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Extreme wet conditions coincident with Bronze Age abandonment of upland areas in Britain

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ABSTRACT

Abandonment of farming systems on upland areas in southwest Britain during the Late Bronze Age – some 3000 years ago – is widely considered a 'classic' demonstration of the impact of deteriorating climate on the vulnerability of populations in such marginal environments. Here we test the hypothesis that climate change drove the abandonment of upland areas by developing new chronologies for human activity on upland areas during the Bronze Age across southwest Britain (Dartmoor, Exmoor and Bodmin Moor). We find Bronze Age activity in these areas spanned 3900–2950 calendar years ago with abandonment by 2900 calendar years ago. Holocene Irish bog and lake oak tree populations provide evidence of major shifts in hydroclimate across western Britain and Ireland, coincident with ice rafted debris layers recognized in North Atlantic marine sediments, indicating significant changes in the latitude and intensity of zonal atmospheric circulation across the region. We observe abandonment of upland areas in southwest Britain coinciding with a sustained period of extreme wet conditions that commenced 3100 calendar years ago. Our results are consistent with the view that climate change increased the vulnerability of these early farming communities and led to a less intensive use of such marginal environments across Britain.

1. Introduction

The impacts of climate change on past human populations remains unresolved and complex (McCormick et al., 2012; Zhang et al., 2007). Although some studies have suggested deteriorating climate conditions impacted cultures (Büntgen et al., 2011; Huntley et al., 2002; Magny, 2004; Rosen and Rivera-Collazo, 2012; Turney and Hobbs, 2006; Williams et al., 2015), the biased selection of palaeoclimate proxies, the 'smearing' of archaeological chronologies and non-linear societal responses risk 'false positive' associations (Baillie, 1991; Caseldine and Turney, 2010; Coombes and Barber, 2005; Plunkett et al., 2013). Of particular significance in this regard is the Bronze Age, where climate change has been proposed to have played a significant role in large scale abandonment and migration around 1000 BC across the British Isles (i.e. 3000 calendar years ago or cal. BP) (Baillie, 1999; Burgess, 1985; Tipping et al., 2008; Turney et al., 2006; Warner, 1993), Europe (Burgess, 1989; Menotti, 2002; van Geel et al., 2004; Weiss, 1982) and the Near East (Frank et al., 2002; Kaniewski et al., 2010; Kaniewski et al., 2015; Weiss, 1982). Recent work, however, has questioned this association, suggesting socio-economic or political factors may have initiated population collapse instead (Armit et al., 2014; Plunkett, 2009). High-precision dating and correlation of archaeological and palaeoclimate evidence are crucial for resolving this apparent impasse.

One of the earliest studies suggesting an impact of climate on early European communities was the late Bronze Age abandonment of moor-wide boundaries known as 'reaves' on Dartmoor, an upland area in southwest Britain reaching 621 metres above sea level (Fleming, 1988). Interpreted as a planned and systematic land division, the reaves are thought to have been established during the middle Bronze Age in response to grazing land pressure, but were proposed to have been later abandoned due to cooler, wetter conditions (Caseldine, 1999; Fleming, 1994). This pioneering work had limited age control (being based on just three radiocarbon ages) while the changing conditions were inferred from vegetation (pollen) responses to climate (which can be problematic given

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competing influences such as ecological succession and human activity in the landscape) (Caseldine, 1999; Dark, 2006; Fyfe et al., 2003).

To what extent the abandonment of the reaves was a reflection of depopulation or simply a reduction in the intensity of human activity across the region is unclear. Although some parts of Dartmoor and other upland areas in the region were exploited for arable cultivation (Caseldine, 1999) as a consequence of population expansion (Woodbridge et al., 2014), most were probably used for pastoral purposes alongside mining to access mineral-rich seams (Webster, 2007). Whilst it seems likely that society and/or internal social systems would have played a role in individual and group decision making (Wickstead, 2008), subsequent archaeological studies have largely supported the idea of a less intense upland settlement during the late Bronze Age (Quinnell, 1997), suggesting a common cause for the shift away from permanent mixed agriculture in the region. It has long been recognised that new excavations on upland areas in the southwest of Britain will allow the archaeological evidence for abandonment of upland areas to be robustly tested against climate datasets (Caseldine, 1999). However, there has been limited development of radiocarbon datasets from archaeological contexts, whilst climate records from peat sequences in southwest Britain (Amesbury et al., 2008) have precluded a robust test of abandonment. Here we explore the value of a more expansive radiocarbon dataset for testing the hypothesis of climate change driven abandonment of upland areas during the Bronze Age using Bayesian age modelling and an annually-resolved record of hydroclimate from northern Ireland that is representative of upland areas across western Britain and Ireland.

2. Methods

2.1. Archaeological datasets and radiocarbon calibration

To test for a societal response to hydroclimate change during the Bronze Age, we analysed a comprehensive suite of radiocarbon ages taken from southwest Britain upland archaeological sites (incorporating Dartmoor, Exmoor and Bodmin Moor; Fig. 1) described as ceremonial (including cairns and barrows), field boundaries (including reaves) and 'settlements' (incorporating sites of occupation, including fortifications), spanning the Bronze and Iron ages (Table 1). Importantly, with regards the permanent agricultural use of these areas, the settlements investigated to date include large clusters of roundhouses, implying relatively large concentrations of populations e.g. Leskernick (Bender et al., 2007), while others have evidence for long-term use, with stone constructions replacing timber e.g. Shaugh Moor (Wainwright and Smith, 1980) (Fig. 1). Due to uncertainties over the possible inclusion of young material from roots and percolating humic acids within bulk peat samples in high rainfall areas (Head et al., 2007), we focused our analysis on published radiocarbon-dated charcoal and wood samples which we interpret to be associated with the construction, use or abandonment of a feature. Those samples that did not have a direct stratigraphic relationship with the feature being dated were not included in our

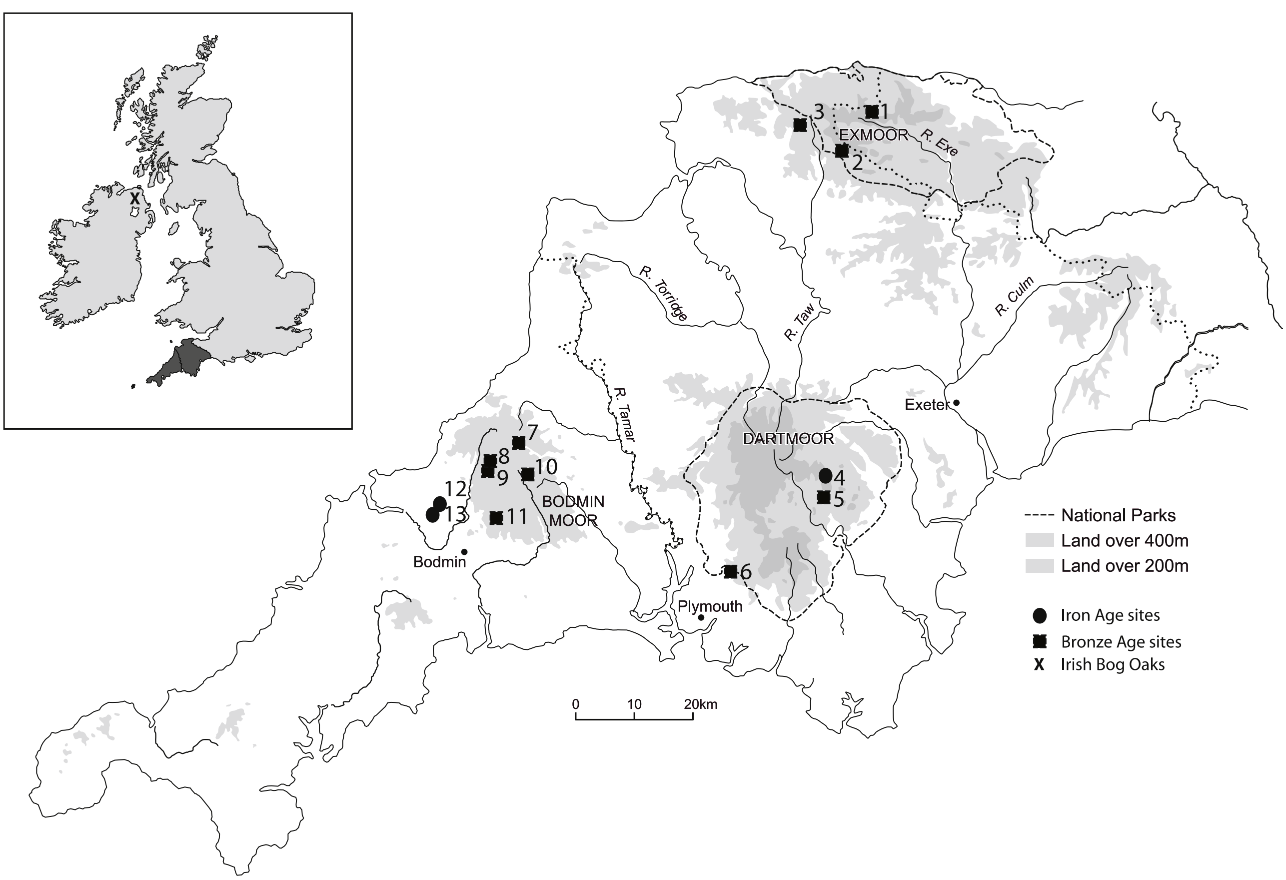

Fig. 1. Location of Bronze (filled squares) and Iron (filled circles) Age sites investigated during this study. Sites numbered as follows: (1) Lanacombe (Gillings et al., 2009); (2) Shallowmead (Quinnell, 1997); (3) Bratton Down (Quinnell, 1997); (4) Gold Park (Ambers et al., 1989); (5) Holne Moor (Bowman et al., 1990); (6) Shaugh Moor (Jordan et al., 1994); (7) Davidstow (Christie, 1988); (8) Cataclews (Christie, 1988); (9) Stannon Down (Jones, 2006; Jordan et al., 1994); (10) Leskernick (Bender et al., 2007); (11) Colliford Reservoir (Jordan et al., 1994); (12) St Kew (Jordan et al., 1994); and (13) Killibury (Jordan et al., 1994). The location of the Irish bog oak record is shown as a cross in the inset panel of the British Isles.

Table 1
Radiocarbon dated Bronze and Iron age sites from across southwest Britain with calibrated age ranges (Bayesian 'Phase' modelled in OxCal 4.2 using IntCal13) (Bronk Ramsey and Lee, 2013; Reimer et al., 2013). Only wood and charcoal samples were used where the stratigraphic association with the archaeological context was reported as unambiguous.

Site name	Type	Material dated	Laboratory number	14C age	1sd	Median cal. BP (±1σ)	Reference
Bronze Age Construction (Phase 1)					Start	3960 ± 60	
Colliford Reservoir, Bodmin Moor	Ceremonial pit	Charcoal (oak)	HAR-2622	3490	90	3740 ± 130	Jordan et al. (1994)
Colliford Reservoir, Bodmin Moor	Ceremonial pit	Charcoal	HAR-2617	3500	80	3750 ± 120	Jordan et al. (1994)
Colliford Reservoir, Bodmin Moor	Ceremonial pit	Charcoal (oak)	HAR-2991	3580	80	3810 ± 120	Jordan et al. (1994)
Colliford Reservoir, Bodmin Moor	Cairn	Charcoal (oak)	HAR-2994	3510	80	3760 ± 120	Jordan et al. (1994)
Colliford Reservoir, Bodmin Moor	Cairn	Charcoal	HAR-2624	3610	70	3840 ± 130	Jordan et al. (1994)
Cataclews	Barrow	Charcoal	HAR-8089	3510	70	3760 ± 110	Christie (1988)
Davidstow, Bodmin Moor	Barrow	Charcoal	HAR-6635	3580	70	3820 ± 120	Christie (1988)
Davidstow, Bodmin Moor	Barrow	Charcoal	HAR-6640	3740	90	3820 ± 210	Christie (1988)
Davidstow, Bodmin Moor	Barrow	Charcoal	HAR-8098	3440	100	3690 ± 130	Christie (1988)
Davidstow, Bodmin Moor	Barrow	Charcoal	HAR-6634	3520	70	3770 ± 120	Christie (1988)
Davidstow, Bodmin Moor	Barrow	Charcoal	HAR-6643	4130	70	3600 ± 280	Christie (1988)
Stannon Down, Bodmin Moor	Cairn	Hazel	OxA-13389	3274	31	3500 ± 50	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Hazel	OxA-13388	3223	30	3440 ± 60	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Hazel	OxA-13387	3919	31	3600 ± 280	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Oak sapwood	OxA-13385	3385	30	3620 ± 60	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Hazel	OxA-13386	3254	31	3480 ± 50	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Hazel	OxA-13391	3215	30	3430 ± 50	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Oak sapwood	OxA-13392	3076	32	3280 ± 50	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Hazel	OxA-13446	3200	28	3420 ± 30	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Hazel	OxA-13390	3267	31	3490 ± 60	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Oak roundwood	OxA-13384	3326	31	3550 ± 60	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Oak roundwood	OxA-13381	3127	31	3330 ± 60	Jones (2006)
Stannon Down, Bodmin Moor	Cairn	Charcoal	HAR-5130	3440	70	3700 ± 110	Jordan et al. (1994)
Shallowmead, Exmoor	Cairn	Charcoal (oak)	HAR-2829	3060	80	3250 ± 100	Quinnell (1997)
Bratton Down, Exmoor	Barrow	Charcoal	BM-1148	2832	42	2990 ± 60	Quinnell (1997)
Lanacombe, Exmoor	Cairn	Charcoal (oak)	SUERC-27928	3230	30	3440 ± 60	Gillings et al. (2009)
Lanacombe, Exmoor	Cairn	Charcoal (oak)	SUERC-27929	3605	30	3870 ± 110	Gillings et al. (2009)
Lanacombe, Exmoor	Cairn	Charcoal	SUERC-27930	3835	30	3610 ± 280	Gillings et al. (2009)
Holne Moor, Dartmoor	Field boundary	Charcoal	BM-1609R	3400	110	3650 ± 140	Bowman et al. (1990)
Shaugh Moor, Dartmoor	Field boundary	Charcoal	HAR-2986	3270	80	3500 ± 100	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Field boundary	Charcoal	HAR-3418	3210	70	3430 ± 90	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Field boundary	Charcoal	HAR-2475	3160	70	3370 ± 100	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Field boundary	Wood	HAR-4003	3340	90	3580 ± 120	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Field boundary	Charcoal	HAR-2669	3680	70	3850 ± 170	Jordan et al. (1994)
Killibury, near Bodmin Moor	Fortification	Charcoal	HAR-1952	2880	70	3060 ± 80	Jordan et al. (1994)
Killibury, near Bodmin Moor	Fortification	Charcoal	HAR-2191	2790	70	3010 ± 70	Jordan et al. (1994)
Leskernick, Bodmin Moor	Settlement	Charcoal (oak)	Beta-42321	3220	50	3440 ± 70	Bender et al. (2007)
Leskernick, Bodmin Moor	Settlement	Charcoal (oak)	Beta-125239	3100	40	3300 ± 60	Bender et al. (2007)
Leskernick, Bodmin Moor	Settlement	Charcoal (applewood)	Beta-164589	3320	40	3540 ± 70	Bender et al. (2007)
Leskernick, Bodmin Moor	Settlement	Charcoal (oak)	Beta-146722	3260	40	3480 ± 60	Bender et al. (2007)
Leskernick, Bodmin Moor	Settlement	Charcoal (oak)	Beta-42322	2890	50	3050 ± 70	Bender et al. (2007)
Leskernick, Bodmin Moor	Settlement	Charcoal (oak)	Beta-142324	3040	50	3240 ± 80	Bender et al. (2007)
Leskernick, Bodmin Moor	Settlement	Charcoal (oak)	Beta-142325	3110	50	3310 ± 70	Bender et al. (2007)
Leskernick, Bodmin Moor	Settlement	Charcoal (oak)	Beta-142323	2769	60	2990 ± 60	Bender et al. (2007)
Holne Moor, Dartmoor	Settlement	Charcoal	BM-1611R	3300	120	3540 ± 150	Bowman et al. (1990)
Holne Moor, Dartmoor	Settlement	Charcoal	BM-1608R	3190	100	3400 ± 130	Bowman et al. (1990)
Holne Moor, Dartmoor	Settlement	Charcoal	BM-1610R	3290	120	3530 ± 150	Bowman et al. (1990)
Holne Moor, Dartmoor	Settlement	Charcoal	BM-1612R	2580	140	3030 ± 90	Bowman et al. (1990)
Holne Moor, Dartmoor	Settlement	Charcoal	BM-1607R	3390	100	3640 ± 140	Bowman et al. (1990)
Shaugh Moor, Dartmoor	Settlement	Charcoal (alder)	HAR-2960	3060	80	3250 ± 100	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Settlement	Charcoal	HAR-3419	2930	90	3120 ± 110	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Settlement	Charcoal	HAR-2473	2880	70	3060 ± 80	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Settlement	Charcoal	HAR-2474	3430	90	3680 ± 130	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Settlement	Charcoal	HAR-2472	3020	70	3210 ± 100	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Settlement	Charcoal	HAR-3358	3320	80	3550 ± 110	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Settlement	Charcoal	HAR-2989	3280	90	3510 ± 120	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Settlement	Charcoal	HAR-2983	3260	80	3490 ± 100	Jordan et al. (1994)
					End	2880 ± 70	
Bronze Age Abandonment (Phase 2)					Start	2940 ± 50	
Shaugh Moor, Dartmoor	Post-Settlement	Mixed species; some mature wood in drain fill	HAR-2987	3260	120	2810 ± 100	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Post-Settlement	Oak, hawthorn, Leguminosae and heather (from mature timbers) in drain fill	HAR-2976	2940	90	2830 ± 90	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Post-Settlement	Hazel, birch, oak and heather charcoal (some mature timbers) in drain fill	HAR-2979	3220	80	2800 ± 100	Jordan et al. (1994)

Table 1 (*Continued*)

Site name	Type	Material dated	Laboratory number	14C age	1sd	Median cal. BP (±1σ)	Reference
Shaugh Moor, Dartmoor	Post-Settlement	Quercus, hawthorn, willow and Alnus charcoal (some mature timbers) in drain fill	HAR-2978	2640	70	2800 ± 70	Jordan et al. (1994)
Shaugh Moor, Dartmoor	Post-Settlement	Hawthorn, oak and hazel charcoal (some mature timbers) in drain fill	HAR-2968	3070	70	2810 ± 100	Jordan et al. (1994)
					End	2720 ± 130	
Iron Age Construction (Phase 3)					Start	2220 ± 75	
Killibury, near Bodmin Moor	Fortification	Charcoal	HAR-1950	2180	70	2140 ± 70	Jordan et al. (1994)
Killibury, near Bodmin Moor	Fortification	Charcoal	HAR-745	2210	70	2150 ± 60	Jordan et al. (1994)
Killibury, near Bodmin Moor	Fortification	Charcoal	HAR-1953	2110	70	2110 ± 60	Jordan et al. (1994)
St Kew, near Bodmin Moor	Fortification	Charcoal	HAR-2227	1980	70	2070 ± 60	Jordan et al. (1994)
Stannon Down, Bodmin Moor	Settlement	Hazel/Alder	OxA-13383	2118	28	2100 ± 40	Jones (2006)
Stannon Down, Bodmin Moor	Settlement	Oak roundwood	OxA-13382	2183	29	2160 ± 60	Jones (2006)
Gold Park, Dartmoor	Settlement	Charcoal (gorse and hazel)	BM-2469	2190	60	2150 ± 60	Ambers et al. (1989)
Gold Park, Dartmoor	Settlement	Charcoal (gorse, hazel and oak)	BM-2467	2050	40	2070 ± 50	Ambers et al. (1989)
Gold Park, Dartmoor	Settlement	Charcoal (gorse, hazel and oak)	BM-2466	2090	120	2110 ± 70	Ambers et al. (1989)
Gold Park, Dartmoor	Settlement	Charcoal (gorse, hazel, oak and poplar)	BM-2470	2200	60	2150 ± 60	Ambers et al. (1989)
Gold Park, Dartmoor	Settlement	Charcoal (gorse, hazel, oak and poplar)	BM-2468	2080	60	2090 ± 70	Ambers et al. (1989)
					End	2030 ± 70	

analysis. To help refine the chronology of Bronze Age activity in southwest Britain we also used Iron Age-dated sites to provide an upper age limit on abandonment.

The ^{14}C ages were calibrated against the Northern Hemisphere calibration (IntCal13) dataset (Reimer et al., 2013). Unfortunately not all biases in the dataset could be satisfactorily identified and removed. In particular, the dating of charcoal has the potential to incorporate large inbuilt ages from long-lived material (Gavin, 2001; Wilmshurst et al., 2011). Using Bayes theorem, the algorithms employed sample possible solutions with a probability that is the product of the prior and likelihood probabilities. Taking into account the deposition model and the actual age measurements, the posterior probability densities quantify the most likely age distributions; the 'Outlier' option was used to detect ages that fall outside the calibration model for each group, and if necessary, down-weight their contribution to the final age estimates. As a result we developed a chronological framework using a three 'Phase' model in OxCal 4.2 (Bronk Ramsey, 2008) with 'Charcoal' analysis detection (probability = 0.05). The first 'Phase' was Bronze Age construction; the second abandonment; and the third 'Phase', Iron Age construction. The age model used here assumes charcoal ages are likely to be slightly earlier than the date of deposition and have a long tail of older ages from old redeposited material (Bronk Ramsey, 2009), therefore allowing outliers to be older than the modelled age. Modelled ages are reported here as thousands of calendar years BP (Table 1).

2.2. Climate datasets

Recent studies have focused on paleoenvironmental records across the southwest of Britain (Amesbury et al., 2008; Dark, 2006; Fyfe and Woodbridge, 2012; Gearey et al., 2000). The climatic and anthropogenic interpretation has, however, proved problematic (Amesbury et al., 2008; Brown, 2008; Gearey et al., 2000), due in part to the ambiguity over assigning pollen changes to reconstructing changing land cover and/or the relatively poor dating and resolution. Although no annually-resolved Holocene climate records are available from southwest Britain, an alternative record is the northern Irish tree-ring chronologies using bog and lakeside growing oaks (*Quercus* spp.).

To test whether the Irish bog oak data can be used as a proxy of climate change in southwest Britain, we compared the Hawkridge monthly mean precipitation data (Exmoor; 51.05°N, 3.60°E; 314 metres above sea level) with the CRU TS3.22 0.5 × 0.5° spatially resolved precipitation dataset (University of East Anglia Climatic Research Unit et al., 2008) (based on daily data) over the common period of 1961–1990 in KNMI Climate Explorer (http://climexp.knmi.nl/) (Fig. 3). The positive correlation of >0.5 between precipitation changes in southwest Britain and the area from which the northern Irish bog oak have been obtained is significant ($p < 0.1$). While not demonstrating a teleconnection through the Holocene, these results are consistent with prevailing westerly airflow, with the highest correlations observed along the upland, western areas of Britain and Ireland, providing confidence in the use of the bog oak dataset as a measure of climate for southwest Britain.

The continuous Irish bog oak chronology of >750 trees exists back to 7468 years ago (Pilcher et al., 1984; Turney et al., 2005) and has been obtained from marginal environments across northern Ireland. Peaks in tree numbers have been interpreted as representing episodes of surface drying conducive for oak colonization (Turney et al., 2005). Mean age analyses demonstrate that troughs in tree populations coincide in the first instance with peaks in the mean age of the populations, suggesting recruitment failure (Leuschner et al., 2002). During periods of elevated water table levels, saplings would have struggled to establish themselves on bog surfaces, skewing the mean age to older members of the population, which subsequently died, resulting in a significant drop in the mean age (Leuschner et al., 2002). Following climatic amelioration (interpreted to be 'drying'), the trees regenerate, returning to intermediate mean age values. The synchronisation of the bog oak sequences was achieved by visual and statistical correlation of tree ring-width patterns compiled during the last three decades (Brown et al., 1986). The method is extremely robust and error-free, and as a result has been used to provide precisely-dated bidecadal wood samples for the international radiocarbon calibration curve (Reimer et al., 2013). Previous studies have demonstrated that bog oaks are highly responsive to precipitation/water table levels (García-Suárez et al., 2009; Scharnweber et al., 2015). However, other work has raised the possibility that tree population data may not represent changes in hydroclimate, and instead favour the use of testate amoeba-based water table reconstructions and humification records from peatlands (Armit et al., 2014; Swindles et al., 2012). Unfortunately, such records typically have large chronological (centennial-scale) uncertainties and the reconstructions themselves have recently been questioned (Charman et al., 2006; Payne et al., 2016; Väliranta et al., 2012).

To test the climate interpretation of changing oak population, we calculated the 5th and 95th percentiles from the Bronze Age period to identify the extremes in oak number; from these we derived the mean ring width (a measure of tree growth). During the downturn in oak number, the mean ring width index was 84.8 ± 17.6 while during the period of high oak number the mean ring width was 122.4 ± 22.8. We undertook a students *t*-test (2 tailed) and obtained a statistically significant difference between the two means ($p < 0.0001$), demonstrating maximum oak population numbers were associated with most favourable (drier/lower water table) growing conditions. In addition to the above, a further set of oaks has been collected from lake margins below present day water levels and appear to coincide with periods of maximum bog oak population numbers, supporting the interpretation of drier conditions during these times. Although the mean age and population size of Irish oaks do not quantify absolute changes in the water table, the parallel trends in the different bog and lake datasets, and response of tree growth across the Bronze Age, suggest a common hydroclimate control via changes in water level whilst the absolute chronology afforded by the tree rings allow precise comparison to archaeological records (Pilcher et al., 1984; Turney et al., 2005).

2.3. Tipping point analysis

To investigate the climate signal of the tree dataset further, we undertook 'tipping point' analysis across the period represented by the Bronze Age in southwest Britain. This technique is based on the fact that abrupt climate changes, if characterised by long-term forcing prior to reaching a tipping point in the system dynamics, can be mathematically detected by looking at the pattern of fluctuations in the short-term trends of the data before the shift takes place (Dakos et al., 2008). This is based on the concept of 'critical slowing down', where on the approach to such an abrupt shift, the equilibrium state of the system takes increasingly longer to recover from small perturbations (Dakos et al., 2012; Held and Kleinen, 2004). This increased recovery time is detected as a short-term increase in the lag-1 autocorrelation or 'memory' of the time series (Ives, 1995). This mechanism is fundamentally inherent to all bifurcational tipping points, since as the system approaches a bifurcation point, the basin of attraction starts to become wider and shallower, allowing the system to travel further from its equilibrium (van Nes Egbert and Scheffer, 2007). An increasing trend in variance is also often found due to the ability of the system to travel farther from its equilibrium point as the basin of attraction shallows and widens (Lenton et al., 2012). The method involves detrending the data to remove the long-term trends using a Gaussian kernel smoothing filter over a suitable bandwidth (such that the long term trends are removed without overfitting the data). The resulting residuals are then measured for autocorrelation at lag-1 and variance over a sliding window of 50% of the length of the dataset, using the R functions ar.ols() and var(), respectively. The Kendall tau rank correlation coefficient is used to provide a quantitative measure of the trend (Kendall, 1948) by assessing the predominance of concordant pairs, providing an objective evaluation of the statistical evidence for the trend.

We also undertook a sensitivity analysis by running repeats with a range of smoothing bandwidths (5–15% of the time-series length) and sliding window sizes (40–60% of the time-series length) to determine whether the results are sensitive to these parameter choices. The results are visualized using contour plots of the Kendall tau values of these repeats. In order to test the significance of these results, we created a surrogate dataset by randomising the original data over one thousand permutations. This method guarantees the same amplitude distribution as the original time series, but removes any ordered structure or linear correlation (Theiler et al., 1992). The autocorrelation at lag-1 and variance were computed for each of the surrogate time series, and the probability of making a Type I statistical error (false positive) for the original data was computed by comparing to the probability distribution of the surrogate data. A histogram is used to illustrate these results; for example, if our data falls outside the 90% quantile limits of the surrogate data, our results are significant at $p = 0.1$.

3. Results and discussion

3.1. Bronze and Iron Age activity

The probability distribution of the combined ages of activity on upland areas are given in Fig. 2 and the individual age ranges are provided in Table 1. The 57 radiocarbon ages obtained from the Bronze Age show a remarkable degree of consistency. Taken as a whole, human activity on upland areas in southwest Britain appears to have spanned a considerable period of time during the mid to late Holocene, encompassing 3900–2950 cal. BP (Table 1). The earliest evidence of activity appears to have been ceremonial, most of which was in the form of barrow and cairn construction from 3900 cal. BP, with the earliest sites being found on both Exmoor and Bodmin Moor at Davidstow (Christie, 1988), Stannon Downs (Jones, 2006) and Lanacombe (Gillings et al., 2009). Within 300 years, there is unambiguous evidence for the commencement of farming and settlement in these upland areas, most notably at Shaugh Moor on Dartmoor (Jordan et al., 1994; Wainwright and Smith, 1980), consistent with paleoecological data which has suggested an increasingly open landscape and intensive land use during the middle Bronze Age (Fyfe and Woodbridge, 2012).

Intriguingly, the dating of field systems in the southwest (which includes reaves) implies formal land division was complete sometime after 3400 cal. BP. A critique of Fleming (1988) questioned whether the field boundaries represented a single, planned phase of enclosure over some 300–400 years (Johnston, 2005). Unfortunately our radiocarbon dataset for Dartmoor field boundary construction remains limited ($n = 6$), and it is not possible to resolve whether this represents a single or sustained period of land division. Importantly, ceremonial use of upland areas persisted throughout this period, accompanied by continued settlement. Ages obtained from fill deposits in drains associated with abandonment of the Shaugh Moor settlement provide a constraint on human activity. We estimate the end of Bronze Age construction on the upland areas in southwest Britain at 2940 ± 50 cal. BP and implied reduction of human use of upland areas by 2880 ± 70 cal. BP (Fig. 2). Iron Age settlement across the area appears to have commenced around 2220 ± 75 cal. BP (Table 1).

3.2. Investigating climate change as a driver of Bronze Age abandonment

To investigate changing climate across the Bronze Age, we undertook tipping point analysis on the annually-resolved

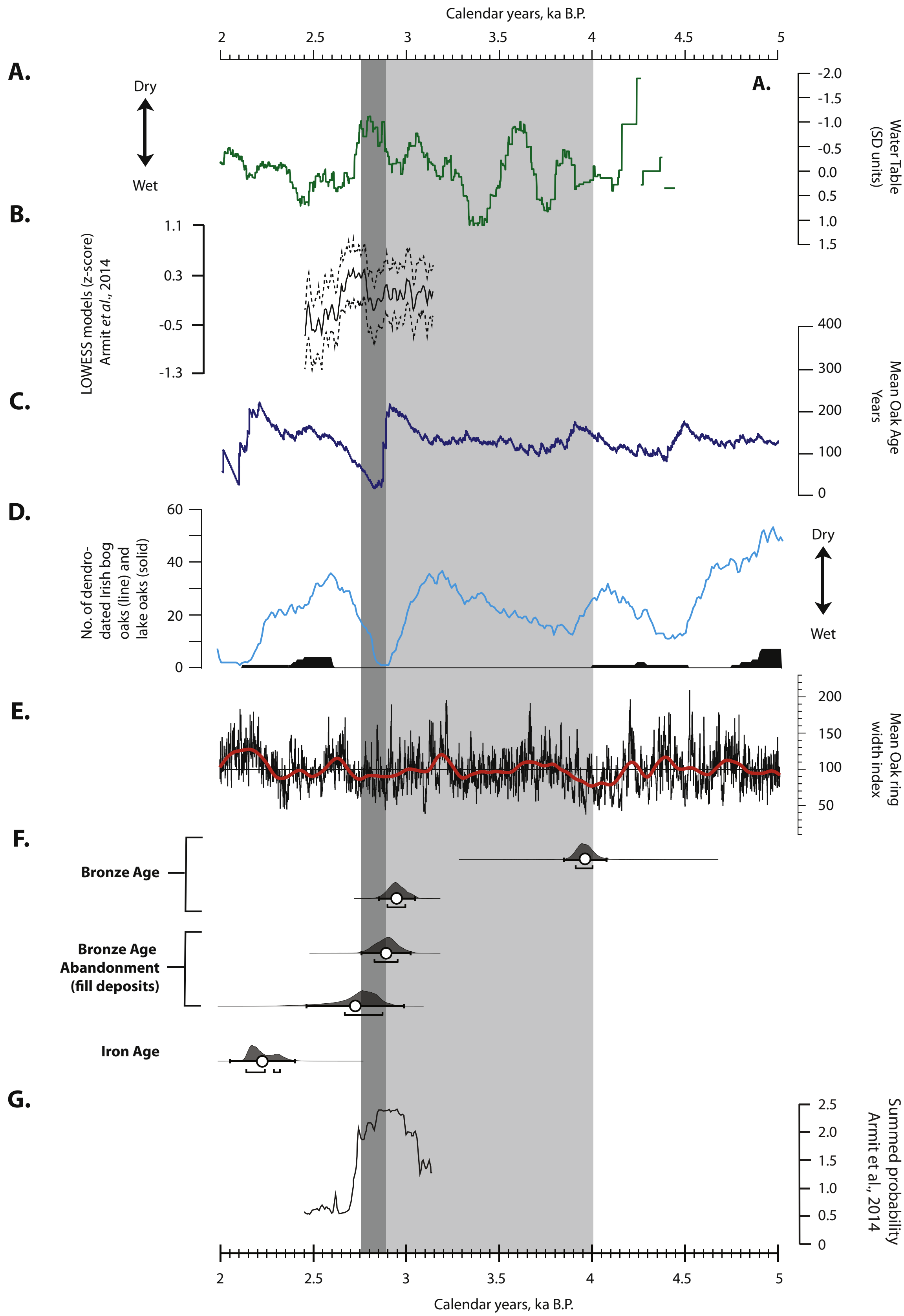

Fig. 2. Changing human activity and hydroclimate in the mid to late Holocene across the British Isles. Reconstructed changes in northern Britain (Charman et al., 2006) and Irish (at 95% confidence limit) (Armit et al., 2014) water table depth (Panels A and B) developed using testate and humification analyses. Mean bog oak age (Panel C), number of tree-ring dated bog oak (line) and lake oak (solid) (Panel D) and mean ring width index (black line) with a LOESS smoothing curve (red line) (Pilcher et al., 1984; Turney et al., 2005). Calibrated age ranges of Bronze and Iron Age activities on upland areas in southwest Britain (Panel F) and summed probability in Ireland (Panel G.) (Armit et al., 2014). Start and end of southwest Britain calibrated age **Phases** show 1σ probability range as horizontal lines. Light grey column denotes Bronze Age activity in southwest Britain; dark grey column, Bayesian age-modelled abandonment of the area.

northern Ireland bog oak population data from 3900 to 3130 cal. BP (Fig. 4). Indicators of 'critical slowing down' are expected to increase in the presence of long-term forcing. We observe a clear positive trend in both autocorrelation and variance up to 3130 cal. BP, with Kendall tau values of 0.660 and 0.839 respectively, implying a long-term forcing of the population data. In addition, visual inspection of Fig. 4b clearly shows the residuals becoming increasingly autocorrelated and with a higher variance on the approach to the abrupt decline in oak numbers. Sensitivity tests show that the results are robust regardless of the size of detrending bandwidth and sliding window sizes used; the contour plots in Fig. 4c and d display a relatively homogenous colour, indicating that the Kendall tau values vary little when repeating the analysis with different sizes of detrending bandwidth and sliding windows. Surrogate data generated from one thousand randomisations of the original data were used to determine the significance of the trend, with autocorrelation and variance $p < 0.1$ and $p < 0.01$ respectively (Fig. 5). These results strongly suggest that the abrupt downturn in oak numbers from 3130 cal. BP was as a consequence of long-term forcing, consistent with a climate-driven shift rather than site specific factors skewing the record (Swindles and Plunkett, 2009). The implication is the climate system in western upland Britain shifted to a wetter state at the termination of the Bronze Age as a result of long-term forcing.

To investigate whether the termination of intensive late Bronze Age activity on upland areas coincided with climate change during this period, we compared the age limits of human activity in upland southwest Britain against the Irish bog and lakeside oak population data (Turney et al., 2005). The Irish bog oaks suggest a major shift to wetter conditions with rising water table (and lake) levels commencing at 3130 cal. BP, with a fall in numbers and a coincident increase in the mean age of the oaks (from 200 years to 218 year by 2908 cal. BP) (Fig. 2). The timing of this change is consistent with a southward migration of polar waters and the associated movement of prevailing westerly airflow over northern Europe from more northerly latitudes (Bakke et al., 2008; Bond et al., 2001; Jonsson et al., 2010; Turney et al., 2005).

The degree of wetness during times of low bog oak numbers cannot be currently quantified though it is clear water tables and lake levels were elevated across western Britain and Ireland around 2900 cal. BP. Within Ireland, a sustained period of wetness has been inferred from peat humification values at this time (wet shift 3 as reported by Plunkett (2006)), and coincident with increasing inorganic levels in peats (Plunkett, 2009). The recently reported Irish-wide record of changing water table levels similarly reports a major shift around this time (within the dating uncertainties of the reconstruction) (Fig. 2) (Armit et al., 2014). In Britain, a stacked testate amobae reconstruction of water table levels also demonstrates a pronounced change to wetter

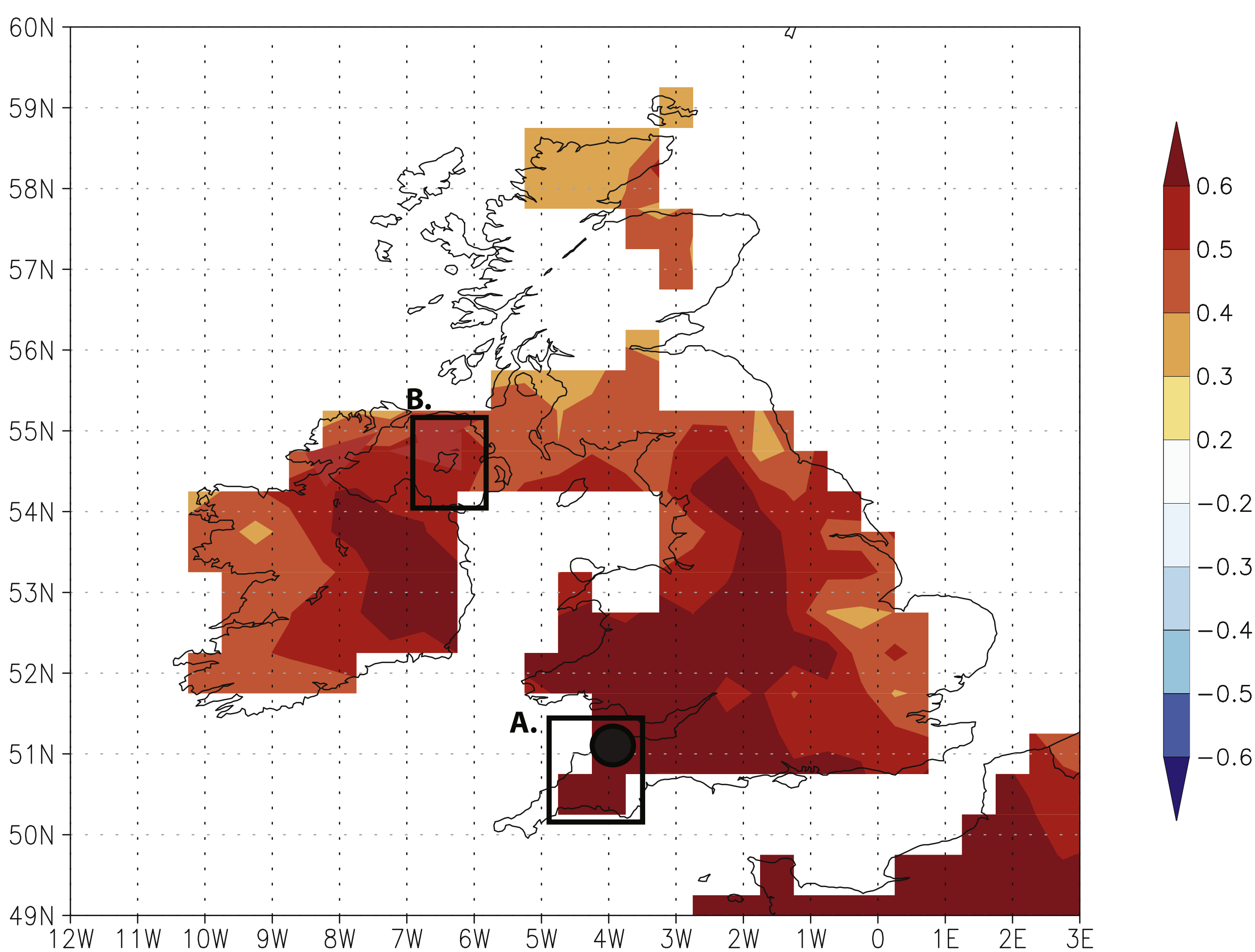

Fig. 3. Correlation between Hawkridge (Exmoor, southwest Britain; solid black circle) and precipitation across the United Kingdom and Ireland (CRU TS3.22) (January–December, 1961–1990) at <10% confidence. Location of archaeological sites in southwest Britain defined by boxed area A., northern Irish bog oaks, boxed area B. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers, 2005).

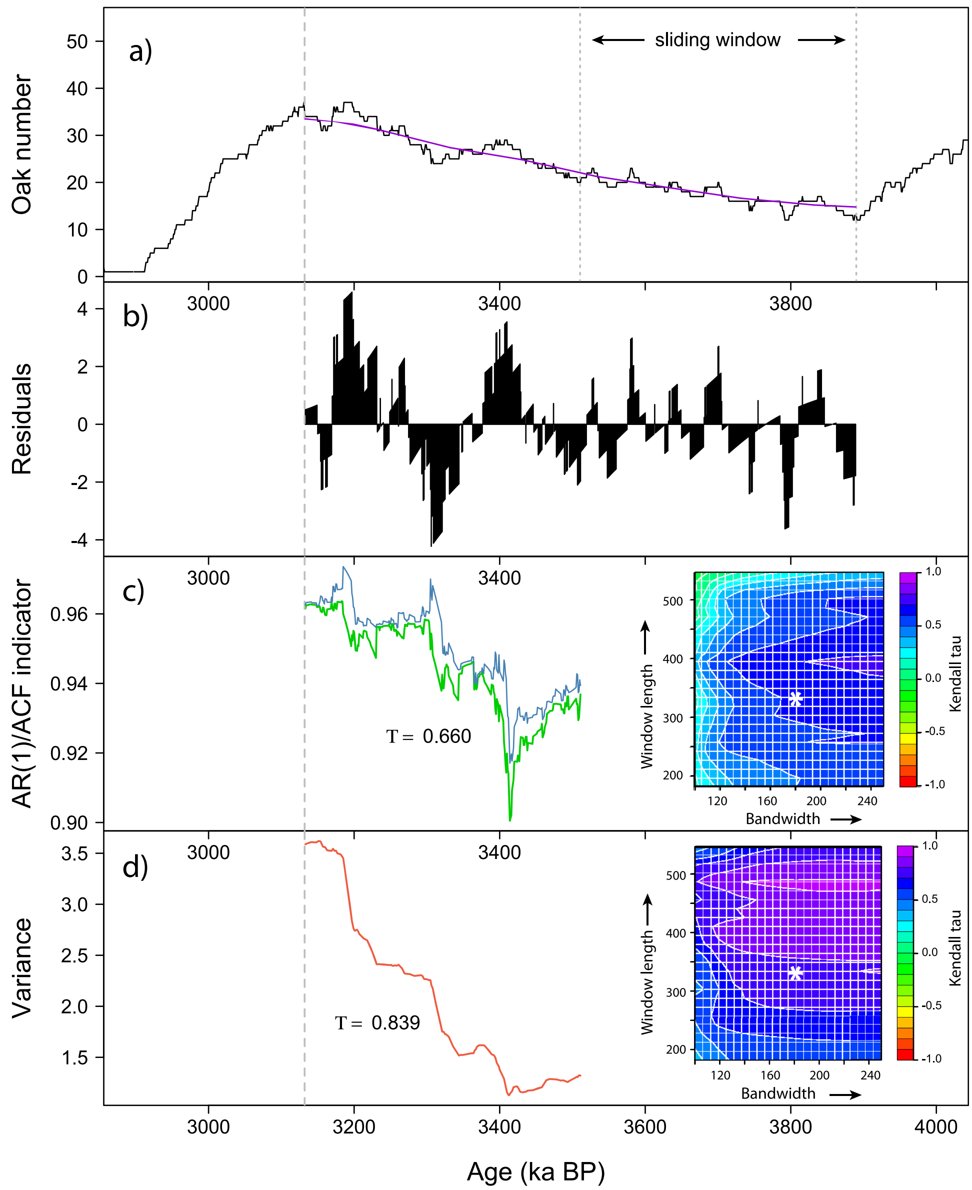

Fig. 4. Tipping point analysis for Irish bog oak numbers with Gaussian-kernel-smoothing filter shown (purple line), and size of sliding window (50% of data length: 333 yrs) (panel a); Residuals from the detrended data (b); Autocorrelation (c) and Variance (d) measured over the sliding window. A clear positive trend in both autocorrelation and variance is apparent, with Kendall's $\tau = 0.660$ and 0.839, respectively. The two contour plots in panels c) and d) indicate the results of a sensitivity analysis, with Kendall τ values (from -1 to 1) for the trends in autocorrelation and variance (white asterisk marks the parameters used to generate the results plotted here).

conditions at around the same time (Charman et al., 2006). Overall, the number of oaks records a shift to wetter conditions after 2942 cal. BP. Critically, this shift to wetter conditions is synchronous with the abandonment of upland areas in southwest Britain, dated here at 2880 ± 70 cal. BP. This change in population parallels a similar shift in human activity recently reported in Ireland (Fig. 2) (Armit et al., 2014) suggesting similar responses to climate forcing across the wider region.

Our results are consistent with increasing wet conditions on upland areas across western Britain and Ireland during the termination of the Bronze Age. Increased rainfall is likely to have had a pronounced impact on agricultural activity driving down yield and overall productivity, whilst reducing the longevity of stored crops. Winter temperatures are likely to have been an important seasonal control due to the annual cycle of autumn sowing and spring flowering (Stevens and Fuller, 2012). Ultimately the sensitivity of Bronze Age upland agricultural communities in the southwest to changing climatic conditions would have been affected by the community's resilience, with respect to the type of agriculture practiced, the degree of population pressure and indeed how attractive/easy the option to simply relocate was. If population pressure was high, even a marginal downturn in productivity could have severely limited the human population that could be sustainably maintained. The types of crop under cultivation in surrounding areas may have also played a role, with relatively more resilient species such as barley commonly grown across northern Britain in the Bronze age, and wheat more common in southwest Britain (Bishop, 2015; Jones and Tinsley, 1999–2000). Further work is now required to elucidate human-environment interaction(s) and population resilience to abrupt and extreme climate change. Regardless, with wetter conditions, populations most probably migrated to drier, more freely draining

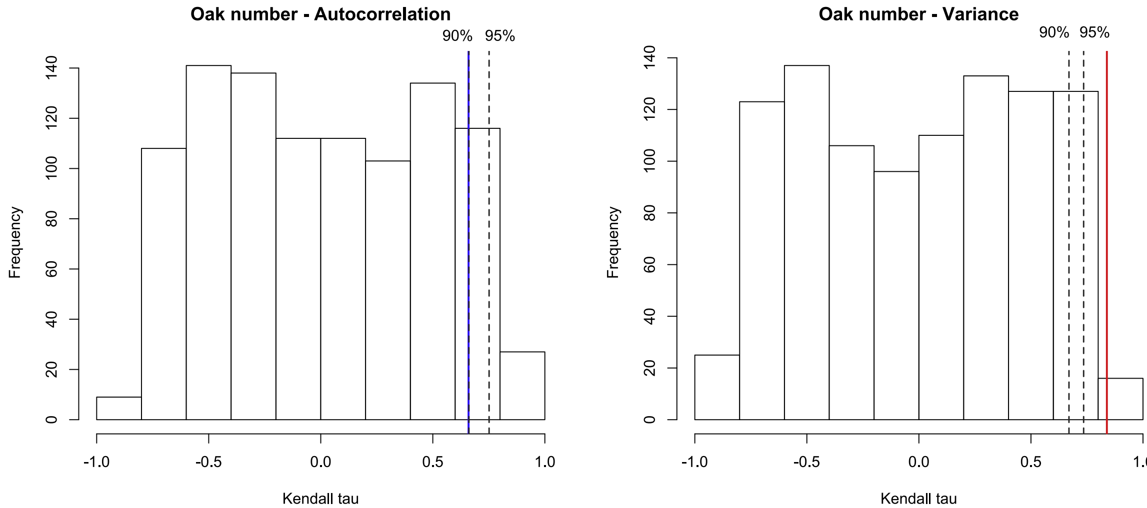

Fig. 5. Histograms showing the Kendall τ distribution of 1000 randomised iterations of the original data for (a) autocorrelation and (b) variance. The black dotted lines show the 90% and 95% significance levels and the blue and red lines indicate the Kendall τ values from analysis on the original data, with corresponding p values of <0.1 and <0.01 for autocorrelation and variance respectively.

areas in the lowlands able to support a permanent mixed agricultural system; though whether there was significant population pressure in these lower areas is unclear from the current archaeological evidence (Webster, 2007).

Through the Holocene, collapses in tree populations appear to coincide with coherent millennial-scale changes in marine sediment ice-rafted debris content and the polar vortex over the North Atlantic (Bakke et al., 2008; Bond et al., 2001; Jonsson et al., 2010; Turney et al., 2005), suggesting region-wide centennial-scale hydrological changes (Bond et al., 2001; Daley and Barber, 2012; Langdon and Barber, 2005; Trouet et al., 2012). Importantly, historical records and reconstructions of climate over the past millennium (Hurrell, 1995; Luterbacher et al., 2010) suggest shifts in the North Atlantic Oscillation led to low frequency circulation changes across the greater North Atlantic region, resulting in antiphase moisture delivery across Europe and the Mediterranean. Thus, at the time of 2950 cal. BP, wetter than normal conditions experienced in northern Europe most probably drove drier than normal conditions in the Mediterranean, impacting communities in the south (Frank et al., 2002; Kaniewski et al., 2015). It therefore seems possible that the archaeological changes experienced in southwest Britain were part of a broader suite of change as different human populations across Europe and the Mediterranean responded in their own way to contrasting trends. Regardless of whether this was a regionally significant event, our findings support the case that deteriorating climate conditions played a significant role in widespread upland abandonment of permanent mixed farming in southwest Britain around 2950 cal. BP.

4. Conclusions

Extreme wet conditions during the late Bronze Age have been widely cited as the principal driver of less intensive use of Dartmoor and other upland areas of southwest Britain. Unfortunately, previous studies have relied on limited radiocarbon dating age control and low-resolution records of inferred climate changes to make comparisons. Here we have undertaken a comprehensive study of published radiocarbon ages from archaeological contexts across upland areas reported over the past three decades and compared to the Irish bog and lakeside population data which can be regarded as a highly-sensitive and precisely-dated measure of wetness for western Britain and Ireland. By calibrating charcoal and wood archaeological ages, we observe an apparent relationship between the end of human activity across upland areas in southwest Britain and a period of maximum wetness around 2950 cal. BP, coincident with the late Bronze Age. Our results support the argument that farming communities operating in marginal environments were highly vulnerable to climate change in the past and that adaptation was most probably through migration to lowland areas. Further work is now needed for more targeted archaeological investigations to comprehensively date records spanning the Bronze and Iron ages across the region.

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