Northern Periphery and Arctic Programme

Northern Cereals – New Markets for a Changing Environment

RECENT WARMING AND THE THERMAL REQUIREMENT OF BARLEY IN ICELAND

Report

Deliverable T2.4.3 i

By

Peter Martin[1], John Wishart[1], Jónatan Hermannsson[2], Ólafur Reykdal[3] and Sæmundur Sveinsson[2]

[1]Agronomy Institute, Orkney College UHI, East Road, Kirkwall, Orkney, Scotland

[2]Agricultiral University of Iceland, 311 Hvanneyri, Iceland

[3]Matis, Vinlandsleid 12, 113 Reykjavik, Iceland

February 2018

Northern Periphery and Arctic Programme
Northern Cereals – New Markets for a Changing Environment
CAV Diary Number 304-8673-2014

Recent Warming And The Thermal Requirement Of Barley In Iceland – Report

Authors:

Peter Martin, John Wishart, Jónatan Hermannsson, Ólafur Reykdal and Sæmundur Sveinsson

With contributions from:

Northern Cereals Partners:

Matis – Icelandic Food and Biotech R&D

Agricultural University of Iceland

Norwegian Institute of Bioeconomy Research

Agronomy Institute, Orkney College UHI

Agricultural Centre, Faroe Islands

Forestry and Agrifoods Agency; Newfoundland and Labrador, Canada

CONTENTS

1 Introduction

The Northern Cereals project was developed to encourage greater cultivation and use of local cereals, especially barley, within the Northern Periphery and Arctic Programme area. Partners in the project include organisations from Newfoundland, Iceland, northern Norway, the Faroes, and the Scottish archipelago of Orkney. One of the drivers for the project was a common perception amongst partners that climate change was resulting in warmer growing seasons, creating more suitable conditions for cereal cultivation. Nevertheless, none of the partners had carried out detailed research into this and so an analysis of forty years of temperature and rainfall data at 11 different sites across the project area, was carried out. The analysis was made relevant to barley by focusing on the months of the cropping season and by including research data from each partner on the thermal requirement of spring barley in their region. The overall results of the analysis were included in a scientific paper (Martin et al., 2017) and, in parallel with this, partner-specific summaries have been produced for each partner so that the information can be passed on to local stakeholders. This report summarises information for Iceland.

2 Context

In spite of Iceland's high latitude, temperatures are milder than expected because of the Irminger Current, a branch of the Gulf Stream, which flows along its southern and western coast. In combination with long summer days, this can result in rapid crop growth. Norse settlement of Iceland took place at the end of the 9th century and coincided with the mild conditions of the Medieval Warm period, allowing the successful introduction of barley as a crop. A return to cold, wet conditions during the Little Ice Age led to the abandonment of barley in Iceland (Sigursbjörnsson 2014) and famines in much of the North Atlantic region in the 16th and 17th centuries. Favourable climatic conditions in the late 1950s and early 1960s encouraged a brief expansion of the barley area in Iceland to about 500 ha in 1961 (Sigurbjörnsson 2014). With a return of cold conditions later in the 1960s, only a few farmers continued to grow the crop until warmer growing seasons again returned in the 1980s and 1990s. It is estimated (Jónatan Hermannsson) that in 1990 there were only about 100 ha of barley grown but since then there has been a gradual major expansion of the crop (Reykdal 2014), peaking at 4,500 ha in 2012. The adoption of barley has been supported by an Icelandic breeding programme which released four new cultivars between 2002 and 2008 (Hilmarsson et al. 2017).

Notwithstanding the recent success in expanding barley cultivation in Iceland, there are still major constraints which Iceland shares with other parts of the North Atlantic region. 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) while in areas with a more continental climate, 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 Iceland's isolation 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).

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).

Against this background, the Northern Cereals Project provided an ideal opportunity to pool research resources across the region to investigate the temperature requirements of barley within the region and to determine how recent changes in temperature might have affected the viability of growing the crop.

3 Methods

3.1 Weather data

Average monthly temperature and total monthly rainfall data from 1975 to 2015 were obtained for 2 Icelandic meteorological sites, Akureyri and Reykjavik (Table 1).

3.2 Barley varieties

Barley data sourced for this study come 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 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. 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.

3.3 Barley cropping season in Iceland

The cropping season for spring barley is defined here as the period from sowing to harvesting. For the present analysis, we assume that in Iceland this starts on 1 May and ends on 30 September, but recognise that differences occur with location and year. In order to investigate the temperature sum over the cropping season, cropping season degree days (CSDD, ^{o}Cd) were calculated at each meteorological site, from the sum of the degree days in each month of the cropping season, with the total for each month (M_{DD}) calculated from:

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

Where, T_A is a month’s average temperature (^{o}C) and N is the number of days in that month. Equation 1 uses a base temperature of 5 ^{o}C which is commonly used for barley in northern areas (Peltonen-Sainio et al. 2009). When a month’s average temperature was less than 5 ^{o}C, it was considered to have zero degree days.

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.

Table 1. *Location of selected weather stations in Iceland and summary temperature and rainfall data (1975 to 2015) affecting the barley cropping season*

Meteorological station	Latitude, longitude and elevation	Data source	Approximate barley cropping season	November to March average temperature (^{o}C)	November to March average rainfall (mm)	Average rainfall of month of sowing (mm)	June to August average temperature (^{o}C)	June to August average rainfall (mm)	Average cropping season degree days (^{o}Cd)
Akureyri, Northeastern Region	65^{o}69' N 18^{o}07' W 23 m	Icelandic Met Office	1 May to 15 September	-0.7 (1.0)	272 (74)	22 (15)	10.4 (0.9)	90 (29)	555 (119)
Reykjavik, Capital Region	64^{o}07' N 21^{o}54' W 52 m	Icelandic Met Office	1 May to 15 September	0.6 (1.0)	414 (103)	50 (29)	10.4 (0.8)	165 (50)	590 (106)

Notes: Values in brackets are standard deviations

Table 2. *Summary site data for i) linear regression analyses of cropping season degree days (CSDD) on year and ii) analyses of the percentage of years when CSDD met the minimum thermal requirement (TR) for dry grain or silage*

	i Linear regression analyses of CSDD on year				ii Analysis of the percentage of years meeting the minimum TR for dry grain and silage					
Meteorological site	Period used to calculate CSDD	Equation for regression line, correlation coefficient (r) and p-values for the regression, and number of years of data (n)	Fitted CSDD value for 2015	Range of actual CSDD values (2010 to 2015)	Estimated minimum TR for dried grain and silage (^{o}Cd)		Percent of years minimum TR met or exceeded, 1975-1994		Percent of years minimum TR met or exceeded, 1995-2015	
					Dry Grain	Silage	Dry Grain	Silage	Dry Grain	Silage
Akureyri	1 May-30 September	$y = 3.145x - 5720$ ($r = 0.317$; $p < 0.05$; $n = 41$)	618	412-790	643	514	15	55	38	81
Reykjavik	1 May-30 September	$y = 7.030x - 13391$ ($r = 0.705$; $p < 0.001$; $n = 41$)	774	624-915	670	536	0	45	38	100

3.4 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 ≤ 22%), and then dried to about 13% for safe storage. In some northern areas, like Iceland, harvesting for dried grain may often be at a higher moisture content, however. Dried grain is required to supply higher value markets for seed, malting or milling.

Although this document deals with Iceland, Icelandic data on DR and TR were limited, and so we have supplemented it with published data from other northern areas, multi-locational trials established by project partners in 2014 (Reykdal et al. 2016), fields of Bere grown in Orkney by supply chains managed by the Agronomy Institute and trial plots grown in Dundee by the James Hutton Institute.

3.5 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 Iceland, we have used data from trials in Alberta, Canada over 12 location-years (Juskiw et al. 2001) and from Orkney (Martin et al. 2017). These indicated that the TR for silage barley is 0.8 that for dry grain.

4 Results

4.1 Day and thermal requirements of barley in northern regions

Using a range of sources (Table 3), we found large differences in DR and TR (at 5^{o}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 at which crops pass through different development stages and these tend to be shorter at high latitudes, resulting in shorter cropping seasons. An extreme example of this in Table 3 is the difference between Bere grown in Orkney (142 days and 938 ^{o}Cd to harvest) and Weal in Alaska (85 days and 791 ^{o}Cd to harvest). The trend for decreasing thermal requirement of barley with increasing latitude can be seen in Fig. 1 (solid circles) for early varieties reported in Table 3. The fitted line indicates a decrease in requirement of about 16.0 ^{o}Cd per 1^{o} increase in latitude. For Iceland's latitudinal range, Fig. 1 indicates average thermal requirements for producing dry grain from 825 ^{o}Cd in the south (63.5^{o}N) to 785 ^{o}Cd in the north (66.0 ^{o}N). It must be stressed, however, that considerable variation in this can occur in individual crops for reasons discussed below.

Table 3. *Day and thermal requirements (5 ^{o}C base temperature) of spring barley grown in northern regions*

Variety (early or late maturing)	Latitude, location and data source	Data collection period	Day requirement (d)	Thermal requirement (^{o}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)	1972-89 n=15	Mean: 85	Mean: 791
Galt (medium)	64°N, Fairbanks, Alaska (Sharratt et al. 2003)	1972-89 n=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)	2003-16 (n=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)	2009-16 (n=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)	2011-16 n=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)	1996-98 n=8	NA	Mean: 1052 Range: 860-1119 SD: 89.5
Chapais (early)	48°N, St John's, Newfoundland (Spaner et al. 2000)	1996-98 n=12	NA	Mean: 1032 Range: 903-1165 SD: 84.4

Notes: 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

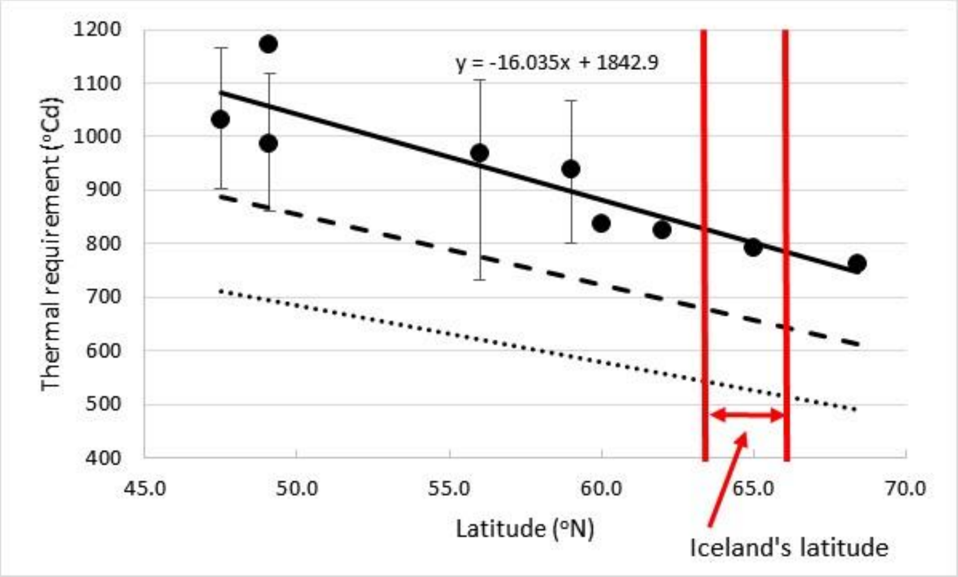
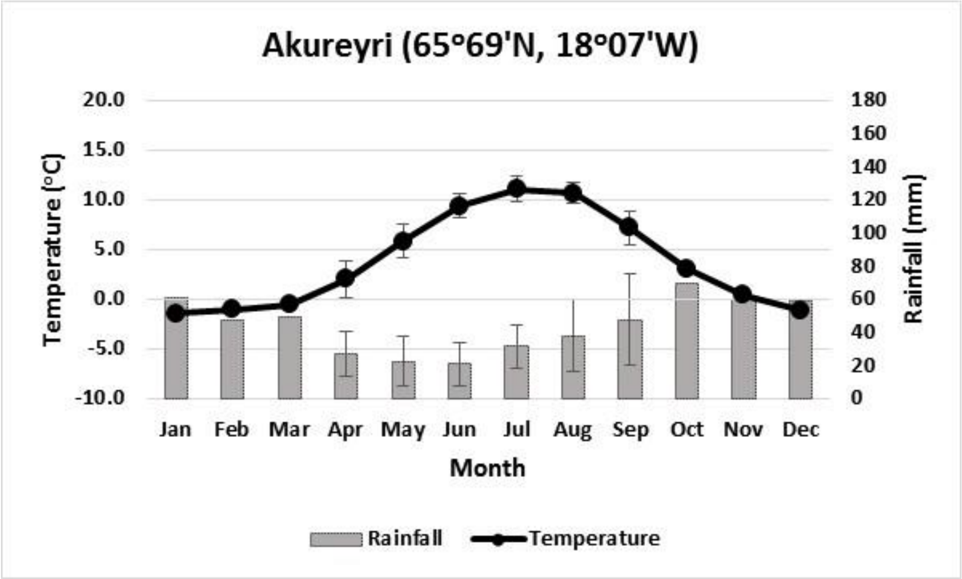


Fig. 1. *Thermal requirement (5 °C base temperature) of early maturing spring barley varieties at different latitudes (solid circles), based on data in Table 3. Bars indicate the range of values where these are available. The correlation coefficient (r) is 0.905 ($p<0.001$) and the equation and solid 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*

Even at the same location, there are differences between the DR and TR of varieties depending upon several factors. For example, early-maturing varieties have shorter requirements than late-maturing ones and late sowing can also result in a shorter requirement. In Orkney, for example, a 10-day delay in sowing Bere was associated with a 6-day shorter DR. Other important sources of variation in both DR and TR in Table 3 are the harvest date, which may be delayed by wet weather, and the grain moisture content which is considered acceptable at harvest.

Although varieties can be harvested successfully for dry grain in northern areas over a range of TR values (Table 3), 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 and yield increased by 1.1 t per 100 °Cd (Martin et al. 2017).

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. Based on the variation which occurred in TR within the data sets used in Fig. 1, the minimum requirement (the dashed line in Fig. 1) was estimated as two standard deviations below the mean. We then estimated the minimum TR for making silage (the dotted line in Fig. 1) as 0.8 of the minimum value for dry grain. These results are used in Section 4.3.



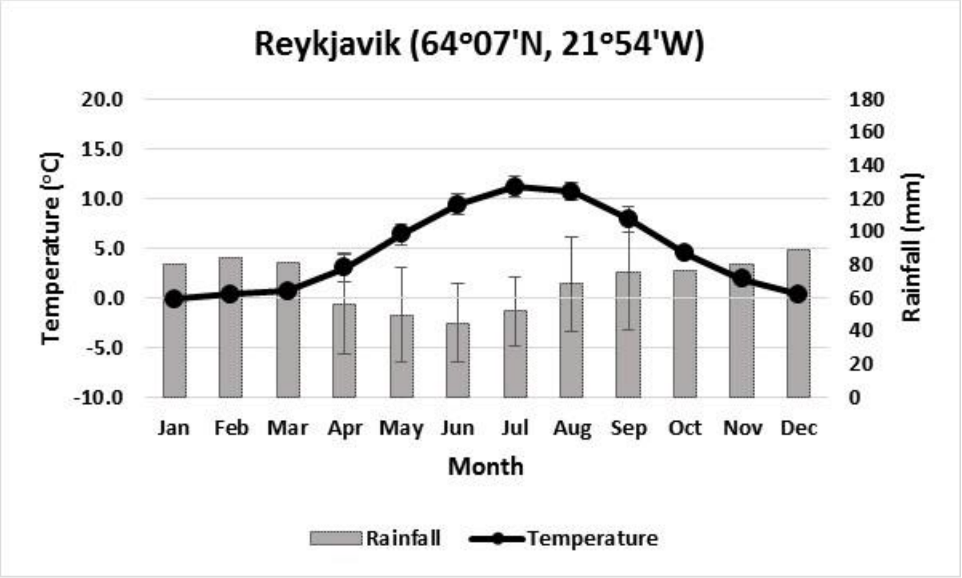


Fig. 2. *Average monthly temperature and rainfall (1975 to 2015) at Akureyri (top and Reykjavik (bottom). Bars indicate one standard deviation above and below the mean for monthly values from April to September*

4.2 Temperature and rainfall patterns at Akureyri and Reykjavik and effects on barley cultivation

Differences between temperature and rainfall patterns at Akureyri and Reykjavik (Fig. 2 and Table 1) demonstrate some of the main differences which can occur in Iceland's barley growing areas. In particular, winter (November to March) temperatures are lower in the north (Table 1) and spring sowing may be later (early to mid-May) 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. In the south of Iceland, suitable temperatures for sowing occur earlier, but because of high winter rainfall (Table 1), cultivations and sowing can only occur when the soil is sufficiently dry (mid-April to early May). After sowing, crop production is predominantly influenced by the number of degree days over the cropping season (Table 1) which is determined by its length and the summer (June to August) temperature (Table 1). This tends to be slightly higher in the south. Barley is grown in Iceland from sea level up to about 200 m and altitude, as well as latitude, will therefore affect a location's temperature. Although monthly rainfall during the cropping season at Akureyri and Reykjavik is very variable, it is normally considerably lower at Akureyri. As a result, low and variable rainfall around sowing or during the cropping season can result in poor crop establishment and growth in the north of the country while in the south high rainfall during late August and September can make harvesting difficult.

4.3 Trends in temperature and degree days at Akureyri and Reykjavik from 1975 to 2015

Linear regression of average monthly temperatures between May and September on year (Table 4) showed that only September had a significant warming trend at Akureyri, although over the entire 5 months, the warming trend was also significant. In contrast, at Reykjavik, the warming trend was significant in all months and highly significant in four of these months. At both sites, the greatest warming trends were at the end of the cropping season (September) and considerably less at the start, in May.

Linear regression of CSDD on year showed significant positive relationships ($p<0.05$ at Akureyri and $p<0.001$ at Reykjavik; Table 2 and Fig. 3), but with a much greater rate of increase at Reykjavik (70.3 ^{o}Cd per decade) than at Akureyri (31.5 ^{o}Cd per decade). The fitted values of CSDD for 2015 (Table 2) were substantially larger than the average for 1975 to 2015 (Table 1), but the range of recent actual values has been large and some were considerably lower than the trend line values (Fig. 3).

Estimated minimum thermal requirements for producing dry grain and silage were calculated for each site (Table 2) using the methods outlined in Section 4.1 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 thermal requirements indicate how the trend for warmer temperatures has affected the potential for growing barley (Table 2). Increased suitability in the more recent period is suggested for both grain and silage at both Akureyri and Reykjavik.

Table 4. *Values for the warming trend (WT; ^{o}C per decade), correlation coefficient (r) and the significance (p), of linear regressions of average monthly temperature on year (1975 to 2015) for Akureyri and Reykjavik*

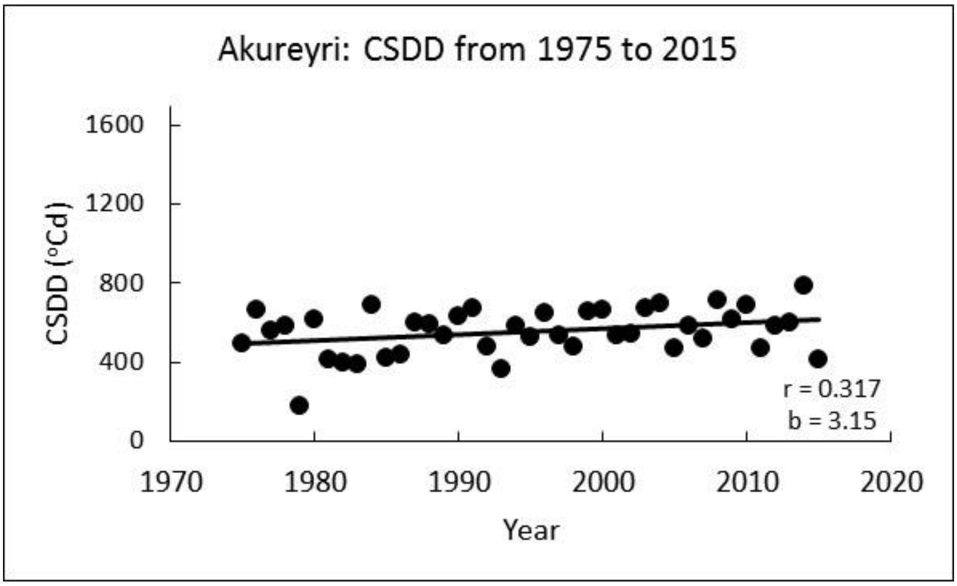
Site		May	June	July	August	September	May to September
Akureyri	WT	0.15	0.28	0.12	0.13	0.79	0.29
	r	0.11	0.27	0.11	0.14	0.32	0.39
	p	0.507	0.089	0.484	0.389	**<0.001**	**0.011**
Reykjavik	WT	0.30	0.54	0.49	0.42	0.60	0.47
	r	0.34	0.64	0.58	0.57	0.56	0.70
	p	**0.032**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

Notes: Significant p-values are highlighted in bold

Table 5. *Values for the rainfall trend (RT; mm per decade), correlation coefficient (r) and the significance (p) of linear regressions of average monthly rainfall on year (1975 to 2015) for Akureyri and Reykjavik*

Site		May	June	July	August	September	May to September
Akureyri	RT	2.2	-2.9	1.0	2.2	4.9	7.4
	r	0.18	0.27	0.09	0.12	0.21	0.23
	p	0.256	0.090	0.572	0.443	0.181	0.143
Reykjavik	RT	-1.7	-3.5	-1.1	-3.1	14.0	4.6
	r	-0.07	-0.18	-0.06	-0.13	0.47	0.08
	p	0.666	0.266	0.706	0.422	**0.002**	0.611

Notes: Significant p-values are highlighted in bold



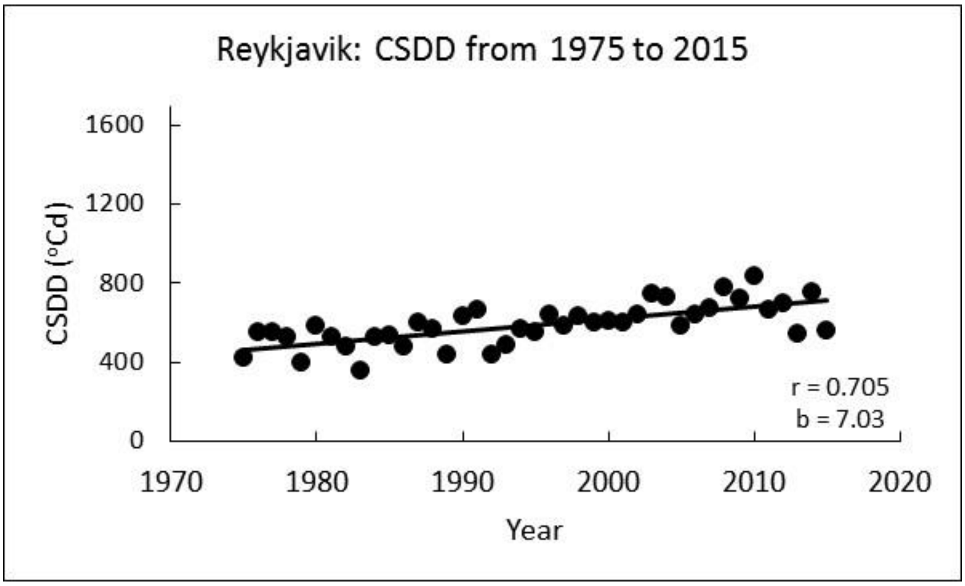


Fig. 3. *Trends in CSDD from 1975 to 2015 for Akureyri and Reykjavik; r and b, respectively, are the correlation coefficient and the slope of the fitted regression line.*

4.4 Trends in monthly rainfall at Akureyri and Reykjavik from 1975 to 2015

Since climate change is generally expected to affect rainfall and temperature, trends in monthly rainfall were also investigated (Table 5). Only September rainfall at Reykjavik showed a significant trend, and this was for an increase in rain. For all the other months at both sites the rainfall trend was small.

5 Discussion

This report has combined an analysis of recent trends in warming and rainfall at two Icelandic meteorological sites with an investigation into the TR of early maturing spring barley varieties in Iceland to allow an initial assessment of the effects of recent warming on spring barley cultivation. Our investigation of TR indicated a decrease in requirement of about 16.0 ^{o}Cd per 1^{o} increase in latitude. While this does not amount to a large difference over Iceland's latitudinal range (approximately 63.5 ^{o}N to 66.0 ^{o}N), the effect will be more important for other project partners, like Norway.

At both Akureyri and Reykjavik, the study identified very significant warming over the barley cropping season (May to September), but this was considerably more at Reykjavik (0.47 ^{o}C per decade) than at Akureyri (0.29 ^{o}C per decade). At both sites, warming was greatest and very significant in September, but it was also significant at Reykjavik in all months from May to August. Higher temperatures at the start and the end of the growing season are especially valuable in northern growing areas as they can help to extend the length of the cropping season. This can make cropping more viable or secure, or allow the use of later, higher yielding varieties (Olesen et al. 2011). Earlier planting is also often associated with higher yields (Martin et al. 2010). 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 spring temperatures.

In Finland, it has been argued that 15 September is the latest appropriate harvesting date (Peltonen-Sainio et al. 2009) as this represents the end of the physiologically effective growing season. Although higher September temperatures may extend this, in more maritime northern areas the ability of growers to exploit this may be limited by high rainfall in this month. In Iceland, this would be particularly likely in the south, where rainfall tends to be higher. In Iceland, 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 would not be appropriate, however, where field size is small. Large, heavy combines are also prone to bogging down under wet ground conditions.

At both sites, there was a significant trend for CSDD to increase between 1975 and 2015. Comparing the first and second halves of this period, there was a higher percentage of years in the second half when CSDD were above the estimated minimum for grain and silage (Table 2). This suggests that recent warming has helped to make barley a more viable crop in Iceland. Support for this comes from the expansion in the area of the crop, from about 100 ha in the early 1990s to between 2,960 and 4,250 ha in recent years (unpublished data for 2015 and 2013, respectively; Icelandic Food and Veterinary Authority). In spite of the trend for CSDD to increase, there is still considerable annual variation (Fig. 3) and years with low CSDD can still result in very poor harvests, as occurred in 2013 and 2015.

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 ^{o}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 from Orkney (Martin et al. 2017) indicated increases in yield with CSDD of 0.9-1.1 t ha^{-1} per 100 ^{o}Cd, it is clear that variable yield responses to increases in CSDD can be expected. Nevertheless, considering that CSDD are often close to the minimum for barley in Iceland, a very positive effect on yield as a result of increasing CSDD would seem likely. However, one constraint on this, especially in the north, could be low rainfall.

Early maturing varieties are important in locations, like Iceland, where CSDD are close to the minimum requirement, but with increases in CSDD farmers may adopt later, higher yielding varieties (Peltonen-Sainio et al. 2013). If warming trends continue, use of a wider range of more productive varieties could make an important contribution to higher cereal yields in Iceland 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 also provide more favourable conditions for growing more specialised varieties for dry grain, allowing growers access to higher value markets like milling, malting or seed production.

Although, other studies have investigated recent long-term changes in the Icelandic climate (Hanna et al. 2004), our study represents a first step in understanding some of the effects of recent changes in climate on barley cultivation in the country. It highlights the need for more extensive information on the TR of barley for producing mature grain and silage, particularly from a wider range of sites and varieties around the country. It would be particularly valuable, for a better understanding of the impact of climate change, if such trials could be co-ordinated with research in neighbouring countries.

Although this 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 in Iceland.

Acknowledgements

The authors would like to thank the Northern Periphery and Arctic Programme (Northern cereals - new markets for a changing environment; CAV Diary Number 304-8673-2014) and Nordic Atlantic Cooperation (NORA; Northern cereals – new opportunities. Project number 515-005) for support for this research. We are grateful to Katrin MacKenzie of Biomathematics and Statistics Scotland (BIOSS) for assistance with the analysis of the data.

References

Bindi M, Olesen JE (2011) The response of agriculture in Europe to climate change. Reg Environ Chang 11 (suppl 1):S151-S158, doi: 10.1007/s10113-010-0173-x

Brown I (2013) Influence of seasonal weather and climate variability on crop yields in Scotland. Int J Biometeorol 57:605-614. doi: 10.1007/s00484-012-0588-9

Chappell A, Scott KP, Griffiths, IA et al (2017) The agronomic performance and nutritional content of oat and barley varieties grown in a northern maritime environment depends on variety and growing conditions. J Cereal Sci 74:1-10, doi: 10.1016/j.jcs.2017.01.005

Hanna E, Jónsson T, Box JE (2004) An analysis of Icelandic climate since the nineteenth century. Int J Climatol 24:1193-1210, doi: 10.1002/joc.1051

Juskiw PE, Jame Y-W, Kryzanowski L (2001) Phenological development of spring barley in a short-season growing area. Agron J 93:370-379

Kovats RS, Valentini R, Bouwer LM et al (2014) Europe. In: Barros VR, Field CB, Dokken DJ et al (eds.) Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the IPCC. Cambridge University Press, pp 1267-1326

Lillemo M, Reitan L, Bjørnstad Å (2010) Increasing impact of plant breeding on barley yields in central Norway from 1946 to 2008. Plant Breed 129:484-490

Martin P (2016) North Atlantic cereals. Brew Distill Int 12:37-39

Martin PJ, Chang X, Wishart J (2010) Yield response of Bere, a Scottish barley landrace, to cultural practices and agricultural inputs. J Agr Env Int Dev 104:39-60

Martin PJ, Dalmansdottir S, Gerdinum JI et al (2017) Recent warming across the North Atlantic region may be contributing to an expansion in barley cultivation. Clim Chang 145: 351-365 https://doi.org/10.1007/s10584-017-2093-y

Olesen JE, Trnka M, Kersebaum KC et al (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96-112. doi: 10.1016/j.eja.2010.11.003

Peltonen-Sainio P (2012) Crop production in a northern climate. In: Meybeck A, Lankoski J, Redfern S et al (eds) Building resilience for adaptation to climate change in the agriculture sector: Proceedings of a Joint FAO/OECD Workshop, pp 183-216

Peltonen-Sainio P, Jauhiainen L (2014) Lessons from the past in weather variability: sowing to ripening dynamics and yield penalties for northern agriculture from 1970 to 2012. Reg Environ Change 14:1505-1516. doi: 10.1007/s10113-014-0594-z

Peltonen-Sainio P, Jauhiainen L, Hakala K, Ojanen H (2009) Climate change and prolongation of growing season: changes in regional potential for field crop production in Finland. Agr Food Sci Finland 18:171-190

Peltonen-Sainio P, Jauhiainen L, Niemi JK, Hakala K, Sipiläinen (2013) Do farmers rapidly adapt to past growing conditions by sowing different proportions of early and late maturing cereals and cultivars? Agr Food Sci Finland 22:331-341

Reykdal O, Kristjánsdóttir T, Hermannsson J, et al. (2014). Status of cereal cultivation in the North Atlantic region. MATIS Report 23-14. ISSN: 1670-7192. http://www.matis.is/media/matis/utgafa/23-14-NORA-NorthernCereals.pdf Accessed 12 September 2017

Reykdal O, Sveinnson S, Dalmansdóttir S, et al (2016) Northern cereals - new opportunities. Matís Report 05-16. http://www.matis.is/media/matis/utgafa/05-16-Northern-Cereals.pdf. Accessed 17 March 2017

Sharratt BS, Knight CW, Wooding F (2003) Climatic impact on small grain production in the subarctic region of the United States. Arctic 56:219-226

Sigurbjörnsson B (2014) Research on small grains in support of a short-lived renaissance in cereal production in Iceland in the 1960s and its recent revival. Rit LbhÍ nr. 52. http://www.lbhi.is/sites/default/files/gogn/vidhengi/rit_lbhi_nr__52_tilbuid.pdf. Accessed 17 March 2017

Spaner D, McKenzie DB, Todd AG et al (2000) Six years of adaptive and on-farm spring cereal research in Newfoundland. Can J Plant Sci 80:205-216

Trnka M, Olesen JE, Kersebaum KC et al (2011) Agroclimatic conditions in Europe under climate change. Glob Chang Biol 17:2298-2318. doi: 10.1111/j.1365-2486.2011.02396.x

Uleberg E, Hanssen-Bauer I, Oort B, Dalmannsdottir S (2014) Impact of climate change on agriculture in Northern Norway and potential strategies for adaptation. Clim Chang 122:27-39. doi: 10.1007/s10584-013-0983-1

Yawson DO, Ball T, Adu MO et al (2016) Simulated regional yields of spring barley in the United Kingdom under projected climate change Climate. *Climate* 2016*, 4,* 54; doi:10.3390/cli4040054