Journal of World Prehistory (2022) 35:87–107
https://doi.org/10.1007/s10963-022-09166-y

Landscapes for Neolithic People in Mainland, Orkney

M. Jane Bunting[1] · Michelle Farrell[2,3] · Elaine Dunbar[4] · Paula Reimer[5] · Alex Bayliss[6] · Peter Marshall[6] · Alasdair Whittle[7]

Accepted: 16 February 2022 / Published online: 15 March 2022

Abstract

Neolithic occupation of the Orkney Islands, in the north of Scotland, probably began in the mid fourth millennium cal BC, culminating in a range of settlements, including stone-built houses, varied stone-built tombs and two noteworthy stone circles. The environmental and landscape context of the spectacular archaeology, however, remains poorly understood. We applied the Multiple Scenario Approach (MSA) to Neolithic pollen records from Mainland, Orkney, in order to understand land cover and landscape openness across the timespan 4200–2200 cal BC. Interpreted within a framework provided by Bayesian chronological modelling, 406 radiocarbon dates from archaeological contexts and a further 103 from palaeoenvironmental samples provide the basis for the first detailed reconstruction of the spatio-temporal patterns of Neolithic people and their environment. Major alterations to the land cover of Mainland took place from 3400 cal BC (reduction in woodland from 20% to 10%) and from 3200 cal BC (increase in disturbed land from 3% to 30%). The dramatic increase in disturbed land coincided with the Grooved Ware phenomenon and the establishment of settlements at Skara Brae and Ness of Brodgar. The upturn in the signal for disturbance communities in the pollen record may indicate an increase in the amount of land used as pasture. This accords with the archaeological record, since the Neolithic Orcadian economy probably relied heavily on cattle for subsistence. By 2800 cal BC in the core of the Orkney Mainland, most settlements appear to have been ending, with people dispersing into the wider landscape, as the MSA modelling indicates a maintenance of disturbed land, and indeed a subsequent slight increase, implying persistence of human activity elsewhere in Mainland. People exhausted themselves rather than their land; that and its varied resources endured, while the intensive social relationships and practices of the peak of late Neolithic Orkney could not be maintained.

Keywords Orkney · Neolithic · Palynology · Multiple Scenario Approach · Chronological modelling

✉ Alasdair Whittle
whittle@cardiff.ac.uk

Extended author information available on the last page of the article

Introduction: Landscape Questions for Neolithic Orkney

Probably beginning somewhere in the mid fourth millennium cal BC, Neolithic people established occupation of the Orkney Islands in the north of Scotland. By the late fourth or early third millennium this had led to the construction of a range of settlements including stone-built houses, varied stone-built tombs, and two notable stone circles. The often exceptional preservation of the stone architecture and the rich accompanying material culture have made this long-studied archaeology justly famous (Downes et al., 2013; Edmonds, 2019), and important discoveries, for example of the major aggregation at Ness of Brodgar (Card et al., 2018, 2020), and of a host of other settlements (Richards & Jones, 2016), continue to be made. The many investigations have produced a wealth of information about the nature of subsistence – especially cattle keeping and cereal cultivation – and of material production. Far-flung connectivity is evident in the forms of monuments, such as passage graves and stone circles, and in the styles of material culture including Grooved Ware pottery, which appears to have emerged in the 32nd century cal BC; more precise chronologies are another important feature of recent and ongoing research (Bayliss et al., 2017; Griffiths, 2016; Griffiths & Richards, 2013; Schulting et al., 2010). There has been a long-running, vigorous debate about the character of early Orcadian society (Renfrew, 1979; Sheridan, 2004, 2016, pp. 204–206), including the recent proposal that the sequence sees the emergence of 'house societies' (Richards & Jones, 2016).

In all this, research on the Orcadian environment has tended to take a back seat. Pollen analysis in Orkney, however, goes as far back as the pioneering investigations by Erdtman (1924), followed by analysis of samples from excavations at Maeshowe (Childe, 1956) and from two partial wetland records (Moar, 1969). But the first widespread attempts to use palynology to understand the environmental and landscape context of Neolithic Orkney only took place in the 1970s, prompted especially by excavations at Skara Brae and Quanterness, with numerous on-site and off-site sequences being studied (e.g. Davidson et al., 1976; Jones, 1979; Keatinge & Dickson, 1979; Renfrew, 1979). By the 1980s, the combined evidence of pollen, land snails, faunal and plant remains, soils and sea-level changes appeared to confirm a picture of a largely treeless landscape from c. 3800 cal BC (Davidson & Jones, 1985; Davidson & Henshall, 1989, p. 14; Ritchie, 1995), with native woodland limited to birch–hazel scrub, although some authors inferred the scattered presence of oak and pine from wetland sedimentary records (e.g. Bunting, 1994, 1996; de la Vega Leinert, 1998; Farrell, 2015). Valuable work in that vein continues; recent reports (e.g. Richards, 2005; Moore & Wilson, 2011; Richards & Jones, 2016) include specialist analyses of faunal and plant remains, charcoal, soils and pollen. A major project on former sea levels is also underway (Bates et al., 2016). But the imbalance in research overall remains; the spectacular archaeology often still lacks a sense of specific landscape setting.

In this paper, therefore, we seek to redress this weakness by using a combined approach. On the one hand, we employ a wide range of date estimates for the archaeology of Neolithic Orkney from formal chronological modelling in a

Bayesian framework (Bayliss et al., 2017; Griffiths, 2016). On the other hand, we use pollen analyses to explore whether Neolithic Orkney had a more varied landscape and vegetation history than previously assumed. This is done through a fresh approach to synthesis of palynological analyses in Mainland, Orkney (Mainland being the name for the major island of the archipelago), interpreted through the Multiple Scenario Approach (MSA) to land cover reconstruction from pollen data (Bunting & Middleton, 2009). Our attempt to establish more robust chronologies for landscape developments aims to integrate and interpret archaeological and palynological results together in a more ordered way, exploiting the interplay between four main variables: the major features of the Neolithic archaeology, the dynamics of birch–hazel and oak–pine woodland, together with variations in the abundance of plant communities of disturbed ground (comprising grassland with weeds typical of pastoralism and/or small-scale cereal cultivation). These three land cover variables are reconstructed from pollen data using the MSA. Placing all four variables on the calendar scale through formal chronological modelling enables a new, united view of how the landscape may have evolved through the Neolithic in Orkney.

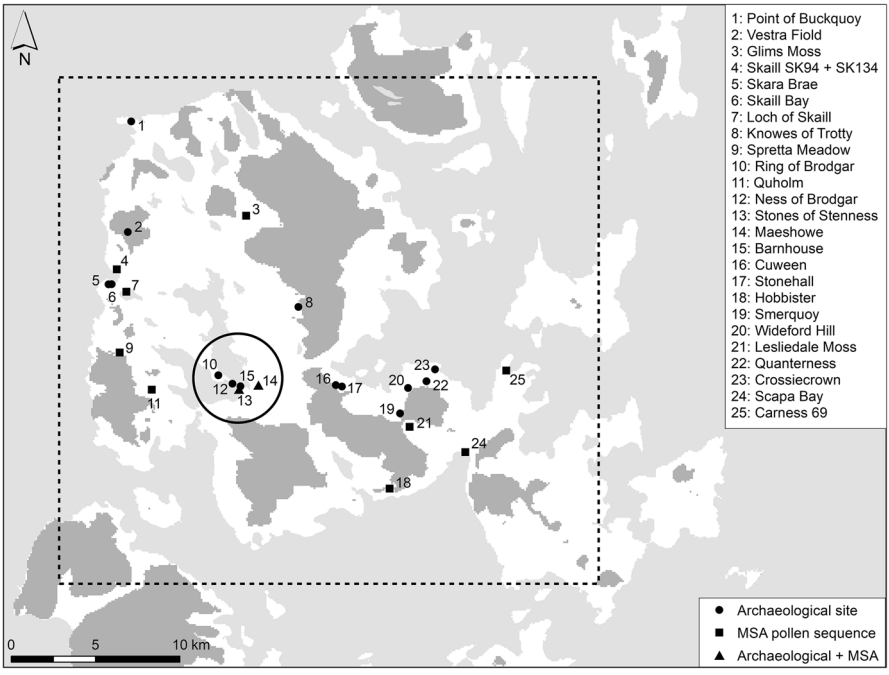


Fig. 1 Location of sites with pollen data included in the MSA modelling (dashed square denotes area of landscape reconstruction and the 'periphery' of Mainland as referred to in the text; solid circle denotes the Stenness-Brodgar 'core') and archaeological sites on Mainland Orkney considered in this review. Light grey shading indicates areas of open water (i.e. lochs and sea); dark grey indicates areas of land above 60 masl

Overall, we consider 509 radiocarbon measurements (406 archaeological and 103 environmental) and 20 luminescence ages (all archaeological) from 16 archaeological sites and 21 environmental sequences (Fig. 1). New age estimates obtained on four sediment sequences are shown in Table 1. Full details of all previously existing age estimates on sediment sequences are given in Table S1a (see online supplementary material), and full details of the measurements from archaeological sites are given by Bayliss et al. (2017, tables S1 and S2), Richards et al. (2016, table 1), Card et al. (2018, table 1), and Clarke and Shepherd (forthcoming, tables 2.4.3/1–2.4.3/3).

The Archaeological Timescape: Neolithic–Early Bronze Age

The archaeological modelling of Neolithic and early Bronze Age activity in Mainland builds on the reviews of Griffiths (2016) and Bayliss et al. (2017), who provide syntheses of the chronology of human activity across the Orcadian archipelago in the fourth–third millennia cal BC. Chronological modelling was undertaken using the program OxCal v4.2 (Bronk Ramsey, 2009) and the calibration dataset of Reimer et al. (2013). The modelling included in this paper was undertaken between 2016 and 2019, and this paper was submitted in January 2020. Following the completion of the Bayesian chronological modelling, in mid 2018, the MSA models themselves took more than a year to run to completion. IntCal20 is extremely similar to IntCal13 over the period considered in this study, with only 125 new datapoints included, and so we have not recalculated all the models using the new calibration as this would take several years of run time. The algorithms used in the model are defined exactly by the brackets and OxCal keywords on the left-hand side of Fig. 2 (http://c14.arch.ox.ac.uk/). In the text and tables, the Highest Posterior Density intervals of the posterior density estimates are given in italics.

Our archaeological model has good overall agreement (Amodel: 124) and estimates that the earliest Neolithic activity in Mainland occurred in *3570–3385 cal BC* (*95% probability*; *start_mainland*; Fig. 2), probably *3485–3395 cal BC* (*68% probability*). Although surprisingly late compared with the estimate for the earliest Neolithic in north-east Scotland (*start NE Scotland*; Fig. 3), this is comparable with estimates derived from 'early Neolithic stalled stone houses and timber structures, and from chambered cairns' (Griffiths, 2016, p. 287) across Orkney (*Start_OrkneyNeolithic*; Fig. 3). Thus, on the basis of the current scientific dating evidence, it seems probable that it took some considerable time for the first Neolithic things and practices to become established in Mainland. We do note, however, the early dates on fragments of short-lived charcoal from a pit containing some cereals at Varme Dale (AA-53157–8; Fig. 3), and the presence of a North-Eastern Neolithic carinated bowl at Vestra Fiold on Mainland (Richards et al., 2013, pp. 273–274), which could well pre-date 3600 cal BC; in addition, potentially early forms of chambered tomb (Davidson & Henshall, 1989, p. 66) have not yet been dated. Estimates for the dates of beginnings and early developments are thus still tentative, as we discuss below.

Other major trends to note are the intensification of settlement in the later fourth and early third millennia cal BC; the decline in activity after c. 2850 cal BC; and the recovery after c. 2600 cal BC in the periphery of Mainland and elsewhere, but not in

Table 1 Radiocarbon and stable isotopic measurements from sediment sequences at Hobbister (A and B), Quholm, and Spretta Meadow

Laboratory number	Sample	Radiocarbon age (BP)	$\delta^{13}C_{IRMS}$ (‰)	$\delta^{13}C_{AMS}$ (‰)	Weighted mean
Hobbister B					
SUERC-55039	Bulk peat (alkali-soluble fraction) from 1.76 m	3509 ± 37	−28.9 ± 0.2	–	3534 ± 27 BP; T' = 0.9
SUERC-55043	Bulk peat (alkali- and acid-insoluble fraction) from 1.76 m	3558 ± 37	−29.2 ± 0.2	–	
UBA-26815	Bulk peat (alkali-soluble fraction) from 1.86 m	3910 ± 33	–	−28.7	3918 ± 23 BP; T' = 0.1
UBA-26816	Bulk peat (alkali- and acid-insoluble fraction) from 1.86 m	3926 ± 32	–	−29.5	
Hobbister A					
UBA-26798	Bulk peat (alkali-soluble fraction) from 2.6–2.61 m	3845 ± 31	–	−29.1	3884 ± 23 BP; T' = 3.5
UBA-26799	Bulk peat (alkali- and acid-insoluble fraction) from 2.6–2.61 m	3931 ± 34	–	−29.3	
SUERC-55028	Bulk peat (alkali-soluble fraction) from 2.7–2.71 m	4016 ± 37	−29.8 ± 0.2		4030 ± 27 BP; T' = 0.3
SUERC-55029	Bulk peat (alkali- and acid-insoluble fraction) from 2.7–2.71 m	4044 ± 37	−30.1 ± 0.2		
UBA-26800	Bulk peat (alkali-soluble fraction) from 2.8–2.81 m	4006 ± 33	–	−30.5	4016 ± 29 BP; T' = 0.4
UBA-26801	Bulk peat (alkali- and acid-insoluble fraction) from 2.8–2.81 m	4044 ± 55	–	−31.7	
SUERC-55033	Bulk peat (alkali-soluble fraction) from 2.90–2.91 m	4089 ± 37	−29.3 ± 0.2	–	4050 ± 27 BP; T' = 2.2
SUERC-55034	Bulk peat (alkali- and acid-insoluble fraction) from 2.90–2.91 m	4011 ± 37	−29.7 ± 0.2	–	
UBA-26802	Bulk peat (alkali-soluble fraction) from 3.0–3.01 m	4151 ± 35	–	−29.1	4168 ± 24 BP; T' = 0.4
UBA-26803	Bulk peat (alkali- and acid-insoluble fraction) from 3.0–3.01 m	4182 ± 32	–	−29.4	
SUERC-55035	Bulk peat (alkali-soluble fraction) from 3.1–3.11 m	4154 ± 37	−28.8 ± 0.2	–	4134 ± 27 BP; T' = 0.6
SUERC-55036	Bulk peat (alkali- and acid-insoluble fraction) from 3.1–3.11 m	4114 ± 37	−28.4 ± 0.2	–	
UBA-26804	Bulk peat (alkali-soluble fraction) from 3.2–3.21 m	4330 ± 32	–	−29.8	4365 ± 25 BP; T' = 3.1
UBA-26805	Bulk peat (alkali- and acid-insoluble fraction) from 3.2–3.21 m	4420 ± 40	–	−30.1	
SUERC-55037	Bulk peat (alkali-soluble fraction) from 3.3–3.31 m	4311 ± 37	−29.6 ± 0.2	–	4286 ± 27 BP; T' = 0.9
SUERC-55038	Bulk peat (alkali- and acid-insoluble fraction) from 3.3–3.31 m	4261 ± 37	−29.5 ± 0.2	–	
UBA-26807	Bulk peat (alkali- and acid-insoluble fraction) from 3.43–3.44 m	4565 ± 33	–	−29.6	

Table 1 (continued)

Laboratory number	Sample	Radiocarbon age (BP)	$\delta^{13}C_{IRMS}$ (‰)	$\delta^{13}C_{AMS}$ (‰)	Weighted mean
Quholm					
SUERC-55026	Bulk peat (alkali-soluble fraction) from 0.25 m	2606 ± 37	−28.4	–	2609 ± 27 BP; T' = 0.0
SUERC-55027	Bulk peat (alkali- and acid-insoluble fraction) from 0.25 m	2611 ± 37	−28.1	–	
UBA-26855	Bulk peat (alkali-soluble fraction) from 1.55 m	4427 ± 38	–	−28.5	4429 ± 26 BP; T' = 0.0
UBA-26856	Bulk peat (alkali- and acid-insoluble fraction) from 1.55 m	4431 ± 35	–	−28.8	
UBA-26857	Bulk peat (alkali-soluble fraction) from 2.25 m	9396 ± 45	–	−29.1	
Spretta Meadow					
UBA-26851	Bulk peat (alkali-soluble fraction) from 0.29 m	1340 ± 43	–	−28.9	1397 ± 24 BP; T' = 2.5
UBA-26852	Bulk peat (alkali- and acid-insoluble fraction) from 0.29 m	1421 ± 28	–	−29.8	
SUERC-55019	Bulk peat (alkali-soluble fraction) from 0.61 m	895 ± 37	−29.1 ± 0.2	–	887 ± 27 BP; T' = 0.1
SUERC-55023	Bulk peat (alkali- and acid-insoluble fraction) from 0.61 m	878 ± 37	−29.1 ± 0.2	–	
UBA-26853	Bulk peat (alkali-soluble fraction) from 0.77 m	2252 ± 32	–	−28.7	2330 ± 25 BP; T' = 14.2
UBA-26854	Bulk peat (alkali- and acid-insoluble fraction) from 0.77 m	2442 ± 39	–	−29.6	
SUERC-55024	Bulk peat (alkali-soluble fraction) from 1.09 m	4894 ± 37	−27.8 ± 0.2	–	4886 ± 27 BP; T' = 0.1
SUERC-55025	Bulk peat (alkali- and acid-insoluble fraction) from 1.09 m	4878 ± 37	−28.3 ± 0.2	–	
UBA-17048	Bulk peat from 1.25 m	4956 ± 35		−26.3	
UBA-17047	Bulk peat from 2.37 m	6410 ± 34		−20.9	

Measurements on replicate fractions have been tested for statistical consistency and combined by taking a weighted mean before calibration as described by Ward and Wilson (1978; T'(5%) = 3.8, $\nu = 1$ for all)

the Stenness–Brodgar 'core' of Mainland (Bayliss et al., 2017, fig. 7). These trends (and the idea of the 'core') are all discussed further in our narrative below. They raise important questions about the sustainability of the intensifying activity seen in the archaeological sequence of Neolithic Orkney.

Land Cover Reconstruction: The Multiple Scenario Approach

We applied the MSA to Neolithic pollen records from Mainland, Orkney, in order to develop a spatially explicit, synthesised, semi-quantitative reconstruction of land cover and landscape openness across the period 4200–2200 cal BC. The MSA (Bunting & Middleton, 2009; Bunting et al., 2018; Farrell et al., 2020, fig. S1a) uses a mathematical model of pollen dispersal and deposition to simulate the pollen signal from hypothetical maps of past land cover at locations with existing palynological records. The results are then compared statistically with the actual pollen assemblages in order to identify likely past vegetation mosaics.

Age-depth models for the 11 sequences included in the vegetation reconstructions (Table 2) were derived from Bchron (Haslett & Parnell, 2008) using IntCal13 (Reimer et al., 2013) (see Supplementary Information S1 for full details). The median age estimates for the depths of particular pollen assemblages were used to assign them to timeslices covering 200-year intervals from 4200 to 2200 cal BC (Table 2). For the two pollen samples without age-depth models, assemblages were assigned on the basis of radiocarbon dates obtained from the same dated horizon as the pollen sample (Maeshowe) and the estimated date of digging of the ditch (Stones of Stenness).

Visualisations of reconstructed land cover for all timeslices are shown in Supplementary Information S2 (Figs. S2b–k). The land cover of Orkney during this period was modelled as a mosaic of birch–hazel woodland, grassland suitable for grazing herbivores, and scattered patches of heathland. Stands of oak and pine woodland were allowed to occur in sheltered, well-drained locations (slope > 5°, altitude < 100 m, aspect E, SE or S). The amount of woodland was varied independently between 'upland' and 'lowland' areas, since we considered it plausible that anthropogenic clearance might be greater in lowlands, or that edaphic processes and exposure might accelerate woodland loss in uplands. The boundary between upland and lowland was set as 60 masl (Lamb, 1989; see Fig. 1). Vegetation growing on each pollen site was modelled on the basis of the published record. Finally, we added a disturbed grassland community to the landscape. We have modelled disturbed areas as modified grassland with fewer pollen-producing grasses and more weedy species than in the 'natural' grassland community, and have allowed them to occur anywhere in the study area. This approach makes relatively few assumptions about the behaviour of Neolithic people, since a wide range of natural occurrences (e.g. storm deposits of sand and/or salt, floods) and human-related activities, such as increased grazing, construction and trampling, or field or garden cultivation of food crops, can lead to an increase in the abundance of 'weed' species and a reduction in flowering grasses. The landscape scenarios use a 50 m × 50 m pixel, which means

Fig. 2 Probability distributions of dates from Neolithic Mainland Orkney. Each distribution represents ▶ the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the chronological model used. Distributions other than those relating to particular samples have been taken from models defined for Cuween (Bayliss et al., 2017, fig. S3); Quanterness (Bayliss et al., 2017, fig. S6); Barnhouse (Richards et al., 2016, figs. 6–8); Ness of Brodgar (Card et al., 2018, figs. 9–11); Crossiecrown (Bayliss et al., 2017, fig. S7); Stonehall (Bayliss et al., 2017, fig. S9); Knowes of Trotty (Bayliss et al., 2017, fig. S4); Smerquoy (Griffiths, 2016, Fig. 10.4); Skara Brae (Clarke & Shepherd, forthcoming, illus 2.4.3/1–4); Skaill Bay (Marshall et al., 2016, fig. S1i); Point of Buckquoy (Marshall et al., 2016, fig. S1k); Ring of Brodgar (Bayliss et al., 2017, figs S7–8); and Stones of Stenness (Bayliss et al., 2017, fig. S10). Other distributions are based on the chronological model defined here, and shown in black. For example, the distribution '*start_mainland*' is the estimated date when the earliest Neolithic activity in Mainland began. The large square brackets down the left-hand side of the figure along with the OxCal keywords define the model exactly

that a single pixel is large enough to represent a stand of trees or a settlement site with surrounding areas of high activity.

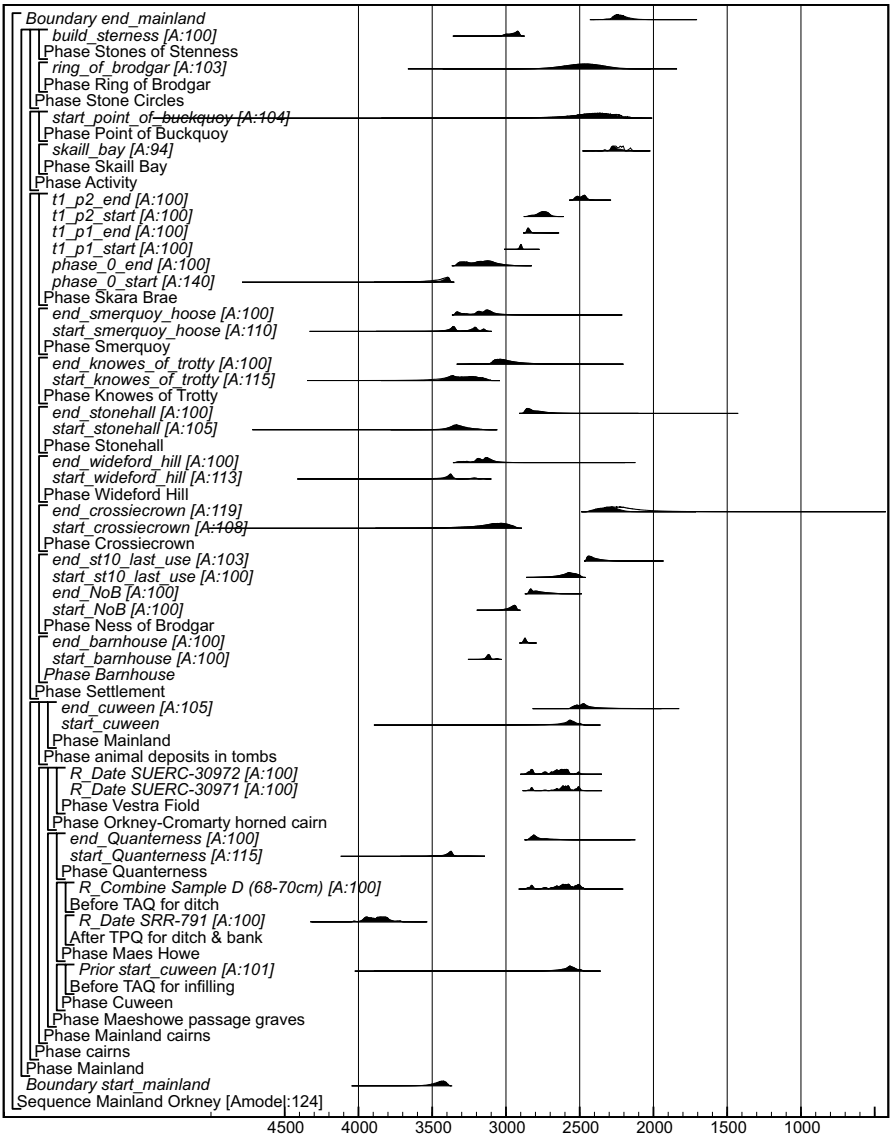
Full details of the modelling strategy are given in Supplementary Information S2, including MSA parameters and inputs. Land cover scenarios with the best overall fit to the pollen targets based on the sum of fit scores for all sites were saved in mapped form, and areal coverage of the communities of interest extracted from these grids using Mosaic3 (Middleton & Bunting, 2004) for comparison with archaeological activity data. The total area of terrestrial habitats in Mainland included in our reconstructions is 54,366 ha; one of the advantages of the MSA is the functionality that it provides in quantifying chosen aspects of land cover and land use, which will run as one thread in the narrative to be presented below.

An Interpretive Narrative for Landscape Change in Neolithic Mainland Orkney

In what follows, we have chosen to present our results as a continuous, interpretive narrative (for discussion of narrative, see Bayliss et al., 2016, pp. 57–58; Whittle, 2018, chapter 2), as we think that best conveys a sense of the spatio-temporal development of the landscape. The MSA modelling was initially carried out in 200-year timeslices, pragmatically reflecting the precision (or better, the imprecision) available for reconstructing environmental change, which is less than that now possible for the biographies of many individual settlements and monuments, but in our narrative we have often imposed a different pattern, and thus deliberately work at varying temporal scales.

The Early Years: Down to c. 3400 cal BC

As already noted, the MSA modelling starts at 4200 cal BC. For the purposes of our narrative, we begin with a long period down to the 35th century cal BC, or in MSA terms down to c. 3400 cal BC. This presumably covers the last hunter-gatherer presence on Orkney (though that is known in very little detail: see Edmonds, 2019, pp. 31–37) and the uncertain circumstances of initial Neolithic



establishment, including the probable arrival of early pioneers from mainland Scotland (Sheridan, 2016; Edmonds, 2019, p. 40). As already noted, although the dating of this process appears late compared with mainland Scotland, it is not yet certainly established. Major features of the early Neolithic presence probably include scattered small settlements, some at least with timber-framed buildings, and simple, tripartite forms of tombs (Davidson & Henshall, 1989; Richards & Jones, 2016).

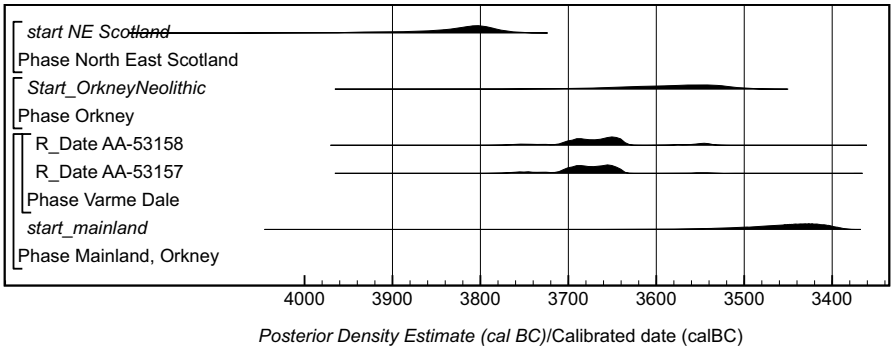


Fig. 3 Estimates for the date of the first Neolithic activity in Mainland Orkney (Fig. 2); the Orkney archipelago (Griffiths, 2016, fig. 10.2; *start_Orkney Neolithic*), and North East Scotland (Whittle et al., 2011, fig. 14.154; *start NE Scotland*), recalculated as necessary using IntCal13 (Reimer et al., 2013). Dates from Varme Dale have been calibrated (Stuiver & Reimer, 1993)

Table 2 Details of pollen data included in each 200-year timeslice (4200–2200 cal BC) – see Supplementary Information S1 for full details of chronological modelling

			Timeslices (cal BC)									
Sequence	**Number of Radiocarbon Dates**	**Age-Depth Model**	**4200–4000**	**4000–3800**	**3800–3600**	**3600–3400**	**3400–3200**	**3200–3000**	**3000–2800**	**2800–2600**	**2600–2400**	**2400–2200**
Bay of Carness: core 69	3	Fig. S1b	■	■	■	■	■	■	■	■	■	■
Scapa Bay: core 23	6	Fig. S1c	■	■	■	■	■	■	■	■	■	
Lesliedale Moss	2	Fig. S1d										■
Hobbister B	8	Fig. S1e									■	■
Hobbister A	22	Fig. S1f			■	■	■	■	■	■	■	■
Glims Moss	7	Fig. S1g		■	■		■		■		■	■
Maes Howe (North) *	2	-								■		
Stones of Stenness*	10	Bayliss *et al.*, 2017, fig. S10							■			
Quholm	6	Fig. S1h		■						■		
Loch of Skaill	10	Fig. S1i		■	■	■	■	■	■	■		■
Spretta Meadow	10	Fig. S1j	■	■	■	■	■	■	■	■	■	■
Bay of Skaill: SK94	3	Fig. S1k			■	■						
Bay of Skaill: SK134	6	Fig. S1l	■	■	■	■	■	■				

Grey shading in cells signifies inclusion of pollen data in that timeslice

*Denotes sequences that do not have age-depth models

The MSA reconstructions of land cover suggest that the pre-Neolithic landscape of Mainland Orkney was dominated by grassland suitable for grazing animals, with heath communities confined to basin mires, limited disturbed land communities (amounting to little more than 1%–2% of the island), and woodland covering c. 20% of the land surface (Fig. 4). Woodland appears to have included a range of tree species, with oak and pine stands in addition to birch and hazel. A natural prevalence of grassland may help to explain the rapid expansion of Neolithic settlement on Mainland, since land suitable for pasture would have been available without the need for extensive clearance. Established Neolithic activity, however, probably began here by the 35th century cal BC (*start_mainland*; Fig. 5). This is about a century later than a similarly modelled date estimate for Orkney as a whole (*start_OrkneyNeolithic*; Fig. 5), and up to 300 years later than the first occurrence of Neolithic things and practices across great swathes of Britain and Ireland in the 38th century cal BC (*start NE Scotland*; Fig. 5). This suggests that Neolithic pioneers took their time establishing themselves on Orkney, and on Mainland in particular, perhaps reflecting at least in part the challenges of navigating the Pentland Firth.

A late date for initial Neolithic settlement on Mainland is supported by the apparent stability of the pre-existing woodlands and disturbed land communities inferred from the MSA reconstructions (Fig. 5). There is a temporary decline in tree cover and an increase in disturbed ground vegetation visible in the 4000–3800 cal BC timeslice, where birch and hazel woodland fell to only 12% of land cover as opposed to 21% in the 4200–4000 cal BC timeslice (Fig. 4), but greater woodland cover returns in the following timeslice. This might indicate a phase of earlier activity by either late hunter-gatherers or farming pioneers (one factor to note could be the presence of red deer, seemingly deliberately introduced by either late hunter-gatherers or

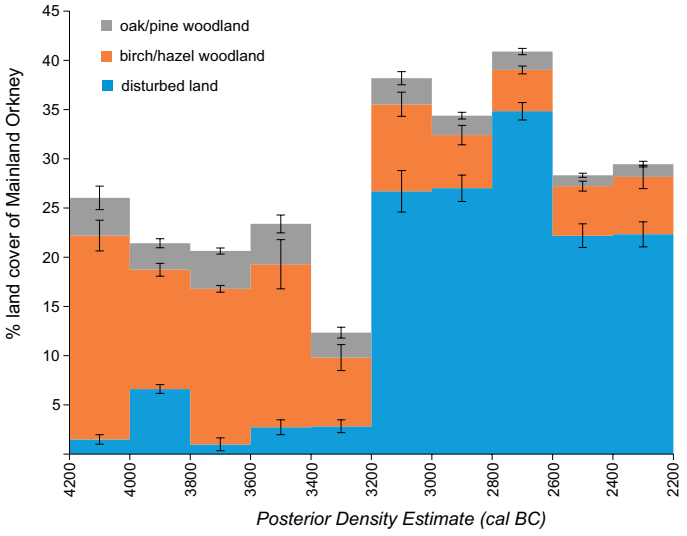


Fig. 4 Area of land cover: birch and hazel woodland, oak and pine woodland, and disturbed land expressed as a percentage of the total land cover of Orkney

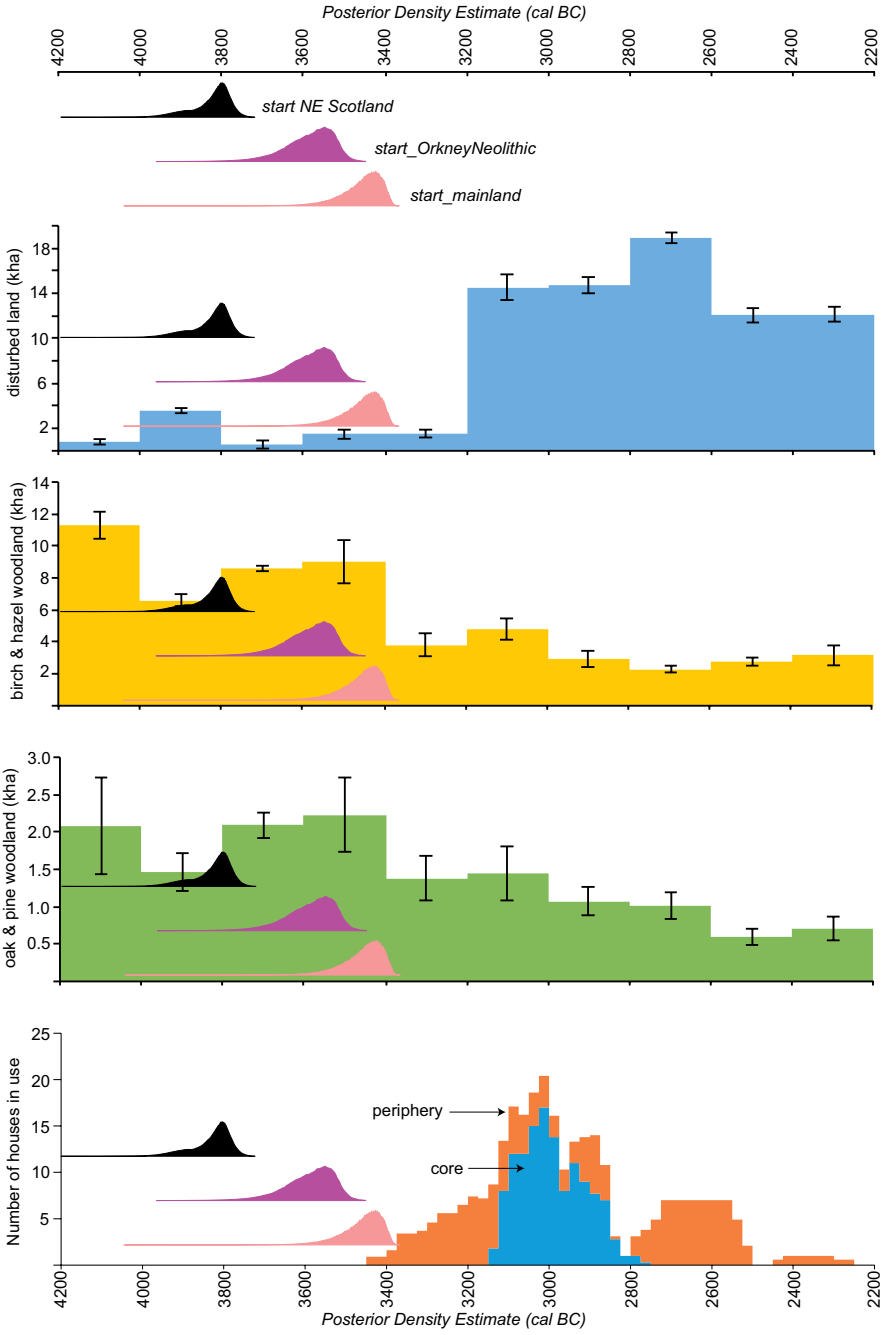


Fig. 5 Estimates for the beginnings of Neolithic lifeways, area of disturbed land (kha) and woodland land cover; birch and hazel; oak and pine (kha) as derived from the best overall fit maps, and the number of dated Neolithic houses in use in Mainland during the later fourth and third millennia cal BC

early farmers, from a so-far unknown source: Stanton et al., 2016), although it could also be attributed to differences in the pollen sites included. The effects of small local stands of birch woodland near individual pollen sites, as well as the assumptions made about woodland composition, may explain why birch–hazel woodland apparently declines more than oak–pine woodland. In landscapes in western Scotland with surviving fragments of birch–hazel woodland, birch-only stands are quite common, and hazel in mixed stands generally grows in inner parts of the stand and in particularly favourable locations such as along stream beds (also seen in Berriedale on Hoy in Orkney, the last fragment of probably natural woodland in the archipelago; see also Edmonds, 2019, p. 13). Whilst this pattern is clearly influenced by the sweeping changes in landscape management of the last few hundred years, our knowledge of woodland ecology suggests that the late Mesolithic woodlands of Orkney likely had greater diversity than is modelled here.

The Beginnings of Well-Established Settlement: 3400–3200 cal BC

Following this long and poorly-understood initial phase of settlement, the 34th century cal BC takes us to what appears to be the start of a long period of well-established settlement. From this time, the appearance of more and more sites suggests rapid expansion of human activity. This is found not only in Mainland but also across the archipelago as a whole. One manifestation is the start of the shift to stone-built houses, a notable area being the Bay of Firth in Mainland, where recent investigations have shown numerous such structures (Richards & Jones, 2016); an estimate for the date of this shift is the late 35th into the 34th century cal BC (Bayliss et al., 2017, fig. 6, *start_linear*). By this sort of time bigger and more varied tombs were being constructed, probably including large stalled cairns and perhaps the first passage graves (Bayliss et al., 2017, fig. 2, *start stalled cairns* and *start Maeshowe passage graves*).

A sustained shift in land cover is seen from 3400 cal BC (Fig. 5). The two timeslices between 3400 and 3000 cal BC cover the first major building of tombs, the shift from timber to stone houses, and the nucleation of settlement in the Stenness–Brodgar area of Mainland (Richards & Jones, 2016; Bayliss et al., 2017; Card et al., 2018, 2020). In the 3400–3200 cal BC timeslice, woodland approximately halved to c. 5000 ha (or c. 10% of the land cover of Mainland). This affected both birch–hazel and oak–pine woodland. In a little more detail, birch–hazel woodland cover shows a marked fall (c. 58%) between the 3600–3400 cal BC and 3400–3200 cal BC timeslices, one timeslice earlier than the abrupt rise in the disturbed ground community shown in Fig. 5.

It is possible that this opening up of the landscape reflects the establishment of larger numbers of people and livestock in a fragile woodland system, with initial increased pressure leading to replacement of woodland by grassland by the 3400–3200 cal BC timeslice. The initial expansion of the disturbance community may not be detected by the pollen records until settlement is solidly established and dispersed in the study area, in the 3200–3000 cal BC timeslice, partly because the taxa producing the pollen signal of disturbance are relatively poorly represented

in pollen diagrams and partly because many of the available records are located at some distance from areas of known archaeological activity (Fig. 1).

Oak–pine woodland shows a more drawn-out decline (Fig. 5), perhaps reflecting its location on steeper slopes within the landscape which were less accessible to livestock and less attractive to early farmers. The offset between the dates of woodland decline (in the 3400–3200 cal BC timeslice) and of an increase in disturbed ground habitats (in the 3200–3000 cal BC timeslice) might also reflect both an initial reliance on felling timber for construction (cf. *start_timber_houses*; Bayliss et al., 2017, fig. 6) and a relatively slow start to exploitation of the comparatively heavy soils of central Mainland (Sharples, 1992). Although woodland cover declines at the start of this period, woodland does not disappear from the landscape, perhaps even as a result of deliberate protection or management to ensure that the resource was not over-used or suppressed by grazing livestock.

The Flourishing of Late Neolithic Orkney: 3200–2800 cal BC

This is the period of the flourishing of the classic late Neolithic of Orkney. One prominent feature is the emergence of the new, flat-based ceramic style of Grooved Ware. This goes on to be variously shared by communities as far south as southern England and Ireland, but there are good arguments for seeing it as originating in Orkney as a deliberate creation resulting from communal politics (Sheridan, 2016). Its appearance in Orkney has been dated from the 32nd century cal BC (Bayliss et al., 2017, fig. 5), initially overlapping with the existing tradition of round-based pottery. To this period belong passage grave tombs, such as at Maeshowe, and large stalled cairns, and strong connections and interactions with eastern Ireland are another prominent feature of this horizon (Carlin, 2017). A ditched stone circle existed at Stones of Stenness from the thirtieth century cal BC, arguably another Orcadian invention. Settlements of stone-built houses (Richards & Jones, 2016) were widespread across the archipelago, coming to prominence especially in the Stenness–Brodgar core area of Mainland; Barnhouse (Richards et al., 2016) and especially its near-neighbour Ness of Brodgar (Card et al., 2018) represent significant aggregations of people and activity. We have used this evident concentration to suggest a core area (Bayliss et al., 2017, pp. 1181–1182; cf. Richards, 1996a, 1996b; Downes et al., 2013; Edmonds, 2019, p. 241), in comparison to which other parts of the archipelago seem less densely used at this time, but we have deliberately not precisely defined its limits or scale. Within this putative core, Ness of Brodgar — from its size, its location and the variety of the piered architecture of its remarkably well-built large buildings — may have been some kind of central place for a much wider constituency. Social models for the archipelago as a whole have ranged from simple chiefdoms (Renfrew, 1979), competitive elites (Sheridan, 2004) and clan leaders (Edmonds, 2019, pp. 278–279) to 'house societies' (Richards & Jones, 2016); whatever the best fit, there is no doubting the intense levels of activity in both settlement and monument building, and the seemingly very active connections with other places far beyond the local horizons.

For the first time, the MSA models for Mainland Orkney presented here begin to give this dynamic scene a more fleshed out landscape context. At the start, in the 3200–3000 cal BC timeslice, there is a slight increase in both birch–hazel and oak–pine woodland (Fig. 5). Might this in part reflect the shift away from the construction of timber buildings to the building of stone houses? By the 3000–2800 cal BC timeslice, however, woodland has further declined (Fig. 5). By contrast, there was a dramatic increase in the extent of disturbed ground communities in the 3200–2800 cal BC timeslices. These disturbed land communities, probably including land given over to cereal cultivation, had been more or less stable at c. 1500 ha (or c. 3% of the land cover of the island) until the 3200–3000 cal BC timeslice, when they increased ten-fold to c. 15,000 ha (or c. 30% of the land cover of the island) (Figs. 4 and 5). This significant impact as modelled here serves as a further index of the intensity of late Neolithic activity.

In terms of specific land use, the signal for a general disturbance community may indicate a higher reliance on pasture than earlier. This accords with the archaeological record since the Neolithic Orcadian economy probably relied heavily on cattle for subsistence (Card et al., 2018; Mainland et al., 2014) with more limited cereal cultivation, perhaps in garden or other infield plots, and a lack of exploitation of marine resources indicated by both isotope and lipid analyses so far undertaken (Schulting et al., 2010, pp. 41–43; Lawrence, 2012; Cramp et al., 2014). The implications are extensive, though there is hardly space to follow them all here. Fifteen thousand hectares would presumably have supported a lot of cattle (Dahl & Hjort, 1976) and give a plausible context for the seemingly extravagant slaughter of more than 400 cattle represented in the slightly later Structure 10 deposit at Ness of Brodgar (Mainland et al., 2014). Recent indications of winter consumption of seaweed by sheep at Skara Brae and Holm of Papa Westray (Balasse et al., 2019) could also suggest an economy geared for the maintenance of high numbers of animals, with cattle being preferentially over-wintered on terrestrial pasture (Balasse et al., 2019, p. 928). The small human sample investigated at Quanterness also indicates an increase in $\delta^{15}N$ values (perhaps related to meat consumption) through time, into the earlier third millennium cal BC (Schulting et al., 2010, p. 23).

Decline: 2800–2600 cal BC

The Stenness–Brodgar core area of Mainland sees a sustained reduction in settlement activity in the 2800–2600 cal BC timeslice (Fig. 5). Examples include the previously prominent Barnhouse, where occupation ended probably in the earlier twenty-ninth century cal BC (Richards et al., 2016, fig. 6, *end Barnhouse*), and Ness of Brodgar, where the spectacular buildings were falling into disrepair and beginning to be covered by midden deposits probably (in the preferred chronological model) from around 2800 cal BC (Card et al., 2018, fig. 9, *end_NoB_piered*). However, the MSA land cover reconstructions show no regeneration of woodland; if anything, there is a slight decline in both birch–hazel and oak–pine woodland (Fig. 5). By contrast, disturbed areas actually increased following the decline in archaeological evidence of activity after c. 2850 cal BC, occupying at their most extensive

about a third of the total land surface of Mainland. Since the available pollen sites are mostly located in the periphery (as opposed to the Stenness–Brodgar core; see Fig. 1), this suggests a shift in activity from the core area into the wider landscape rather than a loss of population. In terms of sustainability, the putative dispersal of population into smaller units of settlement, away from the bigger concentrations of people and activity in the major complexes, may suggest an inability to maintain the previous intensity of social interaction rather than any kind of general abandonment prompted by specific environmental causes.

Endgame: 2600–2200 cal BC

In the final period under consideration here, settlements are found mainly in the periphery of Mainland and in the rest of the archipelago. The Grooved Ware occupation of the site at Pool on Sanday, for example, probably ended around 2400 cal BC (MacSween et al., 2015, fig. 14), and at Links of Noltland on Westray perhaps at a similar time or later, though the overall dating is still incomplete (Clarke et al., 2017, illus. 11); a notable deposit of red deer probably dating to the twenty-second century cal BC coincides with the use of Beaker as opposed to Grooved Ware pottery on the site (Clarke et al., 2017). In the Stenness–Brodgar core, Barnhouse would have been long forgotten, though overlooked by the still-standing Stones of Stenness. The last activity at Ness of Brodgar was a massive feast (or a very short period of repeated feasting) on cattle and the deposition of their remains over the ruins of the once-remarkable Structure 10, around 2500 cal BC in the preferred chronological model (Mainland et al., 2014; Card et al., 2018, fig. 9, *st10_cattle*). The impressive Ring of Brodgar circle could have been constructed in these two timeslices, according to OSL dating of the ditch (Bayliss et al., 2017, fig. 5), but overlooking a now largely deserted Ness of Brodgar.

Such a chronological position for the Ring of Brodgar chimes with the persistent, though reduced, presence of the disturbed land community after 2600 cal BC, which implies ongoing presence of human activity in the landscape despite the lack of dated archaeological sites. Disturbed ground cover decreases in the two timeslices spanning 2600–2200 cal BC, but remains at around 20% of land cover (Fig. 4), several orders of magnitude above levels before the Neolithic. Woodland levels remain more or less constant at this time (Fig. 5). Beyond Mainland, there is still evidence for cultivation and middening above the deer deposit at Links of Noltland (Clarke et al., 2017), and it remains a task for future research to track the nature of such activity on Mainland at this time, hinted at for example in some of the evidence from Crossiecrown in the Bay of Firth (Richards et al., 2016).

Among many possible reasons for the decline of the Grooved Ware phenomenon and related practices in Orkney (reviewed in Clarke et al., 2017), there have been suggestions of environmental stress and climatic downturn. There are to date no published independent palaeoclimate reconstructions covering the mid Holocene for the region, and this therefore remains a tentative hypothesis. Our land cover reconstructions do not show any clear signs of climatic downturn, such as spread of acid heathland or peat, during this period. The persistence of disturbed ground and lack

of woodland regeneration could be interpreted as continuing direct human action, as indirect human action (e.g. feral grazers derived from abandoned domestic herds suppressing woodland recovery and creating habitat for ruderal species), or as a reflection of climatic or edaphic conditions which favoured ruderals and restricted tree regeneration. Given the lack of a clear signal of climate change, we infer that the cause of the Grooved Ware decline is better sought in social than environmental factors. A similar argument for continuity of land use and minimal environmental deterioration at the Neolithic–Bronze Age transition in Orkney is made by Farrell (2009).

Discussion and Conclusions

The palaeoecological signal of Neolithic settlement in Mainland Orkney is subtle, with many classic anthropogenic indicator plants already present and thriving in the grasslands and in naturally disturbed environments such as near-coastal regions subject to salt spray and storm deposits. Neolithic *landnám* or land taking is usually identified in pollen records through increases in pollen from plants found in open areas, which respond as forest canopy is disturbed by both deliberate actions (e.g. creating a clearance for crops) and unintended consequences of actions (e.g. concentrating numbers of grazing animals or introducing new herbivore species), but the landscape in Orkney and other northern European margins already contained large areas of open vegetation suitable for pasture or garden cropping, where the 'indicator' species would have naturally been present. Increases in indicator species and shifts in composition of open vegetation communities have a subdued signal in the pollen record compared with reductions in tree pollen, though Fig. 5 shows how the interpretation of the pollen record made possible by applying the MSA allows us to draw out this relatively subtle signal, producing in this way dramatic results. These have been interpreted here within a framework provided by the archaeological evidence and the more precise archaeological site biographies now available, enabling the construction of much fuller and better-contextualised narratives.

Taken together, the application of Bayesian statistical modelling to produce robust chronologies for both archaeological sites and palaeoenvironmental records and of the MSA to reconstruction of past land cover offers a step-change in our understanding of the interactions between Neolithic people in Orkney and the landscape which they inhabited. Greater emphasis is clearly needed on providing chronologies for sediment sequences that are of equivalent resolution to the generational scale that is now available for many Neolithic archaeological sites, and higher-resolution pollen analysis is clearly needed if the relative contributions of arable and pastoral farming are to be quantified. But this study has, for the first time, provided a coherent account of Neolithic settlement in Mainland, Orkney, which quantifies the impact of people and their livestock on the environment. Future research should also seek to quantify the role of cereal cultivation in land use and diet.

In conclusion, it looks as though the establishment of Neolithic settlement in Orkney was slow and late compared to mainland Scotland, but once begun Neolithic activity in both settlement and monument building steadily intensified. Perhaps

initially low numbers consolidated into a peak of people and activity in the period c. 3200–2800 cal BC. The combination of MSA modelling and archaeological sequences with robust chronologies has provided for the first time a reconstruction of the spatio-temporal patterns of Neolithic people and their environment in Mainland Orkney. There were major alterations to the land cover of Mainland Orkney. Woodland declined substantially from 3400 cal BC, while the dramatic increase in disturbed land was initiated from 3200 cal BC, more or less coinciding with the emergence of all the activity, creativity, connectivity and perhaps competitiveness associated with the Grooved Ware phenomenon.

That situation did not go on for ever, and by 2800 cal BC in the Stenness–Brodgar core of Orkney Mainland, most settlements appear to have been in decline or ending. Rather than a general abandonment, however, we seem to be witnessing a dispersal into the wider landscape, where the MSA modelling indicates a maintenance of disturbed land, and indeed a slight increase in the 2800–2600 cal BC timeslice. Overall, the evidence considered here does not suggest that environmental factors were the primary cause for the Grooved Ware decline after the twenty-fifth century cal BC, and we conclude that the observed changes can better be thought of as related to the conditions of social rather than environmental sustainability. People exhausted themselves rather than their land; that and its varied resources endured, while the intensive social relationships and practices of the peak of late Neolithic Orkney could not be maintained.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10963-022-09166-y.

Acknowledgements We thank all the many colleagues whose cooperation has made the dating reported here possible. *The Times of Their Lives* was funded by the European Research Council (Advanced Investigator Grant: 295412, 2012–2017), and led by Alasdair Whittle and Alex Bayliss. We also thank four anonymous referees for their critical comments on an earlier version of this paper; Mark Edmonds and Alison Sheridan for advice and critical reading; and Kirsty Harding for help in the preparation of the figures.

References

Balasse, M., Tresset, A., Obein, G., Fiorillo, D., & Gandois, H. (2019). Seaweed-eating sheep and the adaptation of husbandry in Neolithic Orkney: New insights from Skara Brae. *Antiquity, 93*, 919–932.

Bates, C. R., Bates, M. R., Dawson, S., Huws, D., Whittaker, J. E., & Wickham-Jones, C. R. (2016). The environmental context of the Neolithic monuments on the Brodgar Isthmus, Mainland, Orkney. *Journal of Archaeological Science: Reports, 7*, 394–407.

Bayliss, A., Beavan, N., Hamilton, D., Köhler, K., Nyerges, É. Á., Bronk Ramsey, C., Dunbar, E., Fecher, M., Goslar, T., Kromer, B., Reimer, P. J., Bánffy, E., Marton, T., Oross, K., Osztás, A., Zalai-Gaál, I., & Whittle, A. (2016). Peopling the past: Creating a site biography in the Hungarian Neolithic. *Bericht Der Römisch-Germanischen Kommission, 94*, 23–91.

Bayliss, A., Marshall, P., Richards, C., & Whittle, A. (2017). Islands of history: The Late Neolithic timescape of Orkney. *Antiquity, 91*, 1171–1188.

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon, 51*, 337–360.

Bunting, M. J. (1994). Vegetation history of Orkney, Scotland: Pollen records from two small basins in West Mainland. *New Phytologist, 128*, 771–792.

Bunting, M. J. (1996). The development of heathland in Orkney, Scotland: Pollen records from Loch of Knitchen (Rousay) and Loch of Torness (Hoy). *The Holocene, 6*, 193–212.

Bunting, M. J., Farrell, M., Bayliss, A., Marshall, P., & Whittle, A. (2018). Maps from mud – using the Multiple Scenario Approach to reconstruct land cover dynamics from pollen records: A case study of two Neolithic landscapes. *Frontiers in Ecology and Evolution, 6*, 36. https://doi.org/10.3389/fevo.2018.00036

Bunting, M. J., & Middleton, R. (2009). Equifinality and uncertainty in the interpretation of pollen data: The Multiple Scenario Approach to reconstruction of past vegetation mosaics. *The Holocene, 19*, 799–803.

Card, N., Edmonds, M., & Mitchell, A. (2020). *The Ness of Brodgar: As it stands*. Orcadian Ltd.

Card, N., Mainland, I., Timpany, S., Batt, C., Bronk Ramsey, C., Dunbar, E., Reimer, P. J., Bayliss, A., Marshall, P., & Whittle, A. (2018). To cut a long story short: Formal chronological modelling for the Late Neolithic site of Ness of Brodgar, Orkney. *European Journal of Archaeology, 21*, 217–263.

Carlin, N. (2017). Getting into the groove: Exploring the relationship between Grooved Ware and developed passage tombs in Ireland c. 3000–2700 cal BC. *Proceedings of the Prehistoric Society, 83*, 155–188.

Childe, V. G. (1956). Maes Howe. *Proceedings of the Society of Antiquaries of Scotland, 88*, 155–172.

Clarke, D., Sheridan, A., Shepherd, A., Sharples, N., Armour-Chelu, M., Hamlet, L., Bronk Ramsey, C., Dunbar, E., Reimer, P., Marshall, P., & Whittle, A. (2017). The end of the world, or just 'Goodbye to all that'? Contextualising the late 3rd-millennium cal BC deer heap at Links of Noltland, Westray, Orkney. *Proceedings of the Society of Antiquaries of Scotland, 146*, 57–89.

Clarke, D. V., & Shepherd, A. (forthcoming). *Skara Brae: A full compendium of the site*. Historic Environment Scotland.

Cramp, L. J. E., Jones, J., Sheridan, A., Smyth, J., Whelton, H., Mulville, J., & Evershed, R. P. (2014). Immediate replacement of fishing with dairying by the earliest farmers of the northeast Atlantic archipelagos. *Proceedings of the Royal Society B Biological Sciences*. https://doi.org/10.1098/rspb.2013.2372

Dahl, G., & Hjort, A. (1976). *Having herds: Pastoral herd growth and household economy*. Department of Social Anthropology, Stockholm.

Davidson, J. L., & Henshall, A. S. (1989). *The chambered cairns of Orkney: An inventory of the structures and their contents*. Edinburgh University Press.

Davidson, D. A., & Jones, R. L. (1985). The environment of Orkney. In C. Renfrew (Ed.), *The prehistory of Orkney* (pp. 10–35). Edinburgh University Press.

Davidson, D. A., Jones, R. L., & Renfrew, A. C. (1976). Palaeoenvironmental reconstruction and evaluation: A case study from Orkney. *Transactions of the Institute of British Geographers, 1*, 346–361.

De La Vega Leinert, A. C. (1998). Flandrian coastal environmental changes: Evidence from three sites in Mainland Orkney, Scotland. Unpublished PhD thesis, Coventry University.

Downes, J., & Gibson, J., with Gibbon, S. J., & Mitchell, A. (2013). *Heart of Neolithic Orkney World Heritage Site: Research strategy 2013–2018*. Historic Scotland.

Edmonds, M. (2019). *Orcadia: Land, sea and stone in Neolithic Orkney*. Head of Zeus Ltd.

Erdtman, G. (1924). Studies in the micropalaeontology of postglacial deposits in northern Scotland and the Scotch Isles, with especial reference to the history of the woodlands. *Journal of the Linnean Society of London, 46*, 449–504.

Farrell, M. (2009). The environmental context of later prehistoric human activity in Orkney, Scotland. Unpublished PhD thesis, University of Hull.

Farrell, M. (2015). Later prehistoric vegetation dynamics and Bronze Age agriculture at Hobbister, Orkney, Scotland. *Vegetation History and Archaeobotany, 24*, 467–486.

Farrell, M., Bunting, M. J., Sturt, F., Grant, M., Aalbersberg, G., Batchelor, R., Druce, D., Hill, T., Hollinrake, A., Jones, J., Tinsley, H., Bayliss, A., Marshall, P., Richer, S., & Whittle, A. (2020). Opening the woods: Towards a quantification of Neolithic clearance around the Somerset Moors and Levels. *Journal of Archaeological Method and Theory, 27*, 271–301.

Griffiths, S. (2016). Beside the ocean of time: A chronology of Neolithic burial monuments and houses in Orkney. In C. Richards & R. Jones (Eds.), *The development of Neolithic house societies in Orkney* (pp. 254–302). Windgather Press.

Griffiths, S., & Richards, C. (2013). A time for stone circles, a time for new people. In C. Richards (Ed.), *Building the great stones circles of the north* (pp. 281–291). Windgather Press.

Haslett, J., & Parnell, A. (2008). A simple monotone process with application to radiocarbon-dated depth chronologies. *Journal of the Royal Statistical Society: Series C (applied Statistics), 57*, 399–418.

Jones, R. L. (1979). Vegetational studies. In C. Renfrew (Ed.), *Investigations in Orkney* (pp. 21–28). Thames & Hudson.

Keatinge, T. H., & Dickson, J. H. (1979). Mid-Flandrian changes in vegetation on Mainland Orkney. *New Phytologist, 82*, 585–612.

Lamb, R. G. (1989). *The archaeological sites and monuments of Scotland, 29: Hoy and Waas*. RCAHMS.

Lawrence, D. M. (2012). Orkney's first farmers: Reconstructing biographies from osteological analysis to gain insights into life and society in a Neolithic community on the edge of Atlantic Europe. Unpublished PhD thesis, University of Bradford.

MacSween, A., Hunter, J., Sheridan, A., Bond, J., Bronk Ramsey, C., Reimer, P., Bayliss, A., Griffiths, S., & Whittle, A. (2015). Refining the chronology of the Neolithic settlement at Pool, Sanday, Orkney. *Proceedings of the Prehistoric Society, 81*, 283–310.

Mainland, I., Card, N., Saunders, M. K., Webster, C., Isaksen, L., Downes, J., & Littlewood, M. (2014). 'Smart fauna': A microscale GIS-based multi-dimensional approach to faunal deposition at the Ness of Brodgar, Orkney. *Journal of Archaeological Science, 41*, 868–878.

Marshall, P., Clarke, D., Sheridan, A., Shepherd, A., Sharples, N., Armour-Chelu, M., Bronk Ramsey, C., Dunbar, E., Reimer, P., & Whittle, A. (2016). *Links of Noltland, Westray, Orkney: Radiocarbon dating and chronological modelling*. Historic England Research Report 39–2016.

Middleton, R., & Bunting, M. J. (2004). Mosaic v1.1: Landscape scenario creation software for simulation of pollen dispersal and deposition. *Review of Palaeobotany and Palynology, 132*, 61–66.

Moar, N. T. (1969). Two pollen diagrams from the Mainland, Orkney Islands. *New Phytologist, 68*, 201–208.

Moore, H., & Wilson, G. (2011). *Shifting sands. Links of Noltland, Westray: Interim report on Neolithic and Bronze Age excavations, 2007–2009*. Historic Scotland.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., … Kromer, B. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon, 55*, 1869–1887.

Renfrew, C. (Ed.) (1979). *Investigations in Orkney.* Thames & Hudson.

Richards, C., & Jones, R. (Ed.) (2016). *The development of Neolithic house societies in Orkney*. Windgather Press.

Richards, C. (1996a). Henges and water: Towards an elemental understanding of monumentality and landscape in late Neolithic Britain. *Journal of Material Culture, 1*, 313–336.

Richards, C. (1996b). Monuments as landscape: Creating the centre of the world in late Neolithic Orkney. *World Archaeology, 28*, 190–208.

Richards, C. (Ed.) (2005). *Dwelling among the monuments: The Neolithic village of Barnhouse, Maes Howe passage grave and surrounding monuments at Stenness.* McDonald Institute for Archaeological Research.

Richards, C., Downes, J., Ixer, R., Hambleton, E., Peterson, R., & Pollard, J. (2013). Surface over substance: The Vestra Fiold horned cairn, Mainland, Setter cairn, Eday, and a reappraisal of late Neolithic funerary architecture. In C. Richards (Ed.), *Building the great stone circles of the north* (pp. 149–183). Windgather Press.

Richards, C., Jones, A. M., Sheridan, A., Dunbar, E., Reimer, P. J., Bayliss, A., Griffiths, S., & Whittle, A. (2016). Settlement duration and materiality: Formal chronological models for the development of Barnhouse, a Grooved Ware settlement in Orkney. *Proceedings of the Prehistoric Society, 82*, 193–225.

Ritchie, A. (1995). *Prehistoric Orkney*. Historic Scotland.
Schulting, R. J., Sheridan, A., Crozier, R., & Murphy, E. (2010). Revisiting Quanterness: New AMS dates and stable isotope data from an Orcadian chamber tomb. *Proceedings of the Society of Antiquaries of Scotland, 140*, 1–50.
Sharples, N. (1992). Aspects of regionalisation in the Scottish Neolithic. In N. Sharples & J. A. Sheridan (Eds.), *Vessels for the ancestors: Essays on the Neolithic of Britain and Ireland in honour of Audrey Henshall* (pp. 322–331). Edinburgh University Press.
Sheridan, J. A. (2016). Scottish Neolithic pottery in 2016: The big picture and some details of the narrative. In F. Hunter & A. Sheridan (Ed.), *Ancient lives: Object, people and place in early Scotland. Essays for David V. Clarke on his 70th birthday* (pp. 189–212). Sidestone Press.
Sheridan, J. A. (2004). Going round in circles? Understanding the Irish Grooved Ware 'complex' in its wider context. In H. Roche, E. Grogan, J. Bradley, J. Coles, & B. Raftery (Eds.), *From megaliths to metal: Essays in honour of George Eogan* (pp. 26–37). Oxbow Books.
Stanton, D. W. G., Mulville, J. A., & Bruford, M. W. (2016). Colonization of the Scottish islands via long-distance Neolithic transport of red deer (*Cervus elaphus*). *Proceedings of the Royal Society B, Biological Sciences*. https://doi.org/10.1098/rspb.2016.0095
Stuiver, M., & Reimer, P. J. (1993). Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon, 35*, 215–230.
Ward, G. K., & Wilson, S. R. (1978). Procedures for comparing and combining radiocarbon age determinations: A critique. *Archaeometry, 20*, 19–31.
Whittle, A., Healy, F., & Bayliss, A. (2011). *Gathering time: Dating the early Neolithic enclosures of southern Britain and Ireland*. Oxbow Books.
Whittle, A. (2018). *The times of their lives: Hunting history in the archaeology of Neolithic Europe*. Oxbow Books.

Authors and Affiliations

M. Jane Bunting[1] · Michelle Farrell[2,3] · Elaine Dunbar[4] · Paula Reimer[5] · Alex Bayliss[6] · Peter Marshall[6] · Alasdair Whittle[7]

1 Department of Geography, Geology and Environment, University of Hull, Cottingham Road, Hull HU6 7RX, UK

2 School of Energy, Construction and Environment, Coventry University, Much Park Street, Coventry CV1 2LT, UK

3 Centre for Agroecology, Water and Resilience, Wolston Lane, Ryton-on-Dunsmore, Coventry CV8 3LG, UK

4 SUERC Radiocarbon Dating Laboratory, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride G75 0QF, UK

5 ^{14}CHRONO Centre, Queen's University Belfast, 42 Fitzwilliam Street, Belfast BT9 6AX, UK

6 Historic England, Cannon Bridge House, 25 Dowgate Hill, London EC4R 2YA, UK

7 Department of Archaeology and Conservation, Cardiff University, John Percival Building, Colum Drive, Cardiff CF10 3EU, UK