Holocene fluctuations in human population demonstrate repeated links to food production and climate

Andrew Bevan[a,1], **Sue Colledge**[a], **Dorian Fuller (傅稻镰)**[a], **Ralph Fyfe**[b], **Stephen Shennan**[a], **and Chris Stevens**[a]

[a]Institute of Archaeology, University College London, London WC1E 6BT, United Kingdom; and [b]School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth PL4 8AA, United Kingdom

Edited by Colin Renfrew, University of Cambridge, Cambridge, United Kingdom, and approved October 3, 2017 (received for review June 6, 2017)

We consider the long-term relationship between human demography, food production, and Holocene climate via an archaeological radiocarbon date series of unprecedented sampling density and detail. There is striking consistency in the inferred human population dynamics across different regions of Britain and Ireland during the middle and later Holocene. Major cross-regional population downturns in population coincide with episodes of more abrupt change in North Atlantic climate and witness societal responses in food procurement as visible in directly dated plants and animals, often with moves toward hardier cereals, increased pastoralism, and/or gathered resources. For the Neolithic, this evidence questions existing models of wholly endogenous demographic boom–bust. For the wider Holocene, it demonstrates that climate-related disruptions have been quasi-periodic drivers of societal and subsistence change.

radiocarbon | archaeology | Britain | Ireland | agriculture

The relationship between human population dynamics, crises in food production, and rapid climate change is a pressing modern concern that is in considerable need of higher-resolution, chronologically longitudinal perspectives. We have collected a large series of radiocarbon dates from archaeological sites in Britain and Ireland, which is a globally unique region because of (*i*) its high density of archaeological radiocarbon sampling, (*ii*) its unusually high proportion of well-identified botanical and faunal material, and (*iii*) its balance of dates from both research projects and rescue archaeology. We consider this high-resolution evidence over four different geographic regions and a broad Holocene timespan as a proxy for human demographic variability and subsistence response. We identify several episodes of regionally consistent population decline—the later fourth millennium BCE, the early first millennium BCE, and the 13th–15th century CE, respectively—that also appear to be associated with episodes of rapid Holocene climate change toward more unstable, cooler/wetter conditions. We also demonstrate the existence of structured responses to these changes in the form of altered human food-production strategies. The most obvious such episodes during the middle and later Holocene are likely consistent with altered North Atlantic storm regimes, reduced solar insolation, and climate-related cultural and demographic impacts across northwestern Europe.

Archaeological radiocarbon dates typically come from samples of bone, charred or waterlogged wood, and seeds that are taken to date specific stratigraphic events in the surviving archaeological record. When considered in large-scale aggregate, however, they also provide an anthropogenic signal of changing overall levels of past human activity and, ultimately, population. Some commentators highlight taphonomic and investigative biases in this record, but there is increasing agreement that, if these biases are controlled for and if the number of available dates is sufficiently high, an important demographic signal remains (*Materials and Methods*). While in many areas of the world the anthropogenic radiocarbon record is insufficient to support such aggregate treatment, in Britain and Ireland there is a long, well-resourced tradition of sampling, both from active-mode academic research and responsive-mode, development-led archaeology. Furthermore, parts of Britain and Ireland lie toward the perceived margins of effective European-type agriculture and thereby can offer many of the same insights on middle and later Holocene population stability, climate change, and food production as other North Atlantic islands (e.g., Greenland and Iceland) but for a much longer and larger history of human settlement. Therefore we have gathered over 30,000 existing archaeological dates from British and Irish databases, publications, and gray literature reports while also recording information about sample provenance, context, and material/species (Fig. 1). The changing intensity of this anthropogenic radiocarbon record through time can be modeled via summation of the postcalibration probability distributions of individual dates (*Materials and Methods*).

Results and Discussion

The overall summed distribution (Fig. 1*C*) shows a dramatic upswing in radiocarbon dates *ca*. 4000–3850 BCE that coincides closely with the first arrival of Early Neolithic cereal agriculture in Britain and Ireland. Although caution is required in inferring actual population growth rates directly from rates of change in summed radiocarbon, the latter values exceed 1% during this earliest phase, are unlikely to be explained by increased fertility among farming groups alone, and therefore must be due in part to migrant farmers from the European mainland, a conclusion

Significance

The relationship between human population, food production, and climate change is a pressing concern in need of high-resolution, long-term perspectives. Archaeological radiocarbon dates have increasingly been used to reconstruct past population dynamics, and Britain and Ireland provide both radiocarbon sampling densities and species-level sample identifications that are globally unrivalled. We use this evidence to demonstrate multiple instances of human population downturn over the Holocene that coincide with periodic episodes of reduced solar activity and climate reorganization as well as societal responses in terms of altered food-procurement strategies.

Author contributions: A.B. designed research; A.B. and S.C. performed research; A.B., R.F., and C.S. analyzed data; and A.B., S.C., D.F., R.F., S.S., and C.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: The full dataset and scripted analysis have been deposited at University College London, discovery.ucl.ac.uk/10025178/ (DOI: 10.14324/000.ds.10025178).

[1] To whom correspondence should be addressed. Email: a.bevan@ucl.ac.uk.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1709190114/-/DCSupplemental.

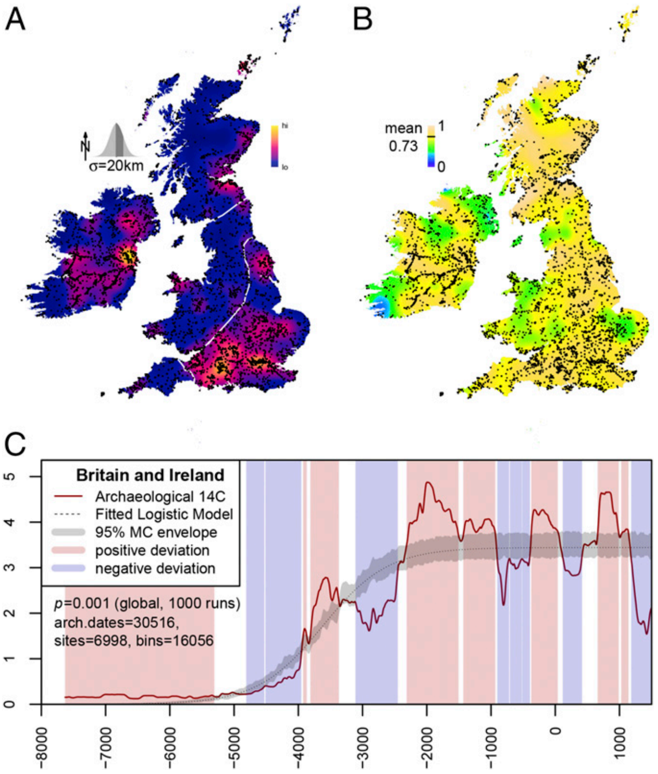

Fig. 1. (*A*) The kernel-smoothed intensity of archaeological radiocarbon dates from Britain and Ireland showing uneven spatial sampling (the subregions used in Fig. 2 are marked with white borders). (*B*) The proportion of dated samples with genus- or species-level identifications. (*C*) A summed probability distribution of all dates compared with a 95% Monte-Carlo envelope of equivalent random samples drawn from a fitted logistic model of population growth and plateau.

that is consistent with current archaeological and genetic evidence (1, 2). After this Early Neolithic peak, there follows decline, *ca*. 3500–3000 BCE, and continued moderate downturn thereafter. This is followed by slow Late Neolithic and Early Bronze Age recovery up to a new peak at ∼2000 BCE, for which there again is a strong isotopic and genetic argument in favor of significant population replacement by groups from continental Europe (2–4). After ∼1000 BCE (the last part of the Bronze Age), there is another striking decline, and, while a higher uncertainty in the calibration curve at this point inhibits precise characterization of timing and duration, substantial recovery is visible again only by ∼400 BCE. The Roman period exhibits a trough in the aggregate radiocarbon time series that is unlikely to represent a valid picture in England and Wales due to the far weaker tradition of dating Roman sites via radiocarbon (instead, pottery and coinage are typically used for dating during the period ∼50–400 CE) but may well be valid in Scotland and Ireland (see below and *Archaeological and Demographic Overview*). After the Roman period, there is evidence for sustained early Medieval growth, followed by an abrupt decline approximately consistent with the demographic collapse surrounding the historically well-documented episodes of the Great Famine and Black Death (∼1270–1450 CE).

This radiocarbon record can be further disaggregated into subregions [following commonly proposed divisions (5)] to consider local consistency with or departure from the pan-regional pattern (Fig. 2). Restricting comparison to within the post-Mesolithic period, when dynamics are more abrupt, north/west England/Wales versus Scotland exhibits the highest pairwise correlation (with the range among all regional pairs being $r = 0.69$–0.86), while Ireland exhibits more volatile dynamics than the others (coefficient of variation = 0.52, with the range of the other three being 0.39–0.42). In addition, the specific local radiocarbon trends exhibited by a given region in excess or deficit of the cross-regional pattern typically match very well with that region's known archaeological record: such as the very reduced archaeological evidence from Ireland in the Roman period ∼1–400 CE and then the sharper-than-average upward Irish growth ∼400–800 CE match periods of peak, archaeologically observed settlement activity and historically documented Irish monastic influence abroad (*Archaeological and Demographic Overview*). However, it is striking that all four chosen subregions show the same sharp Early Neolithic demographic peak∼4000–3500 BCE and then a decline, another peak at the beginning of the Bronze Age ∼2000 BCE, a Late Bronze Age decline ∼1000–800 BCE, a subsequent peak in the Late Iron Age ∼250 BCE, and then a decline in the later Medieval period ∼1250 CE at the end of the sequence. The particular cross-regional consistency

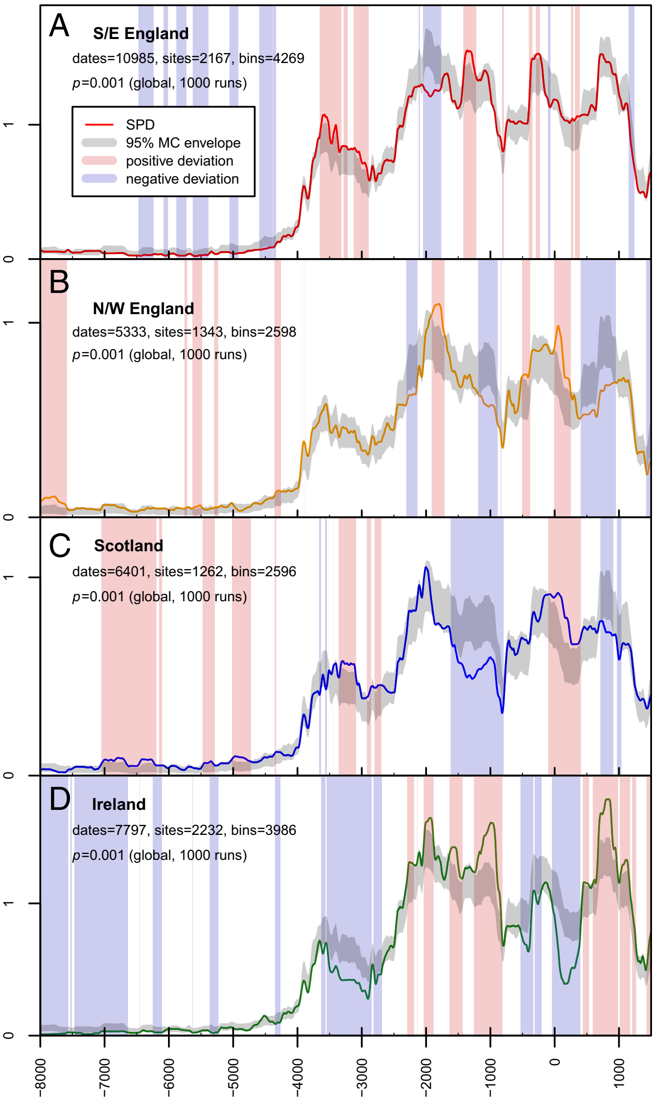

Fig. 2. Regional summed probability distributions for (*A*) south/east England, (*B*) North/west England and Wales, (*C*) Scotland, and (*D*) Ireland compared with a 95% Monte Carlo envelope produced by permutation of each date's regional membership.

at these points in the overall time series suggests an exogenous factor of some kind.

Evidence for an Early Neolithic boom-and-bust in the British Isles has already been noted by previous research, alongside explanations stressing a collapse due either to ecological overreach by incoming farmers or the abandonment of cereal agriculture in response to declining climate conditions (6–8). Fig. 3 compares the radiocarbon record with well-known climate archives and suggests that an exogenous cause is likely for all three observed episodes of cross-regional population stagnation during (*i*) the end of the Early Neolithic, (*ii*) the final Bronze Age and earliest Iron Age, and (*iii*) the late Medieval, associated with relatively rapid changes toward more unstable conditions in Britain and Ireland as well as with colder winters and wetter summers. In particular, pan-regional demographic decline in these three episodes is consistent with reduced insolation at Hallstatt-type grand solar minima [every 2100–2500 y (9–16)]. They are likewise consistent with periodic episodes of increased terrestrial salt input to the Greenland ice sheet, which in historical periods has been shown to be an excellent glaciochemical indicator of stormier, winter-like conditions and the increased dominance of Atlantic westerlies (17–19). Broadly coincident later Holocene changes are also observable in North Atlantic oceanic regimes as separately exhibited by increased ice-rafted surface debris and reduced deep-water contributions (20–22). This evidence collectively suggests quasi-periodic solar forcing of atmospheric and oceanic circulation with wider climatic consequences, associated with accentuated Siberian Highs and Icelandic Lows. We argue that these reorganizations have repeatedly exerted downward pressure on the human population in certain parts of northwestern Europe, as evident for three phases of decline in the high-resolution British and Irish archaeological radiocarbon record. It is very probable that similarly timed impacts were felt by human populations in less well-documented parts of Eurasia [as already partially evident for earlier episodes (23, 24)], albeit with different expression in local weather patterns, varying local human response, and ultimately different positive or negative consequences for local human society. An important proximate downward-forcing mechanism on human population in Britain and Ireland is likely to be reduced food production exacerbated by fewer growing-degree days for cereal agriculture and increased risk of crop loss and food insecurity due to storms. However, social dislocation and intensified epidemic outbreaks are possible accompanying phenomena. By contrast, intervening episodes of climatic amelioration may have provided good conditions for population expansion in certain areas, with the broadly simultaneous Early Neolithic colonization of southern Scandinavia, Ireland, and Britain being one probable example (25).

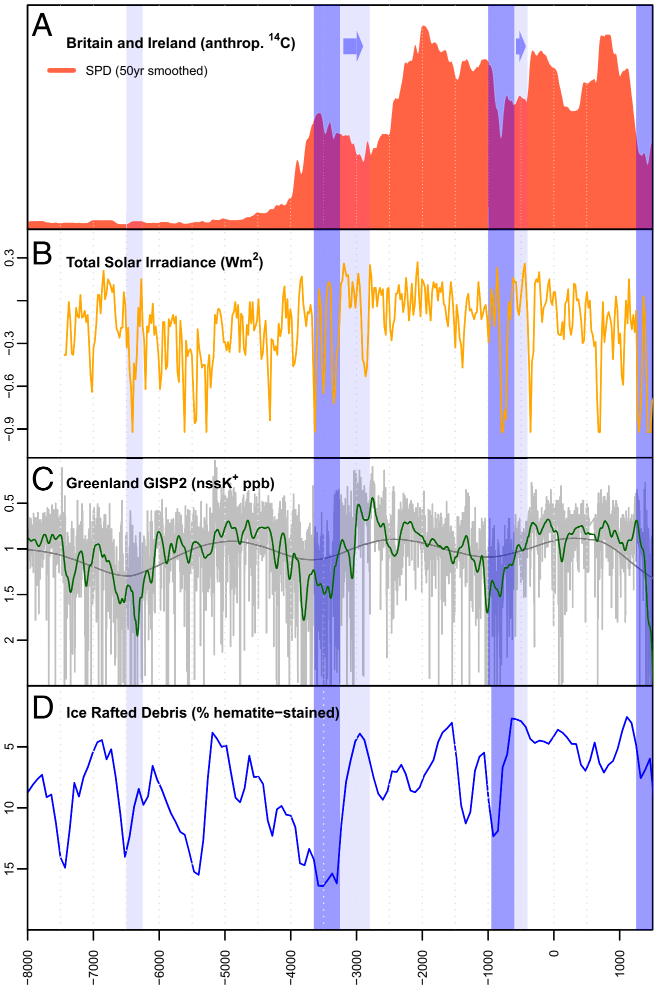

Fig. 3. Radiocarbon-inferred population and North Atlantic climate proxies. (*A*) Aggregate anthropogenic radiocarbon dates from Britain and Ireland (as Fig. 1*C*, the *y* axis is linear). (*B*) Total solar irradiance (12). (*C*) GISP2 potassium ion density (note descending axis) (17). (*D*) North Atlantic ice-rafted debris (note descending axis) (19). Shaded blue zones indicate suggested onset and duration of cold/wet episodes with the first one, the well-known "8.2 ky" event before the Neolithic and not addressed directly here.

Radiocarbon-dated plant and animal food sources further provide an unusually well-resolved time series of potential changes in British and Irish food production (Fig. 4), as long as we are careful to consider the possible confounding effects of changing human depositional practices with regard to food remains (26). Overall, the summed probability distribution of dates from starchy food plants (cereals and hazelnuts) broadly matches the demographic signal observed in the entire radiocarbon dataset, but in contrast the relative proportion of each plant type varies significantly. Hazelnuts (*Corylus avellana*), a key comestible for Mesolithic communities before the arrival of agriculture, dominate the starchy plant data up to ∼4000 BCE, decline in relative popularity with the earliest Neolithic, but then rebound for half a millennium or more during the Middle-Late Neolithic (∼3500–2500 BCE) before declining again (for permutation tests, see *Food Production*). In contrast, wheat (*Triticum* sp.) is a high-value cereal that first appears and increases sharply at the very start of the British and Irish Neolithic and then declines equally sharply by the end of the Early Neolithic. Much later, during the Bronze Age, its relative presence in the radiocarbon record grows slowly again to a peak at ∼1000 BCE before collapsing once more. Barley (*Hordeum* sp.) is a hardier cereal species which also arrives as part of the earliest farming activity and is present throughout later periods. It is less popular than wheat early on but is far more visible during the Middle-Late Neolithic period of inferred population downturn (taking the British Isles as a whole). Oats (*Avena* sp.) appear in consequential amounts in Britain and Ireland only from the Roman period but become increasingly popular in the later Medieval period, partly replacing or complementing barley as a hardier, lower-risk, lower-status food for both humans and foddered animals. The use of oats or oat/barley mixes as spring-sown, back-up crops, especially after initial harvest failures, is also well known from English manorial accounts in the Great Famine/Black Death era (27). Radiocarbon samples for individual food-animal species are fewer and encompass a wider range of meat, hide, wool, and dairying strategies, not to mention different kinds of deposition. However, comparison between the proportion of animal and plant food data suggests the greater importance of animals (as wild food) before the Neolithic and

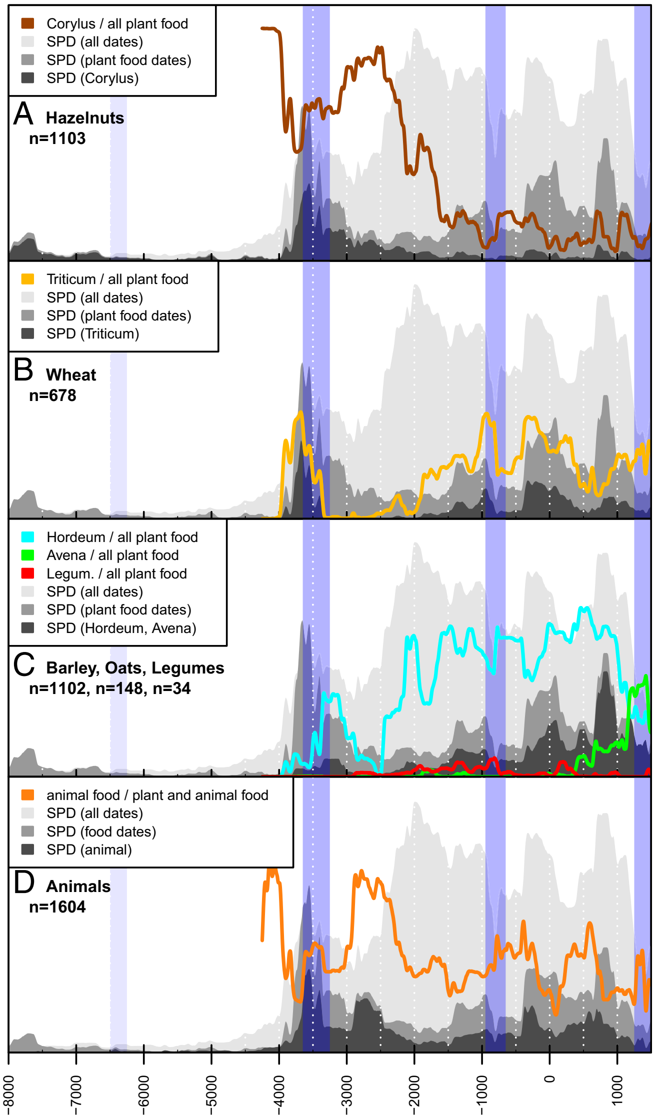

Fig. 4. The changing relative importance of major food sources across Britain and Ireland as visible in food samples directly dated for radiocarbon. (*A*) Hazelnuts. (*B*) Wheat (undifferentiated by species). (*C*) Barley, oats, and legumes. (*D*) Animals regularly used food sources. The colored lines are calculated as the proportions (calculated only from ∼4250 BCE onwards due to small sample sizes before that time). Ordinary summed probability distributions are shown in gray (*y* axes are all rescaled 0–1 for easier comparison). Accompanying permutation tests are provided in Figs. S6 and S7.

then their high visibility (as domesticated herds) again in the Late Neolithic and Early Bronze Age (with a focus on *Bos* and *Sus* sp.); more complicated and regionally differentiated stock-keeping strategies emerge from the Middle Bronze Age onwards (*Food Production*).

Although subject to changing cultural depositional practice and representing only a fraction of the wider archaeobotanical and zooarchaeological record, the above-described highs and lows of directly dated food species offer a temporally high-resolution proxy for shifting food-production strategies under both advantageous and deleterious climate conditions. For example, wheat has always been a higher-value, potentially higher-yield cereal and often was a cash crop in later periods (particularly *Triticum aestivum*). It is therefore unsurprising that the proportion of dated wheat samples grows during peak demographic episodes but declines sharply in at least two of the inferred episodes of demographic stagnation and climate downturn: the Middle/Late Neolithic and Late Bronze Age/Early Iron Age. In the former episode (after ∼3500 BCE), barley takes over as a hardy alternative cereal resource during the initial phase of demographic decline/stagnation, but then gathered hazelnuts and cattle herding become dominant strategies during the later stages and as population slowly rebounds. These indicators are consistent with what we know from larger, indirectly dated bone and crop samples from environmental archaeology (*Food Production*). For the latter episode (after ∼1000 BCE), changes occur over what appears to be a shorter period, but again there are proportional increases in barley, animal products, and possibly hazelnuts and an overall decline in wheat. Underlying the aggregate wheat pattern, however, is also regional variation, with sharper wheat declines in Ireland and north/west England, for example, but actually increased wheat proportions in south/east England. Such gradual regional differentiation is also a clear feature of land cover and land use from the Middle Bronze Age onwards, as inferred from British and Irish pollen archives (*Paleoecological Audit*). Contrasting patterns of wheat investment are also potentially consistent with two alternative responses to harvest failure attested in historical periods: (*i*) resource switching to back-up crops in some areas (or by certain social groups) but also (*ii*) continued speculation by others on high-value wheat production as wider demand for it spikes. South/east England would also be the area that retained the most amenable weather conditions under climate downturn. For the Late Medieval period, crop and animal sample sizes from radiocarbon dates are much lower, and the radiocarbon evidence therefore is more equivocal, but contemporary documentary sources point clearly to heavily adjusted plant and animal husbandry in the period 1270–1450 CE (28). They also offer an important empirical basis for causal linkages between decreased weather stability and lower temperatures, declining food supply per capita, and further lagged human consequences such as multiyear famines, human and animal epidemics, widespread cereal market speculation, labor shortages and agricultural disintensification, increased violent conflict, and overall population decline (29). Given these linkages, it is striking that while a naive assumption might be that food production and resource-switching strategies should have become more successful as populations became more technologically sophisticated over time, the population consequences of climate downturns appear to be no less severe, suggesting no major enhanced resilience in later periods and indeed potentially additional demographic and subsistence risks for economically integrated, socially stratified, and increasingly nucleated late prehistoric to Medieval societies.

Conclusions

Through a data-intensive approach to the British and Irish radiocarbon evidence, we are able to provide a detailed, long-term demographic proxy that, among other things, demonstrates at least three regionally consistent episodes of population downturn. While other Holocene climate changes may also have had human impacts in this region, and other European regions need not have responded in the same way, these shared episodes of demographic change match quasi-period shifts to more unstable weather regimes in the North Atlantic and well-known solar grand minima. Furthermore, each downturn across Britain and Ireland was of varying longer-term consequence, with subsistence responses such as resource switching and food diversification that varied through time. Exogenous climatic factors appear more likely to account for these consistencies than endogenous population over-reach on its own, although both processes may well have operated in tandem. In any case, both archaeological and historical evidence suggests that human action has always played a role in either mitigating or exacerbating climate-driven effects.

Materials and Methods

A radiocarbon date is a measurement of residual radioactivity in a sample containing carbon, with the most widely cited measurement being a "conventional radiocarbon age" that has been corrected for carbon isotopic fractionation (30). This age has a measurement error that is typically assumed to be a Gaussian distribution. Calibrating this radiocarbon age against observed variability in atmospheric radiocarbon through time [as documented by known standards, which are mostly tree-ring sequences for the Holocene (31)] produces a postcalibration probability distribution that is irregular due to the nonlinear shape of the calibration curve (32). For a regional dataset of many such calibrated probability distributions, it has become commonplace to sum them, under the assumption that a large mass of probability in certain parts of this aggregate time series offers a proxy for greater overall anthropogenic activity and higher human population in that timespan (6). Concerns that certain archaeological sites or site phases have garnered disproportionate and misleading numbers of dates (e.g., because they were better-resourced scientific projects) can be addressed by pooling adjacent dates from the same site and rescaling these subsite clusters before summing distributions between different sites. In this paper, we cluster temporally uncalibrated dates from the same site that are within 100 y of each other via a complete-linkage, agglomerative hierarchical method (33). Date distributions falling in the same cluster are pooled and divided by the number of contributing dates in the cluster before these pooled distributions are aggregated overall. Some software for radiocarbon date calibration normalize the postcalibration distribution of each date to ensure it sums to 1 under the curve before summing multiple dates or performing any other modeling procedure. However, this rescaling leads to not all calendar dates having an equal probability of occurrence and creates abrupt spikes in the summed probability distributions at points where the calibration curve is steep (34). Therefore we have chosen not to rescale the calibrated date distributions before summation. We address the methodological implications in greater detail in *Supporting Information* and consider the alternative result where dates are normalized. We conclude that the paper's main conclusions remain consistent in either case.

To explore the degree to which an observed summed probability distribution is well-described by a theoretical null model of demographic change, we first fit such a model (e.g., exponential, logistic, uniform) to the observed data on the calendar scale. In this case, a logistic model was preferred, given the observed distributional shape and an assumption that there might be an upper bound to post-Neolithic, pre-Roman population growth. The model of expected population intensity is then back-calibrated, and a set of conventional radiocarbon ages (equal to the number of observed dates) is simulated proportional to the modeled per C14-year amplitude. These simulated dates are then calibrated and summed. Repeating this process many times (e.g., 1,000) provides a global goodness-of-fit test and a 95% critical envelope with which to assess local departures from the theoretical model (6, 35). A second kind of test used here holds constant the date of a given sample but shuffles its label (e.g., the geographic region it comes from or the material type/species of the sample). This permutation test creates conditional random sets (e.g., 1,000) and a 95% critical envelope with which to assess region-specific or species-specific departures from the global trend (33). Such a technique also addresses the challenge of reduced sample sizes (e.g., for particular plants), as the resulting envelopes are correspondingly larger in such cases.

ACKNOWLEDGMENTS. We thank the very considerable number of people and projects who took the original radiocarbon samples or collected the resulting published dates from secondary literature [see discovery.ucl.ac.uk/10025178/ (DOI: 10.14324/000.ds.10025178) for detailed credits] and Enrico Crema, Mark Thomas, and Adrian Timpson for insightful discussion on methodology. Research by D.F. and C.S. was supported by European Research Council Grant 323842 on "Comparative Pathways to Agriculture."

1. Sheridan A (2010) The neolithization of Britain and Ireland: The big picture. Landscapes in Transition, eds Finlayson B, Warren G (Oxbow Books, Oxford), pp 89–105.
2. Cassidy LM, et al. (2016) Neolithic and Bronze Age migration to Ireland and establishment of the insular Atlantic genome. *Proc Natl Acad Sci USA* 113:368–373.
3. Parker Pearson M, et al. (2016) Beaker people in Britain: Migration, mobility and diet. *Antiquity* 90:620–637.
4. Oloalde I, et al. (2017) The beaker phenomenon and the genomic transformation of northwest Europe. bioRxiv:10.1101/135962.
5. Roberts BK, Wrathmell S (2000) *An Atlas of Rural Settlement in England*, (2003 Corrected Reprint) (English Heritage, London).
6. Shennan S, et al. (2013) Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nat Commun* 4:2486.
7. Whitehouse NJ, et al. (2014) Neolithic agriculture on the European western frontier: The boom and bust of early farming in Ireland. *J Archaeol Sci* 51:181–205.
8. Stevens CJ, Fuller DQ (2015) Alternative strategies to agriculture: The evidence for climatic shocks and cereal declines during the British Neolithic and Bronze Age (a reply to Bishop). *World Archaeol* 47:856–875.
9. Bray JR (1968) Glaciation and solar activity since the fifth century BC and the solar cycle. *Nature* 220:672–674.
10. Magny M (1993) Solar influences on Holocene climatic changes illustrated by correlations between past lake level fluctuations and the atmospheric 14C record. *Quat Res* 40:1–9.
11. Vasiliev SS, Dergachev VA (2002) The ~2400-year cycle in atmospheric radiocarbon concentration: Bispectrum of 14C data over the last 8000 years. *Ann Geophys* 20:115–120.
12. Solanki SK, Usoskin IG, Kromer B, Schüssler M, Beer J (2004) Unusual activity of the Sun during recent decades compared to the previous 11,000 years. *Nature* 431:1084–1087.
13. Steinhilber F, et al. (2012) 9,400 years of cosmic radiation and solar activity from ice cores and tree rings. *Proc Natl Acad Sci USA* 109:5967–5971.
14. McCracken KG, Beer J, Steinhilber F, Abreu J (2013) A phenomenological study of the cosmic ray variations over the past 9400 years, and their implications regarding solar activity and the solar dynamo. *Sol Phys* 286:609–627.
15. Scafetta N, Milani F, Bianchini A, Ortolani S (2016) On the astronomical origin of the Hallstatt oscillation found in radiocarbon and climate records throughout the Holocene. *Earth Sci Rev* 162:24–43.
16. Usoskin IG, Gallet Y, Lopes F, Kovaltsov GA, Hulot G (2016) Solar activity during the Holocene: The Hallstatt cycle and its consequence for grand minima and maxima. *Astron Astrophys* 587:A150.
17. O'Brien SR, et al. (1995) Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* 270:1962–1964.
18. Mayewski PA, et al. (1997) Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *J Geophys Res* 102:26345–26366.
19. Meeker LD, Mayewski PA (2002) A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. *Holocene* 12:257–266.
20. Bond G, et al. (2001) Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294:2130–2136.
21. Oppo DW, McManus JF, Cullen JL (2003) Palaeo-oceanography: Deepwater variability in the Holocene epoch. *Nature* 422:277–278.
22. Debret M, et al. (2007) The origin of the 1500-year climate cycles in Holocene North Atlantic records. *Clim Past* 3:569–575.
23. Weninger B, et al. (2009) The impact of rapid climate change on prehistoric societies during the Holocene in the eastern Mediterranean. *Documenta Praehistorica* 36:7–59.
24. Roberts N, et al. (October 12, 2017) Human responses and non-responses to climatic variations during the last glacial-interglacial transition in the eastern Mediterranean. *Quat Sci Rev*, 10.1016/j.quascirev.2017.09.011.
25. Bonsall C, Macklin MG, Anderson DE, Payton RW (2002) Climate change and the adoption of agriculture in north-west Europe. *Eur J Archaeol* 5:9–23.
26. Jones G, Rowley-Conwy P (2007) On the importance of cereal cultivation in the British Neolithic. *Origins and Spread of Domestic Plants in Southwest Asia and Europe*, eds Colledge S, Conolly J (Left Coast, Walnut Creek, CA).
27. Stone D (2005) *Decision-Making in Medieval Agriculture* (Oxford Univ Press, Oxford).
28. Campbell B (2016) *The Great Transition: Climate, Disease and Society in the Late-Medieval World* (Cambridge Univ Press, Cambridge, UK).
29. Zhang DD, et al. (2011) The causality analysis of climate change and large-scale human crisis. *Proc Natl Acad Sci USA* 108:17296–17301.
30. Stuiver M, Polach HA (1977) Discussion: Reporting of 14C data. *Radiocarbon* 19:355–363.
31. Reimer PJ, et al. (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. *Radiocarbon* 55:1869–1887.
32. Bronk Ramsay C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51:337–360.
33. Crema ER, Habu J, Kobayashi K, Madella M (2016) Summed probability distribution of 14C dates suggests regional divergences in the population dynamics of the Jomon period in eastern Japan. *PLoS One* 11:e0154809.
34. Weninger B, Clare L, Jörisc O, Jung R, Edinborough K (2015) Quantum theory of radiocarbon calibration. *World Archaeol* 47:543–566.
35. Timpson A, et al. (2014) Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: A new case-study using an improved method. *J Archaeol Sci* 52:549–557.
36. Bueno L, Schmidt Dias A, Steele J (2013) The late Pleistocene/early Holocene archaeological record in Brazil: A geo-referenced database. *Quat Int* 301:74–93.
37. Jacobi RM, Higham TFG (2009) The early late glacial re-colonization of Britain: New radiocarbon evidence from Gough's cave, southwest England. *Quat Sci Rev* 28:1895–1913.
38. Edwards RJ, Brooks AJ (2008) The island of Ireland: Drowning the myth of an Irish land-bridge? *Mind the Gap: Postglacial Colonisation of Ireland*, eds Davenport JJ, Sleeman DP, Woodman PC (Irish Naturalists' Journal, Belfast, Ireland), pp 19–34.
39. Woodman P (2015) *Ireland's First Settlers: Time and the Mesolithic* (Oxbow Books, Oxford).

40. Shennan I, et al. (2000) Modelling western North Sea palaeogeographies and tidal changes during the Holocene. *Holocene Land-Ocean Interaction and Environmental Change Around the North Sea*, Geological Society, London, Special Publications, eds Shennan I, Andrews J (Geological Society, London), Vol 166, pp 299–319.
41. Weninger B, et al. (2008) The catastrophic final flooding of Doggerland by the Storegga Slide tsunami. *Documenta Praehistorica* 35:1–24.
42. Whittle A, Healy F, Bayliss A (2011) *Gathering Time: Dating the Early Neolithic Enclosures of Southern Britain and Ireland* (Oxbow, Oxford).
43. Sørensen L, Karg S (2014) The expansion of agrarian societies towards the north: New evidence for agriculture during the Mesolithic/Neolithic transition in southern Scandinavia. *J Archaeol Sci* 51:98–114.
44. Bradley R (2007) *The Prehistory of Britain and Ireland* (Cambridge Univ Press, Cambridge, UK).
45. McLaughlin TR, et al. (2016) The changing face of Neolithic and Bronze Age Ireland: A big data approach to the settlement and burial records. *J World Prehist* 29:117–153.
46. O'Brien W (2004) *Ross Island: Mining, Metal and Society in Early Ireland* (Department of Archaeology, National University of Ireland, Galway, Ireland).
47. Needham S, Lawson AJ, Woodward A (2010) 'A noble group of barrows': Bush barrow and the Normanton Down early Bronze Age cemetery two centuries on. *Antiq J* 90:1–39.
48. Bradley R, Haselgrove C, Vander Linden M, Webley L (2016) *The Later Prehistory of North-West Europe* (Oxford Univ Press, Oxford).
49. Dolan B (2014) Beyond elites: Reassessing Irish Iron Age society. *Oxf J Archaeol* 33:361–377.
50. Zimmermann A, Hilpert J, Wendt KP (2009) Estimations of population density for selected periods between the Neolithic and AD 1800. *Hum Biol* 81:357–380.
51. Fulford M, Allen M (2016) Introduction: Population and the dynamics of change in Roman south-eastern England. *Agriculture and Industry in South-Eastern Roman Britain*, ed Bird D (Oxbow, Oxford).
52. Becker K, O'Neill J, O'Flynn L (2008) Iron Age Ireland: Finding an invisible people. www.ucd.ie/t4cms/iron_age_ireland_project_16365_pilotweb.pdf. Accessed November 7, 2017.
53. Leslie S, et al.; Wellcome Trust Case Control Consortium 2; International Multiple Sclerosis Genetics Consortium (2015) The fine-scale genetic structure of the British population. *Nature* 519:309–314.
54. Martiniano R, et al. (2016) Genomic signals of migration and continuity in Britain before the Anglo-Saxons. *Nat Commun* 7:10326.
55. Schiffels S, et al. (2016) Iron Age and Anglo-Saxon genomes from East England reveal British migration history. *Nat Commun* 7:10408.
56. Bevan A (2012) Spatial methods for analysing large-scale artefact inventories. *Antiquity* 86:492–506.
57. McCormick F (2014) Agriculture, settlement and society in early medieval Ireland. *Quat Int* 346:119–130.
58. McCormick F (2008) The decline of the cow: Agricultural and settlement change in early medieval Ireland. *Peritia* 20:209–224.
59. Bishop RR, Church MJ, Rowley-Conwy PA (2013) Seeds, fruits and nuts in the Scottish Mesolithic. *Proc Soc Antiq Scotl* 143:9–71.
60. Schulting RJ (2014) Hunter-gatherer diet, subsistence and foodways. *Oxford Handbook of the Archaeology and Anthropology of Hunter-Gatherers*, eds Cummings V, Jordan P, Zvelebil M (Oxford Univ Press, Oxford), pp 1266–1287.
61. Robson HK, et al. (February 17, 2016) Scales of analysis: Evidence of fish and fish processing at Star Carr. *J Archaeol Sci Rep*, 10.1016/j.jasrep.2016.02.009.
62. Serjeantson D (2017) Fishing, wildfowling and marine mammal exploitation in northern Scotland from prehistory to Early Modern times. *Oxford Handbook of Zooarchaeology*, eds Albarella U, Rizzetto M, Russ H, Vickers K, Viner-Daniels S (Oxford Univ Press, Oxford).
63. Bishop RR, Church MJ, Rowley-Conwy PA (2009) Cereals, fruits and nuts in the Scottish Neolithic. *Proc Soc Antiq Scotl* 139:47–103.
64. Stevens CJ, Fuller DQ (2012) Did Neolithic farming fail? The case for a Bronze Age agricultural revolution in the British Isles. *Antiquity* 86:707–722.
65. McClatchie M, et al. (2016) Farming and foraging in Neolithic Ireland: An archaeobotanical perspective. *Antiquity* 350:302–318.
66. Kubiak-Martens L, Brinkkemper O, Oudemans TF (2015) What's for dinner? Processed food in the coastal area of the northern Netherlands in the Late Neolithic. *Veg Hist Archaeobot* 24:47–62.
67. Robinson MA (2000) Further considerations of Neolithic charred cereals. *Plants in Neolithic Britain and Beyond*, ed Fairbairn AS (Oxbow Books, Oxford), pp 85–90.
68. Peacock D (2013) *The Stone of Life: Querns, Mills and Flour Production in Europe up to c. AD 500* (Highfield, Southampton, UK).
69. Pelling R, Campbell G (2013) Plant resources. *Stonehenge World Heritage Site Synthesis: Prehistoric Landscape, Environment and Economy*, eds Canti M, Campbell G, Gearey S (English Heritage, Swindon, UK), pp 37–60.
70. Jones JR, Mulville J (2016) Isotopic and zooarchaeological approaches towards understanding aquatic resource use in human economies and animal management in the prehistoric Scottish North Atlantic islands. *J Archaeol Sci Rep* 6:665–677.
71. Woodman PC (2016) The introduction of cattle into prehistoric Ireland: Fresh perspectives. *Cattle in Ancient and Modern Ireland: Farming Practices, Environment and Economy*, eds O'Connell M, Kelly F, McAdam JH (Cambridge Scholars, Cambridge), pp 12–26.
72. Smith C (2000) A grumphie in the sty: An archaeological view of pigs in Scotland, from their earliest domestication to the agricultural revolution. *Proc Soc Antiq Scotl* 130:705–724.
73. Serjeantson D (2011) *Review of Animal Remains from the Neolithic and Early Bronze Age of Southern Britain*, English Heritage Research Department Report Series 29-2011 (English Heritage, Portsmouth, UK).
74. Schulting R (2013) On the northwestern fringes: Earlier Neolithic subsistence in Britain and Ireland as seen through faunal remains and stable isotopes. *The Origins and Spread of Domestic Animals in Southwest Asia and Europe*, eds College S, Connolly J, Dobney K, Manning K, Shennan S (Left Coast, Walnut Creek, CA), pp 313–338.
75. Copley MS, et al. (2005) Processing of milk products in pottery vessels through British prehistory. *Antiquity* 79:895–908.
76. Smyth S, Evershed RP (2016) Milking the megafauna: Using organic residue analysis to understand early farming practice. *Environ Archaeol* 21:214–229.
77. Thomas J (1999) *Understanding the Neolithic. A Revised Second Edition of Rethinking the Neolithic* (Routledge, London).
78. Stevens CJ (2007) Reconsidering the evidence: Towards an understanding of the social contexts of subsistence production in Neolithic Britain. *The Origins and Spread of Domestic Plants in Southwest Asia and Europe*, eds Colledge S, Conolly J (Left Coast, Walnut Creek, CA), pp 375–389.
79. Moffett L, Robinson M, Straker V (1989) Cereals, fruit and nuts: Charred plant remains from Neolithic sites in England and Wales and the Neolithic economy. *Beginnings of Agriculture*, eds Milles A, Williams D, Gardner N (British Archaeological Reports, Oxford), pp 243–261.
80. Watts SR (2012) *The Structured Deposition of Querns: The Contexts of Use and Deposition of Querns in the South-West of England from the Neolithic to the Iron Age*. PhD dissertation (University of Exeter, Exeter, UK).
81. Bogaard A, Jones G (2007) Neolithic farming in Britain and central Europe: Contrast or continuity? *Going Over: The Mesolithic-Neolithic Transition in North-West Europe*, eds Whittle A, Cummings V (British Academy, London), pp 357–375.
82. Bogaard A, et al. (2013) Crop manuring and intensive land management by Europe's first farmers. *Proc Natl Acad Sci USA* 110:12589–12594.
83. Caulfield S, O'Donnell RG, Mitchell PI (1998) 14C dating of a Neolithic field system at Céide Fields, County Mayo, Ireland. *Radiocarbon* 40:629–640.
84. Whitefield A (2017) Neolithic 'Celtic' Fields? A reinterpretation of the chronological evidence from Céide Fields in north-western Ireland. *Eur J Archaeol* 20:257–279.
85. Craig OE, et al. (2015) Feeding Stonehenge: Cuisine and consumption at the Late Neolithic site of Durrington Walls. *Antiquity* 89:1096–1109.
86. Clarke DV, Sharples N (1985) Settlement and subsistence in the third millennium BC. *The Prehistory of Orkney*, ed Renfrew C (Edinburgh Univ Press, Edinburgh), pp 286–305.
87. Bishop RR (2015) Did Late Neolithic farming fail or flourish? A Scottish perspective on the evidence for Late Neolithic arable cultivation in the British Isles. *World Archaeol* 47:834–855.
88. Fleming A (1988) *The Dartmoor Reeves. Investigating Prehistoric Land Divisions* (Batsford, London).
89. Pryor F (1998) *Prehistoric Farmers in Britain* (Tempus, Stroud, UK).
90. Fitzpatrick A, et al. (2007) Later Bronze Age and Iron Age. *The Archaeology of South West England*, eds Grove J, Croft B (Somerset County Council, Taunton, UK), pp 117–144.
91. Yates DT (2007) *Land, Power and Prestige: Bronze Age Field Systems in Southern England* (Oxbow, Oxford).
92. Tipping R, Davies A, McCulloch R, Tisdall E (2008) Response to late Bronze Age climate change of farming communities in north east Scotland. *J Archaeol Sci* 35:2379–2386.
93. Van der Veen M (1992) *Crop Husbandry Regimes. An Archaeobotanical Study of Farming in Northern England 1000 BC-AD 500*. Sheffield Archaeological Monographs 3 (J. R. Collis, Sheffield, UK).
94. Huntley JP (2002) Environmental archaeology: Mesolithic to Roman period. *Past, Present and Future: The Archaeology of Northern England*, eds Brooks CM, Daniels R, Harding A (Architectural and Archaeological Society, Durham, UK), pp 79–96.
95. McClatchie M (2009) *Arable Agriculture and Social Organisation: A Study of Crops and Farming Systems in Bronze Age Ireland*. PhD dissertation (University College London, London).
96. Van der Veen M (1995) The identification of maslin crops. *Res Archaeobotanicae*, eds Kroll H, Pasternak R (Oetker-Voeges Verlag, Kiel, Germany), pp 335–343.
97. Bartosiewicz L (2013) Animals in Bronze Age Europe. *The Oxford Handbook of the European Bronze Age*, eds Fokkens H, Harding A (Oxford Handbooks Online, Oxford), pp 328–347.
98. Rast-Eicher A (2014) Bronze and Iron Age wools in Europe. *Wool Economy in the Ancient Near East and the Aegean*, eds Breniquet C, Michel C (Oxbow Books, Oxford), pp 12–21.
99. Mulville J, Thomas J (2005) Animals and ambiguity in the Iron Age of the Western Isles. *Tall Stories? Broch Studies Past Present and Future*, ed Turner V (Oxbow Books, Oxford), pp 235–246.
100. Bendrey R (2010) The horse. *Extinctions and Invasions: A Social History of British Fauna*, eds O'Connor T, Sykes N (Windgather, Oxford), pp 10–16.
101. Caseldine CJ (1999) Archaeological and environmental change on prehistoric Dartmoor—Current understanding and future directions. *J Quat Sci* 14:575–583.
102. Turney C, Jones RT, Thomas ZA, Palmer JG, Brown D (2016) Extreme wet conditions coincident with Bronze Age abandonment of upland areas in Britain. *Anthropocene* 13:69–79.
103. de Hingh AE (2000) *Food Production and Food Procurement in the Bronze Age and Early Iron Age (2000-500 BC). The Organisation of a Diversified and Intensified Agrarian System in the Meuse-Demer-Scheldt Region (The Netherlands and Bel-*

gium) and the Region of the River Moselle (Luxemburg and France) (Faculty of Archaeology, Leiden Univ Press, Leiden, The Netherlands).

104. Treasure ER, Church MJ (2017) Can't find a pulse? Celtic bean (Vicia faba L.) in British prehistory. *Environ Archaeol* 22:113–127.
105. Dickson C, Dickson J (2000) *Plants and People in Ancient Scotland* (NPI Media Group, Stroud, UK).
106. Leivers M, Chisham C, Knight S, Stevens C (2006) *Excavations at Ham Hill Quarry, Hambledon Hill, Montacute, 2002* (Somerset Archaeology and Natural History Society Somerset, UK), pp 39–62.
107. Stevens CJ (2009) The Iron Age agricultural economy, *Cambourne New Settlement: Iron Age and Romano-British Settlement on the Clay Uplands of West Cambridgeshire*, Wessex Archaeology Report No. 23, eds Wright J, Leivers M, Seager Smith R, Stevens CJ (Wessex Archaeology, Salisbury, UK) pp 78.
108. Stevens CJ (2009) The Romano-British agricultural economy, *Cambourne New Settlement: Iron Age and Romano-British Settlement on the Clay Uplands of West Cambridgeshire*, Wessex Archaeology Report No. 23, eds Wright J, Leivers M, Seager Smith R, Stevens CJ (Wessex Archaeology, Salisbury, UK), pp 110–114.
109. Hambleton E (1999) *Animal Husbandry Regimes in Iron Age Britain*, BAR British Series 282 (Archaeopress, Oxford).
110. Maltby M (2014) The exploitation of animals in Roman Britain. *The Oxford Handbook of Roman Britain*, eds Millett M, Revell L, Moore A (Oxford Univ Press, Oxford).
111. Dobney K, Ervynck A (2007) To fish or not to fish? Evidence for the possible avoidance of fish consumption during the Iron Age around the North Sea. *The Later Iron Age in Britain and Beyond*, eds Haselgrove C, Moore T (Oxbow Books, Oxford), pp 403–418.
112. Rippon S, Pears B, Smart C (2015) *The Fields of Britannia. Continuity and Change in the Late Roman and Early Medieval Landscape* (Oxford Univ Press, Oxford).
113. McClatchie M (2011) A long tradition of cereal production. *Seanda* 6:8–1.
114. Straker V (1984) First and second century carbonised cereal grain from Roman London. *Plants and Ancient Man: Studies in Palaeoethnobotany*, eds van Zeist W, Casparie WA (A.A. Balkema, Rotterdam), pp 323–329.
115. Cambell G (2017) Market forces—A discussion of crop husbandry, horticulture and trade in plant resources in southern England. *Agriculture and Industry in South-Eastern Roman Britain*, ed Bird D (Oxbow Books, Oxford), pp 134–155.
116. Barclay AJ, Stevens CJ (2015) Chronology and the radiocarbon dating programme. *Imperial College Sports Ground and RMC Land, Harlington: The development of prehistoric and later communities in the Colne Valley and on the Heathrow Terrace*, Wessex Archaeology Report 33, eds Powell AB, Barclay AJ, Mepham L, Stevens CJ (Oxbow, Oxford), pp 295–302.
117. Wilcox G (1977) Exotic plants from Roman waterlogged sites in London. *J Archaeol Sci* 4:269–282.
118. Lodwick L (2014) Condiments before Claudius: New plant foods at the Late Iron Age oppidum at Silchester, UK. *Veg Hist Archaeobot* 23:543–549.
119. Van der Veen M (2014) Arable farming, horticulture, and food: Expansion, innovation, and diversity in Roman Britain. *The Oxford Handbook of Roman Britain*, eds Millett M, Revell L, Moore A (Oxford Univ Press, Oxford).
120. Van der Veen M (1989) Charred grain assemblages from Roman period corn driers in Britain. *Archaeol J* 146:302–319.
121. Fowler P (2002) *Farming in the First Millennium AD* (Cambridge Univ Press, Cambridge, UK).
122. Jones MK (1981) The development of crop husbandry. *The Environment of Man. The Iron Age to the Anglo-Saxon Period*, British Archaeological Report, eds Jones MK, Dimbleby GW (Tempus Reparatum, Oxford), pp 95–127.
123. Seetah K (2006) Multidisciplinary approach to Romano-British cattle butchery. *Integrating Zooarchaeology*, ed Maltby M (Oxbow Books, Oxford), pp 111–118.
124. Banham D, Faith R (2014) *Anglo-Saxon Farms and Farming* (Oxford Univ Press, Oxford).
125. Hall D (2014) *The Open Fields of England* (Oxford Univ Press, Oxford).
126. O'Conner T (2017) Animals in urban life in medieval to early modern England. *Oxford Handbook of Archaeolozoology*, eds Albarella U, Russ H, Vickers K, Viner-Daniels S (Oxford Univ Press, Oxford), 10.1093/oxfordhb/9780199686476.013.13.
127. McCormick F, Kerr T, McClatchie M, O'Sullivan A (2014) *Early Medieval Agriculture, Livestock and Cereal Production in Ireland, AD 400-1100* (Oxbow Books, Oxford).
128. Murphy P (1985) The cereals and crop weeds. *West Stow the Anglo-Saxon Village*, East Anglian Archaeology 24, ed West S (Suffolk County Planning Department, Ipswich, UK), Vol 1, pp 100–108.
129. Moffet P (2011) Food plants on archaeological sites: The nature of the archaeobotanical record. *The Oxford Handbook of Anglo-Saxon Archaeology*, eds Hamerow H, Hinton DA, Crawford S (Oxford Univ Press, Oxford), pp 346–360.
130. McClatchie M, McCormick F, Kerr TR, O'Sullivan A (2015) Early medieval farming and food production: A review of the archaeobotanical evidence from archaeological excavations in Ireland. *Veg Hist Archaeobot* 24:179–186.
131. McErlean T, Crothers N (2007) *Harnessing the Tides. The Early Medieval Tide Mills at Nendrum Monastery, Strangford Lough*. Northern Ireland Archaeological Monographs (NI Environment and Heritage Service Stationary Office, Belfast, Northern Ireland).
132. Thomas G, McDonnell G, Merkel J, Marshall P (2016) Technology, ritual and Anglo-Saxon agriculture: The biography of a plough coulter from Lyminge, Kent. *Antiquity* 90:742–758.
133. Kelly F (1997) *Early Irish Farming* (Dundalgan Press, Dundalk, Republic of Ireland).
134. Fox HSA (1986) The alleged transformation from two-field to three-field systems in medieval England. *Econ Hist Rev* 39:526–548.
135. Oosthuizen S (2016) Recognizing and moving on from a failed paradigm: The case of agricultural landscapes in Anglo-Saxon England c. AD 400-800. *J Archaeol Res* 24: 179–227.
136. Cramp LJE, Whelton H, Sharples N, Mulville J, Evershed RP (2015) Contrasting patterns of resource exploitation on the Outer Hebrides and Northern Isles of Scotland during the Late Iron Age and Norse Period revealed through organic residues in pottery. *J North Atlantic* 9:134–151.
137. Sen A (1981) *Poverty and Famines: An Essay on Entitlement and Deprivation* (Clarendon Press, Oxford).
138. Albarella U (1997) Size, power, wool and veal: Zooarchaeological evidence for late medieval innovations, Albarella, UmbertoSize, power, wool and veal: Zooarchaeological evidence for late medieval. *Environment and Subsistence in Medieval Europe*, eds De Bow G, Verhaeghe F (Instituut voorhet Archeologisch Patrimonium, Zellik, Belgium), pp 19–30.
139. Overton M (1996) *Agricultural Revolution in England: The Transformation of the Agrarian Economy 1500-1850* (Cambridge Univ Press, Cambridge, UK).
140. Hawkes JG (1998) The introduction of New World crops into Europe after 1492. *Plants for Food and Medicine*, eds Prendergast H, Etkin NI, Harris DR, Houghton PJ (Royal Botanical Gardens, Kew, London), pp 147–159.
141. Anderson Stamnes A (2016) Effect of temperature change on Iron Age cereal production and settlement patterns in mid-Norway. *The Agrarian Life of the North 2000BC- AD1000: Studies in Rural Settlement and Farming in Norway*, eds Iversen F, Petersson H (Portal, Oslo), pp 27–39.
142. Bonafaccia G, et al. (2000) Characteristics of spelt wheat products and nutritional value of spelt wheat-based bread. *Food Chem* 68:437–441.
143. Buerstmayr H, Krenn N, Stephan U, Grausgruber H, Zechner E (2007) Agronomic performance and quality of oat (*Avena sativa* L) genotypes of worldwide origin produced under central European growing conditions. *Field Crops Res* 101:343–351.
144. Gill NT, Vear KC (1980) *Agricultural Botany. 2. Monocotyledonous Crops*, eds Vear KC, Barnard DJ (Duckworth, London), 3rd Ed.
145. Hansen LI (1990) *Samisk Fangstsamfunn og Norsk Høvdingeøkonomi* (Novus, Oslo).
146. Hillman GC (1981) Reconstructing crop husbandry practices from charred remains of crops. *Farming Practice in British Prehistory*, ed Mercer RJ (Edinburgh Univ Press, Edinburgh), pp 123–162.
147. Kirleis W, Klooß S, Kroll H, Müller J (2012) Crop growing and gathering in the northern German Neolithic: A review supplemented by new results. *Veg Hist Archaeobot* 21:221–242.
148. Kirleis W, Fischer E (2014) Neolithic cultivation of tetraploid free threshing wheat in Denmark and northern Germany: Implications for crop diversity and societal dynamics of the Funnel Beaker Culture. *Veg Hist Archaeobot* 23(Suppl 1):S81–S96.
149. Percival J (1902) *Agricultural Botany* (Duckworth, London).
150. Percival J (1921) *The Wheat Plant* (Duckworth, London).
151. Reynolds PJ (1992) Crop yields of the prehistoric cereal types emmer and spelt: The worst option. *Préhistoire de l'Agriculture: Nouvelles Approches Expérimentales et Ethnographiques*, ed Anderson PC (CNRS, Monographie du CRA, Paris).
152. Van der Veen M, Palmer C (1997) Environmental factors and the yield potential of ancient wheat crops. *J Archaeol Sci* 24:163–182.
153. Van Veldhuizen RM, Knight CW (2004) *Performance of Agronomic Crop Varieties in Alaska 1978-2002*. Agricultural and Forestry Experimental Station Bulletin (University of Alaska, Fairbanks, AK), Vol 111, pp 1–132.
154. Magny M (2004) Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quat Int* 113:65–79.
155. Magny M, Leuzinger U, Bortenschlager S, Haas JN (2006) Tripartite climate reversal in central Europe 5600-5300 years ago. *Quat Res* 65:3–19.
156. Charman D (2002) *Peatlands and Environmental Change* (John Wiley and Sons, Chichester, UK).
157. van Geel B, et al. (2004) Climate change and the expansion of the Scythian culture after 850 BC: A hypothesis. *J Archaeol Sci* 31:1735–1742.
158. Armit I, Swindles GT, Becker K, Plunkett G, Blaauw M (2014) Rapid climate change did not cause population collapse at the end of the European Bronze Age. *Proc Natl Acad Sci USA* 111:17045–17049.
159. Charman D, Blundell A, Chiverrell RC, Hendon D, Langdon PG (2006) Compilation of non-annually resolved Holocene proxy climate records: Stacked Holocene peatland palaeo-water table reconstructions from northern Britain. *Quat Sci Rev* 25:336–350.
160. Hughes PDM, Mauquoy D, Barber KE, Langdon PG (2000) Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. *Holocene* 10:465–479.
161. Roland TP, Caseldine CJ, Charman DJ, Turney CSM, Amesbury MJ (2014) Was there a '4.2 ka event' in Great Britain and Ireland? Evidence from the peatland record. *Quat Sci Rev* 83:11–27.
162. McDermott F, Mattey DP, Hawkesworth C (2001) Centennial-scale Holocene climate variability revealed by a high-resolution speleothem delta 18O record from SW Ireland. *Science* 294:1328–1331.
163. Schibler J, Jacomet S (2010) Short climatic fluctuations and their impact on human economies and societies: The potential of the Neolithic lake shore settlements in the Alpine foreland. *Environ Archaeol* 15:173–182.
164. Caseldine C, Thompson G, Langdon C, Hendon D (2005) Evidence for an extreme climatic event on Achill Island, Co. Mayo, Ireland around 5200-5100 cal. yr BP. *J Quat Sci* 20:169–178.
165. Roland TP, et al. (2015) The 5.2 ka climate event: Evidence from stable isotope and multi-proxy palaeoecological peatland records in Ireland. *Quat Sci Rev* 124:209–223.
166. Van Vliet-Lanoë B, et al. (2014) Middle- to late-Holocene storminess in Brittany (NW France): Part I—Morphological impact and stratigraphical record. *Holocene* 24: 413–433.

167. Hinz M (2015) Growth and decline? Population dynamics of Funnel Beaker societies in the 4th millennium BC. *Neolithic Diversities: Perspectives from a Conference in Lund, Sweden*, eds Brink K, Hydén S, Jennbert K, Olausson DS (Lund University, Lund, Sweden), pp 43–51.
168. Meller H, Arz HW, Jung R, Risch R, eds (2015) *2200 BCE – A Climatic Breakdown as a Cause for the Collapse of the Old World?* (Landesdenkmalamt für Denkmalpflege und Archäologie Sachsen-Anhalt Halle, Germany).
169. van Geel B, Buurman J, Waterbolk HT (1996) Archaeological and palaeoecological indications of an abrupt climate change in the Netherlands, and evidence for climatological teleconnections around 2650 BP. *J Quat Sci* 11:451–460.
170. Brown T (2008) The Bronze Age climate and environment of Britain. *Bronze Age Rev* 1:7–22.
171. Mauquoy D, Yeloff D, Van Geel B, Charman DJ, Blundell A (2008) Two decadally resolved records from north-west European peat bogs show rapid climate changes associated with solar variability during the mid–late Holocene. *J Quat Sci* 23:745–763.
172. Martin-Puertas C, et al. (2012) Regional atmospheric circulation shifts induced by a grand solar minimum. *Nat Geosci* 5:397–401.
173. Swindles GT, et al. (2013) Centennial-scale climate change in Ireland during the Holocene. *Earth Sci Rev* 126:300–320.
174. Campbell B (2010) Nature as historical protagonist: Environment and society in preindustrial England. *Econ Hist Rev* 63:281–314.
175. Slavin P (2012) The Great Bovine Pestilence and its economic and environmental consequences in England and Wales,1318–501. *Econ Hist Rev* 65:1239–1266.
176. Dawson AG, Hickey K, Mayewski PA, Nesje A (2007) Greenland (GISP2) ice core and historical indicators of complex North Atlantic climate changes during the fourteenth century. *Holocene* 17:427–434.
177. Dugmore AJ, et al. (2012) Cultural adaptation, compounding vulnerabilities and conjunctures in Norse Greenland. *Proc Natl Acad Sci USA* 109:3658–3663.
178. Streeter R, Dugmore AJ, Vésteinsson O (2012) Plague and landscape resilience in premodern Iceland. *Proc Natl Acad Sci USA* 109:3664–3669.
179. Grant MJ, Waller M (2017) Resolving complexities of pollen data to improve interpretation of past human activity and natural processes. *The Archaeological and Forensic Applications of Microfossils: A Deeper Understanding of Human History*, eds Williams M, Hill T, Boomer I, Wilkinson IP (The Micropalaeontological Society, Bath, UK), pp 103–119.
180. Behre K-E (1986) *Anthropogenic Indicators in Pollen Diagrams* (A.A. Balkema, Rotterdam).
181. Gaillard M-J, et al. (1994) Application of modern pollen/land-use relationships to the interpretation of pollen diagrams: Reconstructions of land-use history in south Sweden 3000–0 BP. *Rev Palaeobot Palynol* 82:47–73.
182. Fyfe RM, Roberts CN, Woodbridge J (2010) A pollen-based pseudo-biomisation approach to anthropogenic land cover change. *Holocene* 20:1165–1171.
183. Prentice IC, Parsons RW (1983) Maximum likelihood linear calibration of pollen spectra in terms of forest composition. *Biometrics* 39:1051–1057.
184. Sugita S (2007) Theory of quantitative reconstruction of vegetation. I. Pollen from large sites REVEALS regional vegetation. *Holocene* 17:229–241.
185. Hellman S, Gaillard MJ, Broström A, Sugita S (2008) The REVEALS model, a new tool to estimate past regional plant abundance from pollen data in large lakes: Validation in southern Sweden. *J Quat Sci* 23:21–42.
186. Sugita S, Parshall T, Calcote R, Walker K (2010) Testing the landscape reconstruction algorithm for spatially explicit reconstruction of vegetation in northern Michigan and Wisconsin. *Quat Res* 74:289–300.
187. Fyfe RM, et al. (2013) The Holocene vegetation cover of Britain and Ireland: Overcoming problems of scale and discerning patterns of openness. *Quat Sci Rev* 73: 132–148.
188. Marquer L, et al. (2014) Holocene changes in vegetation composition in northern Europe: Why pollen-based quantitative reconstructions matter? *Quat Sci Rev* 90: 199–216.
189. Fyfe RM, et al. (2009) The European pollen database: Past efforts and current activities. *Veg Hist Archaeobot* 18:417–424.
190. Giesecke T, et al. (2014) Towards mapping the late quaternary vegetation change of Europe. *Veg Hist Archaeobot* 23:75–86.
191. Trondman A-K (2015) Pollen-based land-cover reconstructions for the study of past vegetation-climate interactions in NW Europe at 0.2 k, 0.5 k, 3 k and 6 k years before present. *Glob Change Biol* 21:676–697.
192. Woodbridge J, et al. (2014) The impact of the Neolithic agricultural transition in Britain: A comparison of pollen-based land-cover and archaeological 14C date-inferred population change. *J Archaeol Sci* 51:216–224.
193. Lechterbeck J, et al. (2014) Is Neolithic land use correlated with demography? An evaluation of pollen derived land cover and radiocarbon inferred demographic change from central Europe. *Holocene* 24:1297–1307.
194. Fyfe RM, Woodbridge J, Roberts N (2015) From forest to farmland: Pollen-inferred land cover change across Europe using the pseudobiomization approach. *Glob Change Biol* 21:1197–1212.
195. Rosen AM (2007) *Civilizing Climate: Social Responses to Climate Change in the Ancient Near East* (Rowman Altamira Plymouth, UK).
196. Weiss H, et al. (1993) The genesis and collapse of third millennium north mesopotamian civilization. *Science* 261:995–1004.