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

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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 harder 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.

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. 1C) 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...
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, northwest 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
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).

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 harder 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 harder, 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

![Graph A: Britain and Ireland (anthrop. 14C)](image)

![Graph B: Total Solar Irradiance (Wm²)](image)

![Graph C: Greenland GISP2 (nssK² pbpp)](image)

![Graph D: Ice Rafted Debris (% hematite–stained)](image)

Fig. 3. Radiocarbon-inferred population and North Atlantic climate proxies. (A) Aggregate anthropogenic radiocarbon dates from Britain and Ireland (as Fig. 1C, 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.
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 stockkeeping strategies emerge from the Middle Bronze Age onwards (Food Production).

Altogether, 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 such calibrated probability distributions, it has become common practice 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 recalcing 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 and generation of the calibration 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 recalcing 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.

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84. O’Brien W (2004) Ross Island: Mining, Metal and Society in Early Ireland (Department of Archaeology, National University of Ireland, Galway, Ireland).
gium) and the Region of the River Misselle (Luxembourg and France) (Faculty of Ar-


106. Leivers M, Chisham C, Knight S, Stevens C (2006) Excavations at Ham Hill Quarry, Hambleton Hill, Monteacute, 2002 (Somerset Archaeology and Natural History So-
ciety Somerset, UK), pp 39–62.


108. Stevens CJ (2009) The Romano-British agricultural economy, Camborne New Set-


111. Dobney K, Ervynck A (2007) To fish or not to fish? Evidence for the possible avoid-


126. Kelly F (1997) Size, power, wool and veal: Zoonarchaeological evidence for late medieval innovations, Albarella, UmbertoSize, power, wool and veal: Zoonarchaeo-
logical evidence for late medieval. Environment and Subsistence in Medieval Europe, eds De Bo G, Verhaegen F (Instituut voor Archeologisch Patri-
monium, Zellick, Belgium) pp 9–38.


endown Press, Oxford).

133. Albarella U (1997) Size, power, wool and veal: Zoonarchaeological evidence for late medieval innovations, Albarella, UmbertoSize, power, wool and veal: Zoonarchaeo-
logical evidence for late medieval. Environment and Subsistence in Medieval Europe, eds De Bo G, Verhaegen F (Instituut voor Archeologisch Patri-
monium, Zellick, Belgium) pp 9–38.


136. Anderson Stannes A (2016) Effect of temperature change on Iron Age cereal pro-


138. Albarella U (1997) Size, power, wool and veal: Zoonarchaeological evidence for late medieval innovations, Albarella, UmbertoSize, power, wool and veal: Zoonarchaeo-
logical evidence for late medieval. Environment and Subsistence in Medieval Europe, eds De Bo G, Verhaegen F (Instituut voor Archeologisch Patri-
monium, Zellick, Belgium) pp 9–38.
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