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Asynchrony in key Holocene chronologies: Evidence from Irish bog pines

Max C.A. Torbenson[1,2*], Gill Plunkett[1], David M. Brown[1], Jonathan R. Pilcher[1], and Hanns Hubert Leuschner[3]

[1]School of Geography, Archaeology and Palaeoecology, Queen's University Belfast BT7 1NN, Northern Ireland

[2]Department of Geosciences, University of Arkansas, Fayetteville, Arkansas 72701, USA

[3]Department of Palynology and Climate Dynamics, Georg-August-Universität Göttingen, 37073 Göttingen, Germany

*E-mail: mtorbens@uark.edu

ABSTRACT

The Greenland Ice Core Chronology 2005 (GICC05) and the radiocarbon calibration curve (IntCal) are the foremost time scales used in paleoclimatic and paleoenvironmental studies on the most recent 10,000 years. Due to varying and often insufficient dating resolution, opportunities to test the synchrony of these two influential chronologies are rare. Here we present evidence for a phase of major pine recruitment on Irish bogs around 8160 cal yr B.P. Dendrochronological dating of subfossil trees from three sites reveals synchronicity in germination across the study area, indicative of a regional forcing. The concurrent colonization of pine on peatland is interpreted in terms of drier surface conditions and provides the first substantive proxy data in support of a significant hydroclimatic change in the north of Ireland accompanying the 8.2 ka event. The date of pine establishment does not overlap with the GICC05 age range for the event,

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and potential lags between responses are unlikely to explain the full difference. In light of recent studies highlighting a possible offset in GICC05 and IntCal dates, the Irish pine record supports the notion of ice core dates being too early during the period of study. If the suggested discrepancy in timing is an artifact of chronological error, it is likely to have affected interpretations of previous proxy comparisons and alignments.

INTRODUCTION

Proxy records are a means by which we understand past climate variability and validate models used to project future scenarios of climate change (Bradley, 2008). Multi-proxy approaches are becoming increasingly important as they offer unrivaled insights into the spatiotemporal evolution of past climatic changes (Li et al., 2010). However, the temporal synchronization of records is crucial in such exercises and one of the main obstacles in proxy alignment is chronological imprecision (Blaauw, 2012). Wide date ranges can lead to the "sucking in" (*sensu* Baillie, 1991) of unrelated evidence and subsequently cause wrongful attribution of shifts in a proxy record to the event of interest. Radiocarbon is one of the most commonly used dating methods and also provides an indirect record of past solar variability, one of the forcing mechanisms that climate science tries to factor in. The Greenland ice cores are arguably the foremost records of climate change over the past 100 k yr and are regularly used in comparisons with other paleoenvironmental and paleoclimatic proxies (e.g., Tinner and Lotter 2001). The commonly accepted chronology for these records is the Greenland Ice Core Chronology 2005 (GICC05; Vinther et al., 2006), a product developed through synchronization of volcanic ash horizons present in the ice cores.

Both GICC05 and the radiocarbon calibration curve (IntCal; Reimer et al., 2009) contain varying amounts of uncertainty throughout their spans. Recently, a number of studies have highlighted the likelihood of a temporal offset between the two chronologies (Lohne et al., 2013; Muscheler et al., 2014; Baillie and McAneney, 2015). These studies focus on different time periods and use a variety of methodologies but the results have in common that the GICC05 dates are significantly older than the radiocarbon ages for supposedly contemporary periods. In order to assess fully the relationship between GICC05 and IntCal, and to quantify any potential asynchrony, date comparisons from throughout the records are needed but because the chronological uncertainties increase with time, finding early Holocene information that will allow such analysis is rare.

Here we present data from three bogs in the north of Ireland that suggest an unprecedented germination event of Scots pine (*Pinus sylvestris* L.) at ca. 8160 yr B.P. We interpret the event as the result of climatically induced drying of the bog surfaces, indicative of a hydroclimatic shift that is in agreement with model outputs of the 8.2 ka event, as well as other proxy evidence. The absolute date for the extra-local germination is compared to the GICC05 date of the 8.2 ka event and, in the context of previous studies, we hypothesize on the synchrony of GICC05 and IntCal.

METHODS AND MATERIALS

Previous research stemming from a decade-long campaign of sampling Northern Ireland bogs for subfossil pines culminated in the development of several local tree-ring chronologies (Pilcher et al., 1995). Pine was present in the area by at least 9000 cal. yr B.P., but the vast majority of collected trees fell into one of two later periods. For the earlier period, an 809 yr floating chronology was also constructed using samples (n = 33) from Sluggan Bog and was radiocarbon dated to the period ca. 8250–7450 cal. yr B.P. A shorter chronology from samples (n = 3) collected at Fallahogy Bog crossdated with the early Sluggan Bog chronology (269 yr overlap).

We investigate the temporal relationship between the inner ring dates of trees (an estimate of germination dates) from Sluggan and Fallahogy bogs, in addition to previously unpublished samples from Ballinderry (Fig. 1). All three are raised bogs, and previous research at Sluggan and Fallahogy has shown that the earliest subfossil pines grew within ombrotrophic peat (Smith, 1958; Smith and Goddard, 1991), thus at levels independent of the ground water table. Pith was present in nearly all cross sections (>95%) from Sluggan Bog and Ballinderry, and the effect of potential pith offset (imprecision when estimating rings to pith when pith is missing) is therefore deemed to be insignificant for the purposes of this study. Materials were collected from the lowest available point on the stem, and rapid growth rates (>2mm/yr) during juvenile stages suggest that the inner rings are close to representing true establishment. Samples were processed and cross-dated according to standard dendrochronological procedures (Baillie, 1982) and site chronologies, representing the average annual growth at the site, were constructed using ARSTAN (a tree-ring standardization program; Cook, 1985). Accelerator mass spectrometry radiocarbon dating was performed on sequences of 10 annual growth rings from the Ballinderry chronologies, complementing high-precision radiocarbon dates previously obtained from 20-yr-long samples from the Sluggan Bog chronology. In total, six radiocarbon dates were used in the analysis.

RESULTS

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Four trees from Ballinderry construct a 374-yr-long chronology that shows highly significant correlation (t = 8.40, P < 0.0001, 374 yr overlap) with the record from Sluggan Bog, which is corroborated by radiocarbon dates from the series that fall around 8000 cal. yr B.P. (Table DR1 in the GSA Data Repository[1]). The wiggle-matching of additional radiocarbon dates from Ballinderry and Sluggan Bog allow a much narrower age range (±18 yr) to be obtained than possible from conventional radiocarbon dating (Fig. DR1), and enables the start of the Sluggan Bog chronology to be placed at 8268 ± 18 cal yr B.P. This date supports a long-distance correlation with the German pine record that places the start of the Sluggan chronology at 8277 yr B.P. (t = 5.87, P < = 0.0032). The dating of the early Irish pine chronologies, and subsequently all trees included in these, can now be considered absolute.

The first major germination phase, represented by the inner rings from eleven trees, is confined to a 25 yr window starting 116 yr after the first year of the chronology (8161 yr B.P.). Two of four trees at Ballinderry also fall within the 25 yr window, and a third tree just outside. Germination at Fallahogy occurs within two decades. Of all trees (n = 40) collected from northern Irish bogs dating to the period 8500–7500 cal. yr B.P., a third of the total number of trees has an inner ring date between 8161 and 8137 yr B.P. (Fig. 2).

INTERPRETATION OF PINE HORIZONS

Subfossil material from Sluggan, Ballinderry, and Fallahogy Bogs provides conclusive evidence for local presence of pine at multiple wetland sites at ca. 8160 yr B.P. The pine horizon represents the greatest regeneration on record in the north of Ireland, both in relative and absolute numbers. Establishment of pine on ombrotrophic bogs has traditionally been seen as an indicator of drier local conditions (Bridge et al., 1990; Eckstein et al., 2009), and bog pine remains have been used as an indicator of low water-table levels (e.g., Edvardsson et al., 2012). As the bog surface becomes dry enough for seedlings to survive, trees will invade the open landscape. Pine is a rapid colonizer and can dominate newly available space within years of a shift to favorable conditions (Richardson, 2000). Although changes in peatland hydrology are not necessarily tied to climate (Swindles et al., 2012), temporal coherence over multiple hydrological systems indicates an extra-local forcing.

A climatic impact on growing conditions on the bogs during the period is further supported by a common ring-width anomaly displayed by the three site chronologies wherein significant negative departures from mean growth lasting for 15–20 yr are recorded from ca. 8020–8000 yr B.P., 130 yr after the start of the establishment episode (Fig. 3). The persistent low growth is the most severe >10 yr period in all three chronologies, and suggests a shift in climate across the north of Ireland. Within two decades of the growth depression, the last of the trees at Ballinderry and Fallahogy successfully germinate. After this, conditions were arguably too wet for new pines to establish on the bog surfaces. Thus, suitable conditions for pine regeneration at these two sites seem not to have been sustained for more than 150–175 yr.

The inferred dry period occurs during major climatic upheaval in the North Atlantic region (Rohling and Pälike, 2005). The 8.2 ka event is typified in the Greenland ice cores by a pronounced cooling lasting 150–160 yr (Thomas et al., 2007) and abrupt changes in environmental and climate proxy records from across the globe have been linked to the anomaly (Morrill and Jacobsen, 2005). The British Isles experienced a sharp drop in temperature, as registered by stable isotope records (Daley et al., 2011) and mollusk assemblages (Rousseau et al., 1998). A speleothem record from southwestern Ireland indicates colder and drier conditions in nearby areas (Baldini et al., 2002), and mires in northern Scotland experienced a pronounced shift toward dry surfaces, likely to have been caused by a decrease in precipitation (Tipping et al., 2008). Modeling of the event suggests that higher northern latitudes would have experienced considerable decreases in precipitation (Bauer et al., 2004), and that the North Atlantic region would have witnessed one of the greatest depressions (Tindall and Valdes, 2011). The coinciding dry episode on Irish bogs is interpreted as a direct result of the larger climate anomaly and thus provides a precise estimate of the timing of the 8.2 ka event in this region.

DISCUSSION

We infer that the pine horizon in the north of Ireland bogs signals a change in precipitation that led to drier bog surface conditions at the time. Effective moisture levels in these environments are governed by evapotranspiration, the mass balance between precipitation and temperature (Lafleur et al., 2005). Proxy temperature records from Ireland and Britain (Baldini et al., 2002; Daley et al., 2011) show significantly colder conditions during the period and it is therefore unlikely that bogs would have experienced increased evapotranspiration. A decrease in precipitation is more likely to be the forcing behind the extra-local signal recorded by the subfossil pines. With supporting evidence from model outputs (Bauer et al., 2004; Tindall and Valdes, 2011), we argue that the hydroclimatic shift associated with the 8.2 ka event is that forcing.

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The earliest individual among the cohort of establishing trees has an inner-ring date of 8161 yr B.P. Although the survival of pine seedlings partly depends on their current year's weather (Gunnarsson and Rydin, 1998), the peak of favorable conditions and successful pine establishment are not always simultaneous due to internal bog mechanisms (Kilian et al., 1995). It has been estimated that the lag between optimal climate conditions and recruitment in the northern boreal zone may be up to 20–30 yr (Zackrisson et al., 1995), although the response can be much more rapid (Ågren and Zackrisson, 1990). In the British Isles, the climate effect on bog water level is limited to sub-decadal timescales (Charman, 2007). It is therefore unlikely that the maximum potential lag between a decrease in precipitation and the earliest pine establishment exceeds 20 yr. Our proposed date for the hydroclimatic shift (8171 ± 10 yr) does not overlap with the GICC05 initiation of the 8.2 ka event (8247 ± 47 yr B.P.; Thomas et al., 2007) and the discrepancy is unlikely to be explained by any lag between the temperature and precipitation response as model outputs suggest that changes in both variables would have occurred within 10 yr of the event (Bauer et al., 2004; Tindall and Valdes 2011). The pine horizon is, however, in agreement with an alternative timing of the 8.2 ka event proposed by Muscheler et al. (2004) based on the synchronization of ^{10}Be values from the Greenland Ice Core Project (GRIP) ice core with the absolutely dated Δ^{14}C record from tree-rings. Their dating puts the start of the climate anomaly in the Greenland Ice Sheet Project 2 (GISP2) ice core at 8175 ± 30 yr B.P. (Kobashi et al., 2007). We propose, therefore, that the GICC05 chronology is overly old at this time by multiple decades. Additionally, the severe growth depression recorded by all three site chronologies at 8020–8000 yr B.P. (Fig. 3) could be concurrent with a secondary drop in ^{18}O values in

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GICC05, if GICC05 is shifted forward the several decades proposed by the discrepancy in start dates for the event. Although the relationship between temperature and tree-growth in this region is complicated, *P. sylvestris* in wetland areas tends to prefer warmer conditions (e.g., Linderholm et al., 2002; Edvardsson et al., 2012) and the prolonged cold spell would likely have had an adverse effect on ring-widths at our sites. When reviewing proxy records from across the globe, Morrill and Jacobsen (2005) found the greatest concentration of climate anomalies dated within the window 8100–8150 cal. yr B.P., which lends further support for an offset between ice cores and radiocarbon-dated proxies at the time.

The dating discrepancy indicated by our results falls in the most problematic part of the Holocene GICC05, during which the ice-core chronology has a maximum counting error of 2% (Rasmussen et al., 2006). It is also the period during which differences between the IntCal ^{14}C and ice-core ^{10}Be values are the greatest, and where no synchronization can be reached without shifting GICC05 in the direction suggested by our interpretation (Muscheler et al., 2014). Records of radionuclide variations (Kobashi et al., 2007; Muscheler et al., 2014) and the Irish pine data independently suggest that the mean GICC05 dates are overly old by 65–75 yr for the early Holocene. Tephrochronological studies of the Vedde and Saksunarvatn ashes (western Norway) suggest a similar magnitude of asynchrony (~70 yr) around the Younger Dryas boundary (Lohne et al., 2013). There are also indications of more recent offsets. New radiocarbon age estimates of Aniakchak II ash layers (Alaska; 3570–3410 cal yr B.P.) (Blackford et al., 2014) are younger than the GICC05 date of 3590 yr B.P. ± 1 yr B.P. for the eruption (Coulter et al., 2012). Furthermore, Baillie and McAneney (2015) have suggested a 7 yr offset prior to 1400 yr. B.P. based on frost damage in tree-rings and the spacing between acid spikes in the Greenland ice. These studies all indicate an asynchrony in the same direction (Fig. 4), implying a systematic overestimation of the true age of the Greenland ice layers. An accumulative offset would therefore seem to be explained by a bias in GICC05 toward double counting of uncertain years.

CONCLUSIONS

Subfossil materials from bogs in the north of Ireland record an unprecedented episode of pine establishment at ca. 8160 yr B.P. Dry conditions inferred from the trees are interpreted as a direct hydroclimatic response to the 8.2 ka event, in agreement with decreased precipitation suggested by other proxy records and climate model outputs. The timing of pine recruitment falls outside of the GICC05 date range for the event and adds to growing concerns about the synchrony between GICC05 and IntCal. Taken together, the results indicate that the widely accepted chronology for Greenland ice cores may contain uncertainty that falls outside the current estimated counting error. If the suggested offset in dates is real it has undoubtedly had a significant impact on previous interpretations of past large-scale climate dynamics and may render some conclusions invalid. We believe that the data currently available warrant a frank discussion on the synchrony of the main Holocene timescales and we urge the paleoclimate community to address this issue. Furthermore, there is a need for additional date comparisons to be undertaken in order to quantify fully the agreement of chronologies during other parts of the Holocene.

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FIGURE CAPTIONS

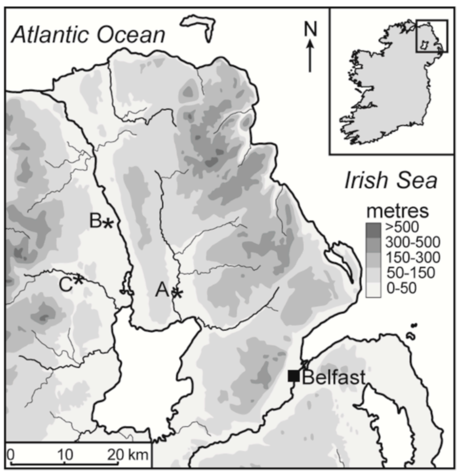

Figure 1. Locations of where samples used in this study were collected. A—Sluggan Bog (54°46′N, 6°18′W), B—Fallahogy (54°54′N, 6°34′W), C—Ballinderry (54°48′N, 6°39′W).

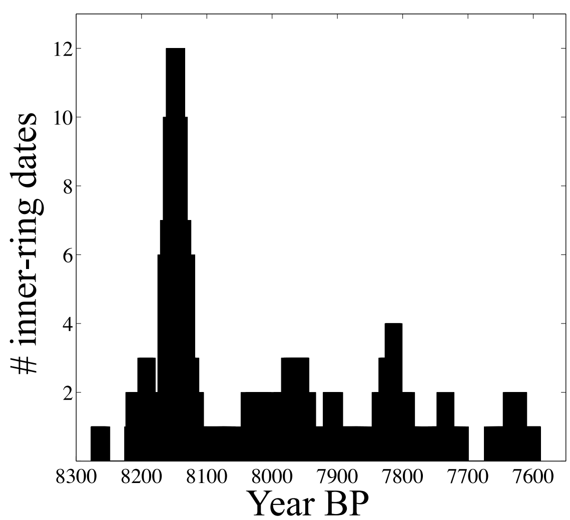

Figure 2. Histogram of inner-ring dates of subfossil pines from three bogs in the north of Ireland. The data are plotted with running bin-sizes of 35 yr to 20 yr to avoid sample bias.

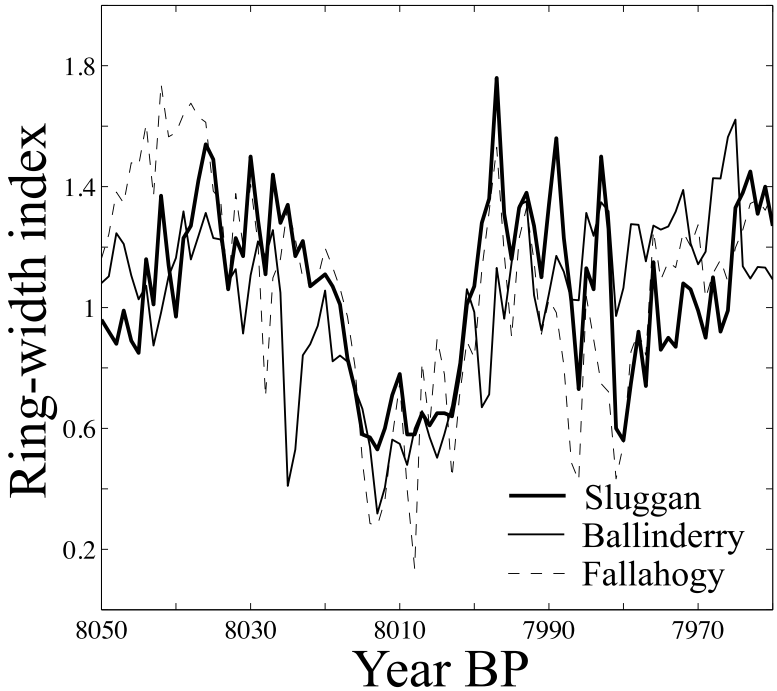

Figure 3. Ring-widths for the period 8050–7980 yr B.P. from Sluggan Bog, Fallahogy (Pilcher et al., 1995), and Ballinderry bog-pine chronologies in the north of Ireland. A pronounced period of low-growth at all sites is evident from 8020 to 8000 yr B.P.

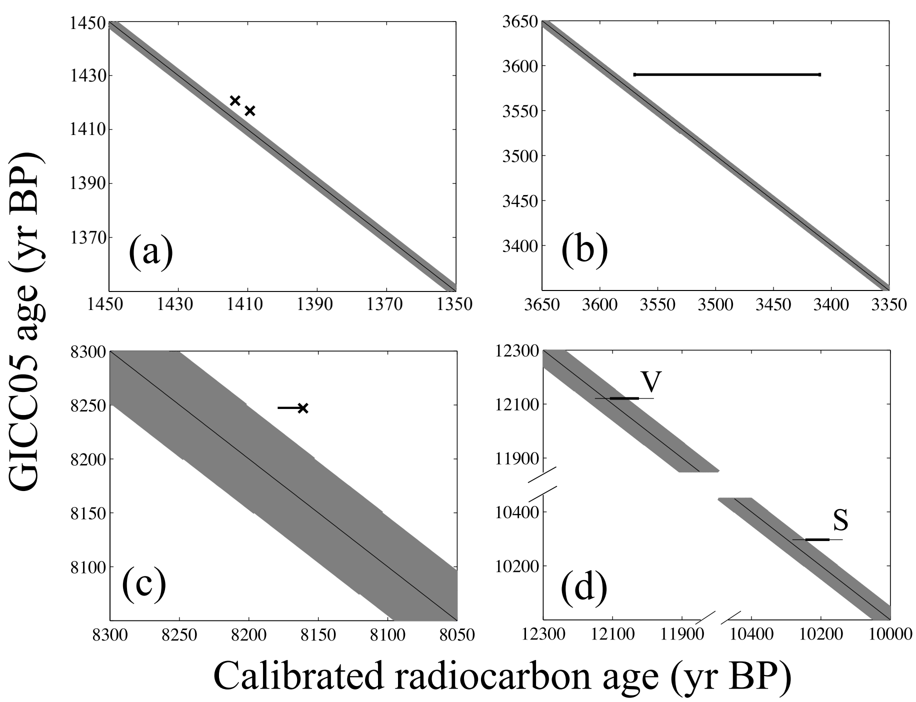

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Figure 4. Comparison of dates from Greenland Ice Core Chronology 2005 (GICC05) and terrestrial records. A: Volcanic eruptions in 1414 yr B.P. and 1410–1409 yr B.P. (Baillie and McAneney, 2015). B: Aniakchak II eruption (Alaska; Blackford et al., 2014). C: The 8.2 ka event (this study). D: Saksarnuvatn and Vedde ash eruptions (Norway; Lohne et al., 2013). Gray bands represent the counting error associated with the GICC05 at any given year of the record. X's represent absolute dates and black horizontal lines estimated uncertainty or radiocarbon age ranges (2σ), with 1σ in wider line-width for D.

[1]GSA Data Repository item 2015xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.