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Adapting to the Little Ice Age in pastoral regions: An interdisciplinary approach to climate history in north-west Europe

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ABSTRACT
This paper uses interdisciplinary methods to investigate responses to the Little Ice Age in regions where livestock farming was dominant, a neglected subject due to the scarcity of detailed written records regarding pastoral land use. It argues that landscape-level histories which include pollen evidence and archaeology can address this challenge and reveal *local* processes of climate adaptation. Here we focus on Ireland and Scotland and a fascinating rise in small-scale cereal cultivation on upland pastures during the Little Ice Age. Bayesian modeling is used to test the chronological resolution of field evidence and compare it with climate reconstructions. We can see that the cultivation emerged in late medieval times, when cattle were facing climate-related stresses, and increased in early modern times during the Little Ice Age's main phase. We suggest that it started in an indirect adaptation to climate change, supplementing supplies of food and fodder for pastoralists, but increased as rural populations and external market demands grew. There is a need for finer temporal resolution in pollen records and archaeology, as well as greater integration with socio-economic history, if we are to be more certain about changes in the relative significance of climate in pastoral land use.

KEYWORDS
Environmental history; pollen records; Little Ice Age; Bayesian modeling; climate adaptation

Introduction

In the last couple of decades historians and other scholars have been taking greater interest in the Little Ice Age and its potential role in societal and economic change in Europe during the medieval-to-modern transition (for recent reviews, see Degroot 2018; Ljungqvist, Seim, and Huhtamaa 2021). Since Europe was largely pre-industrial at this time, a lot of this research has unsurprisingly sought to understand how climatic change impacted agrarian life. For example, the role of extreme weather events and other natural "disasters" in the agrarian crisis of the late 13th and 14th centuries is receiving renewed attention (e.g., Campbell 2016; Pribyl 2017; Slavin 2012; Bauch and Schenk 2020). Furthermore, there is a particularly large body of detailed research on agriculture during what is seen as the harshest phase of the Little Ice Age, i.e., from the late 16th century to the 18th century (e.g., Pfister 1984; Cullen 2010; Parker 2013; see Ljungqvist, Seim, and Huhtamaa 2021, 15).

Within this vast body of literature, though, there is a noticeable bias toward densely-populated "central" regions of Europe that often had a focus on cereal cultivation. For instance, it is telling that a favored method of gauging the severity of climate-related scarcity in the late medieval and early modern periods has been to track grain prices (e.g., Pfister 1988; Camenisch 2015; Esper et al. 2017; Ljungqvist et al. 2022; see discussion in Degroot et al. 2021, 541). The bias toward these areas is understandable insofar as they tend to offer detailed written evidence for changes in productivity and trade, which historians have traditionally used to assess the impact of climate on society.

Be that as it may, the reliance on written evidence means that we now have a skewed picture of the Little Ice Age's impacts in Europe. Less densely-populated areas that depended on livestock have received far less attention, largely because they offer fewer written records. It is only in discussions about the spread

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of zoonotics (Newfield 2009; Slavin 2017; Campbell 2016, 210) and in the relatively well-documented Alps (e.g., Pfister 1984) that animal husbandry has featured prominently in the historiography of Europe's Little Ice Age. Further north, in places like Ireland, Iceland, western and northern Britiain, and the north of Scandinavia, it remains unclear as to how significant climate change was for rural dwellers. Recent attempts to probe the role of the Little Ice Age in Scottish and Irish socio-political change are welcome (e.g., Dodgshon 2005; Oram 2014; Campbell and Ludlow 2020). For the pre-modern period, however, textual sources are rarely detailed enough to see what was happening at a local level, within settlements and out in the fields and pastures. They do not get us to the *landscape*—that physical arena where the decisions of any community living off the land are best assessed.

The lack of more detailed information on the experiences of livestock-rearing communities during the Little Ice Age, particularly at a local level, is a shame. There are many parts of Europe, and indeed the world, which today depend heavily on cattle, sheep and goats, not to mention the cities they are feeding. A long-term perspective on the vulnerability, as well as adaptability, of pastoral farming systems could therefore be of value (e.g., Costello 2020a).

Aim and methodological approach

To see what happened in pastoral uplands and outlands around the north of Europe, and investigate how people in them may have responded to the Little Ice Age (henceforth LIA), we need to draw from landscape archaeology and pollen records as well as written sources. Interdisciplinary landscape-based projects have been undertaken before in the north of Europe (Lagerås 2007; Atkinson 2016). However, it is only in Iceland and Norway that such interdisciplinary projects have given detailed consideration to the role of climate in land-use change (e.g., McGovern et al. 2007; Bajard et al. 2022). Moreover, such projects have tended to focus on the first and very early second millennium AD, in other words before the LIA started. This article moves the focus to more temperate environments of Ireland and Scotland in the period, c.1250–1750, taking advantage of climate proxies that have become available for this part of Europe. Broadly speaking, we follow a "consilient" approach to the study of past climate change in that we draw from different types of evidence (Izdebski et al. 2016). However, we also take a step forward by emphasizing rigorous interdisciplinary research at a *local* level.

The first section of the article summarizes the current state of knowledge in paleoclimatology about the LIA, and outlines how historians and other scholars have conceptualized its impacts on society in northwest Europe. Some have emphasized longer trends while others have focused on crises and "disasters." Nearly all, however, have underestimated the adaptability of farmers at a local level. Targeting this issue, we review historical references, archaeological findings and especially pollen records from around Ireland and Scotland. This reveals a somewhat surprising land-use trend in uplands during the LIA, whereby pastoral farmers increased their involvement in small-scale cereal cultivation. We argue that this may have been an indirect form of adaptation to climate deterioration, designed to bolster local food and fodder supplies as risks to livestock increased.

Having said that, field data can be chronologically vague and the evidence for local land-use change has yet to be compared in a systematic way with wider climatic trends. To test and refine the chronological resolution of local land-use evidence in Ireland and Scotland, and compare it against regional climate proxies, we remodel a selected number of pollen cores using a Bayesian statistics program called "OxCal" (Bronk Ramsey 2008; Bronk Ramsey and Lee 2013). OxCal is informed by Bayes' theorem of conditional probability and can refine a chronology by factoring in "prior" information about each event in the chronology. In pollen studies, important "prior" information would be the depth on a sediment core that each radiocarbon date comes from. With this information, OxCal can produce a Poisson Sequence or "P_Sequence" which constrains the time range for each dated horizon on the core (see Supplementary Material). Many palaeoenvironmental scientists are therefore now using Bayesian modeling programs like OxCal to produce more robust age-depth models (e.g., Albert, Innes, and Blackford 2021; Kearney et al. 2022). However, in OxCal 4.4 it is also possible to model the timing of "events" that fall *between* dated horizons and incorporate palaeoclimatic datasets. In this paper we use it to model the timing of apparent increases or decreases in upland grain cultivation and plot them against temperature and precipitation changes suggested by tree-ring series and speleothems.

This novel application of Bayesian modeling allows us to assess land use in a more chronologically-controlled fashion, and opens up a discussion on the extent to which people were taking climate into account over time in their planning. What is more, placing the "Little Ice Age" in a temporal framework reminds us that climate impacts could have been compounded or offset by other historical trends during the LIA—not least, as we discuss, growing external demands for animal products. The article finishes by outlining what is needed to obtain chronologically finer land-use data for pastoral regions as well as more spatially-relevant climate proxies, and it suggests how researchers ought to conceptualize the relative importance of climate over time in pastoral environments. It is hoped that the article will emphasize the value of archaeological and paleoecological evidence to historians so that, in the near future, these sources can be incorporated into the mainstream narrative about adaptation in the Little Ice Age.

Conceptualizing climate impacts: cumulative change and extreme events

The Little Ice Age has received a lot of attention from paleoclimatologists in recent decades, with ice cores, marine sediment cores and computer modeling together helping to reconstruct changes in weather conditions. Although debate on its timing and nature continues, we can say a number of basic things about the phenomenon in Europe. In terms of onset, it seems that the North Atlantic region started to experience colder temperatures and harsher winters in the second half of the 13th century AD, and especially after c.1300. This is thought by some to have been caused by the southward extension of Arctic sea ice, which itself may have been triggered or partially triggered by major volcanic eruptions (Slawinska and Robock 2018; Miles, Andresen, and Dylmer 2020). Either way, this cooling seems to have been compounded by other factors like a weakening of the North Atlantic Oscillation, periods of reduced solar radiation and further volcanic activity, such that the Little Ice Age is not considered to have ended until the late 19th century (Miller et al. 2012; Brönnimann et al. 2019). Changes in the North Atlantic Oscillation (NAO) are particularly relevant for Ireland and Scotland. While weak or "negative" NAO phases are linked to colder weather in the north of Europe, "positive" NAO phases are linked to warmer (and potentially stormier) conditions in the north of Europe. Because of these changes and also continued variation in solar radiation, the LIA cannot be considered a uniform period of cooling. Indeed, the most recent tree-ring evidence from central Europe, Scandinavia and Scotland suggests that summer temperatures 1 °C or more below the 1961–1990 mean only became frequent after the mid-1500s, and even then the cold spells varied in duration (Luterbacher et al. 2016, Fig. 1; Rydval et al. 2017, Fig. 5). For rainfall and snowfall, it is more difficult to generalize as precipitation varies a lot more over space than temperature does (e.g., Matthews and Briffa 2005). That said, proxies in peat and lake sediments, cave speleothems and tree rings, as well as computer models, are now shedding light on regional precipitation in the past (Wilson et al. 2013; Cook et al. 2015; Webb et al. 2022).

The question here is to what extent these climatic changes affected livestock-rearing communities and how long it took for any impacts to be felt. Climate historians have long recognized that both annual fluctuations and longer cycles have the potential to influence society (De Vries 1980, 601–618), but in practice many studies have prioritized one over the other. For instance, one influential interpretation of climate impacts on rural environments of the North Atlantic has been that extended multi-annual periods of colder and/or wetter weather were the most difficult to deal with. Supported by archaeological and palaeoecolgical evidence, McGovern et al. (2007) and Dugmore et al. (2012) argued that the cumulative effect of these periods had a greater impact on society and land use in northern Iceland and Norse Greenland than year-to-year variations, eventually leading to the extinction of many settlements. This argument found traction in the Scottish Highlands. Oram and Adderley (2008, 77, Fig. 1) and Oram (2014, 227) argue that extended periods of slightly-reduced temperature in the late 13th and 14th centuries were more damaging than annual or seasonal extremes. They claim that the cold suppressed grass growth and, over time, was what led to conflict between the cattle-owning lords of the Highlands.

Year-to-year variation has been given precedence in other studies. Recently, scholars in Europe have been paying increasing attention to the impact of unusually-harsh weather events, and "disasters" and "catastrophes" linked to climate change. Such events are often attested in annals and chronicles, and include cold snaps, heavy snowfalls, extreme floods, extended droughts, and the effects of large volcanic eruptions (e.g., Huhtamaa and Helama 2017; van Bavel, Curtis, and Dijkman 2020; Gerrard, Forlin, and Brown 2021; see also Degroot et al. 2021, Fig. 2a). The issue of winter fodder illustrates how significant sudden events could be in pastoral regions of northwest Europe. In medieval Ireland and Scotland, mild winters seem to have allowed farmers to winter cattle outdoors on preserved meadows.[1] This was highly

Table 1. References to major cattle mortalities in medieval Irish annals that suggest snow as a cause. All quotes are translations from Irish, except those in 1334 and 1338, where the quotes are translations from Latin. Source abbreviations are explained at start of reference list below.

Year	Quote (in translation)	Source
1339	A great plague from frost and snow on the cattle and green cornfields of Erinn, from a fortnight of winter to a part of the spring; The cattle and winter grass of Ireland suffered much from frost and snow, which lasted from the end of the first fortnight in Winter into the Spring.	LC1339.3; AC1339.4
1338	This year was very stormy and harmful to humans and animals; because from the feast of All Saints until Easter, there was mostly rain, snow or frost; This year the oxen and cows were dying, and especially the sheep, almost in ruins …	HC1338.7; HC1338.8
1336	A great plague of snows and of frost prevailed that year from the beginning of a fortnight of winter until a part of spring came, so that much of the cattle of Ireland suffered death and the green crops of Ireland went to nought the same year.	U1336.6
1334	… in the week before the Purification it was a great snow day, very harmful to animals, but more dangerous and bad for humans.	HC1334.6
1297	Very stormy weather this year, with wind, snow, and lightning, and a great murrain of cattle and loss of life also.	I1297.2
1280	Very bad weather in that year; heavy snow in the first week of March therein, so that innumerable cows died and live-stock of all kinds largely perished; And there was severe snow previously in the same year about the Feast of Brigit [February 1]., which killed many cattle and caused much harm.	I1280.2
1115	Very severe weather, with frost and snow, from the 15th of the kalends of January to the 15th of the kalends of March, vel paulo plus, which made great havoc of birds, and cattle, and people.	LC1115.1
1114	Very severe driving snow and frost so that the great droves could go dry-shod over the main lakes of Ireland and it killed many cattle and birds and people.	CS1114
1111	Very bad weather in the form of frost and snow, and it inflicted slaughter on domestic and wild beasts.	U1111.1
1107	Snow fell for a day and night, the Wednesday before the festival of Patrick, which caused a great destruction of the cattle of Erinn; Snow fell for a day and a night on the Wednesday 13 March before the feast of Patrick, and inflicted slaughter on beasts in Ireland.	LC1107.1; U1107.1
1105	Heavy snow this year, and a great loss of cows, sheep, and pigs in the same year.	I1105.2
1095	Snow and heavy frost so that the rivers and principal lakes of Ireland were frozen, and a great loss of cattle in this year; Great snow fell on the Wednesday after the kalends of January, which killed a multitude of men, cattle, and birds; Great snow fell the Wednesday 3rd after the first of January, and killed men and birds and beasts.	I1095.2; LC1095.1; U1095.1
1047	Great snow in this year from the festival of Mary to the festival of Patrick, for which no equal was found, so that it caused a destruction of people, and cattle; A great snowfall this year from the Feast of Mary in the winter 8 Dec. to the Feast of Patrick 17 March, the like of which was never experienced before, and it caused the death of many people and cattle and sea-beasts and birds.	LC1047.1; U1047.1
961	Cattle suffered a great plague, with snow and diseases.	CS961
917	There was great frost in this year and great snow which inflicted destruction on beasts; Snow and extreme cold and unnatural ice this year, so that the chief lakes and rivers of Ireland were passable, and causing death to cattle, birds and salmon.	CS917; U917.1
799	A great snowfall in which many men and cattle perished.	U799.4
748	Snow of unusual depth so that nearly all the cattle of the whole of Ireland perished, and the world afterwards was parched by unusual drought.	U748.3

advantageous in that it saved on labor. However, as several scholars have noted (Ó Corráin 2005, 571–572; Campbell and Ludlow 2020, 237), it also left people and cattle vulnerable if there were unusually harsh winters with heavy snowfall. Of the numerous references to snow in Irish annals from the 5th century AD onwards, fifteen are associated with great mortality of cattle (Table 1). For our period, two significant cattle mortalities were recorded in the late 1200s and two in the late 1330s, with the last entry, in 1339, specifying that cattle had died because the winter fields of Ireland (*gortaib gemair Erenn*) had "suffered much from frost and snow."

Zoonotics like cattle rinderpest underline the significance of year-to-year weather variations (Newfield 2009; Campbell 2016, 210). In addition to colder/wetter conditions potentially facilitating infection, fodder shortages resulting from bad weather would probably have left cattle weaker and more susceptible to illness. For example, in south-west Ireland, the great cattle plague of 1297 (*plagh mor ar inilibh*) took place during a harsh snowy winter (I1297.2), and the famous rinderpest panzootic was at its most devastating in Ireland and Scotland in 1321, when there appears to have been wet and cold weather (Oram 2014, 228, 230; Campbell and Ludlow 2020, 206).

Clearly, we must be aware of climate effects unfolding suddenly as well as cumulatively in pastoral regions. However, it is also apparent that conclusions about the *timing* of societal impacts can be influenced by the form of evidence used. While information from archaeological sites and pollen records is quite precise in spatial terms, its chronological resolution is generally not fine enough to see year-to-year variation. Thus, in the aforementioned studies from Iceland and Greenland, it was arguably inevitable that cumulative effects would receive more attention than sudden impacts. At the same

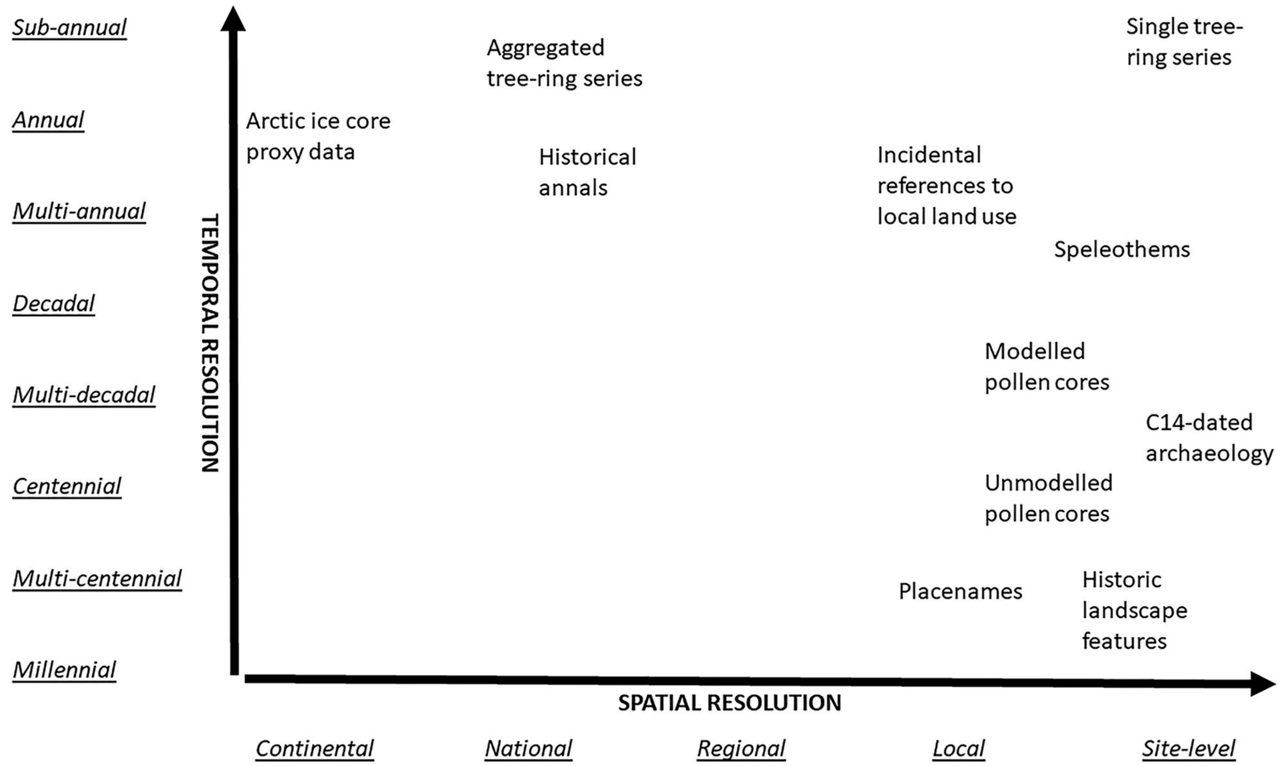


Figure 1. The temporal and spatial resolution of different forms of evidence for this period.

time, while medieval chronicles from Ireland and elsewhere tend to have *finer* chronological resolution (of a year or so), their *spatial* resolution is poorer than landscape evidence. When it comes to land use and weather, they usually only mention events which the scribes saw as regionally or nationally significant (see Figure 1). Without more detailed written records at a *local* level, text-focused studies are therefore unlikely to detect gradual changes in the landscape or small-scale, non-elite attempts to cope with climate change. It is noticeable, for example, that initial studies by environmental historians have portrayed pastoral societies in Ireland and Scotland as quite vulnerable to late medieval change. Warfare and elite-led cattle raiding are seen as the most noteworthy and consequential responses (Oram and Adderley 2008; Oram 2014; Campbell and Ludlow 2020, 239).

Re-evaluating "vulnerability" from the ground up

It is only right to acknowledge the hardships of life in pre-modern times, especially for people regarded as "low-status." However, we are not yet at a stage where we can make firm judgments about the vulnerability of livestock-rearing societies in Ireland, Scotland or indeed elsewhere in Europe. By neglecting evidence from the landscape, historical narratives have arguably missed out on processes of *adaptation* at a local, non-elite level. For instance, some of the aforementioned "disaster" studies elsewhere in Europe have acknowledged the possibility of bottom-up responses by local communities—not only knee-jerk reactions but also strategic planning and mitigation for the future (Oram 2014, 233; van Bavel, Curtis, and Dijkman 2020, 108; Rohr 2021). And the evolving discussion on Viking-Age Iceland has highlighted that anonymous peasants at the so-called "fringes" of medieval Europe need to be considered as rational actors (e.g., Vésteinsson et al. 2014).

In Ireland and Scotland, evidence for cereal cultivation in uplands brings the rationality of livestock farmers during the LIA into sharp focus (Figure 2). There can be little doubt that dairying and cattle fattening expanded in many parts of northern and north-western Europe in the late medieval and early modern periods, in many cases at the expense of arable land. This has rightly received a lot of attention in the historiography (van Bavel and van Zanden 2004, 508, 522; Dyer 2005, 194–197; Hansson et al. 2005, 35, 160; Lagerås 2007; Simms 2015; Campbell 2016, 348, 363; Campbell and Ludlow 2020, 214).

Figure 2. Map of main localities in Ireland and Scotland mentioned in the text. Map made using terrain data from Shuttle Radar Topography Mission (USGS Earth Explorer).

Nevertheless, there is increasing evidence for cereal cultivation either continuing or starting on a small scale in uplands, which may have helped communities to manage risk as periods of cold and/or wet weather became more common.

Pollen evidence for cereals in Irish uplands: a buffer against risk for pastoral farmers?

In the south west of Ireland, which has seen a higher concentration of pollen coring than anywhere else in the country, there is clear evidence for cereals being cultivated in upland valleys during the late medieval and early modern periods. First of all, in the mountainous peninsula of Uíbh Ráthach, a regional pollen record from Ballygisheen Bog shows that cereal-type pollen appears and peaks during the first half of the second millennium AD (Cole and Mitchell 2003, Fig. 4). Since pollen counts for the weed of cultivation knapweed (*Centaurea*-type) follow the same curve, it is reasonable to assume that this was a period in which cereal cultivation occurred. That said, tree pollen is found at slightly increased levels in late medieval times according to the pollen diagram's chronology. So, overall, some reduction in land use is likely. Two more local pollen records from the Bridia valley in the center of Uíbh Ráthach point to an expansion of grazed lands and the appearance of wheat and cereal-type crops sometime in the late medieval period, which continued into early modern times (Lynch 1981, Fig. 4.5; McDonnell 1991, Fig. 4.1a). A full Holocene core from a small lake at the foot of Shehy Mountain near Killarney also recorded a largely pastoral landscape in historic times, though small amounts of cereal-type pollen were present from the mid-first millennium AD onwards and they started to increase in either the late medieval or early modern period (Hawthorne 2015, Fig. 6.1.3).

On the Béara peninsula, Overland and O'Connell (2008) undertook a detailed paleoecological study as part of a larger programme of archaeological survey and excavation. This focused on settlement and field systems laid out during the Iron Age and early medieval period, yet several pollen cores show that human activity continued into the second millennium AD, despite the expansion of blanket peat. According to their diagrams (Overland and O'Connell 2008, Figs. 3 and 4), the slopes around BAR1 sampling site (182 m a.s.l.) were fairly intensively grazed and burned in the much of the first half of the second millennium AD, with small amounts of cereal-type pollen and weeds of cultivation recorded up to roughly the 19th century. Indeed, even though hazel and willow regenerated somewhat, the arable signal is supposed to have got a little stronger from the middle of the second millennium. Two pollen records a little downslope, one a small lake and the other a small peat basin, both point to the most intensive land-use phase ending before the late medieval period. Nevertheless, farming activity remained significant after that and included cereal cultivation as well as pasturage (Overland and O'Connell 2008, Figs. 11 and 13, 63). In the north-east of Ireland, a new pollen record from Slieveanorra on the Antrim Plateau (300 m a.s.l.) appears to echo this trend. Cereal-type pollen and some weeds of cultivation not only persist but increase somewhat for a few decades in the late medieval period in addition to a significant increase in grass pollen (Plunkett and Swindles 2022, Fig. S7).

The presence of cereals at these locations is at odds with a long-standing narrative in European historiography, namely that cereal cultivation retreated from riskier "marginal" soils in the late medieval period (Parry 1975; Simms 2015, 112; Campbell 2016, 348–385; van Bavel, Curtis, and Dijkman 2020, 36). Indeed, contemporary Irish annals give the impression that cereal crops were vulnerable on *all* soils in this period. 1328 saw much thunder and lightning which damaged crops (M1328.7; AC1328.3), and the wet summers of 1329, 1487, 1491, 1496 and 1586 caused delayed and failed harvests (M1329.13; U1487.14; U1491.13; M1491.13; U1496.32; M1586.11). In one exceptional event in 1587, large hailstones destroyed "much corn" on the Plains of Connacht in early August (LC1587.19). Why, then, would people try to grow crops in acidic and elevated locations?

To use an analogy, Kerr, Swindles, and Plunkett (2009) suggested that an expansion of arable farming in the eastern lowlands of Ireland in the later first millennium AD was partly a response to climate deterioration. With more frequent harsh winters causing difficulties for the winterage system that cattle relied upon, they remark that cereals may have been left as "the more viable option" (Kerr, Swindles, and Plunkett 2009, 2872). While they are wrong in thinking that oats, barley and wheat could ever have become *more* viable than native species of grass, their point about land-use strategies remains relevant. In late medieval and early modern times, farmers in pastoral regions may have chosen to cultivate cereals on a small scale as a way of averting disaster.

Whether people were living long enough to *recognize* long-term trends in the climate (see Ljungqvist, Seim, and Huhtamaa 2021, 13) is beside the point. They would still have had to deal with its negative effects on local vegetation. For instance, if winters characterized by heavy rain and/or snow in which many cattle died were becoming more frequent (e.g., once every 5–10 years versus once every 15–20), farmers may well have decided that attempting to harvest and store some cereal grain was vital despite a slightly colder/wetter climate. Cereal grain would have bolstered human food supplies in case cattle mortality was high and supplies of meat and dairy much reduced as a result. If it happened that conditions were too wet and cold for the grain to ripen or if the grain could not be fully dried after harvesting, the crop could then simply be fed to the cattle, helping *them* to survive.

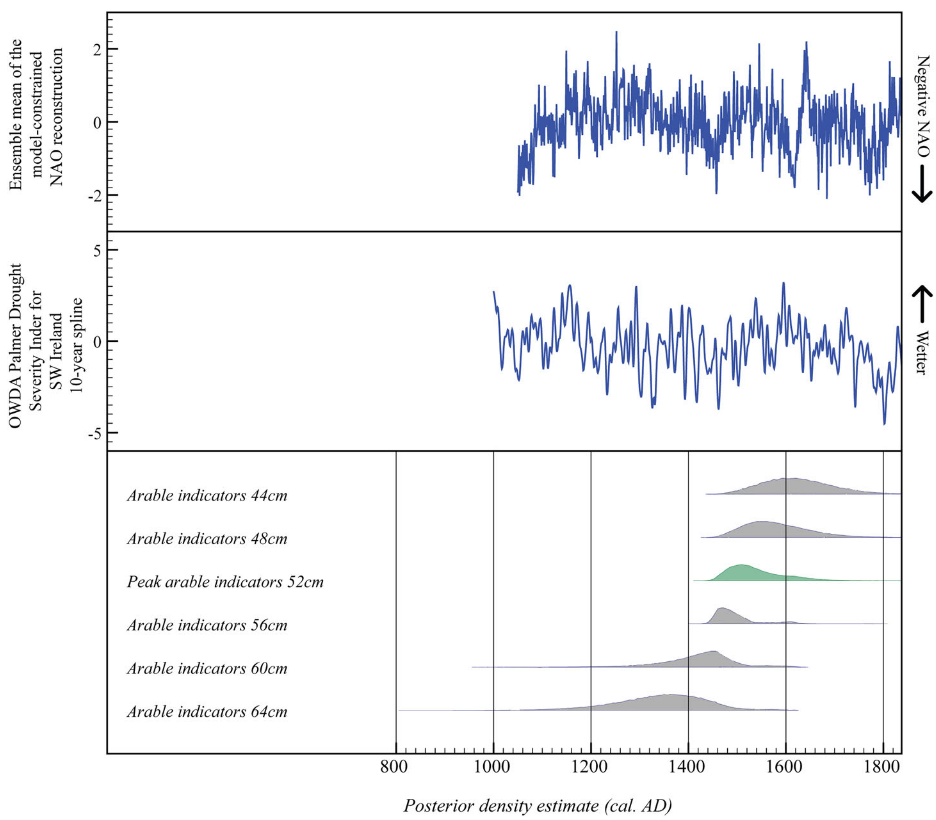


Figure 3. Bayesian model of the pollen evidence for arable farming in BAR L1 core from Beara, Ireland (percentage pollen data from Overland and O'Connell 2008, Fig. 11), with climate data plotted above for comparison. The pollen date ranges are given at 2σ confidence level (95%). *Top*: NAO_{mc}, i.e., ensemble mean of the model-constrained North Atlantic Oscillation reconstruction (Ortega et al. 2015, source data to Fig. 2). *Middle*: Reconstructed June–July–August Palmer Drought Severity Index for south-west Ireland, shown as 10-year spline. Latitude region: 51.46°N, 52.33°N. Longitude region: −10.45°E, −8.94°E. (Extracted from: http://drought.memphis.edu/OWDA/Extract.aspx; Cook et al. 2015.)

Testing the chronological resolution of Irish pollen data

Having said all that, we still do not know the exact chronology of this trend in cereal cultivation and, with that, whether it can be correlated temporally with a particular cold or wet shift in the early LIA. The reason is that most pollen studies in Ireland have focused on either the full Holocene or on late prehistoric and early medieval times, with less attention paid to the second millennium AD. For late medieval and modern times, there are often wide intervals between each pollen sample on a core and/or very little if any radiocarbon dating (e.g., Lynch 1981; Hall 2000; Taylor et al. 2018; O'Connell 2021). The peat cores reviewed above for south-western Ireland do pay greater attention to the last millennium than most, though they still have various chronological issues. For example, Ballygisheen Bog core has only one radiocarbon date from the late first millennium and two tephra-layer dates from the beginning and end of the second millennium (Cole and Mitchell 2003, Tables 1 and 2). With peat accumulating at different rates over time, we cannot therefore be sure of what half-century or even century within the late medieval or early modern period each pollen count for cereals and weeds of cultivation belongs to. The BAR1 core in Béara was subjected to more radiocarbon dating but too many of these dates were found to be too young or too old (Overland and O'Connell 2008, 49–50) to have full confidence in the chronological order of all pollen values presented. The aforementioned pollen study from Slieveanorra in north-east Ireland is a welcome exception in that it has nine radiocarbon dates and micro-tephra layers for the last 1000 years; however, its focus is local and it does not compare the pollen data with wider temperature and precipitation reconstructions.

The increasing sophistication of Bayesian modeling in OxCal means that we can now attempt to refine the chronology of land-use trends like cereal cultivation and, what is more, compare them against regional climate proxies provided by tree-ring series, speleothems and computer simulations.[2] However, if Bayesian modeling is to actually refine a chronology, five or more absolute dates are needed from a core, and this is not always the case. In our review of pollen studies in south-west Ireland we found only one core relevant to the second millennium AD which had five or more reliable radiocarbon dates. This was BAR L1 from Béara (Overland and O'Connell 2008, Fig. 11), and the results of our modeling with OxCal 4.4 are presented in Figure 3 (Bronk Ramsey 2008; Bronk Ramsey and Lee 2013; see also Supplementary Material).

The original pollen analysis of BAR L1 was interesting insofar as it indicated, after a short hiatus, that some crop cultivation started at a depth of 64 cm, and the values increased thereafter. Our model places the onset of this phase sometime in the period, 1124–1516 cal AD, at 95.4% confidence and sometime in the period, 1266–1445 cal AD, at 68.3% confidence. This shows that the "event" at 64 cm probably occurred in the early part of the LIA and it does not rule out a temporal correlation with the slight NAO downturn evident from the mid-14th century (Figure 3). However, the probability curve for it is far too broad to draw a solid temporal link with any one climate shift in the late medieval period. The subsequent peak in arable indicators at 52 cm is better refined in the model—1450–1656 cal AD at 95.4% confidence and 1467–1565 cal AD at 68.3% confidence—and occurs as the main phase of the LIA starts. However, the date range for this arable peak is still too broad to be matched with a specific shift in weather patterns during the early modern period.

Elsewhere Bayesian modeling has helped pollen records achieve a temporal resolution of 10–20 years (e.g., Albert, Innes, and Blackford 2021), but this is not attainable for BAR L1. Despite having relatively many radiocarbon dates, only two of them fall within the last 1200 years (see Supplementary Material). This is not enough to constrain the intervening pollen counts in time and demonstrates the importance of not only plentiful but also *targeted* dating when it comes to testing potential climate responses in land use.

The need for archaeological evidence

Pollen evidence would ideally be supported by other information too. With the Irish annals failing to provide minute details on medieval land use, landscape survey and archaeological excavation at a local level are vital sources. Research on the early medieval expansion of cereals in Ireland's eastern lowlands is, for instance, supported by hundreds of radiocarbon dates from grain-drying kilns and dendrochronological dates from watermills (Kerr, Swindles, and Plunkett 2009; Monk and Power 2012). Unfortunately, a lack of research at higher elevations means that there is so far only one "upland" location where clear archaeological and pollen evidence for *late* medieval cereal growing has been identified, i.e., Glendalough in the Wicklow Mountains (Figure 2). In addition to a local peat core showing a spike in cereal-type pollen

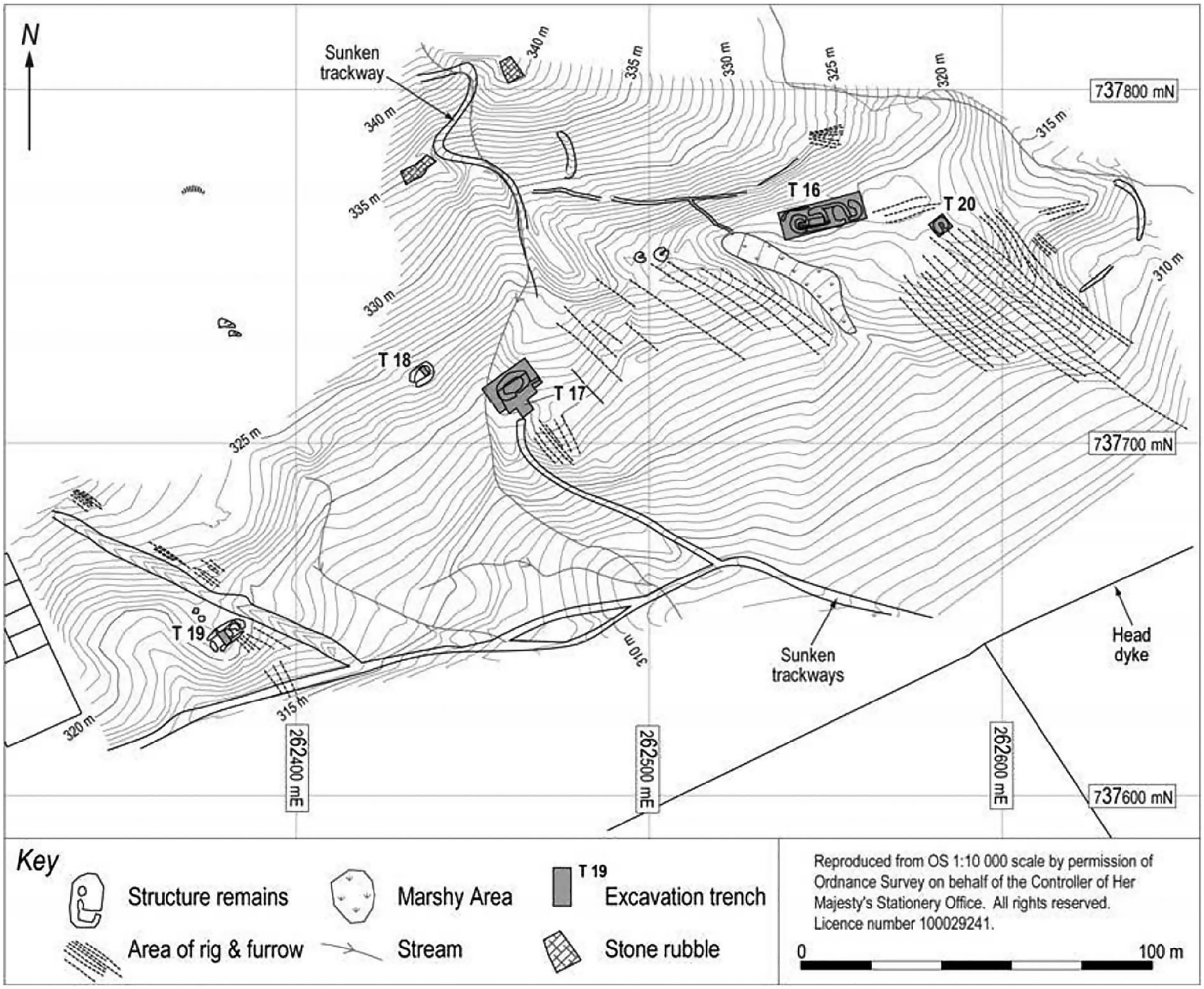
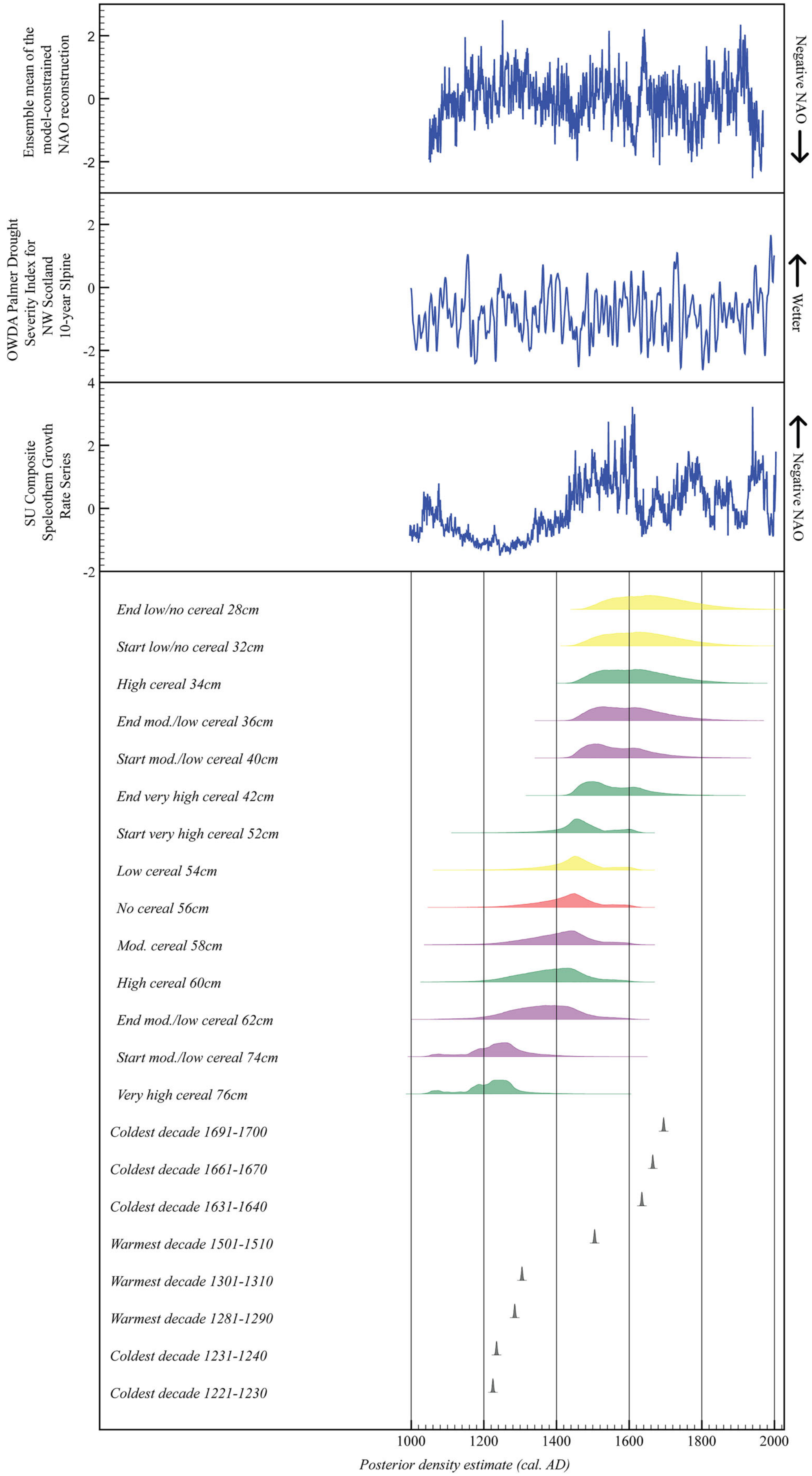


Figure 4. Kiltyrie head-dyke sites T16-T20 on North Lochtayside, Scotland (Atkinson 2016, illus. 5.2). Reproduced by kind permission of John Atkinson.

in roughly the late medieval period, excavation of a grain-drying kiln produced a radiocarbon date of 1415–1493 cal AD (Seaver, McDermott, and Warren 2018, 38). Archaeological evidence like this does not refine the chronology of cereal cultivation enough to make a better assessment of potential climate links. However, as a relatively substantial structure that was built to be used over years, it adds strong support to the pollen evidence and confirms, moreover, that the cereals were processed locally for human consumption.

Small-scale cereal cultivation and the question of climate adaptation in Scotland

The thesis that pastoral farmers used small-scale cereal cultivation as part of a land-use strategy to adapt to climate deterioration can be explored in more depth in Scotland. While not as well served by medieval chroniclers, it does have more climate proxies for the LIA and a greater number of upland sites that have undergone both archaeological and paleoecological investigation. One area with several interesting sites is Lochtayside in the Central Highlands. Among these is the Kiltyrie head-dyke site, where two houses were excavated at an altitude of 320 m (Figure 4; Atkinson 2016, 78–94). Despite being located on what is now open hill pasture, the houses seem to have been occupied year-round as they had relatively conventional central hearths and larger internal floor spaces than seasonal transhumant huts in the area (ibid., 93–94). Radiocarbon dating for house T17 showed that it was in use by the mid-12th century and abandoned by the late 14th century (ibid., Table 5.1, 91), thus apparently fitting the classic model of settlement retreating from the margins in late medieval Europe. However, the other house site, T16, was established around the second half of the 12th century and was then succeeded by another house which continued to be occupied until the late 14th or early 15th century. Indeed, after this, two huts were built on top of the house, as


Ensemble mean of the model-constrained NAO reconstruction
Negative NAO
OWDA Palmer Drought Severity Index for NW Scotland 10-year Slpine
Wetter
SU Composite Speleothem Growth Rate Series
Negative NAO
End low/no cereal 28cm
Start low/no cereal 32cm
High cereal 34cm
End mod./low cereal 36cm
Start mod./low cereal 40cm
End very high cereal 42cm
Start very high cereal 52cm
Low cereal 54cm
No cereal 56cm
Mod. cereal 58cm
High cereal 60cm
End mod./low cereal 62cm
Start mod./low cereal 74cm
Very high cereal 76cm
Coldest decade 1691-1700
Coldest decade 1661-1670
Coldest decade 1631-1640
Warmest decade 1501-1510
Warmest decade 1301-1310
Warmest decade 1281-1290
Coldest decade 1231-1240
Coldest decade 1221-1230
1000
1200
1400
1600
1800
2000
Posterior density estimate (cal. AD)

part of a new transhumance phase possibly (Atkinson 2016, 258–259). There are also small patches of narrow cultivation ridges very close to T16 and T17 (see Figure 4). Morphologically, these appear to post-date the broad-ridge type that would be typical of 12th and 13th century heavy mold board plowing (see Dixon 2016), while pollen data from a gully beside T17 confirms that arable taxa were well-established at this site by the 16th century (Tipping, McCulloch, and Tisdall 2016).[3] Elsewhere in Lochtayside, pollen analysis at the somewhat higher transhumant site of Ardtalnaig (440 m a.s.l.) has revealed continuous barley cultivation from the medieval period onwards (Davies 2016, 280).

It is remarkable that cereal cultivation occurred on these hillsides in the late medieval period and beyond even though they were not necessarily occupied on a year-round basis. What is more, cereals were to be found not very far downslope around permanent settlements. For instance, just over 1 km south of T16 and T17 was the township of Kiltyrie, where pollen analysis reveals that an open agricultural landscape was well-established by the mid-16th century (Richard Tipping, pers. comm.; Atkinson 2016, Illus. 5.2). Meanwhile, 2 km north west of Ardtalnaig was the farmstead of Leadour (350 m a.s.l.). This had both grazing and cultivation of barley and oats from at least the 9th century AD, which continued into the 15th century and beyond despite temporary regeneration of birch (Hamilton et al. 2009, 178).

The results of groundbreaking fine-temporal analysis by Althea Davies in East Glen Affric suggest that increasing cereal cultivation on the hillslopes above primary settlements—yet below the highest mountain pastures—was a widespread trend in the late medieval Highlands. According to her chronology for Carnach Mór (250 m a.s.l.), barley-type pollen was almost continually present from c. 880 AD up to c. 1800, and was well-represented between c. 1270 and c. 1650 (Davies 1999, Table 18; see also Davies and Tipping 2004, 237, Fig. 3). Further up the valley of East Glen Affric, Davies' chronology for the alluvial fan of Camban (307 m a.s.l.) has it that barley-type pollen made its first appearance of the second millennium only around the year 1230, and was almost continually present from c. 1270 up to modern times (Davies 1999, Table 25; Davies and Tipping 2004, 237, Fig. 4).

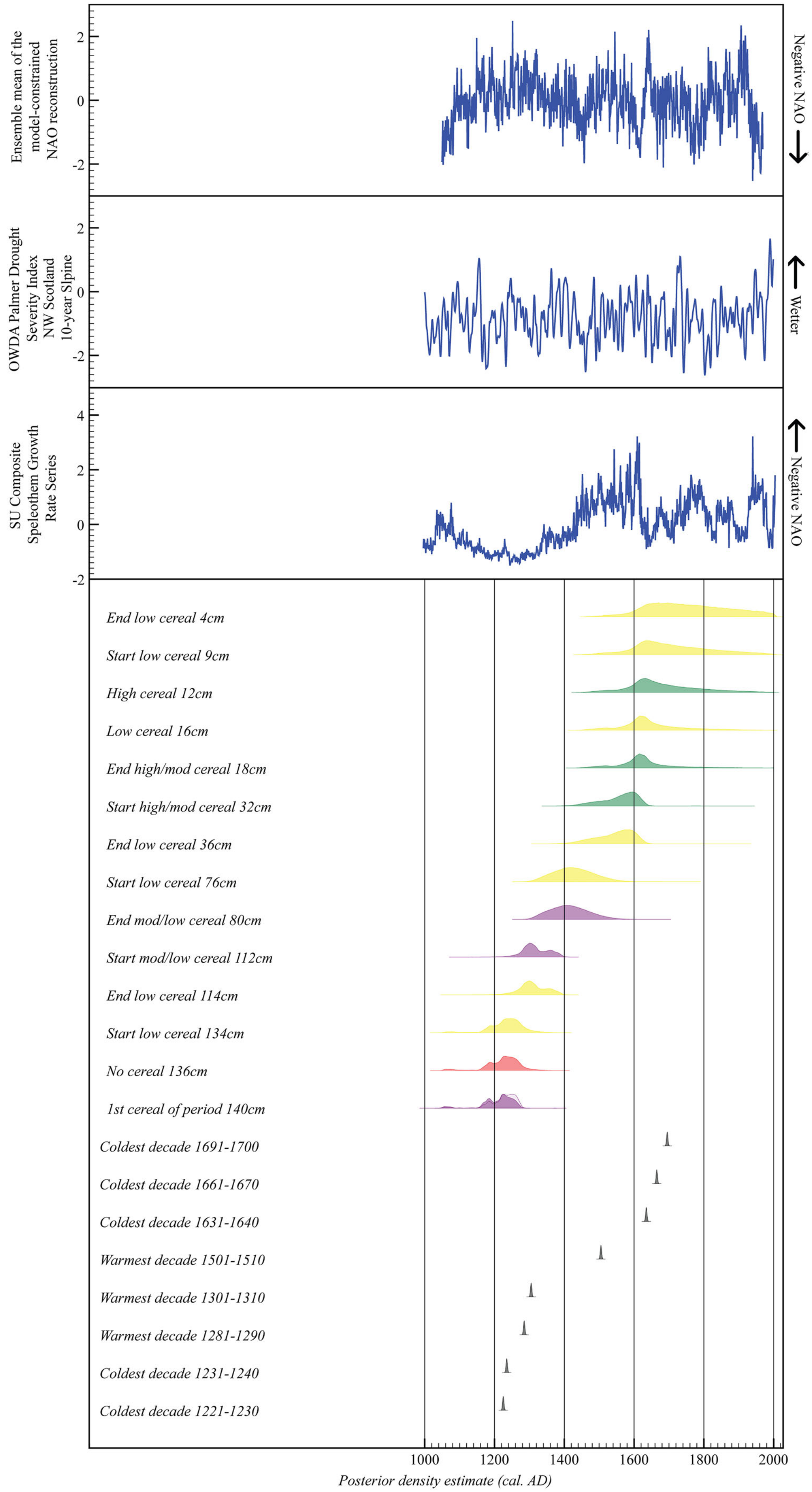
Bayesian models and the analysis of climate correlations

The resolution of these East Glen Affric records is greater than most others in Highland Scotland and Ireland thanks to (a) the frequency of pollen counts for our period (every 2 cm along the core, and sometimes every 1 cm) and (b) the number of radiocarbon dates which cover the last 1000 years (two to three). As such, it *looks* feasible to assess correlations between land-use changes and specific climate shifts in the LIA. To test this, we have carried out Bayesian modeling of the chronologies of Carnach Mór and Camban, again using OxCal 4.4 (see Supplementary Material). Figures 5 and 6 show the results, with the most significant changes in cereal cultivation plotted against several climate reconstructions.[4] In addition to the model-constrained NAO reconstruction and the simulated precipitation data from the Old World Drought Atlas (OWDA), we show a composite speleothem growth-rate series indicating winter NAO conditions in Scotland and tree-ring evidence for temperature extremes in the Highlands.

The new model for Carnach Mór shows that relatively intensive cereal cultivation began not at c.1270, as the original study had it, but sometime in the range, 1172–1281 cal AD with 68% confidence (and 1047–1339 cal AD with 95% confidence). The date of onset originally offered for Camban—c.1230—is more accurate as that sampling depth was also used for radiocarbon dating. Again, however, it is more accurately stated as a range, i.e., 1176 to 1261 cal AD with 68% confidence (and 1054–1276 cal AD with 95% confidence). Furthermore, the new model for Camban shows that consistent barley cultivation started not at "c.1270" but sometime between 1188 and 1280 cal AD with 68% confidence (and 1066 and 1334 cal AD with 95% confidence).

These ranges are significantly earlier than the late medieval downturn in the North Atlantic Oscillation

Figure 5. Bayesian model of pollen evidence for cereal cultivation in Carnach Mór core from East Glen Affric, Scotland (pollen data from Davies 1999, Table 18) at 2σ confidence (95%). The coldest and warmest decades according to Cairngorms pine trees are plotted below (Rydval et al. 2017, Table 2). Above are three climate proxies. *Top*: NAO_{mc}, i.e., ensemble mean of the model-constrained North Atlantic Oscillation reconstruction (Ortega et al. 2015, source data to Fig. 2). *Middle*: Reconstructed June–July–August Palmer Drought Severity Index for north-west Scotland, shown as 10-year spline. Latitude region: 56.35°N, 58.12°N. Longitude region: −6.46°E, −3.22°E. (Extracted from: http://drought.memphis.edu/OWDA/Extract.aspx; Cook et al. 2015.) *Bottom*: SU_{comp} composite of Scottish speleothem growth rate series, showing mean normalized growth (Baker et al. 2015).



Ensemble mean of the model-constrained NAO reconstruction
Negative NAO
OWDA Palmer Drought Severity Index NW Scotland 10-year Slpine
Wetter
SU Composite Speleothem Growth Rate Series
Negative NAO
End low cereal 4cm
Start low cereal 9cm
High cereal 12cm
Low cereal 16cm
End high/mod cereal 18cm
Start high/mod cereal 32cm
End low cereal 36cm
Start low cereal 76cm
End mod/low cereal 80cm
Start mod/low cereal 112cm
End low cereal 114cm
Start low cereal 134cm
No cereal 136cm
1st cereal of period 140cm
Coldest decade 1691-1700
Coldest decade 1661-1670
Coldest decade 1631-1640
Warmest decade 1501-1510
Warmest decade 1301-1310
Warmest decade 1281-1290
Coldest decade 1231-1240
Coldest decade 1221-1230
Posterior density estimate (cal. AD)

and also the 14th century wet shift suggested by the OWDA for north-west Scotland (Figures 5 and 6). Instead, as our supporting probability calculations for Camban show (Table 2), there is a rough correlation with a cold snap in the 1220s and 1230s. This coldness is attested by pine growth rings from the Central Scottish Highlands and may have been forced by a short-lived NAO downturn at that time.

The date ranges for other late medieval cereal counts at Carnach and Camban Mór are less well constrained in the models, however. As such, even these two pollen records would need more radiocarbon dates before Bayesian modeling could confidently refine different land-use changes to less than a half a century.

Increasing activity at the height of the Little Ice Age

Fascinatingly, our review shows that cereal pollen was even more abundant in upland pastures during the early modern period, when the Little Ice Age entered its most prolonged cold phase (Ortega et al. 2015, Fig. 2b; Luterbacher et al. 2016, Fig. 3; Rydval et al. 2017, Fig. 8). This trend is noticeable across Scotland. In Bowmont valley near the English border, Richard Tipping has shown that barley-type pollen and oats or wheat pollen occurred at Sourhope (310 m a.s.l.) from the early first millennium AD into the 17th or 18th centuries (Tipping 2010, 194–199). Indeed, at Swindon Hill (365 m a.s.l.) and Cocklawhead (500 m a.s.l.), the pollen evidence suggests that cereal cultivation resumed at the end of the medieval period and was present until modern times (Tipping 2010, 194–199). Several pollen records in Lochtayside also hint at cereal cultivation intensifying at hill and mountain settlements during the "classic" LIA. North of Loch Tay, the cultivated patch of hillside above Kiltyrie saw an increase in cereals in or around the 1600s, including rare buckwheat (Tipping, McCulloch, and Tisdall 2016), while at the seasonal site of Tarmachan (540 m a.s.l.), grains of barley-type pollen were frequent from the early modern period onwards (Tipping and McEwen 2021, Fig. 2).[5] South of Loch Tay, the pollen studies at Ardtalnaig and Leadour show that representation of barley was greatest in roughly the last four to five centuries; indeed, barley pollen seems to have increased at Ardtalnaig, the seasonal site, before it did so at the farmstead (Davies 2016, Figs. 17.5 and 17.6). Unfortunately, while these Lochtayside studies made innovative use of lead isotope dating on post-1850 sediments, they lack radiocarbon dates for the early modern period and so cannot be scrutinized with Bayesian modeling.

An expansion of cereal cultivation was attested in Davies' Glen Affric studies too (Davies 1999; Davies and Tipping 2004), and here our models enable a slightly more chronologically controlled discussion of the evidence as well as comparison with climatic data. For example, at Camban, cereal pollen did not peak in the period, c.1450 to c.1540, and at c.1790, as the original study has it (Davies 1999, Table 25). Rather it was strongest from 1528–1624 cal AD to 1559–1675 cal AD, with the highest values likely occurring well before 1790 (see Figure 6). For Carnach Mór, our modeling shows that cereal pollen was most abundant from the second quarter of the 15th century up to potentially the early 17th century, with further high values occurring in either the 16th century or first half of the 17th century (see Figure 5).

What the models illustrate is that the highest values for cereal cultivation occurred when the NAO was in a predominantly negative phase. Indeed, precipitation also seems to have been increasing during the 16th and very early 17th century (see Figures 5 and 6). The fact that barley-type pollen formed the *majority* of cereal-type pollen in East Glen Affric (1999, Tables 18, 25, and 35) and several of the sites in Lochtayside (Davies 2016, Figs. 17.5 and 17.6; Tipping and McEwen 2021, Fig. 2) is significant and may help to explain why cultivation remained possible in these circumstances. That is to say, people here were probably using a six-row barley called "bere," which has a relatively short growing season and was therefore less vulnerable to increased storminess than modern two-row barley and oats (see Dodgshon 2004, 10).

Having said all that, it is noticeable in Figures 5 and 6 that the *highest* cereal-pollen values do not continue all the way into the late 17th century, when the very coldest years of the LIA hit the Highlands. This

Figure 6. Bayesian model of pollen evidence for cereal cultivation in Camban core from East Glen Affric, Scotland (pollen data from Davies 1999, Table 25) at 2σ confidence (95%). The coldest and warmest decades according to Cairngorms pine trees are plotted below (Rydval et al. 2017, Table 2). Above are three climate proxies. *Top*: NAO_{mc}, i.e., ensemble mean of the model-constrained North Atlantic Oscillation reconstruction (Ortega et al. 2015, Source data to Fig. 2). *Middle*: Reconstructed June–July–August Palmer Drought Severity Index for north-west Scotland, shown as 10-year spline. Latitude region: 56.35°N, 58.12°N. Longitude region: −6.46°E, −3.22°E. (Extracted from: http://drought.memphis.edu/OWDA/Extract.aspx; Cook et al. 2015.) *Bottom*: SU_{comp} composite of Scottish speleothem growth rate series, showing mean normalized growth (Baker et al. 2015).

Table 2. Statistical probability of land-use changes at Camban (Figure 6; Davies 1999) coinciding with the coldest/warmest decades in the Scottish Highlands (Rydval et al. 2017, Table 2). The percentages were calculated in OxCal using the Order() parameter: 0% indicates certainly earlier than, 100% certainly later than, while circa 50% indicates contemporaneity.

	Coldest decade 1221–1230	Coldest decade 1231–1240	Coldest decade 1631–1640	Coldest decade 1661–1670	Coldest decade 1691–1700	Warmest decade 1281–1290	Warmest decade 1301–1310	Warmest decade 1501–1510
High cereal (12 cm)	0%	0%	45%	59%	69%	0%	0%	4%
High cereal (28 cm)	0%	0%	98%	100%	100%	0%	0%	20%
High cereal (32 cm)	0%	0%	99%	100%	100%	0%	0%	24%
No cereal (72 cm)	0%	0%	100%	100%	100%	0%	0%	86%
Start of moderate cereal (134 cm)	32%	42%	100%	100%	100%	88%	94%	100%
No cereal (136 cm)	38%	49%	100%	100%	100%	93%	97%	100%
First cereal of period (140 cm)	50%	63%	100%	100%	100%	100%	100%	100%

correlation is supported by the probability percentages for Camban (Table 2). It is also somewhat reminiscent of the model for BAR L1 in south-west Ireland, which showed arable values peaking before the late 17th century and disappearing in the 18th century (Figure 3). This correlation requires further investigation, however, as some of the other pollen records reviewed for Scotland and Ireland suggest that arable farming either continued into or resumed in the 18th century (Davies 2016, Figs. 17.5 and 17.6; Tipping and McEwen 2021, Fig. 2; Plunkett and Swindles 2022, Figs. S3 and S7).

From correlation to causation: the intersection of climate with society and economy

The continuation and increase of human signals in pollen records during the LIA has led some palaeoenvironmental scientists to doubt the seriousness of climate change for upland farming or to regard its impacts as easily overstated (Davies 1999, 234; Tipping 2002, 13; Davies 2007, 2059; Tipping and McEwen 2021, 164; Plunkett and Swindles 2022, 1, 11). Clearly, the LIA was not severe enough to prevent cereal cultivation outright—for much of the period, we can see it was still possible. However, the debate on causation is now quite sophisticated and there is a recognition that climate could affect past societies in less direct ways, that is, it could have "second-order" or "third-order" impacts, and elicit unexpected responses from communities (Degroot et al. 2021; Ljungqvist, Seim, and Huhtamaa 2021). With climate variability presenting more frequent harsh winters and facilitating zoonotics, there were more hazards in the way of cattle, sheep and goats in Scotland and Ireland. Increasing cereal cultivation in uplands may represent a form of adaptation to this new situation, providing local people and their livestock with supplementary food as supplies of dairy and met became slightly less certain. It was not without risk given how valuable seed crop was. However, the alternative of focusing entirely on livestock would have presented a *greater* risk. To offer a present-day analogy, some pastoralists in north-east Ethiopia have started supplementing their livestock rearing with small-scale crop farming so as to cope with climate change (in this case, longer droughts). Although these crops can sometimes fail, the households who set them have so far proved more resilient than those who continue to rely on livestock alone (Mekuyie, Jordaan, and Melka 2018).

Growing *external* demands for animal products would have exacerbated the situation facing pastoral farmers in the LIA. The 15th to 17th centuries saw increasing numbers of beef cattle being driven southwards from the Highlands toward central Scotland and England, initially for urban consumption and eventually also to feed British naval crews (Haldane 1952; Adamson 2014). Meanwhile the south of Ireland was exporting hides, wool, skins, tallow and small amounts of butter and beef to England and the Continent from at least the 15th century and the butter and beef trades expanded further in the 17th century, in part due to contacts with the New World (Childs and O'Neill 1987; Dickson 2005). Selling to these markets *on top of* dealing with climate-related hazards to livestock would have placed pastoral communities at greater risk of meat and dairy shortage at a local level. Increasing cereal cultivation at favorable upland niches would have helped pastoral farmers to cope with these combined pressures. At the same time, it would not have significantly compromised the amount of summer pasture available to livestock.

If anything, pastoralism would have *facilitated* the strategy. Labor became scarce in Europe during the late 14th and 15th centuries and as a result many rural societies are thought to have reduced their commitment to labor-intensive cereal cultivation (e.g., Bailey 2007, 220; Hybel and Poulsen 2007, 401; Myrdal and Morell 2011, 87). However, in many parts of Ireland and Scotland, the widespread practice of transhumance required people to re-locate to the mountains *anyway* in the summer, to protect herds and tend to dairy cows. So labor would have been available to cultivate isolated patches of upland, especially in the vicinity of seasonal settlements. In this regard, it is noticeable at Lochtayside that the main period of transhumance begins in the 15th century (Atkinson 2016, 210–260), which coincides with the onset of stronger cereal pollen values. Whether the increased cereal values found elsewhere in Highland Scotland and in south-west Ireland were also facilitated by an expansion of transhumance is an intriguing question and will require more dates from summer herding sites to answer.[6]

Small-scale cultivation would have had limits as a form of adaptation, however. Our three remodeled chronologies suggest less cereal cultivation from the late 17th century onwards. This raises the possibility that the coldest decades of the LIA (Rydval et al. 2017, Table 2) were severe enough to make the ripening of grain more difficult in some uplands—in other words, that climate now had a *direct* effect on what people could produce from the land. As discussed above, though, there are other sites where upland cereal cultivation did not cease until more recent centuries. Ultimately, some variation in the adaptive capacity of pastoral communities is to be expected as they were mainly composed of tenant farmers who were not free agents. In Highland Scotland, Robert Dodgshon (2005, 325) has used documentary sources to show how the adaptability of farmers could be limited by the rental policies of landlords; he argues that these "pressures from above" kicked in first, so that land was abandoned "*before* it had ceased to provide a sufficient subsistence." Indeed, Davies (2007, 2059) reminds us of the rather abrupt impact which the Clearances had on land use on some Scottish estates during the 18th and 19th centuries. As such, sociopolitical events may have provided the final *trigger* for decisions to either end or persist with cereal cultivation in decades where oats and barley were becoming more difficult to ripen.

At the same time, declines in cereal pollen did not necessarily represent a decline of all cultivation on hillsides. In Ireland and those parts of Scotland's Highlands and Islands that were not affected by mass evictions, it may simply reflect their gradual replacement by potatoes. This introduced species became popular on peaty acidic soils in the 17th and 18th centuries because it could feed more people per hectare but is very difficult to detect palynologically due to its extremely poor pollen dispersal. However, oral history and archaeological surveys of narrow spade-dug ridges make clear that livestock herders were increasingly cultivating small patches of potatoes as well as cereals around seasonal transhumant sites in the 18th and 19th centuries (Smith 1987, 452; Bil 1990, 259–263; Costello 2020b, 66; Costello 2021). In this last phase of the LIA, though, a growing labor pool was helping to spread haymaking around Ireland and Scotland (Ross 2008; Costello 2020b, 76) and would have buffered livestock-rearing households against harsh winters. It is therefore likely that upland cultivation was *now* mainly driven by the desire to maximize surplus production for local and distant markets, rather than any fear that cattle would starve *en masse* due to a lack of winter fodder.

Conclusions and recommendations for the study of climate impacts in pastoral regions

Reviewing pollen records as well as archaeological and historical evidence has revealed that small-scale cereal cultivation was common practice in pastoral areas of north-west Europe during the LIA. The trend is particularly noticeable in Scotland from late medieval times and seems to have peaked in the early modern period, when average temperatures are thought to have been at their lowest in the LIA. This begs the question as to whether rural communities were recognizing the increased vulnerability of livestock to fodder shortages in harsh winters and the spread of disease and, in an attempt at adaptation, cultivating patches of higher ground to ensure a supply of food. As with all studies in European climate history, however, it can be difficult to establish clear temporal correlations between societal changes and particular climate shifts, not to mind tease out the processes of causation linking them (Ljungqvist, Seim, and Huhtamaa 2021, 15–16).

To test potential climate/land-use correlations in pastoral areas in a more systematic fashion, we have remodeled three suitable upland pollen chronologies from Ireland and Scotland with Bayesian statistics and plotted the data for increasing cereal cultivation against temperature and precipitation reconstructions. These models reveal how, at present, individual pollen counts can only be tied down to a multi-decadal level at best and multi-centennial level at worst. This is an important finding as many pollen studies for the period quote midpoints (e.g., c.1475, c.1625, c.1725) rather than confidence intervals. Midpoints are misleading and can give subsequent researchers the impression that pollen chronologies are finer than they really are (e.g., fine enough to correlate with historical events; Izdebski et al. 2022). In actual fact, varying rates of sediment accumulation mean that more radiocarbon dates, followed by Bayesian modeling, are needed if links with particular climate shifts are to be scrutinized in detail. As we have shown, percentage probability models on the contemporaneity of certain pollen counts and points of interest in climate proxies can then help to judge how strong correlations are (and prevent mistakes due to casual "eyeballing" of trend lines on a graph). Placenames and archaeological survey are also essential to finding the most appropriate locations for further paleoecological sampling. Indeed, when dated, the remains of settlements, grain-drying kilns, cultivation ridges, fields, commons can serve to critique the pollen evidence. This mixed methodology is widely applicable elsewhere in Europe and the world. Many hills and mountains have escaped more intensive modern agriculture and so contain more plentiful archaeological and ethno-historical evidence for land management as well as peat or lake deposits which either have been, or could in future be, cored.

Climate proxies have much finer chronological resolution but there is still a need for more regional proxies. For example, while Scotland is now well served by speleothem records and an 800-year temperature reconstruction based on pine tree rings, the OWDA does not draw on any Scottish tree-ring records. By contrast, the OWDA *does* use an oak tree-ring series in Ireland. However, these Irish oaks are less sensitive to temperature change than pine because they grew in milder conditions. In the future, multi-species tree-ring studies (García-Suárez, Butler, and Baillie 2009) and isotopic variability in speleothems can help to shed light on temperature as well as hydroclimate in such temperate regions. Supplementary work on pollen cores like bog surface wetness analysis and lake chironomid analysis (Swindles et al. 2013; Taylor et al. 2018; Webb et al. 2022) can provide further indications of hydrological and temperature change at a local level, though they need to be cross-referenced with regional climate reconstructions.

Above all, though, we need a more sophisticated conceptual model of the links we would expect to see between land use and climate in pastoral landscapes. The nature of radiocarbon dating means that we cannot detect *immediate* impacts from cold winters, floods and storms in the archaeological and paleoecological records, and annual changes in the use of uplands and outlands were rarely written about in detail prior to the 17th century. So we are forced to place renewed attention on slower, multi-decadal climate impacts on land use, a complex question which has been overshadowed somewhat in recent years by historical and archaeological research on "disasters." In this article we have argued that decisions to start cultivating small patches of ground in Irish and Scottish mountains are symptomatic of an attempt by pastoral communities to bolster local food and fodder supplies during the LIA. Yet the long timeframe involved means that the role played by climate is indirect and mutable over time. We have suggested that this land-use strategy began, in late medieval times, as a response to more frequent climate-related fodder shortages and zoonotics which were killing valuable cattle. However, the demands of growing local populations and external markets for food are likely to have formed additional considerations in continuing and expanding the tradition during the 16th and 17th centuries (though elite decisions and extreme weather events had a potentially overriding influence).

As such, while we still need finer temporal and spatial resolution for both land-use trends and climate changes, we should not expect a linear correlation between them over long periods of time. Selective cultivation of hillslopes was something that pastoral communities were able to incorporate into their land-use praxis because they were using these landscapes anyway as part of transhumance. However, the motivations behind this and other adaptive strategies could change. Collaborative projects which combine knowledge of late medieval and early modern history with archaeological and paleoecological fieldwork hold the key to disentangling the relative importance of these motivations over time in pastoral regions around the world.

Notes

1. In Ireland there is only one known reference to hay prior to the 13th century (and that for animal bedding; Kelly 1997, 47) while in Scotland, to our knowledge, there is currently no direct historical or archaeobotanical evidence of haymaking before the 15th century.
2. There is one speleothem record available for south-west Ireland (McDermott, Mattey, and Hawkesworth 2001) but it is not used in our Bayesian remodeling for BAR L1 as its chronological precision has been questioned (Swindles et al. 2013).
3. Cereal-type pollen grains do not travel far so we can be confident at this site and the others that cultivation took place locally.
4. For Figures 5 and 6, we considered "Very high cereal" to be 9 or more pollen grains, "High cereal" to be 6–8 pollen grains, "Mod[erate] cereal" to be 3–5 pollen grains, and "Low cereal" to be 1–2 pollen grains. Grains

which qualified as "cereal" were *Hordeum* group, *Avena/Triticum* group and cereal-type *Poaceae* (annulus diameter >8 μm), as originally counted by Davies (1999, Tables 18 and 25). 400 pollen grains counted per sample (Davies 1999, 81).

5. Despite this, Tipping and McEwen (2021) dismiss the idea of cereal cultivation at Tarmachan on the basis that it was not a suitable setting for it.
6. On lower hill ranges, like the Ochills in central Scotland, expansion of arable farming is more likely associated with the establishment of year-round farmsteads, since transhumant sites fell out of use in that area in the 17th century (Given et al. 2019).

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Annalistic sources

AC = *Annála Connacht/Annals of Connacht*. CELT: The Corpus of Electronic Texts. English translation available online: https://celt.ucc.ie/published/T100011/index.html

CS = *Chronicum Scotorum*. CELT: The Corpus of Electronic Texts. English translation available online: https://celt.ucc.ie/published/T100016/index.html

HC = *The Annals of Ireland by Friar John Clyn/Annalium Hiberniae Chronicon ad annum MCCCXLIX*. CELT: The Corpus of Electronic Texts. Available online: https://celt.ucc.ie/published/L100011/index.html

I = *Annals of Inishfallen/Annála Inis Faithlinn*. CELT: The Corpus of Electronic Texts. English translation available online: https://celt.ucc.ie/published/T100004/index.html

LC = *Annals of Loch Cé/Annála Locha Cé*. CELT: The Corpus of Electronic Texts. English translation available online: https://celt.ucc.ie/published/T100010A/index.html; https://celt.ucc.ie/published/T100010B/index.html

U = *The Annals of Ulster/Annála Uladh*. CELT: The Corpus of Electronic Texts. English translation available online: https://celt.ucc.ie/published/T100001A/index.html; https://celt.ucc.ie/published/T100001B/index.html; https://celt.ucc.ie/published/T100001C/index.html

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