**Northern Periphery and Arctic Programme**

**Northern Cereals – New Markets for a Changing Environment**

# RECENT WARMING AND THE THERMAL REQUIREMENT OF BARLEY IN COASTAL NORWAY

## Report

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**By**

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# 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 Norway.

# 2 Context

This study covers the coastal counties of Norway, from Rogaland to Finnmark (approximately, 58°N to 70°N). In spite of this region's high latitude, temperatures are milder than expected because of the influence of the Gulf Stream, which flows northwards along Norway's western coast. In combination with long summer days and high moisture, this can result in rapid crop growth. The area of barley grown in these coastal counties increased from about 36,900 ha in 1969 to about 47,000-50,000 ha in the years between 2001 and 2011. Since then, there has been a slight decrease to about 43,400 ha in 2015. In 2015, the majority of the barley area was grown between 63˚N and 65˚N in Nord Trøndelag and Sør Trøndelag (26,677 and 13,483 ha, respectively), followed by Rogaland (1,926 ha), Møre og Romsdal (1,137 ha), Nordland (202 ha) and Hordaland (18 ha) (Statistics Norway, 2017). Very small areas were also grown in Troms and Finnmark.

While there is evidence (Soltvedt, 2000) for cereal growing at Hjelle in Sogn og Fjordane (about 62 $^{o}$N) from at least the Late Neolithic (approximately 3700 BP), it is clear that growing barley above this latitude has always been a challenge. Notwithstanding the recent expansion in barley cultivation in coastal Norway since 1969, there are still major constraints which Norway 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 the need of remote coastal communities 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 three Norwegian meteorological sites, Alta, Bodø and Stavanger (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 Norway

The cropping season for spring barley is defined here as the period from sowing to harvesting. We recognise that in Norway this varies considerably with latitude and, even in the same location, from year to year. For the present analysis, however, we assume that in Alta, Bodø and Stavanger this starts on 1 June, 1 May and 1 April, respectively, and ends on 30 September. 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 (˚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). When a month's average temperature was less than 5˚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 Norway 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 (°C) | November to March average rainfall (mm) | Average rainfall of month of sowing (mm) | June to August average temperature (°C) | June to August average rainfall (mm) | Average cropping season degree days (°Cd) |
|---|---|---|---|---|---|---|---|---|---|
| Alta, Finnmark | 69°58' N 23°21' E<br>3 m | Norwegian Meteorological Institute | 1 June to 30 September | -5.7<br>(1.6) | 163<br>(43) | 35<br>(23) | 12.0<br>(1.0) | 125<br>(49) | 729<br>(112) |
| Bodø, Nordland | 67°16' N 14°21' E<br>11 m | Norwegian Meteorological Institute | 1 May to 30 September | -0.2<br>(1.2) | 453<br>(132) | 60<br>(30) | 12.1<br>(1.2) | 216<br>(90) | 869<br>(136) |
| Stavanger, Rogaland | 58°52' N 05°38' W<br>9 m | Norwegian Meteorological Institute | 1 April to 30 September | 2.9<br>(1.5) | 542<br>(149) | 59<br>(25) | 14.3<br>(1.1) | 273<br>(65) | 1282<br>(151) |

*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 (°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 |
| Alta | 1 June-30 September | y = 4.934x – 9115 (r= 0.527; p<0.005; n=41) | 828 | 631-960 | 593 | 474 | 70 | 100 | 100 | 100 |
| Bodø | 1 May-30 September | y = 6.272x – 11643 (r= 0.551; p<0.001; n=41) | 995 | 751-1118 | 628 | 502 | 95 | 100 | 100 | 100 |
| Stavanger | 1 April-30 September | y = 7.087x – 12857 (r= 0.563; p<0.001; n=41) | 1423 | 1214-1590 | 739 | 591 | 100 | 100 | 100 | 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 Norway, 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 Norway, Norwegian 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°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 °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. 1 (solid circles) for early varieties reported in Table 3. The fitted line indicates a decrease in requirement of about 16.0 °Cd per 1° increase in latitude. For the latitudinal range between Stavanger and Alta, Fig. 1 indicates average thermal requirements for producing dry grain from 897 °Cd in the south to 720 °Cd in the north. It should be noted, however, that estimation of the value for Alta requires extrapolation of the line beyond the last data point and there is therefore some uncertainty in this value. Also, considerable variation around the values predicted by the line can occur in individual crops for reasons discussed below.

**Table 3.** *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 | Day requirement (d) | 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) | 1972-89 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<br>Range: 104-168<br>SD: 12.6 | Mean: 938<br>Range: 802-1069<br>SD: 68.5 |
| Tartan (medium) | 59°N, Orkney, Scotland (Agronomy Institute trials) | 2009-16 (n=35) | Mean: 156<br>Range: 135-169<br>SD: 9.0 | Mean: 1008<br>Range: 847-1104<br>SD: 59.1 |
| Bere (early) | 56°N, Dundee, Scotland (James Hutton Institute trials) | 2011-16 n=5 | NA | Mean: 924<br>Range: 733-1105<br>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<br>Range: 860-1119<br>SD: 89.5 |
| Chapais (early) | 48°N, St John's, Newfoundland (Spaner et al. 2000) | 1996-98 n=12 | NA | Mean: 1032<br>Range: 903-1165<br>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

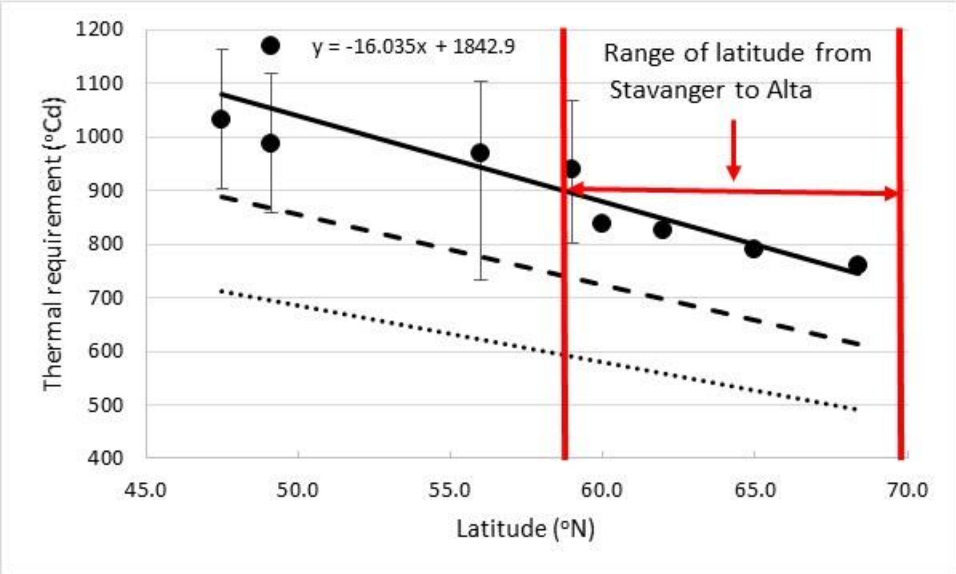


**Fig. 1.** *Thermal requirement (5 °C base temperature) of early maturing spring barley varieties at different latitudes (solid circles), based on data in Table 3. Bars indicate the range of values where these are available. The correlation coefficient (r) is 0.905 (p<0.001) and the equation and solid 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. The vertical red lines show the approximate latitudinal range of coastal Norway from Stavanger to Alta*

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.

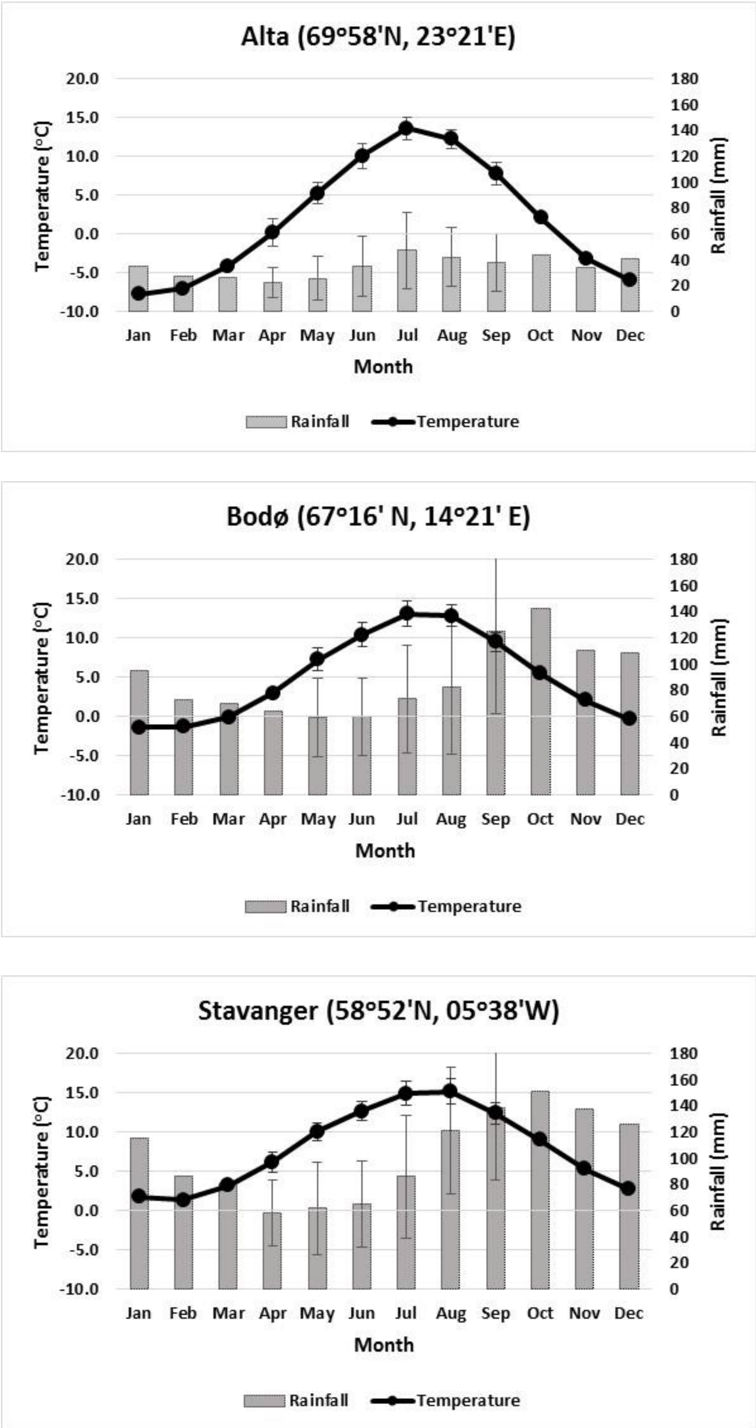


**Fig. 2.** *Average monthly temperature and rainfall (1975 to 2015) at Alta, Bodø and Stavanger. Bars indicate one standard deviation above and below the mean for monthly values from April to September*

## 4.2 Temperature and rainfall patterns at Alta, Bodø and Stavanger and effect on barley cultivation

There are major differences between temperature and rainfall patterns at Alta in Finnmark compared with Bodø and Stavanger (Fig. 2 and Table 1) and these have a marked effect on the cultivation of barley in these areas. In particular, winter (November to March) temperatures are much lower in Alta (Table 1) and spring sowing is late (early 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. Further south, 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 (approximately early May in Bodø and early April in Stavanger). 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 increases with decreasing latitude and the average (1975 to 2015) was 12.0 °C for Alta and 14.3 °C for Stavanger. Apart from latitude, however, altitude can also have a marked effect on a location's temperature, although barley is mainly cultivated at low altitudes in coastal Norway. Rainfall during the cropping season tends to decrease with increasing latitude and low and variable rainfall around sowing or during the cropping season can result in poor crop establishment and growth in the far north while in the south high rainfall during late August and September can make harvesting difficult.

## 4.3 Trends in temperature and degree days at Alta, Bodø and Stavanger from 1975 to 2015

Linear regression of average monthly temperatures between April and September on year (Table 4) showed warming trends which were significant at the 3 locations in April and, mostly, for all months from July to September. The largest warming trend at all locations was for September followed by April. At Stavanger, there was little change in the average May and June temperature over the period.

Linear regression of CSDD on year showed very significant positive relationships at all 3 sites (Table 2 and Fig. 3), with rates of increase ranging from 49.3 °Cd per decade at Alta to 70.9 °Cd per decade at Stavanger. 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). The data indicate that, even during the first period, CSDD were mostly above the threshold for both dry grain and silage production as far north as Bodø. At Alta, however, the percentage of years in which the threshold TR for dry grain production was met increased from 70% in the first to 100% in the second period, suggesting that recent warming has improved the potential for growing barley in the far north of Norway.

**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 Alta, Bodø and Stavanger*

| Site | | April | May | June | July | August | September | May to September |
|---|---|---|---|---|---|---|---|---|
| Alta | WT | 0.50 | 0.32 | 0.32 | 0.30 | 0.40 | 0.61 | 0.37 |
| | r | 0.34 | 0.28 | 0.24 | 0.25 | 0.38 | 0.51 | 0.51 |
| | p | **0.032** | 0.072 | 0.125 | 0.120 | **0.015** | **0.001** | **0.001** |
| Bodø | WT | 0.50 | 0.21 | 0.34 | 0.44 | 0.47 | 0.58 | 0.41 |
| | r | 0.41 | 0.18 | 0.26 | 0.32 | 0.41 | 0.56 | 0.55 |
| | p | **0.008** | 0.259 | 0.106 | **0.039** | **0.008** | **<0.001** | **<0.001** |
| Stavanger | WT | 0.66 | 0.02 | 0.07 | 0.49 | 0.48 | 0.67 | 0.34 |
| | r | 0.61 | 0.01 | 0.07 | 0.39 | 0.37 | 0.57 | 0.47 |
| | p | **0.001** | 0.925 | 0.684 | **0.012** | **0.017** | **<0.001** | **0.002** |

*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 Alta, Bodø and Stavanger*

| Site | | April | May | June | July | August | September | May to September |
|---|---|---|---|---|---|---|---|---|
| Alta | RT | 4.4 | 1.2 | 6.0 | 4.4 | 3.2 | -0.5 | 14.4 |
| (Norway) | r | 0.45 | 0.09 | 0.31 | 0.18 | 0.17 | -0.03 | 0.29 |
| | p | **0.003** | 0.592 | **0.048** | 0.260 | 0.292 | 0.871 | 0.064 |
| Bodø | RT | 11.4 | 4.0 | 1.7 | -3.1 | -3.4 | 4.8 | 4.0 |
| (Norway) | r | 0.40 | 0.16 | 0.07 | 0.09 | -0.08 | 0.09 | 0.04 |
| | p | **0.009** | 0.324 | 0.673 | 0.580 | 0.625 | 0.572 | 0.796 |
| Stavanger | RT | 6.8 | 2.0 | -3.2 | 6.5 | 10.7 | -5.9 | 10.1 |
| (Norway) | r | 0.32 | 0.07 | 0.12 | 0.16 | 0.27 | -0.13 | 0.11 |
| | p | **0.039** | 0.667 | 0.457 | 0.301 | 0.092 | 0.423 | 0.471 |

*Notes:* Significant p-values are highlighted in bold

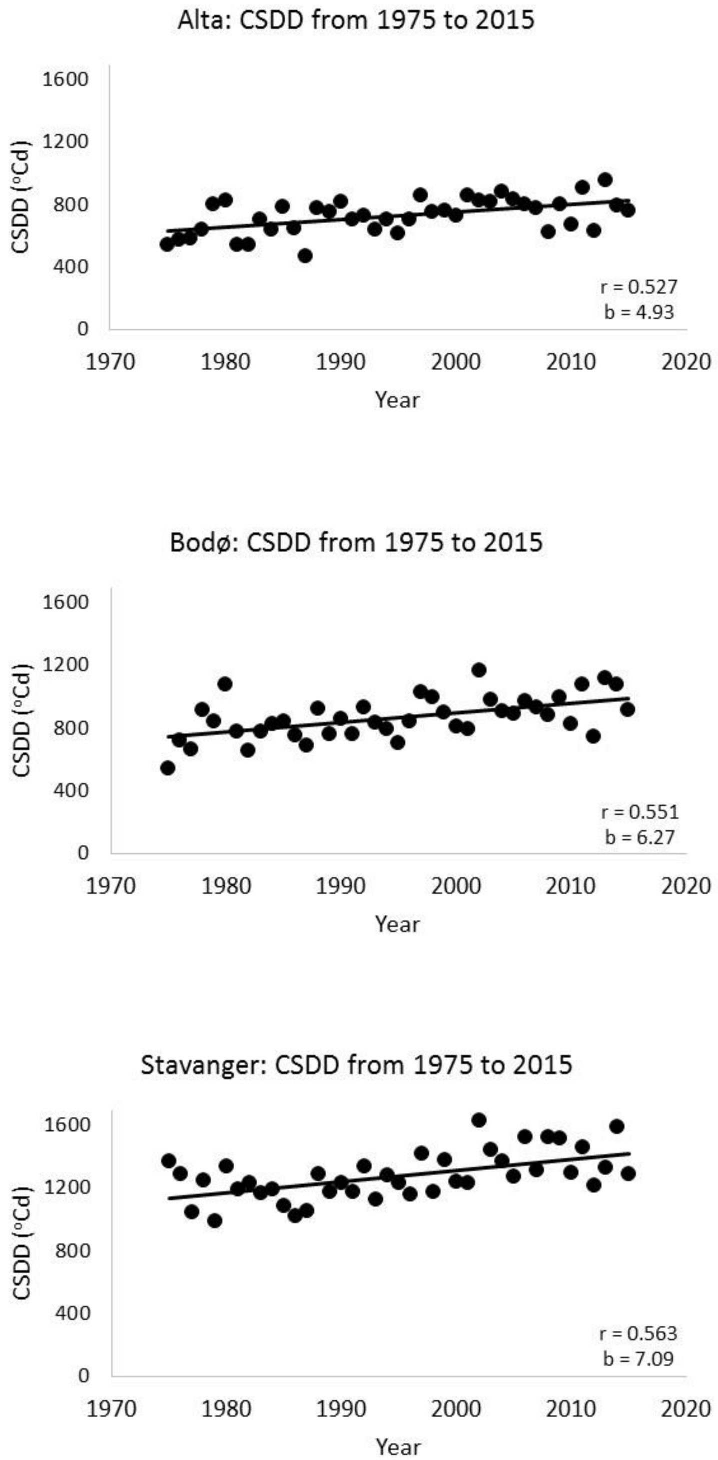


**Fig. 3.** *Trends in CSDD from 1975 to 2015 for Alta, Bodø and Stavanger); r and b, respectively, are the correlation coefficient and the slope of the fitted regression line.*

### 4.4 Trends in monthly rainfall at Alta, Bodø and Stavanger from 1975 to 2015

Since climate change is generally expected to affect rainfall and temperature, trends in monthly rainfall were also investigated (Table 5). At all sites, April showed a significant trend for increased rainfall, but in the other months only July rainfall at Alta showed a significant trend, which was for an increase. For the 3 sites the total May to September rainfall also showed a trend to increase (from 4.0 to 14.4 mm per decade), but at no site was this significant. With generally low monthly rainfalls during the cropping season, small increases in rainfall in Alta are likely to be beneficial to crop growth. On the other hand, the increase in rainfall which is indicated during August at Stavanger could make harvesting more difficult. It should be noted, though, that monthly rainfall at all locations is extremely variable as indicated by the large standard deviations in Fig. 2 and this also makes it difficult to identify significant trends.

## 5 Discussion

This report has combined an analysis of recent trends in warming and rainfall at three coastal Norwegian meteorological sites with an investigation into the TR of early maturing spring barley varieties in Norway to allow an initial assessment of the effects of recent warming on spring barley cultivation. Our investigation of TR indicated a decrease in requirement from 897 °Cd in Stavanger to 720 °Cd at Alta which equates to about 16.0 °Cd per 1$^{o}$ 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 varieties grown at three locations in Norway between 60 and 67$^{o}$N indicated a decrease in requirement of 14.9 °Cd per 1$^{o}$ increase in latitude using a base temperature of 0 °C (M Åssveen 2017, personal communication, 24 April).

At all 3 sites, the study identified very significant warming over the barley cropping season (May to September), but this was slightly higher at Alta and Bodø (0.37 and 0.41 °C per decade) than at Stavanger (0.34 °C per decade). At all sites, warming was greatest and very significant in September, but it was also significant at all sites in August and at Bodø and Stavanger in July. Significant warming trends also occurred at all sites in April, but only at the Stavanger site does sowing currently start sufficiently early to potentially benefit from this trend. 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 and it was notable that all sites showed a significant trend for increased rainfall in April.

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. With the exception of areas like Alta in the far north which have a more continental climate, this would be especially likely in much of coastal Norway where the average September rainfall exceeds 100 mm. 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 all sites, there was a significant trend for CSDD to increase between 1975 and 2015. Since CSDD at the start of this period already mostly exceeded the TR of early varieties for grain and silage at both Stavanger and Bodø, our analysis (Table 3) indicated little change in the potential for growing barley as a result of warming. At Alta, however, it indicated that warming has increased the potential for growing barley for dry grain. The effects of increases in CSDD as a result of warming are, however, likely to be more complex than the simple analysis in Table 3 suggests. Table 3 assumes the use of early maturing varieties which are important in locations, like the north of Norway, where CSDD are close to the minimum requirement, but as CSDD rise above this farmers may adopt later, higher yielding varieties (Peltonen-Sainio et al. 2013). Use of a wider range of more productive varieties can make an important contribution to higher cereal yields as demonstrated for the Trøndelag region (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 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 °Cd, it is clear that variable yield responses to increases in CSDD can be expected. In Norway, the extent to which the increase in CSDD which has been described results in higher yields will be considerably influenced by rainfall. In the extreme north, low rainfall can be a constraint at any time in the cropping season while further south high rainfall in August and September can result in delayed grain ripening, poor grain quality and difficult harvest conditions.

Although, other studies have investigated recent changes in climate in Norway (Hanssen-Bauer et al. 2010; Uleberg et al. 2014), our study makes a particular contribution to 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 coastal Norway.

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