

Recent warming across the North Atlantic region may be contributing to an expansion in barley cultivation

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Abstract Although grass dominates most agricultural systems in the North Atlantic region (NAR), spring barley is the most important cereal and is used for animal feed and food and drink products. Recent changes in climate have resulted in warmer conditions across the NAR which have major implications for crop production. In this paper, we investigate the thermal requirement of spring barley in the region and use the results to examine the effects of recent trends in temperature and rainfall on barley cultivation, based on 11 regional meteorological sites. At these sites, between 1975 and 2015, we found significant warming trends for several months of the cropping season and significant trends for increases in the cropping season degree days (CSDD). In recent years, this has resulted in an increased proportion of years

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when the estimated minimum thermal requirement for barley has been met at sites above about 60°N. However, annual variations in CSDD are large and years still occur at these sites where this is insufficient. While warming could potentially allow an earlier start and later end to the cropping season, it is likely that high rainfall at maritime sites, and low rainfall at continental sites, will limit the ability of growers to benefit from this. Warming is considered to have been one of the main factors contributing to the large expansion of the area of barley cultivated in Iceland since the 1990s.

1 Introduction

In most of the North Atlantic region (NAR), defined here as Newfoundland, Greenland, Iceland, coastal Norway (from Rogaland to Finnmark), the Faroes, and the Scottish archipelagos of Shetland, Orkney and the Western Isles, grassland or rough grazing dominate the agricultural area (Peltonen-Sainio 2012). Nevertheless, cereals are also common, especially spring barley, which is well-adapted to the low temperatures and short growing season of northern regions (Dofing 1992; Chappell et al. 2017). Within the region, most of the barley is grown in Iceland (2960 ha in 2015; unpublished data from Icelandic Food and Veterinary Authority), Norway (about 43,440 ha in 2015 in the coastal counties from Rogaland to Finnmark; Statistics Norway 2017) and Orkney (4260 ha in 2015; Scottish Government 2016). Elsewhere, small areas continue to be grown in Shetland and the Western Isles, early stage commercialisation has started in Newfoundland, and research trials have recently started in the Faroes and Greenland (Reykdal et al. 2016).

Although much of the NAR is at a high latitude, temperatures are milder than expected because of the Gulf Stream, and long summer days promote rapid crop growth. In parts of the region, barley has been grown for thousands of years, but even here, this can be challenging. Constraints vary with location, but the main one is the short growing season, which is also often cool, resulting in a low number of effective growing days (Trnka et al. 2011). Most areas also have difficult harvesting conditions because of high rainfall (Chappell et al. 2017). In more continental parts of the region, late frosts and dry weather after sowing can result in poor establishment (Peltonen-Sainio 2012). Considering these challenges, it is likely that the main driver for barley cultivation in the past was the isolation of this region and the need for self-sufficiency. In this respect, the versatility of barley was important as it was a source of grain for food and drink, animal feed, and straw for animal bedding and thatching. Recently, new methods of preserving high moisture grain and ensiling the crop have increased its use as an animal feed. With renewed interest in sustainability and a growing tourist market across the region for high provenance food and drink products, there has been a resurgence of interest in growing barley for these markets (Martin 2016).

The area of this study extends from 49°N (Newfoundland) to 69°N (Northern Norway). The higher latitudes are close to the limit for barley cultivation, and have been dramatically affected by previous changes in climate. Favourable conditions during the Medieval Warm period coincided with Norse colonisation of the area and an expansion of barley cultivation, including its introduction to Iceland. A return of cold, wet conditions during the Little Ice Age led to the abandonment of barley cultivation in Iceland (Sigurbjörnsson 2014) and famines in parts of the region in the sixteenth and seventeenth centuries. Recent changes in climate have seen particularly high rates of warming in northern regions (Kovats et al. 2014) which are projected to result in expansion of cropping to new areas and higher yields, partly resulting

from extended growing seasons (Bindi and Olesen 2011). While production in continental northern areas can be constrained by high summer temperatures and low rainfall (Peltonen-Sainio 2012), this does not normally affect maritime northern areas where high productivity is projected to continue with climate change (Kovats et al. 2014).

In this study, we consider the thermal requirement for growing spring barley in the NAR, analyse recent trends in temperature, rainfall and degree days during the barley growing season, and consider the implications of our results for spring barley cultivation. Since there are few published results for barley research within the NAR, we supplement our results and discussion by reference to continental northern areas, especially Finland and Alaska.

2 Methods

2.1 Study area and weather data

Average monthly temperature and total monthly rainfall data from 1975 to 2015 were obtained for 11 meteorological sites in Newfoundland, Greenland, Iceland, coastal Norway, the Faroes, Orkney, Shetland and the Western Isles of Scotland. All sites are coastal or island locations, of low elevation in the NAR (Fig. 1 and Table S1).

2.2 Barley varieties

Barley data sourced for this study come mainly from early maturing six-row (6-r) or two-row (2-r) spring barley varieties which have been grown successfully for several years in northern

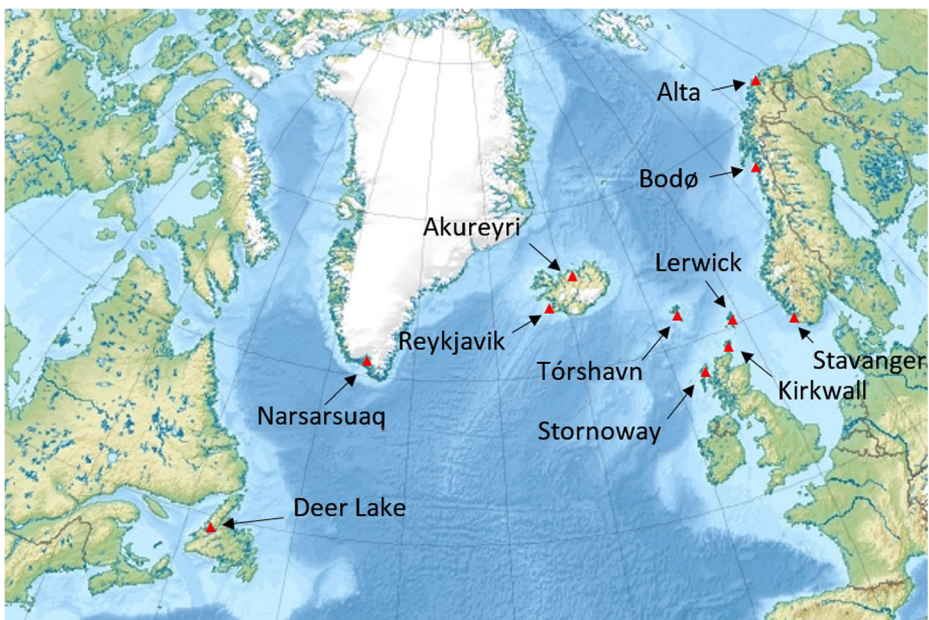


Fig. 1 Map of the North Atlantic region showing the location of meteorological sites used in this study. The figure uses a map sourced from https://commons.wikimedia.org/wiki/File:North_Atantic_Ocean_laea_relief_location_map.jpg (original author, Uwe Dederig). Accessed on 26 August 2017

regions. Iskria (2-r; released in 2005) and Tiril (6-r; released in 2006), respectively, are Icelandic and Norwegian varieties. Bere (6-r) is an ancient Scottish landrace which is still grown in Scotland's Northern and Western Isles. Tartan (2-r) is a medium-maturing modern malting variety which was given provisional approval for grain distilling in the UK in 2007 and was grown in Orkney from 2009 to 2016. Weal is a hooded 6-r barley developed in Alaska, while Galt (6-r) and Chapais (6-r) were developed in Canada and released in 1966 and 1988, respectively. Data on silage barley grown in Alberta, Canada and reported by Juskiw et al. (2001) came from three 6-r barley varieties (Brier, Duel and Tukwa) and two 2-r varieties (Manley and Seebe). These varieties are all Canadian and were released between 1989 and 1992.

2.3 Barley cropping season in the NAR

Within the NAR, the spring barley cropping season, defined here as the period from sowing to harvesting, varies as a result of differences in sowing and harvesting dates. In order to investigate the temperature sum over the cropping season, cropping season degree days (CSDD, °Cd) were calculated at each meteorological site, based on our knowledge of the approximate start of sowing and end of harvesting to the nearest half month. The start- and end-dates used for calculating CSDD at each site are given in Table S1. CSDD were calculated from the sum of the degree days in each month of the cropping season, with the total for each month (M_{DD}) calculated from:

$$M_{DD} = (T_A - 5) \times N \quad (1)$$

Where T_A is a month's average temperature (°C) and N is the number of days in that month. Equation 1 uses a base temperature of 5 °C which is commonly used for barley in northern areas (Peltonen-Sainio et al. 2009; Supplementary Note 1). When a month's average temperature was less than 5 °C, it was considered to have zero degree days. Where the date of the start of sowing or end of harvesting was the 15th of the month, the M_{DD} for that month was calculated by multiplying T_A of that month by the number of days left in the month (for sowing months) or by 15 (for harvest months).

In order to avoid confusion with CSDD, we use the term thermal requirement (TR) for the number of degree days between sowing and harvest for specific crops of barley. Day requirement (DR) is used for the number of days in this period.

2.4 Crop data for producing dry grain

There are often major differences in DR and TR of a crop depending upon whether it is being grown for dry grain or animal feed, as crops for feed are usually harvested at an earlier stage of development. For dry grain, the crop is normally allowed to ripen in the field, harvested at a low moisture content (ideally $\leq 22\%$) and then dried to about 13% for safe storage. Dried grain is required to supply higher value markets for seed, malting or milling.

Data on the DR and TR of spring barley for dry grain were obtained from several sources. From multi-locational trials established across the region in 2014 (Reykdal et al. 2016), data were selected for the varieties Bere, Iskria or Tiril at sites where they were harvested at a moisture content below 27%. From Orkney, data for DR, TR and grain yield were obtained for fields of Bere and Tartan grown by supply chains managed by the Agronomy Institute. Typically, three to five fields of each variety were grown per year (from 2003 to 2016 for

Bere and from 2009 to 2016 for Tartan). Mostly, fields were sown as early as possible each year, and since the grain was for malting, the application rate of nitrogen fertiliser was not high (averages about 50 and 65 kg N ha⁻¹ year⁻¹ for Bere and Tartan, respectively). Grain yields are presented at 15% moisture content and were calculated from the area of the field and the weight and moisture content of the grain harvested. The TR of Bere in Dundee was determined from data collected in heritage barley trials at the James Hutton Institute between 2011 and 2016, but excluding 2015.

2.5 Crop data for producing animal feed

Grain can be harvested for animal feed at about 25–35% moisture and treated with preservatives. Alternatively, the whole crop can be cut earlier, when the grain is between the milky and soft dough stage (Juskiw et al. 2001), to make silage.

The TR of silage barley is important because it represents the threshold for using barley on farms. Since we had little data on this from the NAR, we have supplemented this from trials in Alberta, Canada over 12 location-years (Juskiw et al. 2001). Averaged over these trials, the soft dough stage was reached at 1375 °Cd (at 0 °C base temperature) which was about 0.86 of the TR for mature grain (1588 °Cd). In Orkney, this stage was reached at about 0.76 of the TR for mature grain in 2 years when Tartan was used for making whole crop silage (unpublished Agronomy Institute research). In this paper, we assume that the TR for silage barley is 0.8 that for dry grain.

2.6 Data analyses

Complete data sets for monthly temperature and rainfall were obtained for all meteorological sites except Narsarsuaq and Tórshavn where data were incomplete for some months in 1 year. For these sites, data from these months and years were excluded from the analysis.

Analysis of trends in temperature, rainfall, CSDD and other derived variables with time (1975 to 2015) were performed using linear regression, treating observations between years as independent, with Genstat version 9 software (VSN International Ltd). The analyses of temperature and rainfall focused on the months from May to September because the cropping season includes these months in most of the region.

3 Results

3.1 Day and thermal requirements of barley in northern regions

Using a range of sources (Table 1), we found large differences in DR and TR (at 5 °C base temperature) of spring barley in northern regions when grown for dry grain. Much of this is associated with the latitude at which the crop is grown because of its link with important factors like temperature, day length and radiation intensity. Temperature and day length, in particular, have a strong positive effect on the rates of crop phenological phases which tend to be shorter at high latitudes, resulting in shorter cropping seasons. An extreme example of this in Table 1 is the difference between Bere grown in Orkney (142 days and 938 °Cd to harvest) and Weal in Alaska (85 days and 791 °Cd to harvest). The trend for decreasing thermal requirement of barley with increasing latitude can be seen in Fig. 2 (solid circles) for early

Table 1 Crop day and thermal requirements (5 °C base temperature) of spring barley grown in northern regions

Variety (early or late maturing)	Latitude, location and data source	Data collection period	Crop day requirement (day)	Crop thermal requirement (°Cd)
Bere, Iskria, Tiril (early)	68°N Vestvågøy, Norway (Reykdal et al. 2016)	2014	97	761
Weal (early)	64°N Fairbanks, Alaska (Sharratt et al. 2003)	1972–1989 <i>n</i> = 15	Mean: 85	Mean: 791
Galt (medium)	64°N Fairbanks, Alaska (Sharratt et al. 2003)	1972–1989 <i>n</i> = 15	Mean: 90	Mean: 837
Spring barley (early)	60–65°N Finland (Peltonen-Sainio et al. 2013)	1985–2009 (MTT Variety trials)	83–91	784–866
Spring barley (late)	60–65°N Finland (Peltonen-Sainio et al. 2013)	1985–2009 (MTT Variety trials)	96–102	913–961
Iskria, Tiril (early)	60°N Shetland, Scotland (Reykdal et al. 2016)	2014	121	859
Bere (early)	59°N Orkney, Scotland (Agronomy Institute trials)	2003–2016 (<i>n</i> = 58)	Mean: 142 Range: 104–168 SD: 12.6	Mean: 938 Range: 802–1069 SD: 68.5
Tartan (medium)	59°N Orkney, Scotland (Agronomy Institute trials)	2009–2016 (<i>n</i> = 35)	Mean: 156 Range: 135–169 SD: 9.0	Mean: 1008 Range: 847–1104 SD: 59.1
Bere (early)	56°N Dundee, Scotland (James Hutton Institute trials)	2011–2016 <i>n</i> = 5	NA	Mean: 924 Range: 733–1105 SD: 110.5
Bere, Iskria, Tiril (early)	49°N Newfoundland, Canada (Reykdal et al. 2016)	2014	117	1171
Chapais (early)	49°N Pasadena, Newfoundland (Spaner et al. 2000)	1996–1998 <i>n</i> = 8	NA	Mean: 1052 Range: 860–1119 SD: 89.5
Chapais (early)	48°N St John's, Newfoundland (Spaner et al. 2000)	1996–1998 <i>n</i> = 12	NA	Mean: 1032 Range: 903–1165 SD: 84.4

Crop thermal requirement for Weal and Galt were calculated from the average cropping season temperature and days to maturity provided in the reference

SD standard deviation

varieties reported in Table 1. The fitted line indicates a decrease in requirement of about 16.0 °Cd per 1° increase in latitude.

Even at the same location, there are differences between the DR and TR of varieties depending upon whether they are early- or late-maturing (Table 1). Figure S1 demonstrates for Bere (early-maturing) and Tartan (medium-maturing) that these differences persist over different seasons at the same site. Even for a variety grown in the same location, however, there is considerable annual variation in requirement as demonstrated in Fig. S1 and indicated

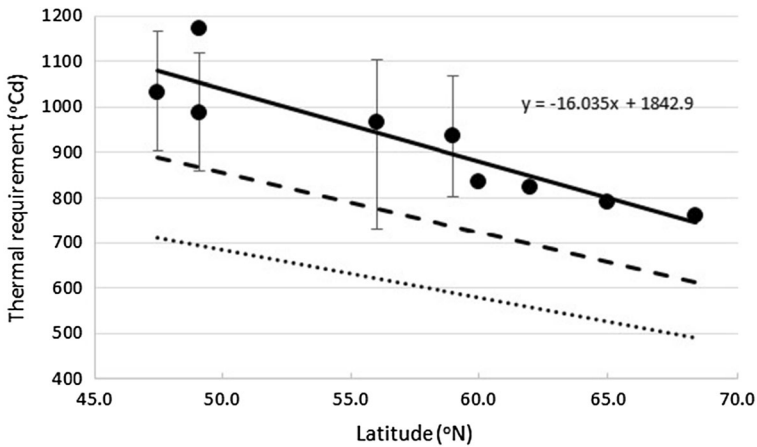


Fig. 2 Thermal requirement (5 °C base temperature) of early maturing spring barley varieties at different latitudes (solid circles), based on data in Table 1. Bars indicate the range of values where these are available. The correlation coefficient (r) is 0.905 ($p < 0.001$) and the equation and solid line is the line of best fit through the data points. The heavy dashed and dotted lines, respectively, are the estimated minimum thermal requirements for producing dry grain and silage

by the standard deviations for Bere, Tartan and Chapais in Table 1. Sowing date can be an important source of variation in both DR and TR, and for Bere grown in Orkney between 2004 and 2016 (Fig. S2), it accounted for about 25% of the variation in DR over these years. The fitted line indicated that a 10-day delay in sowing resulted in about a 6-day shorter DR. Another important source of variation in both DR and TR is the harvest date, which may be delayed by wet weather. Some variation in TR also results from using monthly average temperatures rather than daily average temperatures for calculating degree days during the months of sowing and harvesting.

Although varieties can be harvested successfully for dry grain in northern areas over a range of TR values (Table 1), Spaner et al. (2000) found the greatest yields at the highest values of TR and a positive correlation between TR and yield. This was also the case for Tartan grown in Orkney between 2010 and 2016 (Fig. S3) and yield increased by 1.1 t per 100 °Cd.

Given the large variation which occurs in barley TR from year to year at a site, it is useful to identify a minimum requirement as an indicator of the threshold for producing a successful crop. For four data sets of early varieties in Table 1, it was possible to calculate a standard deviation and therefore a coefficient of variation (standard deviation/mean), which averaged 0.089. We used the regression equation in Fig. 2 to estimate the mean TR for growing barley for dry grain at specific latitudes and then assumed a coefficient of variation of 0.089 in order to calculate a standard deviation for the requirement. The minimum requirement (the dashed line in Fig. 2) was assumed to be 2 standard deviations below the mean. We then estimated the minimum TR for making silage (the dotted line in Fig. 2) as 0.8 of the minimum value for dry grain. These results are used in Section 3.3.

3.2 Temperature and rainfall patterns across the NAR and effects on barley cultivation

There was a diverse range of monthly temperatures and rainfall at the meteorological sites (Fig. S4), and Table S1 summarises parameters derived from these data which have an important

effect on spring barley and its cultivation. At sites with more continental climates (especially Narsarsuaq, Alta and Deer Lake), winter (November to March) temperatures are low (Table S1) and spring sowing is late (mid-May to mid-June) because of the need to wait for snow to melt, the ground to thaw and some soil drying to occur. Late frosts after emergence or early frosts during grain maturation can also damage crops at these sites. At the remaining sites, suitable temperatures for sowing occur earlier, but because of high winter rainfall (Table S1), cultivations and sowing can only occur when the soil is sufficiently dry, about early-April to mid-May. After sowing, crop production is predominantly influenced by the number of degree days over the cropping season (Table S1) which is determined by its length and the summer (June to August) temperature (Table S1). This tends to be highest at continental sites and at low latitudes. During the cropping season, rainfall is often problematic—at some of the more continental sites (Narsarsuaq and Alta) and Akureyri, low and variable rainfall around sowing or during the cropping season can result in poor crop establishment and growth. At most sites, rainfall increases progressively from June to September (Fig. S4) and wet weather in August and September can make it particularly difficult to harvest dry grain. As a result of proximity to the sea, most sites are often exposed to strong winds and storms which can result in serious crop lodging near harvest.

3.3 Trends in temperature and degree days across the NAR from 1975 to 2015

Linear regression of average monthly temperatures between May and September on year showed there were several months at most sites where the regression was significant and, in all cases, the slope was positive, indicating a warming trend (Table 2). There were similarities and differences between sites in the months which were most affected. Reykjavik and Kirkwall both had significant warming trends in all months. At the other sites, most had very significant trends at the end of the growing season, in August and September, and to a lesser extent from May to July. At Narsarsuaq, warming trends were significant for the months from June to August. Averaged over sites, warming was least in May (0.22 °C per decade), intermediate from June to August (0.29–0.34 °C per decade) and highest in September (0.53 °C per decade). For the average temperature from May to September, the increase was highest at Reykjavik (0.47 °C per decade) and least at Tórshavn (0.20 °C per decade). Sowing takes place in April at some sites, and at these locations there were also significant warming trends in this month: Tórshavn, 0.36 °C per decade ($p < 0.05$); Lerwick, 0.46 °C per decade ($p < 0.001$); Kirkwall, 0.58 °C per decade ($p < 0.001$).

Linear regression of CSDD on year showed significant positive relationships ($p < 0.05$ to $p < 0.001$; Table S2 and Fig. 3) at all sites, with the greatest rates of increase at Kirkwall and Reykjavik (77.0 and 70.3 °Cd per decade, respectively) and the lowest at Akureyri and Tórshavn (31.5 and 38.3 °Cd per decade, respectively). At the remaining sites, increases were all within the range of 41.9 to 49.3 °Cd per decade. The fitted values of CSDD for 2015 (Table S2) were all substantially larger than the average for 1975 to 2015 (Table S1), but the range of recent actual values has been large and some were considerably lower than the fitted values for 2015 (Fig. 3).

Estimated minimum thermal requirements for producing dry grain and silage were calculated for each site (Table S2) using the methods outlined in Section 3.1 and were then compared with the actual site values of CSDD for the periods 1974–1994 and 1995–2015. Differences between the two periods in the percentage of years with CSDD values greater than the minimum indicate how the trend for warmer temperatures has affected the potential for

Table 2 Values for the warming trend (WT; °C per decade), correlation coefficient (*r*) and the significance (*p*), of linear regressions of average monthly temperature on year (1975 to 2015) for coastal North Atlantic meteorological sites

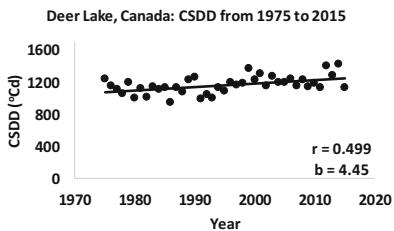
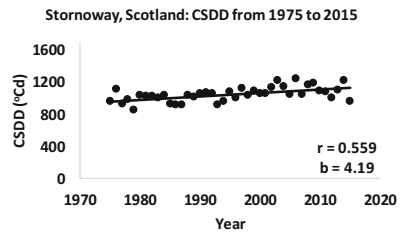
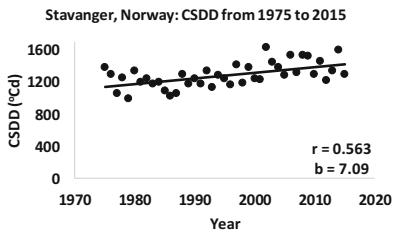
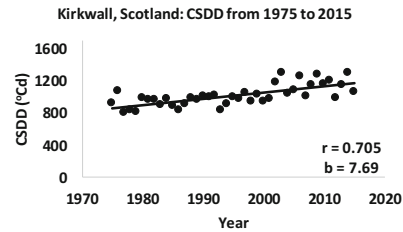
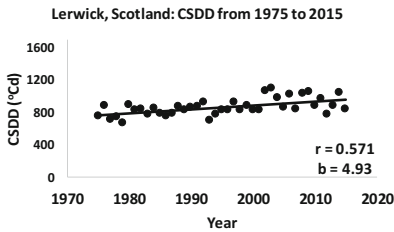
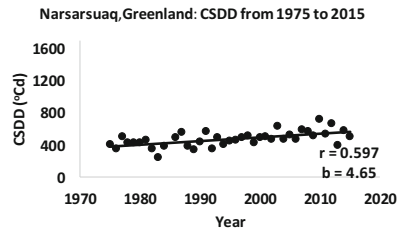
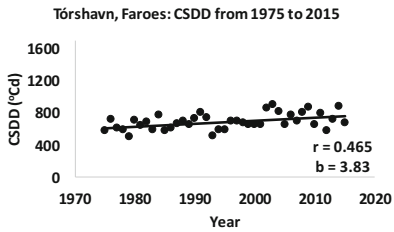
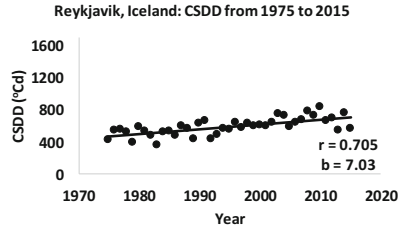
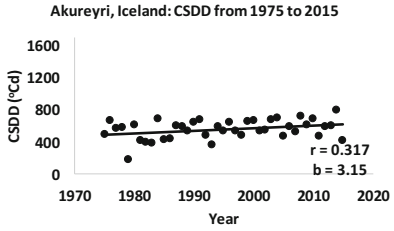
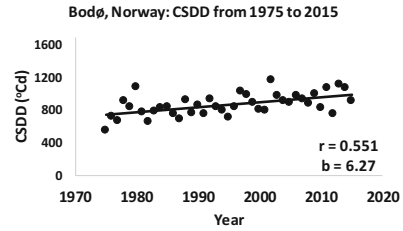
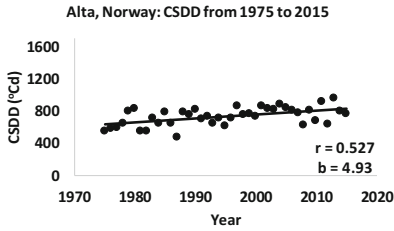
Site/(country)		May	June	July	August	September	May to September
Alta (Norway)	WT	0.32	0.32	0.30	0.40	0.61	0.37
	<i>r</i>	0.28	0.24	0.25	0.38	0.51	0.51
	<i>p</i>	0.072	0.125	0.120	0.015	0.001	0.001
Bodø (Norway)	WT	0.21	0.34	0.44	0.47	0.58	0.41
	<i>r</i>	0.18	0.26	0.32	0.41	0.56	0.55
	<i>p</i>	0.259	0.106	0.039	0.008	< 0.001	< 0.001
Akureyri (Iceland)	WT	0.15	0.28	0.12	0.13	0.79	0.29
	<i>r</i>	0.11	0.27	0.11	0.14	0.32	0.39
	<i>p</i>	0.507	0.089	0.484	0.389	< 0.001	0.011
Reykjavik (Iceland)	WT	0.30	0.54	0.49	0.42	0.60	0.47
	<i>r</i>	0.34	0.64	0.58	0.57	0.56	0.70
	<i>p</i>	0.032	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Tórshavn (Faroes)	WT	0.09	0.10	0.15	0.18	0.50	0.20
	<i>r</i>	0.13	0.15	0.26	0.31	0.64	0.44
	<i>p</i>	0.421	0.336	0.096	0.045	< 0.001	0.004
Narsarsuaq (Greenland)	WT	0.39	0.62	0.34	0.32	0.16	0.37
	<i>r</i>	0.25	0.53	0.39	0.39	0.18	0.51
	<i>p</i>	0.119	< 0.001	0.011	0.013	0.262	0.001
Lerwick (Scotland)	WT	0.21	0.18	0.28	0.27	0.45	0.28
	<i>r</i>	0.31	0.26	0.37	0.39	0.59	0.54
	<i>p</i>	0.046	0.096	0.016	0.011	< 0.001	< 0.001
Kirkwall (Scotland)	WT	0.35	0.36	0.37	0.36	0.52	0.39
	<i>r</i>	0.52	0.49	0.45	0.45	0.65	0.65
	<i>p</i>	0.001	0.001	0.003	0.003	< 0.001	< 0.001
Stavanger (Norway)	WT	0.02	0.07	0.49	0.48	0.67	0.34
	<i>r</i>	0.01	0.07	0.39	0.37	0.57	0.47
	<i>p</i>	0.925	0.684	0.012	0.017	< 0.001	0.002
Stornoway (Scotland)	WT	0.21	0.28	0.26	0.21	0.42	0.28
	<i>r</i>	0.28	0.38	0.33	0.29	0.56	0.56
	<i>p</i>	0.079	0.014	0.034	0.069	< 0.001	< 0.001
Deer Lake (Canada)	WT	0.14	0.15	0.28	0.49	0.54	0.32
	<i>r</i>	0.11	0.13	0.23	0.52	0.47	0.44
	<i>p</i>	0.493	0.405	0.149	< 0.001	0.002	0.011
Average WT across sites		0.22 (0.13)	0.29 (0.17)	0.32 (0.11)	0.34 (0.12)	0.53 (0.15)	0.34 (0.07)

Significant *p* values are highlighted in italics

growing barley (Table S2). Particularly increased suitability in the more recent period is suggested for grain at Alta and grain and silage at both Akureyri and Reykjavik. Also, there were years between 1995 and 2015 when the thermal requirement for growing silage barley was met at Narsarsuaq.

3.4 Trends in monthly rainfall in the NAR from 1975 to 2015

Since climate change is generally expected to affect rainfall and temperature, trends in monthly rainfall were also investigated (Table S3). There were only four sites where significant trends occurred and these were either negative or positive. At both Narsarsuaq and Reykjavik, the trends were negative from May to August, and while none were significant at Reykjavik, June was significant at Narsarsuaq. Also, the periods May to June, May to July and May to August all had significant negative trends ($p < 0.02$ to $p < 0.04$) at Narsarsuaq. All three sites in the



◀ **Fig. 3** Trends in CSDD from 1975 to 2015 for coastal North Atlantic meteorological sites; r and b , respectively, are the correlation coefficient and the slope of the fitted regression line

north of Scotland (Lerwick, Kirkwall and Stornoway) showed trends for reduced rainfall in September and, although this was only significant in Stornoway, it was almost significant at Kirkwall. The trend for total rainfall from May to September was not significant at any site, although it was mostly positive and was greatest (14.4 to 20.1 mm per decade) at Alta, Tórshavn and Deer Lake. At Narsarsuaq, the trend was negative (− 14.5 mm per decade).

4 Discussion

This study has combined an analysis of recent trends in warming and rainfall at sites across the NAR with an investigation into the TR of early maturing spring barley varieties at different northern latitudes to allow an initial assessment of the effects of recent warming on spring barley cultivation in the NAR. Our investigation of TR indicated a decrease in requirement of about 16.0 °Cd per 1° increase in latitude. We are not aware of any other published study on this, although unpublished data from the Institute for Plant Culture for barley grown at three locations in Norway between 60 and 67°N indicated a decrease in requirement of 14.9 °Cd per 1° increase in latitude using a base temperature of 0 °C (M Åssveen 2017, personal communication, 24 April).

At most sites in the study, there were several months between May and September where significant positive warming trends occurred and at all sites the trend was significant for the average May to September temperature. In northern regions with short cropping seasons, warming trends in spring and autumn are potentially important as they may extend its duration, making cropping more viable or secure, or allowing the use of later, higher yielding varieties (Olesen et al. 2011). Earlier planting is also often associated with higher yields (Martin et al. 2010). Elsewhere, there is evidence that sowing dates are advancing as spring temperatures increase (Kaukoranta and Hakala 2008; Olesen et al. 2011) and the positive warming trends we have identified around sowing make it likely that this is occurring in parts of the NAR. Other factors, however, like high or low rainfall, the risk of frosts, or the need to wait for some soil drying (Peltonen-Sainio and Jauhiainen 2014; Uleberg et al. 2014) may limit the ability of farmers to take advantage of warmer temperatures, but only two sites (Alta and Stornoway) had a significant trend for higher rainfall around this time.

Generally, the largest and most significant warming trends occurred towards the end of the cropping season, in August and September. In Finland, it has been argued that 15 September is the latest appropriate harvesting date (Peltonen-Sainio et al. 2009) and that this represents the end of the physiologically effective growing season. In the milder NAR, harvesting may continue in some areas into October, although with an increased risk of reduced grain quality or crop loss because of wet weather. With most sites having an average September rainfall above 80 mm and a small proportion of dry days, there are limited opportunities for later harvesting in the NAR. But, at sites like Alta and Akureyri where this is below 50 mm, it may be more feasible. Opportunities for earlier sowing or later harvesting are likely to come as narrow windows and farmers will be most able to take advantage of this if they have ready access to high-output machinery. This is only available in parts of the region, however, and would not be appropriate where field size is small.

At all sites, there was a significant trend for CSDD to increase between 1975 and 2015. At sites above 60°N, there was a higher percentage of years when CSDD were above the estimated

minimum for grain or silage in the second half of this period (Table S2), suggesting that recent warming has helped to make barley a more viable crop here. Support for this comes from Iceland where the area of barley expanded from about 100 ha in the early 1990s to between 2960 and 4250 ha in recent years (unpublished data for 2015 and 2013, respectively; Icelandic Food and Veterinary Authority). Although it does not seem likely that other increases in the barley area which have occurred in the NAR over the study period (Supplementary Note 2) can primarily be linked to warming, we believe that the trend for warmer cropping seasons is helping to expand the range of varieties which can be grown and stimulate interest in the crop amongst growers, end-users and policy makers.

In spite of the trend for CSDD to increase across the region, there is still considerable annual variation (Fig. 3), and at the more northerly sites (e.g. Iceland), years with low CSDD can still result in very poor harvests, as occurred in 2015. Annual variations in CSDD at Narsarsuaq has also meant that recent years have had CSDD values well below the minimum for silage, even though the trend line reached the estimated minimum for this in 2015 (Table S2). At this site, it is also clear from the variability of monthly average rainfall data (Fig. S4) and the trends for reduced rainfall from May to August (Table S3) that rainfall could adversely affect crop growth in some years. Low rainfall around sowing and during the cropping season could also be a constraint around Alta and Akureyri.

Although increases in CSDD are expected to result in higher yields (Bindi and Olesen 2011), this will depend upon the importance of other constraints. In Finland, only a small increase in yield was found from higher CSDD (about 0.1 t ha^{-1} per $100 \text{ }^\circ\text{Cd}$), possibly because farmers applied insufficient inputs (Peltonen-Sainio et al. 2009) or as a result of dry weather and high temperatures (Trnka et al. 2011). In Scotland, national barley yields showed no correlation with temperature, but appeared to be limited by high rainfall in July and overcast conditions from April to July (Brown 2013). Modelling has also indicated that saturated soil conditions resulting from future changes in climate may reduce yields in parts of Scotland in some years (Yawson et al. 2016). In contrast, in Alaska, low precipitation was considered to be the most important climatic limitation (Sharratt et al. 2003). While trials in Newfoundland (Spaner et al. 2000) and data for Tartan in Orkney (Fig. S3) indicated increases in yield with CSDD of $0.9\text{--}1.1 \text{ t ha}^{-1}$ per $100 \text{ }^\circ\text{Cd}$, it is clear that variable yield responses to increases in CSDD can be expected across the region and from year to year.

Early maturing varieties are important in locations where CSDD are close to the minimum requirement or early harvesting is necessary, but with increases in CSDD farmers may adopt later, higher yielding varieties (Peltonen-Sainio et al. 2013). Use of a wider range of more productive varieties could make an important contribution to higher cereal yields in the NAR as demonstrated for the Trøndelag region of Norway (Lillemo et al. 2010) where these were estimated to have contributed 78% of the yield increase observed on farmers' fields between 1980 and 2008. Increases in CSDD may provide more favourable conditions for growing more specialised varieties for dry grain, allowing growers access to higher value markets. This has happened in Orkney on a small scale since 2000, with more barley being grown for milling, malting and seed (Martin 2016).

While warmer temperatures in most of the region are likely to be associated with positive effects on barley, in some of the more continental areas excessively high summer temperatures could have adverse effects. In Finland, for example, high ($\geq 25 \text{ }^\circ\text{C}$) and very high ($\geq 28 \text{ }^\circ\text{C}$) temperatures around heading were associated with significant yield losses over a 40-year period (Hakala et al. 2012). In the NAR, temperatures above $25 \text{ }^\circ\text{C}$ can occur in July or August

in most of coastal Norway and Newfoundland. Such temperatures would be particularly serious if they coincide with low rainfall, as sometimes occurs around Alta.

This study represents a first step in understanding some of the effects of recent changes in climate on barley cultivation in the NAR. It highlights the need for more extensive information on the TR of barley for producing mature grain and silage, including that from later varieties, and the need for additional multi-locational trials across the region with common varieties to develop a more robust understanding of the growth of the crop.

5 Conclusions

Although recent temperature and rainfall trends have been described for individual countries within the NAR (Barnett et al. 2006; Hanna et al. 2004; Zhang et al. 2000), the present study is the first to specifically investigate these trends for the barley cropping season at diverse locations across the region and to explore their implications for cultivation of the crop. This was done by collecting new data on the TR of barley as part of collaborative trials across the NAR and analysing this together with limited previously published data. As a result of the study, we draw attention to the potential for increasing barley production in parts of the NAR but recognise that there are still important constraints. In particular, rainfall still challenges this—in more continental areas it can be too low and elsewhere it tends to be too high. Adverse rainfall in the spring and autumn may also limit the ability of growers to benefit from the extension of the thermal growing season. Both monthly temperature and rainfall show high variability from year to year across the region, which can result in very variable growing seasons. As a result, in continental parts of the region and above about 60°N in maritime areas, low temperatures can still seriously affect crop performance, in spite of the recent warming trend.

The capacity of different areas within the region to take advantage of warmer barley growing conditions depends on a number of factors, apart from rainfall, which vary with location and have not been included in this study. These include basic issues like the availability of suitable land, appropriate barley varieties and machinery for starting or expanding its cultivation, and local knowledge about growing and processing the crop. Market forces, particularly the high cost of imported cereals or the potential high value of niche local products can also provide an important stimulus for developing barley cultivation, reinforcing the effect of warming.

Although our study focused on spring barley, the warming trends we describe also have important implications for the growth of a wide range of other plant species across the region.

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