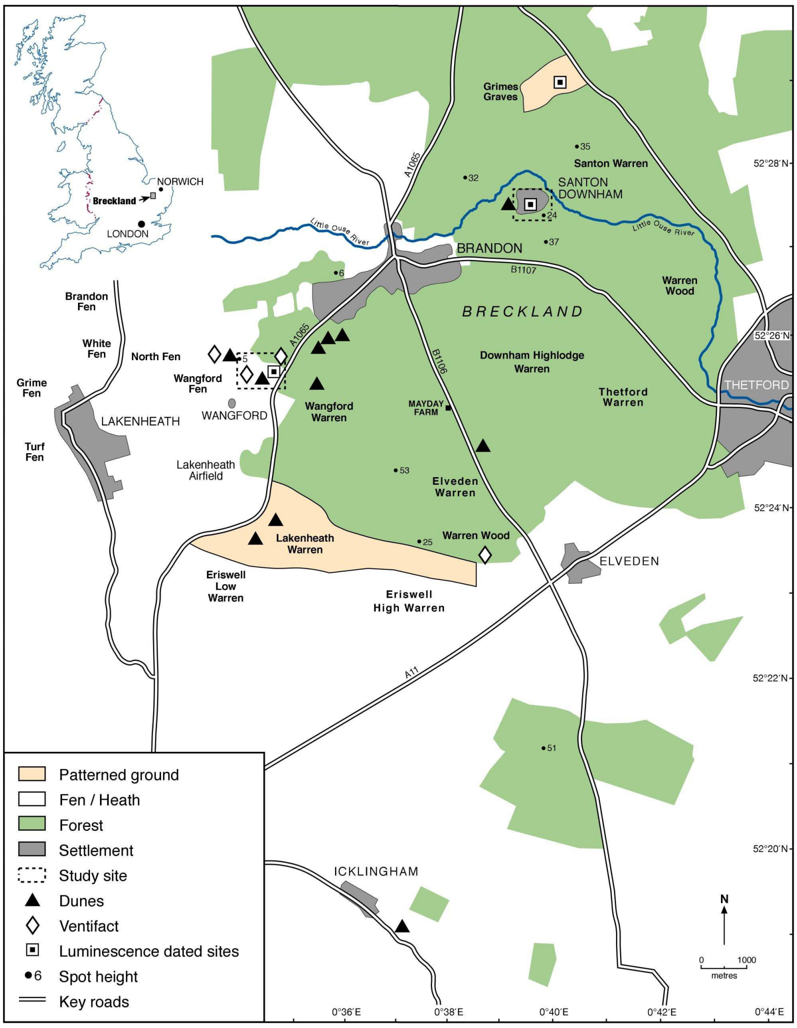

Figure 1: Site Location map of Wangford Warren, Santon Downham and Thetford Forest in Breckland, East Anglia. Ventifacts sites as reported by Whitaker (1891) and Corbett (1973) and SPG 2001, Grimes Graves site as reported by Bateman (1995) and patterned ground as reported by Corbett (1973).

Study Area

Breckland, East Anglia

The Breckland region encompasses approximately 1,036 km^2 of north-west Suffolk and south-west Norfolk (Fig 1; Corbett 1973). It is a gently dissected Upper Cretaceous Chalk plateau lying at an altitude of 30-45 m OD which is bounded to the west by the thick peat and silt deposits of the low lying Fens. The sandy soils of the area are derived, certainly in part, from Late Pleistocene aeolian sand which once formed a coversand sheet across the region (e.g. Chorley *et al.* 1966; Bristow 1990; Bateman 1995; Clarke *et al.* 2001). These coversands, up to 2.5 m thick (Watt *et al.* 1966), are now largely preserved only by their incorporation into periglacial structures, e.g. involutions at Brandon (Corbett 1973; p. 9) and stripes at Grimes Graves (Bateman 1995). Much of Breckland has undergone extensive disturbance by human endeavours but sporadic dunes on top of these coversands, including two dune fields at Wangford Warren and Icklingham (Figs 1-2), have survived throughout the region.

Breckland, at present, has a pronounced continental-type climate with a mean annual temperature of 10 ^{o}C. Monthly averages range from 3.4 ^{o}C in January to 16.8 ^{o}C in July. Breckland is also very susceptible to low night-time temperatures so that no month is completely frost free (Corbett 1973). It is one of the driest regions in Britain with an average annual precipitation less than 600 mm (Corbett 1973). It is particularly dry in spring/early summer months when, on average, less than 50 mm of precipitation is received (*ibid*). The low precipitation, coupled with the free-draining sandy soils and losses through transpiration and evaporation, leads to a significant negative soil moisture budget. Thus the climate, low relief and pre-existing aeolian superficial sediments all provide conditions favouring aeolian activity.

Archaeological excavations suggest that Breckland inland dunes have been sporadically active on a number of occasions throughout the Holocene, although the timing of these events is only broadly known. Mesolithic artefacts have been found on dunes and within interdunal sand on the Lakenheath airbase (Jo Caruth pers. com.) whilst excavations in Cavenham Mere (TL 7645 7070) found aeolian sand sealing Neolithic deposits and a Roman settlement (*ibid*). In addition, there are a number of historical accounts of dune activity which have been described by several eminent travellers (Evelyn 1677; Gilpen 1805). The first recorded sand blow was at Thetford in the eleventh century, with others recorded at West Stow in the thirteenth century (Postgate 1961 in Sheail 1978). Another extensive sand blow occurred around Wangford and Lakenheath Warrens and lasted more than 40 years in the early part of the seventeenth century (Wright 1668). In this event the village of Santon Downham, 8 km southwest of the source was buried to a depth of at least 2.75 m (*ibid*). More recent and localised aeolian activity in Breckland has also been recorded, especially in the Wangford area (Whitaker 1891, Clarke 1937). Examination of aerial photographs of the area show that sand movement was taking place at a number of nearby locations as recently as 1958 (Figure 3). Later photographs show declining areas of bare sand indicating increased stability of the dunes.

Figure 2: View of part of the dunefield at Wangford Warren showing the location of sites 1-3.

Despite being referred to in various publications (e.g. Williams 1968; Catt 1977) no detailed work has been carried out on these dunes. Wright (1668) recorded to the seventeenth century sandflood described above and that remnants survived this event. Goudie and Gardner (1985), based on field observations, attributed the original formation of this inland dunefield to sand blown out from till during the last glacial phase (Dimlington Stadial) 18,000 years BP. They attributed the most extensive blow out on the Wangford Warren site to the seventeenth century sandflood event (see above). They also alluded to a possible third phase, based on the reporting of a buried soil. If the dunes were formed from Late Devensian sand derived from till, this would correlate them with the widespread Breckland coversand deposits (e.g. Chorley *et al* 1966) which recent thermoluminescence dates from nearby Grimes Graves have shown to have accumulated around 14,500 years from the present day (Bateman 1995).

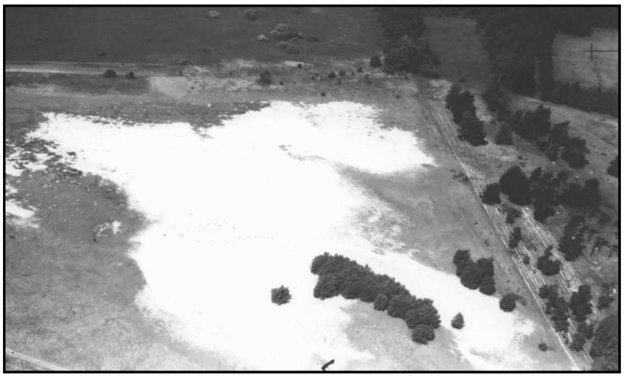

Figure 3: Oblique aerial photograph of Wangford Warren taken in 1953. Note the extensive amount of exposed sand which is not connected to the later practise of artificially rotovating part of the site clear of vegetation. Crown Copyright, reproduced with kind permission of the Ministry of Defence (1958).

Wangford Warren

The inland dunefield at Wangford Warren [TL756842; 52^{o} 25’ N, 0^{o} 35’ E] is 5 m above ordnance datum (OD) and is bounded by the low-lying Wangford Fen to the west and the chalk plateau to the east (Figs. 1-3). The dunes rise approximately to 6 m above the surrounding countryside but as they are much dissected by blowouts and reworking, their orientation and form is difficult to determine. The dunes cover an area of approximately 0.8 km^2 and are probably a remnant of a much larger dune system which once extended between the settlements of Lakenheath and Brandon (Gilpen 1805; Whitaker 1891).

Santon Downham

The village of Santon Downham [TL817877; 50^{o} 26' N, 0^{o} 39' E] is located 3.5 km northwest of Brandon and adjacent to the Little Ouse river at a height of 24 m OD. Geological maps show the whole vicinity of the village to be covered with blown sand. Santon Downham is mentioned by Wright (1668) as having been overrun by windblown sand sometime around 1650. This sand buried walls approximately 2.75 m high, destroyed houses and, through the removal of the sand to maintain road access caused sand banks nearly 18 m high (*ibid*). Subsequent building and agrarian activity has destroyed much of this evidence but sporadic dunes (2-4 m high) do occur within the village and on its outskirts. In addition, the road leading to the remains of the old manor house passes through a sandy embankment. No previous work has been carried out on these features.

Methodology

Stratigraphy and sedimentology

Wangford Warren is a Site of Special Scientific Interest (SSSI); this status limited both the amount and extent of any excavations to reveal the site stratigraphy; however, detailed stratigraphic logging was undertaken at three sites (Figs 2 & 4). Site 1 was a pit excavated on the crest of the most prominent dune. Site 2, located at the lowest point of the dune system, was chosen in order to try and extend back the stratigraphy as far as possible. Site 3 was located on the degraded blowout scar depicted in Goudie and Gardner (1985, p. 99). In Santon Downham, construction of a new property provided a temporary (3.6 m deep) exposure into the crest of a dune very close to the ruins of the manor house described by Wright (1668; Fig. 4).

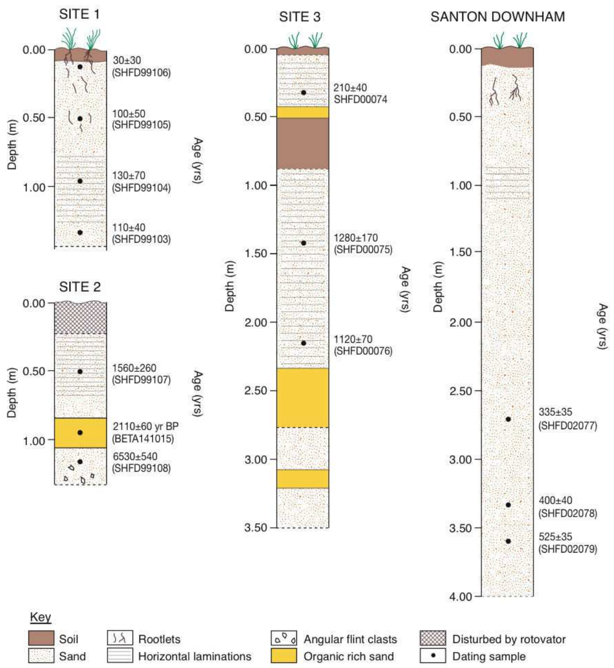

Figure 4: Stratigraphy of the sections logged at Wangford Warren and Santon Downham and the position of the samples collected for luminescence and radiocarbon dating. OSL ages (SHFD) in years before AD 2000 and uncalibrated radiocarbon age (BETA) in years before present (1950).

At each site, stratigraphic units were identified, described and sampled for loss-on-ignition (LOI). particle size and OSL dating. Details of stratigraphic units and OSL sample location for each site are presented in Figure 4. Correlation between the stratigraphical units of the logged sites at Wangford Warren was facilitated by augured transects between the three sites. A full survey of the Wangford Warren dune field not attempted because the dunes do not show clearly defined forms and are more akin to coalesced dunes with copious blowout scars. However, in order to give an idea of the magnitude of the dunes and to allow correlation of the site stratigraphy, a hillslope profile along the augered locations was surveyed (Fig 5).

All sediment samples underwent LOI to determine organic content (Gale and Hoare 1991) and particle size was determined using a Cilas 1180 laser diffraction system after a pretreatment in boiling hydrogen peroxide (20 Mols). For comparative purposes additional samples were collected and analysed for particle size from dunes near Mayday Farm and within Santon Downham (Fig 1) and from Late Glacial coversands at Grimes Graves (Bateman 1995) and Leziate (Hoare *et al*. 2002). The particle size and LOI results are shown in Table 1.

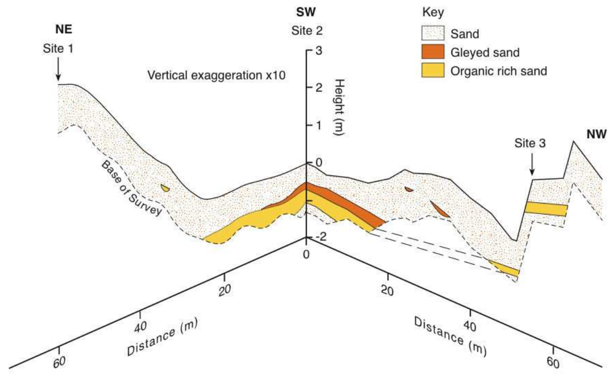

Figure 5: Combined results of the slope profile and auger transects survey from Wangford Warren site 1 to 2 and from site 2 to 3 with heights plotted relative to the ground surface of site 2.

Luminescence Dating

Extraction and purification of quartz from the samples followed the procedures of Bateman and Catt 1996. All samples were measured in a modified Risø TL-DA-12 luminescence reader fitted with a filtered 150 W Halogen lamp. The purity of the quartz extraction was tested using infrared stimulated luminescence, and no samples showed any signs of feldspar contamination. Equivalent doses (D_e) were determined using the single aliquot regenerative protocol (see Murray and Wintle 2000 for details). The D_e for each sample was interpolated from a five point regeneration curve. D_e values were calculated for a minimum of 12 repeat measurements per sample but only data where the ratio between the first and fifth points was within 0.9-1.1 (indicating adequate correction for sensitivity change) was used in the calculation of the final weighted (by variance) mean D_e.

Dose rates for each sample were based on data collected in the field with a EG & G MicroNomad portable gamma-spectrometer for the Wangford Warren sites and on the basis of inductive couples plasma spectroscopy for the Santon Downham site. The cosmic dose contribution was calculated using the equation given by Prescott and Hutton (1994). This will be an under-estimate for sample Shfd99106

Table 1: Particle size and loss on Ignition (LOI) data for Wangford Warren and selected aeolian deposits from the East Anglian Region.

Site	Unit Description	Depth (m)	Mean (M_z)	Sorting (σ_I)	Skewness (SK_I)	Kurtosis (K_G)	Sand (%)	Silt (%)	Clay (%)	LOI (%)
Wangford Warren	Sand	0.10	2.60	0.58	0.25	0.72	94.4	5.1	0.3	0.2
Site1	Sand	0.50	2.49	0.49	0.34	0.76	95.3	4.3	0.3	0.2
	Sand	1.35	2.58	0.53	0.33	0.75	94.8	4.7	0.3	0.2
Site 2	Sand	0.10	2.59	0.56	0.29	0.70	94.8	4.8	0.3	0.1
	Sand	0.50	2.53	0.51	0.30	0.78	95.0	4.6	0.3	0.1
	Organic rich sand	0.80	2.90	0.53	0.21	0.88	89.7	5.9	0.5	4.1
	Sand	1.15	2.48	0.60	0.35	1.05	93.5	5.9	0.4	0.2
Site 3	Modern Soil	0.10	2.26	0.93	-0.14	1.23	90.9	4.7	0.4	4.2
	Sand	0.20	2.32	0.98	-0.17	1.33	93.4	5.7	0.5	0.4
	Sand	0.30	2.28	0.98	-0.21	1.28	93.8	5.2	0.5	0.5
	Buried Soil	0.40	2.37	1.43	0.07	1.91	86.2	9.8	1.1	3.0
	Buried Bfe horizon	0.50	2.16	1.00	-0.12	1.04	93.6	5.1	0.5	0.9
	Sand	1.45	2.17	1.01	-0.11	0.74	95.0	4.3	0.3	0.4
	Sand	1.60	2.24	0.99	-0.12	1.13	93.6	5.5	0.5	0.4
	Sand	2.15	2.11	0.91	-0.13	0.93	98.4	1.0	0.3	0.3
	Buried Soil	2.45	2.40	1.15	0.01	1.53	89.2	9.2	0.6	1.0
Santon Downham	Sand	0.35	2.23	0.71	0.37	0.93	93.9	5.8	0.3	-
(Dune)	Sand	1.00	2.33	0.87	0.47	1.38	91.0	8.4	0.6	-
Mayday Farm (Dune)	Sand	0.30	2.16	1.03	-0.05	1.21	93.2	6.2	0.7	-
Grimes Graves	Coversand		2.40	1.62	0.31	1.41	83.0	15.8	1.2	-
	Coversand		2.11	1.33	0.15	1.19	90.4	8.8	0.8	-
Leziate Beds	Coversand		2.13	1.02	-0.03	2.21	91.4	7.8	0.8	-

as its shallow burial depth means it will have received a 'soft' cosmic dose which has not be calculated. Palaeomoisture contents were based on present-day values with errors of ± 5% assumed to make allowance for past moisture fluctuations. OSL data and the calculated ages (in years from present day) are shown in Table 2 and Figure 4.

Radiocarbon Dating

Only one stratigraphic unit contained enough concentrated organic material to warrant radiocarbon dating. This was the buried organic-rich sand found at 80 cm below the surface at site 2 at Wangford Warren. A 10 cm thick block of this organic horizon was sampled from 80-90 cm, concentrated in the laboratory by flotation in de-ionised water, and submitted to Beta Analytic Inc for radiocarbon assay (Table 2 and Fig 4). No wood fragments were found in the sample, so problems associated with modern root penetration were deemed to be insignificant.

Results

Chronology

At Wangford Warren the uppermost sand unit at site 3 above the buried soil dates to 210 ± 40 years (Shfd00074) whilst three of the OSL ages from the crest of the dune at site 1 date to 110 ± 40, 130 ± 70 and 100 ± 50 years (Shfd99103 - Shfd99105). When errors are considered, the over-lapping age ranges suggest that sand was deposited across the site within the last 250 years. Aerial photography indicates that the dune at site 1 was active as recently as the late 1950's (Fig 3) which supports the OSL age from 10 cm below the surface at this site of 30 ± 30 years (Shfd99106).

The upper OSL age from Wangford Warren site 2 (1560 ± 260 years; Shfd99107) also ties in with the ages obtained from the sand unit below the buried soil in site 3 of 1280 ± 170 and 1120 ± 170 years (Shfd00075, Shfd00076) suggesting a site-wide period of sand mobilisation at this time. The calibrated radiocarbon age of cal. 2120-1840 years BP (Beta 141015) provides independent age control for the OSL derived chronology and conforms with the chronostratigraphy for site 2 with OSL age determinations of 1560 ± 260 years (Shfd99107) from above it and 6530 ± 540 years (Shfd99108) from below it.

The three age determinations from Santon Downham show sand deposition occurred between c. 515 to 335 years ago. The upper two OSL ages (Shfd02077, Shfd02078), of 335 ± 35 years and 400 ± 40 years before the present or 1665 ± 35 and 1600 ± 40 years AD, fit remarkably well with the seventeenth century sandflood event as described by Wright (1668). Wright's account indicates that significant amounts of sand did not reach the village until around 1650. The OSL chronology shows that at least 2.7 m of sand must relate either to this event or later depositional events. Assuming episodic aeolian activity, the age of 515 ± 35 years (Shfd02079) indicates that the seventeenth century sandflood event was not unique and that at least one previous sand deposition event has taken place in Santon Downham.

Table 2: Luminescence and radiocarbon data for Wangford Warren and Santon Downham (OSL ages in years before 2000 AD).

Site	Lab Code	Depth (m)	U (ppm)	Th (ppm)	K (%)	Moisture (%)	D_{cosmic} (µGy/a)	D_{total} (µGy/a)	Palaeodose (Gy)	OSL Age (a)
Wangford Warren	Shfd99103	1.35	0.55	1.34	0.78	4.7	175 ± 8	1150 ± 168	0.128 ± 0.047	**110 ± 40**
	Shfd99104	0.95	0.37	1.48	0.85	4.0	185 ± 9	895 ± 130	0.155 ± 0.078	**130 ± 70**
	Shfd99105	0.50	0.57	1.41	0.76	1.3	196 ± 9	1203 ± 176	0.116 ± 0.063	**100 ± 50**
	Shfd99106	0.10	0.57	1.41	1.19	2.3	208 ± 10	1627 ± 113	0.051 ± 0.042	**30 ± 30**
	Shfd99107 *	0.50	0.38	1.20	0.61	11.7	196 ± 9	891 ± 134	1.386 ± 0.094	**1560 ± 260**
	Shfd99108	1.15	0.38	1.20	1.06	14.2	180 ± 9	1231 ± 88	8.04 ± 0.33	**6530 ± 540**
	Shfd00074	0.35	0.50	1.49	0.75	3.6	187 ± 9	1134 ± 124	0.243 ± 0.043	**210 ± 40**
	Shfd00075	1.45	0.56	1.61	0.74	2.5	161 ± 8	1134 ± 126	1.45 ± 0.10	**1280 ± 170**
	Shfd00076	2.15	0.49	1.47	0.74	2.2	147 ± 7	1101 ± 125	1.24 ± 0.12	**1120 ± 170**
Santon Downham	Shfd02077	2.70	0.52	1.30	0.49	0.2	136 ± 7	863 ± 69	0.293 ± 0.021	**335 ± 35**
	Shfd02079	3.30	0.34	0.90	0.40	1.8	126 ± 6	673 ± 40	0.273 ± 0.016	**400 ± 40**
	Shfd02078	3.60	0.33	0.90	0.42	3.5	122 ± 6	671 ± 40	0.347 ± 0.041	**525 ± 35**

* An organic-rich horizon just below this sample yielded a radiocarbon age of 2110 ± 60 years BP (Beta 141015) or cal. BP 2120 – 1840 year BP

The chronometric data therefore indicate that at least three phases of sand deposition have occurred at Wangford Warren, with at least one punctuated by a significant hiatus during which peat formed across low-lying parts of the site. The sand phases are: from the end of the 20th century to around 200 years ago; between at least 1100-1600 years ago; and a third *c.* 6500 years ago. The period of aeolian quiescence dates to around cal. 2120-1840 years BP. Sand at Santon Downham accumulated in at least 2 periods one *c.* 335-400 years ago and another *c.* 500 years ago.

Particle Size

In general, particle size analysis (PSA) data shows that all unaltered sand from Wangford Warren has a mean size of between 2.10 - 2.60 phi, and is moderately sorted, with less than 7% of particles smaller than 63 µm (Table 1). This, coupled with the similarity of the PSA data to other previously reported aeolian deposits, strongly suggests an aeolian origin for the sands at Wangford Warren and from Mayday Farm and Santon Downham. Within the PSA data from Wangford Warren there is a notable difference in mean size, sorting and skewness between the sand of historical age found at site 1 and the upper part of site 3 and the mid-Holocene sand found at sites 2 and 3. Sand from the former site is finer (mean = 2.55 phi) better sorted (0.55), and positively skewed compared with the older sand which is more bimodally distributed with a secondary coarse peak. This coarser component may have been winnowed out prior to deposition of the historical age sand at sites 1 and 3.

Palaeoenvironmental History

The earliest identified sand deposition phase took place during the middle Holocene *c.* 6500 years during which the lowest gleyed sand units at sites 2 and 3 at Wangford Warren were laid down. As no Late Glacial sands were found, the relationship of this lower sand unit to the regional coversand has yet to be established. However, the presence of ventifacts at the site, similar to those described in Hoare *et al.* (2002), suggest underlying coversands have been reworked in this area.

There then follows a considerable hiatus in the palaeoenvironmental record between *c.* 6500 and *c.* 2100, in which the lack of evidence for pedogenesis of the underlying sand unit suggests that there was a net erosion of sand from the site. At some stage around 2100 years ago, water-tables across Wangford Warren rose allowing the fen, <1 km to the west, to encroach onto the low lying areas of the site. This formed the organic-rich horizon found at site 2 and at the base of the exposure in site 3. The high sand content of this organic-rich layer, and its gradational lower boundary, suggests that fen encroachment was gradual and that throughout this time sand was still being blown around. This is the case today at the fen/Breckland boundary where interdigitated peats and sand are visible when crops permit. Following a period of fen encroachment sand deposition resumed, as indicated by sharp upper boundaries of the organic-rich unit at both sites 2 and 3, continuing at least until *c.* 1100 years ago.

At sometime after 1100 and before 200 years ago, an iron-rich brown podzolic soil developed on the dunes at Wangford Warren, indicating that the sand was free-draining and stabilised. The maturity of this podzol at site 3, with well developed horizons and mottling down to 75 cm below the top of the soil, suggests this quiescence was likely to have been at the centurial timescale (R. Evans pers com.). Within the same time period, but after the soil had developed, significant erosion across much of Wangford Warren took place with the buried soil at site 3 being truncated by a blowout, and the soil being completely eroded from site 2. Whilst no ages for this erosion event(s) are available it would seem probable that this is the result, at least in part, of the early seventeenth century 'sandflood' event described by Wright (1668). Wright describes the soil as being 'broken', thus allowing deflation of the sand, and intimates that not all the dunes were eroded. This fits with the truncated buried palaeosol and lower sand units found at site 3. Also it would appear that Wangford Warren, juxtaposed to Lakenheath Warren, was a sediment source for the 'sandflood' and most of the sand moved was not locally deposited. Thus it would appear unlikely that sediments dating to this event would be found at Wangford Warren. Evidence from Santon Downham shows significant sand accumulation did occur at this time as well as in the fifteenth century.

A final phase of sand deposition buried the soil at site 3 with 45 cm of sand and formed at least the upper 1.4 m of sand at site 1. This was initiated just prior to 200 years ago and, supported by photographic evidence (Fig 2), continued through to the final decades of the last century. Such aeolian activity is also supported by the observations of Clarke (1937) which recall frequent sand movement by gales. Modern soils developed on this sand unit are thin, weak and immature, reflecting their youth and the results of the land management practices.

Discussion

Regional and sub-continental Dune Activity

The new chronology for Breckland dunes is significant in that the dunes, as previously supposed, are not the result of Late Glacial aeolian activity. Although this is the first work to investigate the timing of Holocene aeolian activity in Breckland, reworking of the nearby Leziate aeolian sand-sheet in west Norfolk around 1565 ± 455 years (LB-064, Clarke *et al.* 2001) shows that wider regional aeolian activity coincident with some of the sand movement in Breckland has occurred. Inland dune fields are relatively rare in Britain, but some work has been carried out on those found on the coversands in Lincolnshire. Twigmoor Woods has well-developed dunes up to 10 m in height which appear to be mostly the result of dune building contemporaneous with coversand deposition (Bateman *et al.* 1999). However on the crest of the most prominent dune, evidence was found of a second sand deposition phase which occurred at *c.*1310 ± 200 years (Shfd96041) and which buried a well developed palaeosol with a further 75 cm of sand (*ibid*). Also in Lincolnshire, a sand unit directly below a low (1 m high) dune near Caistor was reported to date from 6460 ± 600 years (Bateman *et al.* 2000), which is similar to the oldest identified aeolian phase on Breckland.

The direct correlative of Breckland dunes are the drift sands of The Netherlands and Poland. These are often formed into chaotic inland dunefields whose provenance is quite local (e.g. Kozarski and Nowaczyk 1991, Koster *et al.* 1993). Van Mourick (1988), on the basis of palynological and radiocarbon data, identified three main phases of drift sand sedimentation in The Netherlands: after *c.* cal. 3,800 years BP; after *c.* cal. 1,300 years BP; and after *c.* cal. 500 years BP. Castel (1991) added a fourth phase of activity occurring after *c.* cal. 2110 years BP. The Late Middle Age period seems to have been the dominant phase of activity in The Netherlands, although minor drift sedimentation appears throughout the Holocene (Koster 1988, Table 3). Phases of activity in Breckland appear to correlate, using the terminology of Koster (1988), with the latter half of the Older Drift sand phases and the Younger Drift sands in The Netherlands. In Poland, long stabilised inland dune fields were reactivated after c. cal. 5800 years BP and show multiple cycles of aeolian activity and stabilisation marked by palaeosols (Kozarski and Nowaczyk 1991). Two widespread palaeosols from dunes south of Cedynia dating to *c.* cal. 2300 and *c.* cal. 1000 years BP are similar in age to the inferred periods of stability in Breckland (Kozarski and Nowaczyk 1991). Elsewhere, inland dunes in Germany and Scandinavia also show multiple but diachronous reactivation phases over the last 5000 years (Selsing and Mejdahl 1994, Janotta *et al.* 1997, Käyhkö *et al.* 1999). In Finland the latest widespread episode of aeolian activity dates to 900-350 years ago.

More work has been carried out on the coastal dune systems around the UK (e.g. Knight *et al.* 1998; Orford *et al.* 2000; Bailey et al. 2001; Wilson *et al.* 2001) and elsewhere on the coastline of North West Europe (e.g. Clemmensen *et al.* 1996, Clarke *et al* 2002). Whilst processes responsible for formation may not be exactly the same as inland dunes, comparison to coastal dune systems show a high degree of concordance. In the UK, on the nearby north Norfolk coast, dunes were initiated from c. cal. 600 years BP onwards (Knight *et al.* 1998; Orford *et al.* 2000). Elsewhere, aeolian activity on the Northumberland coast began after c. cal. 3627-3400 years BP with much falling between cal. 2700 and 1300 years BP. Further dune building occurred in the period after cal. 956-782 years BP (Wilson *et al.* 2001). In the Culbin area of Scotland the late seventeenth century saw major mobilisation of the dunefield there (Lamb and Frydendahl 1991). Further west in the Hebrides, Gilbertson *et al.* (1999) reported development of machair sands at 3800-3300 years ago, 1700-1300 years ago and 600-300 years ago. In France on the North Aquitaine coast, Clarke *et al.* (2002) found three coastal dunes phases occurring at 4000-3000 years ago, 1300-900 years ago and 550-250 years ago. In Denmark a number of phases of coastal dune formation have been identified from Vejers and Lodbjerg, Jutland between *c.* 4400-4000 years ago, *c.* 2700-2000 years ago, *c.* 1700-1000 years ago and *c.* 350-150 years ago (Clemmensen *et al.* 1996; 2001). Thus coastal dune systems in Eastern England, Eastern and Western Scotland, Northern France and Denmark were active during at least two of the identified dune building phase in Breckland and during the seventeenth century sandflood event.

Causal Factors for Holocene Dune Activity in Breckland

Palaeohydrology

Undoubtedly the palaeohydrology of Breckland and coastal dune systems has strongly influenced sand availability/mobility. The effect of palaeohydrology on aeolian activity has been demonstrated by Van Vliet-Lanoë *et al.* (1993) in Finland where locally higher moisture levels caused much earlier stablisation within the same dune field. Given the Wangford Warren site is only 5 m OD, a rise in sea level causing the inundation of the adjacent fens will have had an impact in terms of higher water-tables. No correlation of aeolian activity and sea-level occurs prior to the organic-rich unit found at both site 2 and site 3, as sea levels were still –6.5 to –5.5 m OD at Great Yarmouth *c.* 5000-4000 years BP (Jones and Keen 1993; p. 261). However, the organic-rich unit was formed in the Roman period, when sea levels are known to have been relatively high in the region (Lamb 1977; Fig 6). The buried palaeosol at Wangford Warren formed sometime within the period 1100–300 years which encompasses two periods (1000 and 800-600 years) during which, based on historical evidence, sea levels are also known to be have been relatively high (Lamb 1977; Fig 6). Conversely, a marine regression is reported for the Norfolk Broads between 1800-550 years BP (Alderton 1983), a time period when one of the phases of aeolian sand deposition at Wangford occurred (Fig 6). Sea levels are also thought to have been relatively low during the seventeenth and nineteenth centuries (Lamb 1977), when the aeolian erosive (‘sandflood’) event took place and when the most recent period of aeolian activity seems to have been initiated (Fig 6).

Anthropogenic

The Drift sand dunes of The Netherlands are widely attributed to the strong expansion of arable fields of the so called ‘plaggen’ soil type, and to sheep grazing in the Late Middle Ages (e.g. Koster *et al.* 1993). Likewise, the discovery of Upper Neolithic and Early Bronze to Early Middle age archaeological artefacts in the dunes in Poland led Kozarski and Nowaczyk (1991) to attribute dune reactivation to human impacts on vegetation. In Breckland, the aeolian phase between 1600-1100 years coincides with the period when the palynological record from Hockham Mere shows increasing woodland clearance and cultivation (Bennett 1983; Fig 6). However 900-800 years BP saw the most intensive arable usage of Breckland (Randall and Dymond 1996) but there is no evidence of sand movement at that time.

Animals

Another local factor for Breckland, given the large number of places which include 'warren' in their name (Fig 1), is the role of rabbits as a cause of sand movement. The erosion caused by rabbits is well documented and in a dune setting/system they can remove the protective vegetation, break surface crusts and reduce soil cohesion by disturbing sand whilst grazing and burrowing (e.g. Rutin 1992). The effect is greatly exacerbated on land where both sheep and rabbits are grazing (Evans 1997). Widespread damage due to rabbits has been reported in Breckland, and seems to have increased when harsh winter weather drove the normally gregarious rabbit further a field to find food (Sheail 1978, 1984). The number of warrens peaked in the mid-eighteenth century, when they covered up to 6100 hectares of Breckland. This increase in rabbit population broadly coincides with the erosive ‘sandflood’ event at Wangford Warren (Fig 6).

Fire

It has been reported from both Canada and Finland that Holocene inland dunefield activity can be related in part to vegetation destruction by human-induced or natural forest fires (Filion 1984; Käyhkö *et al.* 1999). This is primarily based on modern-day observations and the incidence of charcoal layers within aeolian units, but no charcoal was found in Breckland dunes. This may reflect in part that much of Breckland has been clear of forest for at least the last 2000 years (Bailey 1989) but also the fact that Breckland during the Holocene, unlike the boreal and tundra forests of Quebec and Lapland, has not been in the Pine forest zone in which fires are relatively frequent and form an important integral part of the ecosystem.

Bateman and Godby (2004) as published in The Holocene 14, pp. 579–588

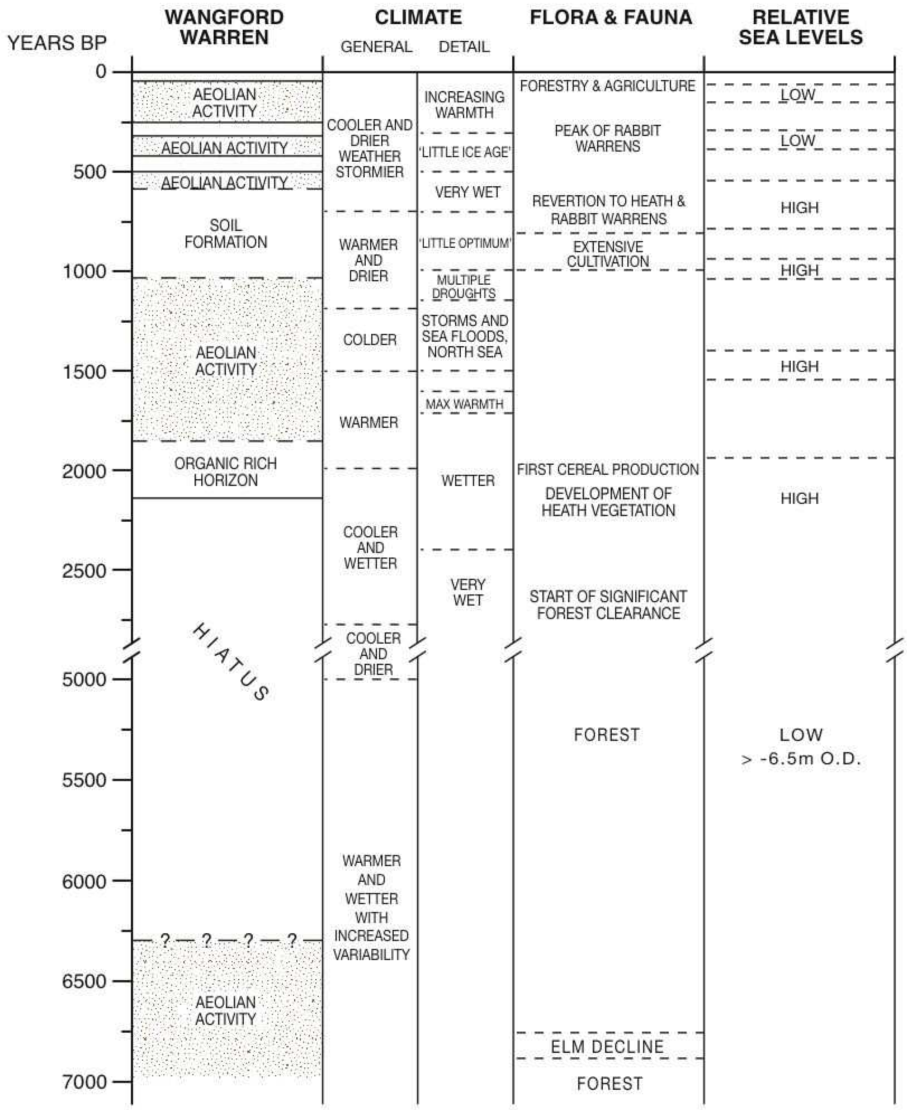

Figure 6: Summary of inferred events at Wangford Warren dunefield and key regional events which may have been causal factors (climate partially modified from Evans, in press; flora after Bennett 1983; after Sheail 1978; sea levels compiled from Lamb 1977).

Sub-continental Scale Causal Factors of Dune Activity

In simple terms one would expect aeolian activity to increase during periods of relatively high temperatures and low rainfall, i.e. with reduced effective precipitation. The earliest phases of inland dune activity found in both Lincolnshire and Breckland (up to *c.* 6500 years ago) did indeed occur during the Holocene altithermal. However, during the 'Mediaeval warm period' most inland and coastal dunes (Northumberland excepted) appear to have been stable. Multiple droughts were reported in England and elsewhere during ninth century AD (Lamb 1977) and Lamb (1984, p. 40) identified the period 300 to 600 years ago in England as drier than average. Inland dune activity in Breckland partly coincides within this former drought-ridden period whilst dune activity both on Breckland and the Norfolk coast occurs during the latter dry period (Fig 6). However, both these periods of dune activity occur during cold periods, with the seventeenth century sandflood occurring during the coldest century in the last millennium. This suggests a more complex relationship between inland aeolian dune activity and climate than just an effective precipitation control. A relatively cooler climate inhibiting vegetation growth and/or reducing the growing season would effectively lead to reduced vegetation cover which, coupled with a drier climate, allow sand to become more susceptible to movement by aeolian process. Such a conclusion is supported by the work of Filion (1984) who, working on inland dunes in Quebec, found that cold dry conditions were most conducive to increased aeolian activity whilst increased humidity and temperatures reduced aeolian activity to localised areas or allowed complete stabilisation.

Wilson *et al.* (2001) pointed out that the proxy records from the GISP 2 icecore and from North Atlantic sediment cores show a number of sudden climatic shifts in which Icelandic waters were advected south to the latitude of the British Isles. During such shifts climate variability is thought to have increased with more frequent extremes of weather at a decadal scale and an increased propensity for severe storms. The latter will have increased the number of days when wind velocities would have had the capability of moving sand, whilst the former may have disturbed the vegetation cover which bound sand together. The last two such climatic shifts are centred on cal. 1400 years BP and cal. 650-50 years BP, the latter being commonly referred to as the 'Little Ice Age' (LIA) (Wilson *et al.* 2001). The former event coincides with aeolian deposition of the 1600-1100 year old sand unit at Wangford Warren, Twigmoor Woods in Lincolnshire, some of the Older Drift sands of The Netherlands (Koster 1988) and aeolian activity in Denmark and the Hebrides. The LIA event includes the time period in which the basal sand found at Santon Downham and the upper sand units at site 3 and at site 1 at Wangford Warren were deposited, as well as encompassing the early seventeenth century 'sandflood' event. Evidence from England, Scotland, France, The Netherlands, Denmark, Poland and Finland shows that inland and coastal dune building was widespread during the LIA. This synchronicity across such a large area of Northern Europe suggests that climatic forcing over and above other local controlling factors has been the primary driving force in causing aeolian activity both in inland and coastal dunes in the Late Holocene.

Conclusions

Multiple phases of aeolian activity have been identified in Breckland typified by well sorted sand, the presence of ventifacts, and a dune morphology. The OSL dating programme has shown that sand depositional phases occurred at *c.* 6500, *c.* 1600-1100, *c.* 500, *c.* 400-335 and from *c.* 200–30 years. Sand erosion events occurred sometime after 6500 and before 2100 years and at Wangford Warren which was the source of the 'sandflood' event of the early seventeenth century. Two quiescent phases have also been identified with fen peat forming around *c.* 2100 years BP and a podzol soil forming sometime in the period *c.* 1100 and 300 years (Fig 6).

Local controls on the occurrence of aeolian activity on Breckland are complex. Mid-Holocene aeolian activity occurred whilst sea-levels were relatively low and temperatures were warm. Late Holocene aeolian activity (1600-1100 years) occurred when sea-levels were regressing, temperatures and precipitation had fallen reducing vegetation cover and when humans were clearing the forests (Fig 6). The seventeenth century 'sandflood' is attributed to low temperatures and high rabbit and sheep populations which reduced vegetation cover, combined with relatively lower sea-levels and lower precipitation which reduced water-tables. The final phase of aeolian activity between 200 and 30 years is attributed to the demise of the rabbit warren system and to moves towards arable farming, both combined with increased temperatures.

The timing of the 1600-1100 year, the 'sandflood' and 200-30 year aeolian phases coincide with inland and coastal dune building elsewhere in the UK, continental Europe and Scandinavia. During these periods, ocean, ice core and documentary evidence suggest the North Atlantic region underwent climatic instability which caused increased storminess. Thus regional external forcing is seen as a significant underlying trigger for aeolian activity.

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References

Alderton, A.M. (1983). *Flandrian vegetational history and sea-level change of the Waverney Valley*. Ph.D. Thesis, University of Cambridge.

Bailey, M. (1989). *A Marginal Economy? East Anglian Breckland in the Later Middles Ages*. Cambridge University Press, Cambridge.

Bailey, S.D., Wintle, A.G., Duller, G.A.T. and Bristow, C.S. (2001). Sand deposition during the last millennium at Aberffraw, Anglesey, North Wales as determined by OSL dating of quartz. *Quaternary Science Reviews*, **20**, 701-704.

Ballantyne, C.K. (1998). Aeolian deposits on a Scottish mountain summit: characteristics, provenance, history and significance. *Earth Surface Processes and Landforms*, **23**, 625-641.

Bateman, M.D. (1995) Thermoluminescence dating of the British coversand deposits. *Quaternary Science Reviews*, **14**, 791-798.

Bateman, M.D. and Catt, J.A. (1996). The age and origin of the raised beach at Sewerby, East Yorkshire, UK. *Journal of Quaternary Science*, **11**, 389-395.

Bateman, M.D., Hannam, J. and Livingstone, I. (1999). Late Quaternary dunes at Twigmoor Woods, Lincolnshire, UK: a preliminary investigation. *Zeitschrift für Geomophologie*, **116**, 131-146.

Bateman, M.D., Murton, J.B. and Crowe, W. (2000). Late Devensian and Holocene depositional environments associated with coversands around Caistor, N. Lincolnshire, UK. *Boreas*, **29**, 1-15.

Bennett, K.D. (1983). Devensian Late Glacial and Flandrian vegetation history at Hockham Mere, Norfolk, England. *New Phytologist*, **95**, 457-487.

Bristow, C.R. (1990). *The Geology of the Country around Bury St. Edmunds*. HMSO, Harpenden.

Castel, I. (1991). Micormorphology of the transition peat-Holocene drift sand deposits in the northern Netherlands. *Zeitschrift für Geomophologie,* **90**, 20-43.

Catt, J.A. (1977) *Loess and Coversand*. In Shotton, F.W. (ed) 'British Quaternary studies: recent advances'. Clarendon Press, Oxford, 221-229.

Chorley, R.J., Stoddart, D.R. and Haggett, P. (1966). Regional and local components in the areal distribution of surface sand facies in Breckland, Eastern England. *Journal of Sedimentary Petrology*, **36**, 209-220.

Clarke, R.R. (1937). *In Breckland wilds*. Heffer & Sons, Cambridge.

Clarke, M.L., Rendell, H.M., Hoare, P.G., Godby, S.P. and Stevenson, C.R. (2001). The timing of coversand deposition in northwest Norfolk, UK: a cautionary tale. *Quaternary Science Reviews*, **20**, 705-714.

Clarke, M.L., Rendell, H., Tastet J-P., Clavé, B. and Massé, L. (2002). Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine Coast, southwest France. *The Holocene*, **12**, 231-238.

Clemmensen, L.B., Andreasen, F. Nielsen, S.T. and Sten, E. (1996). The late Holocene coastal dunefield at Vejers, Denmark: characteristics, sand budget and depositional dynamics. *Geomorphology*, **17**, 78-98.

Clemmensen, L.B., Pye, K., Murray, A. and Heinemeier, J. (2001). Sedimentology, stratigraphy and landscape evolution of Holocene coastal dune system, Lodbjerb, NW Jutland, Denmark. *Sedimentology*, **48**, 3-27.

Corbett, W.M. (1973). Breckland forest soils. Soil survey special survey, 7, HMSO, Harpenden.

Edwards, W. (1936). Pleistocene dreikanter in the Vale of York. Summary of Progress of the Geological survey of Great Britain for 1934, Part 2, 8-18.

Evans, R. (1997). Soil erosion in the UK initiated by grazing animals. *Applied Geography*, **17**, 127-141.
Evans, R. (in press). *Influence of climate on past erosion in the UK*. In Boardman, J. and Favis-Mortlock, D. (Eds) Climate change and soil erosion, Imperial College Press, London.

Evelyn J. (1677). Unpublished Diary from 10 September.

Filion, L. (1984). A Relationship between dunes, fire and climate recorded in the Holocene deposits of Quebec. Nature, **309**, 543-546.

Frechen, M. (1999). Upper Pleistocene loess stratigraphy in Southern Germany. *Quaternary Geochronology*, **18**, 243-269.

Frechen, M., Hovrath, E., Gaebris, G. (1997). Geochronology of middle and upper Pleistocene loess sections in Hungary. *Quaternary Research*, **48**, 291-312.

Gale, S.J. and Hoare, P.G. (1991). *Quaternary Sediments*. Belhaven Press, London.

Gilbertson, D.D., Scwenninger, J.-L., Kemp, R.A. and Rhodes, E.J. (1999). Sand drift and soil formation along an exposed North Atlantic coast-line: 14,000 years of diverse geomorphological, climatic and human impacts. *Journal of Archaeological Science*, **26**, 439-469.

Gilpen W. (1805). *Some observations on several parts of Cambridgeshire, Norfolk, Suffolk and Essex made in 1769*. London.

Goudie, A. and Gardner, R. (1985). *Discovering Landscape in England and Wales*. Allen and Unwin, London.

Hoare P.G., Stevenson, C.R. and Godby, S.P. (2002). Sand sheets and ventifacts: The legacy of aeolian action in West Norfolk, UK. *Proceedings of the Geology Association* (in press).

Högbom, I. (1923). Ancient inland dunes of northern and middle Europe. *Geografiska Annaler*, **5**, 113-243.

Jannota, A., Radtke, U., Czwielung, K. and Heidger, M. (1997). Luminescence dating (IRSL/TL) of Lateglacial and Holocene dune sands and sandy loesses near Bonn, Gifhorn and Diepholz (Germany). *Quaternary Science Reviews (Quaternary Geochronology),* **16**, 349-355.

Jones, R.L. and Keen , D.H. (1993). *Pleistocene Environments in the British Isles*. Chapman and Hall, London.

Käyhkö, J.A., Worsley, P., Pye, K. and Clarke, M.L. (1999). A revised chronology for aeolian activity in subarctic Fennoscandia during the Holocene. *The Holocene*, 9, 195-205

Knight, J., Orford, J.D., Wilson, P., Wintle, A.G. and Braley, S. (1998). Facies, age and controls on recent coastal sand dune evolution in north Norfolk, eastern England. *Journal of Coastal Research Special Issue,* **26**, 154-61.

Koster, E.A. (1988). Ancient and Modern cold-climate aeolian sand deposition: a review. *Journal of Quaternary Science*, **3**, 69-83.

Koster, E.A., Castel, I.I.Y. and Nap, R.L. (1993). *Genesis and sedimentary structures of late Holocene aeolian drift sands in northwest Europe*. In Pye, K. (Ed.) 'The Dynamics and Environmental Context of Aeolian Sedimentary Systems'. Geological Society Special Publication, **72**, 247-267.

Kozarski, S. and Nowaczyk, B. (1991). Lithofacies variation and chronostratigraphy of Late Vistulian and Holocene aeolian phenomena in northwestern Poland. *Zeitschrift für Geomophologie,* **90**, 107-122.

Lamb, H.H. (1977). *Climate Past, Present and Future: Volume 2: Climatic History and the Future*. Methuen & Co, London.

Lamb, H.H. (1984). *Climate in the Last Thousand Years: Natural climatic fluctuations and change.* In Flohn, H. and Fantechi, R. (Eds.) 'The Climate of Europe: Past, Present and Future'. Reidel, Dordrecht, 25-64.

Lamb, H.H. and Frydendhal, K. (1991). Historic storms of the North Sea. British Isles and northwest Europe. Cambridge University Press, Cambridge.

Matthews, B. (1970). Age and origin of aeolian sand in the Vale of York. *Nature*, **227**, 1234-1236.

Murray, A.S. and Wintle, A.G. (2000). Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements,* **32**, 57-73.

Orford, J.D., Wilson, P., Wintle, A.G., Knight, J. and Braley, S. (2000). *Holocene coastal dune initiation in Northumberland and Norfolk, eastern UK: climate and sea-level changes as possible forcing agents for dune initiation*. In Shennan, I. and Andrews, J. (Eds) Holocene land-ocean interaction and environmental change around the North Sea. *Geological Society, London. Special Publication*, **166**, 197-217.
Parks, D.A., Rendell, H.M. (1992). TL geochronology of brickearths from south-east England. *Quaternary Science Reviews,* **11**, 7-12.

Perrin, R.M.S., Davies, H. and Fysh, M.D. (1974). Distribution of Late Pleistocene aeolian deposits in eastern and southern England. *Nature*, **248**, 320-324.

Postgate, M.R. (1961). *Historical geography of Breckland 1600-1850*. Unpublished MA thesis, University of London.

Prescott, J.R., and Hutton, J.T. (1994). Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiation Measurements*, **23**, 497-500.

Randall R. and Dymond D. (1996) *Why Thetford Forest? The human and natural history of Breckland before the early 20th century*. In Ratcliffe P. and Claridge J. (Eds) Thetford Forest Park: The Ecology of a Pine Forest. Forestry Commission Technical Paper 13, Edinburgh, 1-16.

Rousseau, D-D., Zoller, L., Valet, J.P. (1998). Late Pleistocene climatic variations at Achenheim, France, based on magnetic susceptibility and TL chronology of loess. *Quaternary Research*, **49**, 255-263.

Rutin, J. (1992). Geomorphic activity of rabbits on a coastal sand dune, De Blink dunes, The Netherlands. *Earth Surface Processes and Landforms*, 17, 85-94.

Selsing, L. and Mejdahl, V. (1994). Aeolian stratigraphy and thermoluminescence dating of sediments of late Holcoene age from Sola, southwest Norway. *Boreas*, **23**, 92-104.

Sheail, J. (1978). Rabbits and agriculture in post-medieval England. *Journal of Historical Geography*, **4**, 343-355.

Sheail, J. (1984). The Rabbit. *Biologist*, **31**, 135-139.

Van Mourik, J.M. (1988). *Landschap in beweging: Ontwikkeling en bewoning van een stuifzandlandscap in de Kempen*. Netherlands Geographical Studies N°. 74, Amsterdam.

Van Vliet-Lanoë, B. Seppälä, M. and Käyhkö, J.A. (1993). Dune dynamics and cryoturbations features controlled by Holocene water-level change, Hietatievat, Finnish Lapland. *Geologie en Mijnbouw*, **72**, 211-224.

Watt, A.S., Perrin, R.M. and West, R.G. (1966). Patterned ground in Breckland: structure and composition. *Journal of Ecology*, **54**, 27-29.

Whitaker, W. (1891). *The Geology of parts of Cambridgeshire and of Suffolk*. Memoirs of the Geological Survey of England and Wales. HMSO, London.

Williams, R.G.B. (1968) Periglacial climate and its relationship to landforms. Unpublished PhD thesis University of Cambridge.

Wilson, P., Orford, J.D., Knight, J., Braley, S.M. and Wintle, A.G. (2001). Late-Holocene (post-4000 years BP) coastal dune development in Northumberland, northeast England. *The Holocene,* **11**, 215-229.

Wright, T. (1668). A curious and exact relation of a Sandfloud. *Philosophical Transactions of the Royal Society of London*, **3**, 722-725.

Zeeberg, J.J. (1998). The European sand belt in eastern Europe - and comparison of Late Glacial dune orientation with GCM simulation results. *Boreas,* **27**, 127-139.