Climatic controls on the survival and loss of ancient types of barley on North Atlantic Islands

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Abstract

For ancient types of barley at sites in the Scottish Isles, Faroes, and Iceland, we calculated minimum temperature requirements for grain production (grain production threshold, GPT) as accumulated degree days over the cropping season. Site suitability for barley from AD 1200 to 2000 was investigated by comparing these thresholds with reconstructions of annual cropping season degree days (CSDD) using temperature and tree-ring data. In Iceland, between AD 1200 and 1500, reconstructed CSDD were more favorable in the southwest (Reykjavik), with fewer years below the GPT, than in the North, East and West, but there were two periods (1340–1389 and 1426–1475) with low average CSDD and several years below the GPT which possibly influenced the abandonment of barley cultivation around this time. Reconstructed CSDD for the Faroes (Tórshavn) had only one year below the GPT, but 15 periods of four or more consecutive years with low CSDD which would have challenged barley cultivation, especially in the thirteenth century. Reconstructed CSDD were highest for the Scottish Isles, allowing a more prominent role of barley in the farming system and economy. Nevertheless, years with poor harvests or famines were common and about half were associated with low CSDD, resulting in a significant temperature link but also demonstrating the important contribution of other factors. Despite frequent unfavorable years in both the Faroes and Scottish Isles, resilient production systems, well-adapted barley strains and socio-economic factors allowed barley cultivation to continue, and some ancient types to survive to the present day.

Keywords Bere barley · Temperature reconstruction · Faroes · Iceland · Scottish Isles

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1 Introduction

Norse occupation of Scotland's Northern and Western Isles during the ninth century AD (Barrett 2008) was followed by migrations and settlement of the Faroes (Arge 2008) and Iceland (Zori 2016). While farming and the utilization of natural resources were at the core of Norse society, the balance between the two, and the importance of arable crops varied with environment (Keller and Perdikaris 2015). Amongst Norse crops, barley (*Hordeum vulgare* L.) was the main cereal which, potentially, had a diversity of end-uses including food (meal and grain), brewing, in-kind payments, and straw for animal bedding or thatching. The prominence of barley resulted from its versatility and hardiness in northern latitudes (Martin et al. 2017), an adaptation which probably evolved over thousands of years following its introduction to the region around 3500 BC (Bishop et al. 2010). Norse cultivation of barley in the Faroes and Iceland started under the relatively mild climatic conditions of the Medieval Climate Anomaly (MCA, c. AD 950–1250). While there may initially have been an ambition for barley self-sufficiency, the realities of climatic constraints, poor harvests, and socio-economic factors in the transition to, and during, the Little Ice Age (LIA; c. AD 1570–1900; Matthews and Briffa 2005) resulted in barley abandonment in Iceland and a restricted range of uses in the Faroes. In contrast, the milder climate of the Scottish Isles, although often very challenging, allowed greater reliance on the crop and a wide range of end-uses (Martin et al. 2009).

The climates of the North Atlantic islands in this study are significantly affected, although to a different extent, by the same ocean currents and atmospheric systems. The North Atlantic Drift (Gulf Stream) brings relatively warm water from the south into the North Atlantic and around the west coast of Iceland while cold polar water is carried south by the East Greenland Current and around the east coast of Iceland (East Iceland Current; Humlum and Christiansen 1998). In cold periods, the North Atlantic Drift weakens, and the East Iceland Current brings ice to the coast of Iceland (Ogilvie and Jónsson 2001) resulting in large temperature reductions (Humlum and Christiansen 1998). These effects also influence the climate of the Faroes and the North of Scotland. The main atmospheric system affecting the region is the North Atlantic Oscillation which predominantly affects European winter temperature (Hanna et al. 2004) and storminess through its effect on westerly winds (Folland et al. 2009). A similar system, the summer North Atlantic Oscillation, also affects summer temperatures, precipitation, and cloudiness (Folland et al. 2009).

A major common challenge for barley cultivation on North Atlantic islands was the short, cool growing season. Climate restricted the barley grown to spring types, sown in the spring and harvested in late summer. With land cultivations often delayed by low spring temperatures and/or very wet soil, sowing in April–May was later than in more southerly areas and resulted in a late August–September harvest (Guttesen 2001; Dodgshon 2004). In cold years, both operations could be significantly delayed. Other important constraints were infertile soils (Schmidt et al. 2019) and unsuitable land, high rainfall leading to difficult harvesting and high grain moisture, early frosts or snow, a lack of sunshine delaying grain ripening, and strong winds damaging crops (Martin et al. 2017).

Although there is little information about the varieties of barley grown on North Atlantic islands in Norse times, they were mainly 6-row, hulled types (Church et al. 2005). In Scotland, they included ancestral types of today's bere, an ancient barley which probably

existed in the region before the Norse occupation (Drosou et al. 2022). Bere exhibits several adaptations which make it well suited to the Scottish Isles. In particular, it grows rapidly in the spring and quickly reaches maturity (Martin et al. 2010), is tolerant of poor soils (Schmidt et al. 2019), and has some resistance to grain loss in strong winds ("shake"; House of Commons 1804). With a significant proportion of Norse settlers in both the Faroes and Iceland originating from Scandinavian colonies in the British Isles (Zori 2016; Als et al. 2006), it is possible that bere was taken to these other islands. A close relationship between traditional Faroese barley and bere is suggested by grain morphometrics and genotyping (Wallace et al. 2019; Drosou et al. 2022), similarities in agrophenology (Agronomy Institute unpublished results) and historic references (Trevelyan 1835; Williamson 1970). Bere is therefore a valuable model for investigating historic barley cropping in the North Atlantic region.

For the Scottish Isles, there are many historic references to years when grain harvests were very poor and these often suggest an underlying role of low temperatures through events like cold springs resulting in late sowing (e.g., 1835; Macgregor 1839), cool growing seasons, or early frosts or snow (e.g., 1782; Cullen 2019). However, heavy rain or strong winds near harvest (e.g., 1836; MacAskill 2010) were also important. Late sowing often resulted in late harvests which were especially vulnerable to damage from adverse weather, producing reduced yields and inferior grain unsuitable for milling, malting, or seed (Cullen 2010).

Previous studies in Finland (Holopainen and Helama 2009) and Norway (Nordli et al. 2003) have shown the potential for combining historical data on crop yields or agrophenology to reconstruct previous cropping season temperatures and improve understanding of fluctuations in historic crop production. Tree-ring data can enhance such reconstructions as they are a particularly valuable climate proxy, providing exact calendar dated records of growing season conditions and, in areas with a high food dependence on local crops, can be used to investigate years of poor harvests and famines (Dybdahl 2012; D'Arrigo et al. 2020) and periods of agricultural transformation (Huhtamaa and Helama 2017).

The aim of this study was to investigate how changes in temperature of the barley cropping season in North Atlantic islands between AD 1200 and 2000 affected the suitability of these islands for growing barley and the ability of islanders to continue to cultivate and depend on traditional local types for sustenance. This was explored for selected locations by using data from Orkney-grown bere to identify the thermal requirements of barley crops under pre-modern conditions and comparing these with reconstructions of the temperature sum over the cropping season using temperature and tree-ring data from AD 1200 to 2000. We discuss our results in the context of other environmental, agronomic and socio-economic factors which are also likely to have played an important role in the loss or survival of barley cultivation on these islands since AD 1200.

2 Methods

2.1 Study area and weather data

This study covered barley cultivation in several North Atlantic islands or archipelagos—Iceland, the Faroes and the Scottish Isles which included the Northern Isles (Orkney and Shetland) and the Western Isles (Outer Hebrides) (Fig. 1a).
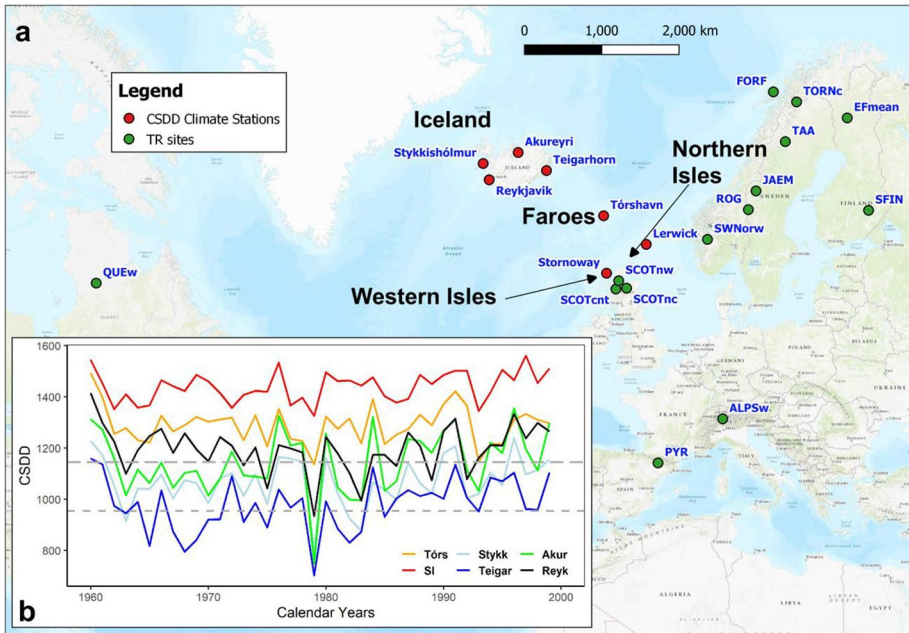
Fig. 1 **a** Map showing locations of islands, climate stations, and tree-ring data sites referred to in this study. **b** Cropping season degree days (CSDD) for the Scottish Isles (SI), Tórshavn (Tórs), Reykjavik (Reyk), Akureyri (Akur), Stykkishólmur (Stykk), and Teigarhorn (Teig) from 1960 to 1999. The upper and lower horizontal lines are the LYI and GPT for barley at Reykjavik (1145 and 954 DD, respectively). Thresholds for the other sites are provided in Table 1

We used monthly meteorological data, principally temperature, from several sources for this research (see Table S1 for details). The main Scottish data (Jones and Lister 2004) were the Scottish Isles temperature series (SIT), covering Orkney, Shetland, and the Outer Hebrides and the Scottish Mainland temperature series (SMT). Faroes data were from Tórshavn, while Iceland data came from four regional stations—Reykjavik (south west), Stykkishólmur (west), Akureyri (north), and Teigarhorn (east). We also used temperature, precipitation, and sunshine data from Lerwick (Shetland), Kirkwall (Orkney), Stornoway (North Uist), Tórshavn, and Reykjavik (Fig. 1a) to demonstrate different climatic features between the islands.

2.2 Cropping season degree days

Cropping season degree days (CSDD) is the accumulated daily temperature, expressed as degree days (DD, °Cd), over the barley cropping season (from sowing to harvest). In northern regions, it is a useful indicator of an area's suitability for barley cultivation and is often correlated with grain yields (Martin et al. 2017). Crop growth only occurs above a minimum, or base temperature (T_b) and each day's DD is calculated as the average daily air temperature minus T_b. We describe the method used to calculate T_b in Section 2.3. Since we used monthly, rather than daily, temperature data, we first calculated monthly DD (MDD) for each month of the cropping season and then summed these to give CSDD. We calculated MDD from:

$$MDD = (T_{MA} - T_b)N \tag{1}$$

where T_{MA} is the monthly average daily temperature and N is the number of days in the month which fell in the cropping season.

The start date for calculating CSDD was the sowing date. Although this varies from year to year, the following dates were adopted in each region: 24 April for the Faroes, 1 May for Iceland, and 15 May for the Scottish Isles. The Scottish Isles date reflects traditional practice (Martin et al. 2010) and that for the Faroes is about the middle of a range of start dates recorded in farm journals (Guttesen 2001). Since the traditional date for sowing in Iceland is not known, we adopted a date which is close to current practices (Hilmarsson et al. 2017). Depending on conditions, barley can be harvested between late August and October in the region (Dodgshon 2004; Guttesen 2001) and so we used 30 September as the end of the cropping season in all locations.

2.3 Calculation of a base temperature for bere and threshold CSDD values

For reconstructing pre-twentieth century cropping seasons, we used data for Orkney-grown bere because of its adaptations to North Atlantic island conditions, especially its short period from sowing to grain maturity.

The base temperature (T_b) for bere was calculated (Gallagher et al. 1983) as the intercept on the x-axis from a linear regression of the reciprocal of the number of days from sowing to harvest on the average daily temperature over this period. For 78 crops of bere between 2003 and 2019, this was 1.1 °C (Eq. 2, Table S2) which we rounded down to 1.0 °C for this study.

The average CSDD for the Orkney crops was 1467 DD and the minimum for producing a crop under modern conditions was estimated as 1271 DD (the average minus twice the standard deviation). Modern bere crops are harvested by combine after senescence when grain moisture is around 22%. In the past, with manual harvesting, crops were cut at an earlier stage. Although this stage is not well defined, in the Faroes, Williamson (1970) described the crop as being "still green and far from ripe" when it was cut. We assume this was at about the stage of grain physiological maturity, when it still had a high moisture content but was capable of good germination (Filho and Ellis 1991). This would have been crucial for farmers dependent on using their grain for seed. This stage is reached in Orkney at about 0.85 of a crop's CSDD and so we estimated the minimum for Orkney under pre-modern conditions to be 1080 DD from sowing. We refer to this minimum as the grain production threshold (GPT) and assume that below the GPT a crop would have produced very little viable grain for seed, although it may have had some food value. This is discussed further with reference to published grain production data in Supplementary Note 2.

There is a negative relationship between the latitude at which barley is grown and its thermal requirement (Martin et al. 2017). The data used for determining the relationship in Martin et al. (2017) were re-calculated using a 1.0 °C base temperature for degree days (Eq. 3, Table S2), enabling the GPT to be calculated for Tórshavn (986 DD) and Reykjavik (954 DD).

2.4 Reconstruction of CSDD

Annual values of CSDD for the Scottish Isles were calculated from SIT back to 1827. For the Faroes, CSDD from 1890 to 1999, calculated from Tórshavn data, were more highly correlated with SIT (r^2, 0.78; Eq. 7, Table S2) than with CSDD at other

locations (Stykkishólmur, Iceland; Utsira lighthouse and Vestlandet, Norway; the Scottish Mainland (SMT); Eqs. 4, 5, 6, and 9, Table S2) and so SIT was used to reconstruct Tórshavn CSDD back to 1827. In Iceland, temperature data for Stykkishólmur allowed CSDD to be calculated back to 1830 and relationships between CSDD at Stykkishólmur and the other Icelandic sites (Eqs. 10–12, Table S2) were used to reconstruct their CSDD back to 1830.

To derive an extended reconstruction beyond the available instrumental data, we utilized the tree-ring (TR) data from Wilson et al. (2016). This network of TR proxy data (Fig. 1a and Table S3) represents published summer temperature reconstructions, based on ring-width, maximum latewood density (MXD) and blue intensity, for varying summer months during the growing season. The network was expanded with the inclusion of two new delta blue intensity (Björklund et al. 2014) regional records for central-west (1550–2018) and north-west (1680–2018) Scotland as they could provide geographically more representative summer temperature proxies than the published northern Cairngorm reconstruction (1200–2010; Rydval et al. 2017). A MXD record from the southwest Norwegian region and a stable carbon isotope record from northern Sweden, representing a growing season sunshine proxy record (Loader et al. 2013), were also included.

Figure 1a shows the sites of the tree datasets (described in Table S3) that were utilized for the CSDD reconstructions derived for this study. All datasets are located where some coherence (positive or negative) exists between CSDD data and regional May–September mean temperatures. Fig. S1 shows the spatial correlations for Tórshavn and the Scottish Isles (SI) which are representative of the spatial coherence pattern for all the CSDD records. Following the same methodological approach as Anchukaitis et al. (2017), and due to the disparate nature of the TR proxy network, a stepwise linear regression was performed for annual values of CSDD for each meteorological site and the available individual TR records. The calibration period for the modelling was 1931–1999, with the data sets entering the model if the regression coefficient was significant at 85% and the sign was consistent with the zero-order correlation between each individual TR dataset and the target CSDD data. Further, the variance inflation factor was used to ensure no serious multi-collinear issues existed in the final regression model. The fidelity of the longer-term variance in the models were explored by examining for both linear trends and significant first order autocorrelation in the residuals. The modelling was made using two nested periods, 1611–1999 and 1200–1999, with the earlier 1200–1610 period spliced onto the later period to create the full-length reconstructions for each CSDD record.

2.5 Barley grain production data

We used data for grain returns (harvested grain weight divided by weight of seed sown) summarized from farm journals for 1813–1892 (Guttesen 2001) to validate threshold values of CSDD for the Faroes. For the Scottish Isles, bere exports from Kirkwall for 1780–1804 (Shirreff 1814) were used to investigate their relationship with annual CSDD and the thresholds calculated for this region. The data were recorded as bolls (one boll is approximately 136 kg of bere grain). No historic grain production data exist for barley in Iceland, so we used reported yields from research trials in the 1960s (Sigurbjörnsson 2014) and 1987–2014 (Hilmarsson et al. 2017) to compare with CSDD for these years and the Icelandic thresholds.

3 Results

3.1 Climate context

To place our analysis of CSDD within a wider climate context, we provide a separate analysis (Supplementary Note 1) for selected sites (Reykjavik, Tórshavn and Lerwick) of recent temperature data and other climatic factors affecting the regional barley crop. The analysis showed that the highest temperatures were at Lerwick followed by Tórshavn and Reykjavik (Fig. S2a) and highlighted the large fluctuations in cropping season temperature which can occur in Iceland (Fig. S2b) between cold and relatively warm periods. There were significant correlations between May–September temperatures between the three sites, but these were strongest (r^2, 0.72) between Lerwick and Tórshavn, indicating strong climatic connections between the Northern Isles and the Faroes.

3.2 The relationship between reconstructed CSDD at Tórshavn during the nineteenth century and barley farm returns

Our reconstruction of CSDD for Tórshavn (Fig. S3a) was used to investigate variations in Faroese farm barley grain returns on seed sown between 1827 and 1891 (Guttesen 2001). There was good correspondence between the fluctuations in grain returns and CSDD (Fig. S3b) and several of the years with very poor returns (1 or 2) had reconstructed CSDD approaching the GPT. Furthermore, there was a significant correlation (r^2, 0.46) between barley returns and reconstructed CSDD (Eq. 8, Table S2) demonstrating that CSDD can be a good indicator of grain returns. The regression line predicted zero return at 914 DD which is close to our GPT (986 DD). With many of the low returns occurring in years when CSDD were below 1188 DD, we adopted the formula ($1.2 \times GPT$) as an indicator of low grain yield (low yield indicator, LYI) at Tórshavn and the other locations. The LYI line for Tórshavn is shown in Fig. S3b and is further validated for other locations below and discussed in Supplementary Note 2.

3.3 Reconstruction of CSDD for Icelandic sites and comparison with Tórshavn and the Scottish Isles during the nineteenth and twentieth centuries

Although barley cultivation ceased in the Faroes in the 1970s, while small scale growing only re-started in Iceland from about the middle of the twentieth century, we have included an analysis of CSDD during the nineteenth and twentieth centuries because the period experienced cold conditions similar to those during the main phase of the LIA. Our analysis focuses on two cold periods (1859–1925 and 1962–1995) and one relatively warm period (1931–1960). We calculated CSDD either from each site's temperature records or reconstructed them from temperature data for other sites (Eqs. 7 and 10–12, Table S2).

During the 1962–1995 cold period (Table 1 and Fig. 1b), CSDD values did not fall below the barley GPT or the LYI in the Scottish Isles and there were just 2 years at Tórshavn below the LYI. In contrast, there were between 9 and 33 years below the LYI at the Icelandic sites. Amongst these, conditions were worst in the east (Teigarhorn) and the west (Stykkishólmur). Even at Reykjavik, the mildest location, about 1 in 4 years was below the

Table 1 Summary CSDD statistics for the Scottish Isles, Tórshavn and different Icelandic locations during contrasting climatic periods during the nineteenth and twentieth centuries

Period/statistic	Scottish Isles	Tórshavn	Reykjavik	Stykkishólmur	Akureyri	Teigarhorn
All periods						
GPT (DD)	1080	986	954	938	939	939
LYI (DD)	1296	1188	1145	1126	1127	1127
1962–95 (cold period)						
Average CSDD (SD in brackets)	1430 (54)	1278 (65)	1175 (81)	1050 (86)	1127 (116)	961 (96)
Number of years below the GPT	0	0	1 (3%)	4 (12%)	1 (3%)	13 (38%)
Number of years below the LYI	0	2 (6%)	9 (27%)	27 (79%)	19 (56%)	33 (97%)
Longest number of consecutive years below the GPT	0	0	1	2	1	5
Longest number of consecutive years below the LYI	0	1	2	14	5	29
1859–1925 (cold period)						
Average CSDD (SD in brackets)	1390 (79)	1226 (87)	1179 (96)	1016 (112)	1097 (123)	862 (121)
Number of years below the GPT	0	0	1 (2%)	16 (24%)	6 (9%)	47 (70%)
Number of years below the LYI	12 (18%)	21 (31%)	24 (36%)	56 (84%)	40 (60%)	67 (100%)
Longest number of consecutive years below the GPT	0	0	1	4	1	8
Longest number of consecutive years below the LYI	2	4	4	11	7	67
1931–1960 (warm period)						
Average CSDD (SD in brackets)	1477 (72)	1330 (82)	1293 (94)	1157 (114)	1213 (147)	1034 (96)
Number of years below the GPT	0	0	0	0	0	5 (17%)
Number of years below the LYI	0	0	2 (7%)	12 (40%)	8 (27%)	24 (80%)
Longest number of consecutive years below the GPT	0	0	0	0	0	2
Longest number of consecutive years below the LYI	0	0	1	3	2	12

GPT grain production threshold, *LYI* low yield indicator, *DD* degree days, *SD* standard deviation

LYI. Reports from Icelandic barley trials support our adopted GPT and LYI. In 1963, when the average CSDD across the four sites was 994 DD (close to the average GPT for these sites, 942 DD), many trials failed to be harvested (Sigurbjörnsson 2014) and only a few had grain yields of 0.4–2.0 t ha^{-1}. In trials from 1987 to 2014 (Hilmarsson et al. 2017), the smallest average grain yields (about 0.7 t DM ha^{-1} for a range of sites) occurred in 1989 and 1992 when the CSDD at Reykjavik was 1074 and 1079 DD, respectively. In 1993, when the CSDD at Reykjavik (1162 DD) was very close to our LYI (1145 DD), the average yield was about 2.0 t DM ha^{-1}. In contrast, the highest annual yield over the 28 years (5.6 t DM ha^{-1}) occurred in 2009 when the CSDD at Reykjavik was 1388 DD. For comparison with Fig. 1b, CSDD in the Scottish Isles (1975–1999; Fig. S4) were consistently greater in the Western Isles than the Northern Isles, where Orkney had higher values than Shetland.

The same trends in CSDD occurred in the 1859–1925 cold period as for 1962–1995 except that it was more severe. This is shown (Table 1 and Fig. S5) by the lower average CSDD at most sites and the higher percentage of years at most Icelandic sites below the GPT and LYI. In comparison with Reykjavik (36% of years below the LYI), temperature conditions were better at Tórshavn and the Scottish Isles (31% and 18% of years below the LYI, respectively). The large number of consecutive years below the LYI at Teigarhorn and Stykkishólmur during both cold periods is also notable.

Through the 1920s in Iceland, there was a dramatic shift from a cold to a relatively warm period reflected by an increase in the 3-year average CSDD at Stykkishólmur from 930 DD in 1921 to 1204 DD in 1931 (Fig. S5). During the 1931–1960 warm period (Table 1), CSDD at Reykjavik were below the LYI in only 7% of years, but at Akureyri, Stykkishólmur, and Teigarhorn, they were still below this threshold in 27%, 40%, and 80% of years, respectively, showing clearly the greater suitability of climatic areas like Reykjavik for barley production. There was also a smaller difference in CSDD between Reykjavik and Tórshavn (Table 1, Fig. S5) compared with differences during the two cold periods.

3.4 Tree-ring-based reconstruction of CSDD for the Scottish Isles, Tórshavn, and Iceland

Table S4 shows the TR data included in the multiple linear regression models used to reconstruct CSDD at each of the island sites for the two nested calibration periods and summarizes the calibration statistics for each model. In both periods, the highest r^2 values were obtained for the Scottish Isles and Tórshavn (0.55 and 0.35, respectively, for 1611–1999; 0.51 and 0.33, respectively, for 1200–1999). Results for the Iceland sites were poorer (r^2 values ranging from 0.16 to 0.34), but with slightly better results for Akureyri. For Reykjavik, there was also a significant decreasing linear trend in the model residuals. Sliding 31-year correlations between the CSDD data and the reconstructions of the full period of overlap (Fig. S6) also show that the Scottish Isles, Tórshavn, and Akureyri generally show significant and temporally consistent correlations, with those for the Scottish Isles being particularly good, even back to the nineteenth century. In view of the poorer fit of the Icelandic models, we cautiously use them in the following sections to indicate trends in the data rather than for detailed annual analysis. Reconstructed CSDD for the six sites are shown in Fig. S7.

During the eighteenth and early nineteenth centuries, Orkney was mainly an exporter, but sometimes an importer of bere. Annual exports and imports for 1780–1805 (Shirreff 1814) provide an indication of Orkney grain production for validating our reconstruction of CSDD for these years and the thresholds we use (Fig. S8). Substantial exports (> 1000

bolls) only occurred in 15 of the 26 years (58%) and ten of these followed a year with a CSDD above the LYI (1296 DD). In the 6 years when there were no exports, bere imports exceeded 1000 bolls and there were even greater imports of oatmeal (Shirreff 1814), indicating a high frequency of poor harvests (23% of years). Half of these years followed years with CSDD below the LYI. There was a significant correlation (r^2, 0.26) between grain exports and CSDD in the previous year (Eq. 13, Table S2), the delay probably reflecting the time required to thresh the grain and prepare it for export. The fitted line indicated zero exports at 1130 DD and helps to validate the Scottish Isles' GPT (1080 DD) as some grain production for local consumption would have been required before exports started. A petition to Parliament (House of Commons 1804) by Lord Dundas, Lieutenant of the County of Orkney, also supports our reconstruction and thresholds: the crop of 1801 (1261 DD) was barely sufficient for Orkney consumption and seed for the following year while that of 1802 (1158 DD) could only meet local needs for three months and was described as a worse crop failure than that of 1782 (1194 DD) which, in Shetland, was the worst of the century (Cullen 2019). The 3 years preceding 1802 were also below the LYI (Fig. S8), suggesting a series of poor harvests may have increased vulnerability to that of 1802. There were seven other periods in the Scottish Isles reconstruction when four or more consecutive years were below the LYI (Table S5), including two well-documented famine periods in the 1630s and 1690s.

   Table S6 lists years when famine and poor harvests have been documented in Scotland between 1256 and 1836 (Supplementary Note 3) and provides the reconstructed CSDD for these years and, in the case of famine years, the previous year. Notably, out of 69 years in the Table, 46% had CSDD less than or equal to the Scottish Isles' LYI (1296 DD) compared with 16% below the LYI in the remaining 512 years. The incidence of famine/poor harvest years in relation to reconstructed CSDD is shown in Fig. 2a. In Orkney, particularly
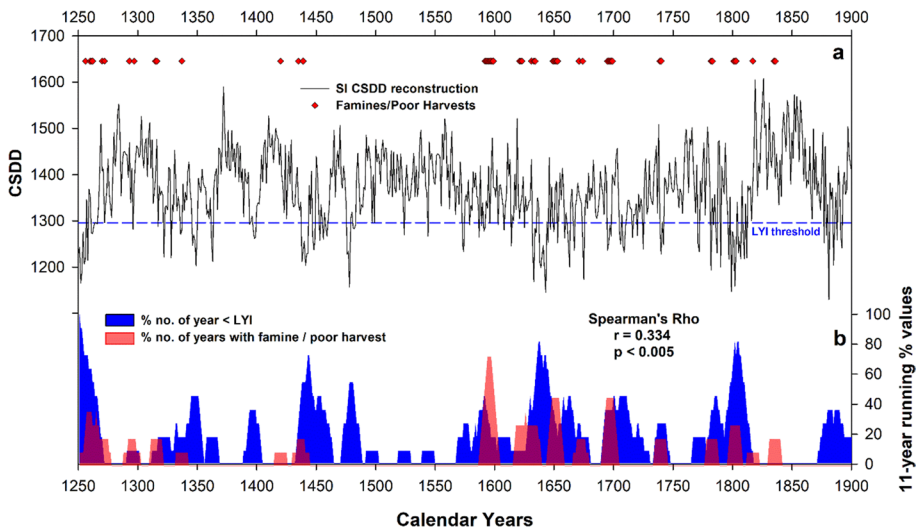

Fig. 2 a Scottish Isles (SI) CSDD reconstruction with highlighted famine and poor harvest years (see Table S6 and Supplementary Note 3). The LYI threshold for the SI is 1296 DD. **b** Running 11-year plots detailing the % number of years in the SI CSDD reconstruction below the LYI threshold compared to the % number of years defined as famines or poor harvests. The Spearman's correlation value is calculated between the two data-sets

poor harvests are well documented during the 1630s, 1674–1676, 1690s, 1739–1740, 1782, and 1801–1803 and for most of the critical years in these periods the reconstructed CSDD was below the LYI. There is a weak, but significant, correlation between 11-year running averages of the % of poor harvest/famine years and the % of years in the Scottish Isles reconstruction below the LYI (Fig. 2b). Although demonstrating an association between the two variables, 89% of the variance remained unaccounted for by CSDD, showing an important contribution from other factors.

For the Faroes, reconstructed CSDD from TR data was not significantly correlated with farm returns (r^2, 0.015) unlike CSDD derived from SIT (Eq. 9, Table S2). Notably, the TR-based reconstruction failed to capture low CSDD values between 1835 and 1845 indicated by both SIT (Fig. S3b) and Vestlandet (West Norway) temperature-based reconstructions and by the occurrence of famines in parts of Norway from 1835 to 1841 (Nordli 2001). This reflects the weaker correlation from 1890–1999 between CSDD at Tórshavn and the TR data compared with SIT. While we have not found other barley production data for the Faroes, serious grain scarcity occurred from 1629 to 1633 (Wylie 1987), when five out of six reconstructed years were below the LYI. Especially harsh conditions were also recorded in winter 1694–1695 and a very late sowing giving little prospect of a harvest in 1717 (West 1985). The reconstructed CSDD for 1695 and 1717 (1185 and 1187 DD, respectively) were both below the LYI for Tórshavn. Particularly difficult conditions were likely in periods where several consecutive years were below the LYI (Table S5). These were more common in the Faroes than the Scottish Isles and especially protracted in 1223–1232, 1241–1256, and 1452–1461.

Comparisons of decadal average values of reconstructed CSDD and the number of years per decade below the LYI and GPT from AD 1200 to 2000 (Fig. 3) indicate the same ranking of site suitability for barley cultivation as the temperature-based reconstructions. Thus, Reykjavik (255 and 25 years, respectively, below the LYI and GPT) was the most suitable of the Icelandic sites but was less suitable, mainly because of the higher frequency of years below the GPT, than Tórshavn (253 and one year, respectively, below the LYI and GPT). The Scottish Isles were considerably more favorable (162 and 0 years, respectively, below the LYI and GPT).

For the Scottish Isles, Tórshavn, Akureyri, Stykkisholmur, and Teigarhorn, the time trends of decadal reconstructed CSDD (Fig. 3) are similar and indicate low values until the mid-thirteenth century followed by a period of increase up to about 1300. A fall in CSDD after 1300 coincides with a drop in temperatures identified around this time in several North Atlantic studies (Cunningham et al 2013) and is often considered to be the start of the transition from the MCA to the LIA. In our reconstructions, the transitional period and the LIA are characterized by alternating periods with high and low CSDD values, with the high values frequently being near those of the late twentieth century. Although there was variation between sites, decadal averages of CSDD were often low during the following periods: 1310–1360, 1440–1460, 1630–1640, 1695–1720, 1790–1810, and 1870–1895. While some of these overlap with periods of reduced solar activity (see Fig. S7), they also sometimes include major volcanic events (Rydval et al. 2017) which are considered to have had a greater influence on cooling (Schurer et al 2014). The reconstruction for Reykjavik differed from the others in having high CSDD values throughout the thirteenth and for most of the eighteenth centuries which may be related to the poor fidelity of the calibrated signal (i.e., a significant linear trend in the model residuals). It was similar, however, in showing a marked decline around 1300, resulting in low values for 1310–1380 and periods with low values in 1430–1480, 1630–1640, and around 1700.
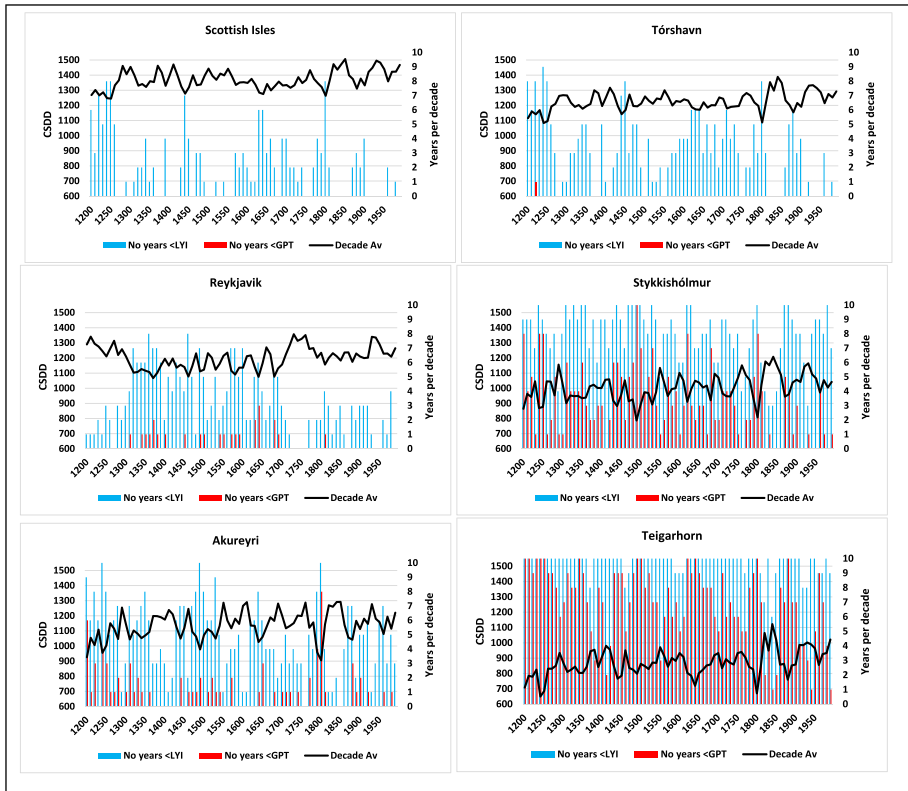
Fig. 3 Average reconstructed CSDD per decade (Decade Av) from AD 1200 to 2000 and number of years per decade with CSDD below the LYI and GPT for the Scottish Isles, Tórshavn and Icelandic sites

In Iceland, changes in CSDD between 1250 and 1500 are important because of their possible influence on barley abandonment which occurred during this period. Conditions were less severe at Reykjavik than at the other Icelandic sites (Fig. 3) but were considerably worse than at Tórshavn and the Scottish Isles. Thus, for 1250–1500, 47% of years at Reykjavik were below the LYI compared with 53%, 86%, and 98% at Akureyri, Stykkisholmur and Teigarhorn, respectively; this compares with 33% for Tórshavn and 20% for the Scottish Isles. Two protracted periods with mostly low CSDD occurred at Reykjavik around 1310–1380 and 1430–1480 when the average CSDD was 1115 and 1131 DD. With 62% and 56% of years, respectively, below the LYI, barley cultivation during these periods would have been challenging and yields would likely have been low.

The reconstruction for Akureyri suggested that, notwithstanding its far-north location, CSDD were often as high during warm periods as at Reykjavik but were usually considerably lower during cold periods. This may reflect the special microclimate of the town which is at the head of a long fjord and protected by high mountains.

4 Discussion

The important relationships we have demonstrated between temperature, represented as CSDD, and barley production (Eqs. 8 and 13, Table S2) and poor harvests/famines (Fig. 2b) on North Atlantic islands can probably be attributed to many factors. A major effect would have been on determining the time from sowing to harvesting (Eq. 2, Table S2 and Cammarano et al. 2019). This would have been longer with low temperatures, so that crops may not have ripened completely and were more likely to be damaged by poor weather around harvest. With higher cropping season temperatures, production would be expected to increase as a result of increases in the rates of plant physiological processes like photosynthesis, root and shoot growth and nutrient uptake. Higher air temperatures would also have raised soil temperatures, possibly increasing the availability of nutrients from both soil and manures. While demonstrating a significant temperature link, the above relationships also leave a large proportion of unexplained variance (55% for Eq. 8, 74% for Eq. 13 and 89% in Fig. 2b). Most of this is likely to stem from factors related to other weather conditions discussed in Supplementary Note 1; differences between the average actual and assumed sowing and harvesting dates; uncertainties in our reconstructions (e.g., Table S4 and Figs S6 and S7) and the historical data (see Supplementary Note 3); and a range of factors contributing resilience to production systems and reducing vulnerability to poor harvests (Supplementary Note 4). We discuss some of the limitations of our analysis in Supplementary Note 5.

In exploring the use of TR data to reconstruct CSDD, the best correlations were for the Scottish Isles followed by Tórshavn, but with much weaker ones for Iceland. This generally reflects the spatial climatology of the North Atlantic and the distance of the islands from the TR sources used in the models and therefore demonstrates the need for close-proximity data sources to obtain the strongest temporally stable relationships (Fig. S6). From the recent trends in CSDD calculated from Iceland temperature records (Fig. 1b), we would expect reconstructed CSDD for the Icelandic sites to all show similar trends. The Reykjavik reconstruction differed from the others during the thirteenth century and in most of the eighteenth century. This probably resulted from the different TR data sets entering the models, with Reykjavik being the only site not including data from Québec (Table S4). For Iceland, we are therefore cautious with our use of the reconstructions.

The reconstructed CSDD for all sites except Reykjavik suggested low values during the first 60 years of the thirteenth century reflecting a period of low temperatures identified in TR reconstructions for the North of Scotland (Rydval et al. 2017), Northern Europe (Esper et al. 2014), and the Northern Hemisphere (Wilson et al. 2016). There are also historic references to sea ice off Iceland during the thirteenth century (Ogilvie and Jónsson 2001) and proxy evidence for a marked drop in sea surface temperature off North Iceland around the middle of the century (Cunningham et al. 2013; Massé et al. 2008; Ran et al. 2011; Sicre et al. 2011). Throughout the British Isles, a very poor harvest in 1256 was followed by famine in 1257 (Oram 2015). In our reconstructions, 1256 is exceptional for both the Scottish Isles and Faroes because it comes at the end of 15 and 16 years, respectively, with CSDD below their LYI. It was followed in 1258 by another year with a low CSDD, probably attributable to the large eruption of Samalas (in today's Indonesia; Guillet et al. 2017). Our reconstructions suggest that the cold cropping seasons of the early part of the thirteenth century may have been as challenging as those of the better documented seventeenth century.

During cold periods, our CSDD analyses clearly demonstrated the less favorable conditions for barley production in Iceland than in the other islands of the study. Between 1200 and 1500, it also showed better conditions at Reykjavik than in the East, North or West of the country. This reflects archeological evidence suggesting that barley cultivation was limited to coastal parts of the south of the country by the twelfth century and had been abandoned by about AD 1500 (Riddell et al. 2018). All the Icelandic reconstructions indicated protracted periods with very low CSDD around 1310–1380 and 1430–1510 and both periods overlap with periods of low reconstructed sea surface temperatures off Iceland (Massé et al. 2008; Patterson et al. 2010; Sicre et al. 2011; Ran et al. 2011). For Reykjavik, 1340–1389 is prominent for having the highest frequency of years below the GPT (6) and LYI (36) in any 50-year period of our reconstruction; it also included the large eruption of Öræfajökull in south east Iceland in 1362 which resulted in widespread ash deposition. The period 1426–1475 was almost as severe (2 and 30 years, respectively, below the GPT and LYI). The average CSDD at Reykjavik for these periods was 1104 and 1122 DD, respectively, which are lower than that of the 1962–1995 cold period (1175 DD, Table 1) when barley cultivation was hardly viable in Iceland, even with the advantages of mechanized farming. In Iceland, just as for marginal, high elevation land in Scotland (Parry 1975), farmers' decisions about crop abandonment were probably highly influenced by the frequency of crop failure and climate variability. Crop failure would be very likely below our GPT. While climatic deterioration was probably a major reason for the abandonment of barley, other factors probably contributed to this. It is thought that barley became a prestige crop in Iceland which was mainly grown at high status farms because of the large input of resources required to cultivate it successfully (Zori et al. 2013; Riddell et al. 2018). If so, it is perhaps not surprising that decline and abandonment occurred when grain imports were common as a result of the stockfish trade (Mehler 2011) and when outbreaks of plague in the fifteenth century (Streeter et al. 2012) probably reduced the supply of labor needed for cultivation and applying manures (Simpson et al. 2002). Increasing erosion on lowland farms (Streeter et al. 2012) may have further reduced productivity.

Our analyses of CSDD showed marked differences in the suitability of Reykjavik for barley cultivation between cold and warm periods. Although outside our reconstruction, this suggests that conditions for barley were probably relatively favorable after the Norse settlement during the MCA.

In contrast to Iceland, we suggest that barley cultivation continued in the Faroes from the Norse settlement up to its abandonment in the twentieth century. This seems likely because of the survival into the twentieth century of old types of barley together with a well-adapted traditional system of cultivating it, *reinavelta*, both of which would likely have been lost if barley cultivation had lapsed for a significant period. *Reinavelta* was already well established by the seventeenth century (Christiansen 1989) and amongst its adaptations to Faroese conditions (Supplementary Note 4) were sloping beds with drainage channels to cope with high rainfall, and heavy applications of seaweed and manure to maintain soil fertility. The surviving lines of Faroese barley are closely related to bere and, although one suggestion is that they were eighteenth or nineteenth century introductions (Wallace et al. 2019), they might also be descended from barley introduced by Norse settlers from Scotland as discussed in Drosou et al. (2022). However, our reconstruction of CSDD identified 15 periods from 1200 to 1900 with four or more consecutive years below the LYI (Table S5) and with three in the thirteenth century being especially protracted. Very poor grain production during these periods is indicated (Fig. S3b) by the low average return (2.6) for 1836–1841, when all years of our temperature-based CSDD reconstruction were below the LYI and the average CSDD was similar to those in the thirteenth century.

Spanning the three periods in the thirteenth century, the 50 years from 1206 to 1255 had the lowest average CSDD and the highest frequency of years below the LYI (39) of any 50-year period in the Faroes reconstruction, making it comparable with 1340–1389 at Reykjavik (36 years below the LYI) during the period leading up to barley abandonment. However, the two periods differ in two important respects: firstly, the smaller number of years below the GPT at Tórshavn (one compared with six) when crop failures would have been likely; secondly, the trend at Tórshavn for marked increases in CSDD after 1255 compared with the continuation of a high frequency of years below the LYI at Reykjavik after 1380 (Fig. 3). It is therefore possible that during the thirteenth century and other periods identified in Table S5, barley cultivation continued without catastrophic crop failure, although with low grain returns. This suggests considerable resilience in the Faroese production system. Apart from the strengths of *reinavelta* (Supplementary Note 4), there were other factors contributing resilience from at least the eighteenth century, although not all of these may have applied before then. Firstly, local production only supplied about one third of the barley consumed in the Faroes and the remainder was imported (Guttesen 1999; West 1985); in poor years, imports would have allowed local barley to have been saved for seed (Landt 1810), thereby conserving specially adapted local strains. With a range of marine resources (Church et al. 2005) to supplement domestic livestock products (Guttesen 1999) there would have been a variety of alternative foods in most years, reducing the need to eat barley seed in poor years. Furthermore, barley was grown in a diversity of micro-environments (Supplementary Note 4), partly a result of the large number of islands (18) in the archipelago, and this would have reduced the likelihood of barley cultivation failing at all sites. Finally, there was a well-developed procedure for grain drying (Landt 1810), including dedicated buildings, which would have helped produce good quality seed.

In the Scottish Isles reconstruction, 1206–1255 was also the 50-year period with the lowest average CSDD, but it had fewer years below the LYI than Tórshavn (32 compared with 39 years) and none below the GPT. Overall, our reconstructions indicated better conditions in the Scottish Isles than the Faroes or Iceland because of higher CSDD, a lower frequency of years below the LYI and an absence of years below the GPT. Nevertheless, even on Orkney, a relatively favorable location, surpluses were insufficient for grain exports in 23% of years between 1780 and 1805, and imports were required to meet local needs. Other estimates of the frequency of scarcity or famine in the Highlands and Islands between 1600 and 1800 have varied between one in four to one in 7 years (Dodgshon 2004). In the 1780–1805 period, significant exports (> 1000 bolls) occurred in 68% of years after a year above the LYI and 45% of years following one below the LYI. Assuming similar relationships with CSDD in other centuries, our reconstruction suggests the potential for reasonable grain exports in about 58–65 years per century from 1200 to 1900. Grain was already being exported from Orkney to Iceland and Norway in the thirteenth century (Barrett et al. 2000) and grain exports continued until the latter part of the nineteenth century (Thomson 2001). Grain production was less viable in Shetland because of its lower temperatures (Fig. S4) and limited area of suitable soils, and grain was often imported from Orkney (Thomson 2001). From the seventeenth century, throughout Scotland's Highlands and Islands region, surpluses of bere also became important for whisky production, and distilling allowed impoverished rural communities to add value to bere (Devine 1994). This provided an additional incentive for its continued cultivation and one Orkney distillery was still using it up to the early twentieth century (Martin et al. 2009).

With many periods of adverse climate through much of the last millennium, locally adapted production systems were crucial for continued growing of barley and increasing the resilience of communities in both the Faroes and Scottish Isles. Some of their main

features (Supplementary Note 4) included: selecting south-facing growing sites with a low altitude; using and maintaining well-adapted strains of barley; investing considerable labor and manure resources in the crop; developing specialized cultivation systems (*reinavelta* in the Faroes, lazy beds in parts of the Scottish Isles) and evolving a range of risk reduction strategies.

Independent of climate, a gradual decline in the cultivation of traditional types of barley in the Scottish Isles and Faroes probably started from about the beginning of the nineteenth century as a result of several factors (Supplementary Note 6) including adoption of the potato (*Solanum tuberosum* L) as an alternative food source; the development of improved trade connections reducing the need for self-sufficiency; shortages of farm labor; and changes in farming systems, including mechanization and the adoption of higher yielding barley varieties in the twentieth century.

Recent warming trends within the study area (Martin et al. 2017) are creating temperature conditions for barley cultivation which are more favorable than those experienced during much of the AD 1200–2000 period. This has already contributed to a major expansion of barley growing in Iceland (Martin et al. 2017), but the indications from the present study are that the ability of barley producers in the study area to benefit from climate warming will also, as in the past, depend significantly on other weather conditions as well as diverse socio economic and agronomic factors.

5 Conclusions

For the islands in this study, our analyses of actual and reconstructed CSDD indicated that the most favorable temperature conditions for barley production over most of the last millennium were in the Scottish Isles followed by the Faroes and then Iceland. Within Iceland, CSDD in the southwest (Reykjavik) were higher than at other locations, but multi decadal-scale changes in Icelandic temperatures caused large fluctuations in Reykjavik's suitability for barley growing. During cold periods, there was a much higher frequency of years with low CSDD when extremely poor harvests were likely. Considerably worse conditions usually prevailed at the other Icelandic sites. Particularly low CSDD occurred at Reykjavik over the periods AD 1340–1389 and 1426–1475 and may have contributed to the abandonment of barley cultivation by about AD 1500.

Despite several periods with many consecutive years of low CSDD, especially in the thirteenth century, barley cultivation was not abandoned in the Faroes until the mid-twentieth century allowing old types of Faroese barley to be conserved in gene banks. We identified a number of resilience mechanisms in the Faroes which may have assisted continued cultivation during cold periods.

The higher CSDD of the Scottish Isles allowed greater reliance on local barley for food and the production of grain surpluses in better years. This was used for export, especially in Orkney, and in most areas for brewing and distilling. The high dependence of the Isles on local cereals made them very vulnerable to poor harvests and ensuing famines. These have been well documented from the seventeenth century and about half of the affected years had low reconstructed CSDD. Although demonstrating an important temperature link, this also indicates a major contribution from other factors, several of which are discussed further in Supplementary Notes 1, 3, 4 and 5.

The survival of bere barley in cultivation through the large climatic changes of the last 800 years highlights its valuable adaptations to Scottish island conditions and its potential importance as a genetic resource for improving the resilience of modern barley.

Our research demonstrates the value of combining data from extant ancient crop types with TR data and climate records to better understand the impact of past growing conditions. For the first time, we have produced reconstructions from AD 1200 to 2000 of the annual temperature sum over the cereal cropping season for the North Atlantic islands in this study. These reconstructions and their ensuing interpretation could, however, probably be improved by further research (Supplementary Note 5), particularly: the identification of other TR or proxy temperature data more highly correlated with Faroese and, especially, Icelandic conditions; incorporating variables related to other weather factors, especially rainfall; and by more detailed analyses of historical records.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. N-TREND 2016 tree-ring data are available from: Paleo Data Search | Study | National Centers for Environmental Information (NCEI) (noaa.gov) NCairn (SCOTnc) reconstruction is available from: Paleo Data Search | Study | National Centers for Environmental Information (NCEI) (noaa.gov)

Declarations

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