Modelling the potential impact of recent climate change on potato, barley, and wheat yield in Norway

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Master Thesis in Climate Change Management

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Western Norway University of Applied Sciences

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Preface

This study was conducted to complete a master's degree in Climate Change Management at the Western Norway University of Applied Sciences. It was conducted over one semester and counted as 30 ECTS. Figures are produced by the author, unless stated otherwise.

Firstly, I would like to thank all teachers and students at the Department of Environmental Sciences for making these two years a great experience for me. I want to especially thank my supervisor, Mark Gillespie, and my co-supervisor, Knut Rydgren, for their valuable help during data collection, analyses, and the following thesis writing process. It has been a great honor for me to be your student and learn from you during the last months.

I would like to thank my family and friends who supported me during the last two years and encouraged me to make an effort to reach my goals; I am proud of all of you.

I dedicate my master thesis to all women in my homeland, Iran, who struggle for equality, especially my mother, for raising me to believe that everything is possible for a woman with an effort.

Sogndal, June 8, 2021

Shirin Mohammadi

Abstract

Food security and eliminating hunger are fundamental to fulfilling the global sustainable development goals, but the sensitivity of food production to climate change has made this goal challenging as it accounts for a third of yield reduction for major crops globally. Wheat, barley, and potato are three of the main crops in Norway where their cultivation is limited by low temperature, high precipitation, and limited available land. As the Norwegian agriculture area cannot expand due to limited suitable land, studies are needed to help elucidate the possibilities for improving these crops' yield by exploiting influential factors, including changes in the climate. In this study, I used statistical modelling of crop yield and climate datasets to evaluate the effect of changes in temperature and precipitation on wheat, barley, and potato yield during 1980–2018 in Norway's major crop-growing counties. The ultimate aim was to develop models that could help identify the general impact of climate change in Norway and would be useful to help predict future impacts and develop adaptation measures.

The results showed that using a single set of climate predictors for the entire country is challenging, and the impacts of climate variables on wheat, barley, and potato vary widely by county. Meanwhile, it is apparent that some counties should focus on climate change during specific crucial months that correspond with certain crop growth stages. Moreover, it seems that these crops are not under immediate threat from climate change in Norway, and other factors such as policies, management practices, and crop varieties selection are more likely to have had an impact on crop yield during the last 39 years. According to this study, climate change may present opportunities in eastern and southern parts of Norway to grow crops that require higher temperatures and opportunities in the mid and western areas to grow more barley and potato.

Samandrag på norsk

Matsikkerhet og eliminering av hungersnød er grunnleggende for å oppfylle de globale bærekraftige utviklingsmålene, men matproduksjonens følsomhet overfor klimaendringer har gjort dette målet utfordrende ettersom det utgjør en tredjedel av avkastningsreduksjonen for store avlinger globalt. Hvete, bygg og potet er tre av de viktigste avlingene i Norge, der dyrking er begrenset av lav temperatur, høy nedbør og begrenset tilgjengelig areal. Ettersom det norske landbruksområdet ikke kan utvides, er det behov for studier for å bidra til å belyse mulighetene for å forbedre avlingenes avling ved å utnytte innflytelsesrike faktorer, inkludert endringer i klimaet. I denne studien brukte jeg statistisk modellering av avlingsutbytte og klimadatasett for å evaluere effekten av endringer i temperatur og nedbør på hvete, bygg og potetutbyttet i løpet av 1980–2018 i Norges største avlsdyrkende fylker. Det endelige målet var å utvikle modeller som kan bidra til å identifisere den generelle virkningen av klimaendringene i Norge som helhet, forutsi fremtidige konsekvenser og utvikle tilpasningstiltak.

Resultatene viste at det er utfordrende å bruke et enkelt sett med klimaprediktorer for hele landet, og effekten av klimavariabler på hvete, bygg og potet varierer fra fylke til land. I mellomtiden bør noen fylker fokusere på klimaendringer i spesifikke viktige måneder som tilsvarer visse vekststadier. Videre ser det ut til at disse avlingene ikke er under umiddelbar trussel fra klimaendringene i Norge, og andre faktorer som politikk, forvaltningspraksis og utvalg av avlinger hadde en mer betydelig innvirkning på avlingens avling de siste 39 årene. I følge denne studien kan klimaendringer gi muligheter i østlige og sørlige deler av Norge til å dyrke avlinger som krever høyere temperaturer og muligheter i de nordlige og vestlige områdene for å dyrke mer bygg og potet.

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1. Introduction

Food security and eliminating hunger is a fundamental aim to fulfill the global sustainable development goals. Food production demands appropriate temperatures, adequate water, and arable soil, but sensitivity to climate change has made this production challenging (Porter et al., 2014). For example, while extreme weather events are not new to farmers, the impacts of climate change may be unprecedented in history and cause heatwaves, droughts, and heavy and prolonged precipitation in different regions with significant impacts on agricultural production (Lobell et al., 2013, Vermeulen et al., 2013). According to assessments of the Food and Agriculture Organization of United Nations (FAO), climate-related challenges are one of the leading factors of food insecurity, and it caused a third of yield reduction for major crops globally (Ray et al., 2015). This situation becomes more critical as the current global warming trend continues, and the average global temperature will likely increase 0.3 – 4.8˚C by 2100 (Zhu and Troy, 2018).

During the last twenty years, the fluctuation of crop production in various regions has contributed to a strong focus on evaluating the impact of climate change on crops at national and regional levels. These studies showed that crops respond non-linearly to climate change, and these impacts vary by prevalent local climatic conditions, crop, soil types, geography, management system, and technology (Persson and Kværnø, 2017, Rötter et al., 2013, Zhu and Troy, 2018, Ortiz, 2019). In the regions at the lower latitudes, temperatures may exceed the optimum threshold for crop productivity with only a slight increase of local temperature (1–2˚C), subsequently decreasing yield due to heat and drought stresses. However, if the local mean temperature rises by 1–3˚C at mid to high latitudes, productivity may be improved as it can provide optimum temperature for a longer growing season with fewer days of frost (Harkness et al., 2020, Seehusen and Uhlen, 2020). Therefore, regions in the mid to high latitudes with colder climates are more resilient to climate change with respect to agriculture, and moderate temperature increases and subsequent higher crop yield can be an opportunity to increase crop production (Mendelsohn, 2008, Lobell et al., 2011).

Norway's mountainous topography and large latitudinal range provide several types of climate with two strong regional climate gradients: the oceanity and temperature gradients (Moen, 1999).

These diverse climates in Norway become highly important when it comes to agricultural production. Norway has 9,863,000 decares of agricultural area (3% of total area), of which 8,072,000 decares (81%) are fully cultivated, and eastern counties with more continental and warmer climates include the highest percentage of the agricultural area by 49% (Statistics Norway, 2020). The climate condition in Norway does not allow cultivating many kinds of crops, but the three main crops are wheat, barley, and potato, which together account for 2,175,970 decares (24%) of agricultural area (Statistics Norway, 2020). These are annual crops with a growing season of four months, but their cultivation in Norway is limited by low temperature, high precipitation, and limited available land (Seehusen and Uhlen, 2020). As the Norwegian agriculture area cannot expand due to land availability, studies are needed to help elucidate the possibilities for improving these crops' yield by exploiting influential factors, including changes in the climate. Hence, we require baseline information about how wheat, barley, and potato are affected by climate change in Norway.

To the best of my knowledge, there are no studies on wheat, barley, and potato specific for Norway, where the impact of temperature and precipitation changes is explored for all major crop growing counties. Assessments in neighboring countries, such as Denmark and Finland, suggest that the response of these crops to climate change in Nordic countries may be difficult to predict, as increasing temperature may make these regions more hospitable to these crops or the optimum temperature threshold may be passed, leading to less productivity (Hakala et al., 2012, Rötter et al., 2011, Ozturk et al., 2017, Fleisher et al., 2017). Therefore, studies are needed to make an appropriate evaluation in Norway by considering the country's diverse climates and the different sensitivity of wheat, barley, and potato to temperature and precipitation variation.

In this study, I used statistical modelling of publicly available crop yield and climate datasets to evaluate the effect of changes in temperature and precipitation on wheat, barley, and potato yield during 1980–2018. I aimed to answer the following questions:

- How did wheat, barley, and potato yield change in Norway's major crop-growing counties during 1980–2018?
- What was the impact of growing season climate variables on wheat, barley, and potato yield in each county?
- What was the impact of monthly climate variables on each crop in each county?

In line with the findings from other Scandinavian countries (Jensen et al., 2021, Dijkman et al., 2017, Fleisher et al., 2017), I expected yield to increase and be positively affected by temperature and the effects to vary somewhat across counties. In some similar studies, it was shown that pooling or averaging climate variables over the entire growing season could mask effects on finer timescales (An and Carew, 2014, Lobell et al., 2007). Therefore, I hypothesized that monthly climate variables could provide a useful alternative predictor for wheat, barley, and potato yield, and their changes positively affected these crops.

The ultimate aim of this study was to develop models that could help identify the general impact of climate change on crop yield in Norway as a whole. Such a study can assist farmers, agribusiness, and policymakers develop adaptation measures and successfully manage potential climate risks in the following decades. These studies can pave the way for strategic plans to maintain agricultural productivity, minimize susceptibility, and improve the agricultural system's resilience to climate change.

2. Method

2-1. Study area

In this study, I included all counties in Norway except Nordland, Tromsø, and Finnmark, which were excluded because of the limited agricultural area in these counties. Furthermore, as some counties had an approximately similar climate, I clustered the counties into Mid, West, East, and South regions to aid later interpretation of county-level patterns. It should be mentioned that I categorized Telemark in the South region because several of the meteorological stations I used for Telemark were close to Aust-Agder. The regions and their counties are as below:

Mid: Nord-Trøndelag and Sør-Trøndelag

West: Rogaland, Sogn og Fjordane, Hordaland, Møre og Romsdal

East: Vestfold, Oslo & Akershus, Oppland, Buskerud, Østfold and Hedmark

South: Telemark, Aust-Agder and Vest-Agder

During 1980–2018, the annual mean temperature of Norway increased by approximately 1˚C, that is approximately the same as the global temperature (Norsk Klimaservicesenter, 2020). According to the climate projections, Norway's annual temperature will increase by 1.6˚C for emission scenario RCP2.6, 2.7˚C for RCP4.5, and 4.5˚C for RCP8.5 until 2100 compared to the reference period of 1971–2000 (Figure 1a). Meanwhile, the northern areas of Norway are expected to have the highest increases in annual mean temperature, while western areas will have the smallest, and the warming rate will be higher in winter than summer in all regions (Hanssen-Bauer et al., 2017).

In addition, annual precipitation in Norway increased by 18% during 1980–2018 compared to the reference period of 1971–2000, with the biggest seasonal rise in spring and the smallest in summer (Norsk Klimaservicesenter, 2020). The projection illustrates an increase of 3–14% for RCP4.5 and 7–23% for RCP8.5 until the end of the century (Figure 1b). Meanwhile, western areas are likely to have the greatest change in annual precipitation. Precipitation is expected to rise in all seasons, with the greatest increases in the eastern areas in the winter and in northern and central areas in the summer (Hanssen-Bauer et al., 2017).

From the agricultural perspective, growing season length is a critical factor in crop cultivation which is defined by the number of days with an average temperature above 5˚C (Førland et al., 2016). In comparison to the reference period (1971–2000), the growing season will get longer by 2100 in Norway (Figure 2). For emission scenario RCP4.5, the growing season will be extended by one to two months, and the expected lengthening of the growing season for RCP8.5 is nearly one month longer than for RCP4.5 (Hanssen-Bauer et al., 2017). It should be mentioned that the length of the required growing season for each crop is different, and various crops may use all the length of this period (perennial crops) or part of it (annual crops).

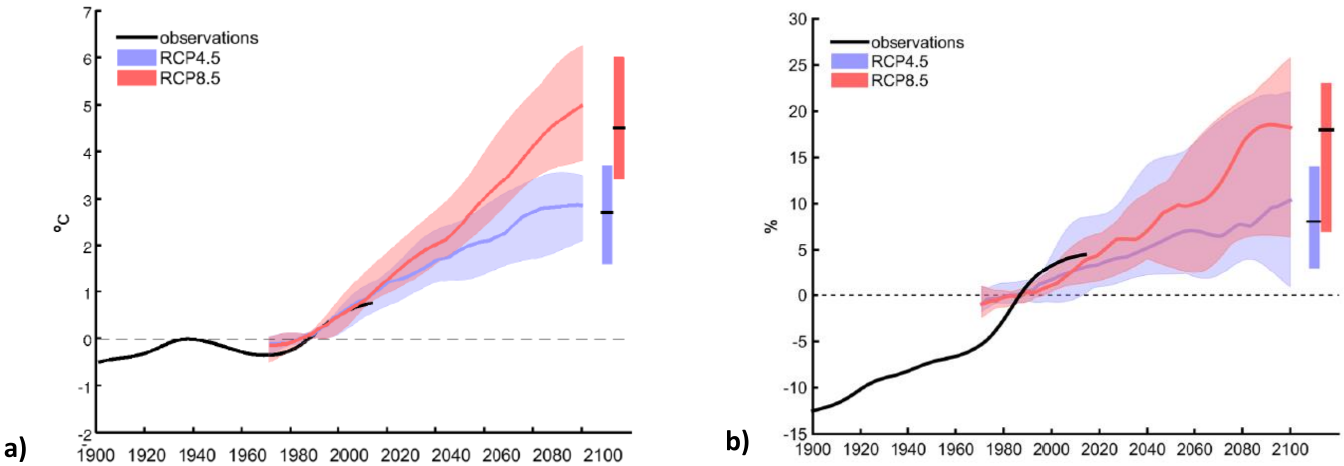

Figure 1. Annual temperature change (a) and annual precipitation change (b) for Norway compared to the reference period (1971–2000). Black curve: observations, blue and red: median value for RCP4.5 and RCP8.5, respectively. The box plots: values for 2071–2100 for both scenarios. The shaded areas illustrate the spread between low and high climate simulation (redrawn from Hanssen-Bauer et al., 2017).

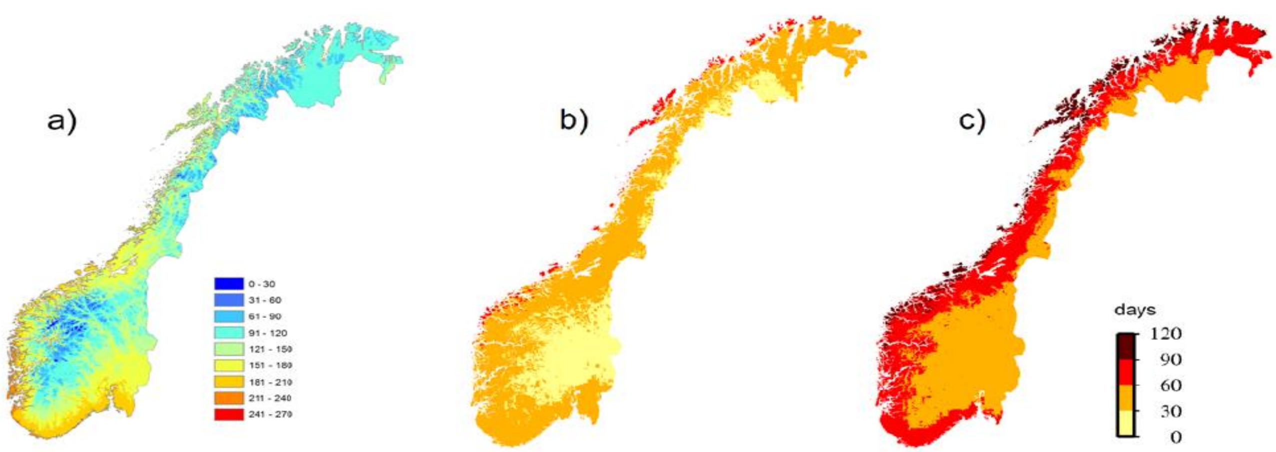

Figure 2. Length of the growing season (days) during 1971– 2000 (a), an increase in the length of growing season from 1971– 2000 to 2071– 2100 for RCP4.5 (b) and RCP8.5 (c) (redrawn from Hanssen-Bauer et al., 2017).

2-2. Study species

Barley (*Hordeum vulgare* L.) is the most important cereal crop in terms of the area and production in Norway (Statistics Norway, 2020), and the leading counties in the production of barley are Hedmark, Trøndelag, and Oslo & Akershus (Table 1). Barley's growth and development consist of five main stages: germination, stem elongation, anthesis, grain filling, and physiological maturity (Whitechurch et al., 2007, Cattivelli et al., 2011). The first two stages are the vegetative phases, the third stage denotes reproductive growth and spikelet initiation, and the fourth stage includes grain filling, which has an impact on grain size and weight (Ahmed et al., 2016). Unlike many cereal crops, barley does not flourish in hot weather especially when daily maximum temperatures surpass 24˚C, and it stops growing at temperatures over 31˚C (Hakala et al., 2012). Even though it is a rainfed crop, too much rain can negatively impact it as it is sensitive to excessive moisture but rather resistant to dry conditions (An and Carew, 2014).

Wheat (*Triticum aestivum* L.) is the second most cultivated cereal crop in Norway and is grown mainly in eastern counties, such as Østfold, Oslo & Akershus, and Vestfold (Table 1). Wheat in Norway is cultivated as a winter and spring crop, but this study assessed only spring wheat which is more common. The wheat growth cycle in Norway takes about 100–120 days and is divided into five main stages with varying sensitivity to temperature and precipitation as germination, stem elongation, anthesis, grain filling, and maturity (Ortiz, 2019, Seehusen and Uhlen, 2020). This crop can be produced in various climates, though its optimum temperature is 16–22˚C, and it is also susceptible to very hot or cold conditions since it enters dormancy below 0˚C and beyond 37˚C (Ortiz et al., 2008). Wheat is produced as a rainfed crop in Norway, and it is susceptible to lack of and excess precipitation, although drought is the most severe environmental stress to wheat (Harkness et al., 2020).

Potato (*Solanum tuberosum* L.) is the most important tuber and non-grain crop in Norway and is cultivated in most counties, especially in Hedmark, Vestfold, and Trøndelag (Table 1). The six stages of potato growth and development are tuber dormancy, sprouting and emergence, canopy development, tuberization (tuber initiation), tuber bulking, and maturity (Pulatov et al., 2015, Akoumianakis et al., 2016). The start and end of each stage, as well as the partitioning of carbohydrates, are temperature sensitive; the optimum temperature is 13–24˚C, while growth and development are negligible at average temperatures below 5˚C (Raymundo et al., 2018). Potato is irrigated in Norway and is more susceptible to inadequate and excessive water than many other crops. This sensitivity is because of a shallow root system, with 85% of roots in the upper 300 mm of soil, and potato's poor capacity to carry water from roots efficiently (Fleisher et al., 2013, Levy and Coleman, 2014).

The important point to note about these crops is that barley and potato yield in Norway is 3% and 25% higher than the global average, respectively, while wheat yield is 32% lower than global yield. Compared with Northern Europe's average, all three crops have lower yields as 60%, 32%, and 13% for wheat, barley, and potato, respectively (FAOSTAT, 2020).

Table 1. Wheat, barley, and potato area (decare) and percentage in each county in 2018. Note that Trøndelag comprises Sør-Trøndelag and Nord-Trøndelag.

County	Agricultural area (decare)	Wheat (decare)	Wheat %	Barley (decare)	Barley %	Potato (decare)	Potato %
Østfold	727136	190987	26	190994	26	4708	0.64
Oslo & Akershus	756284	99853	13	237977	31	5921	0.78
Buskerud	508924	66708	13	67961	13	2913	0.57
Hedmark	1055978	59519	6	339313	32	47656	4.51
Oppland	1002326	16838	2	139431	14	8777	0.87
Vestfold	403335	119915	30	57988	14	14351	3.55
Telemark	245677	20782	8	16789	7	1719	0.69
Aust-Agder	112711	241	0.01	1698	2	1946	1.72
Vest-Agder	188592	0	0	1957	1	912	0.48
Rogaland	996774	1118	0.01	18411	2	5526	0.55
Hordaland	408335	0	0	174	0.01	64	0.01
Sogn og Fjordane	425845	0	0	0	0	922	0.21
Møre og Romsdal	539979	0	0	9764	2	1856	0.34
Trøndelag	1605616	10535	1	395161	25	14585	0.90

2-3. Crop yield data

Annual production and harvested area of each crop during 1980–2018 were collected from Statistics Norway (Statistics-Norway, 2020), and crop yield (kg/decare) was calculated by dividing production by area in each county. Some counties lacked yield data in some years, so I selected counties with crop yield data for more than 25 years over the study period to develop more reliable models (Table 2). The wide range of findings at county levels suggested a more complex picture than that provided by focussing on Norway as a whole, so the decision was made to focus on the counties.

Table 2. Number of years of available crop yield data for each county 1980-2018 (full time series = 39 years).

County	Wheat	Barley	Potato
Aust-Agder	13	31	39
Buskerud	38	38	38
Hedmark	39	39	39
Hordaland	0	5	39
Møre og Romsdal	3	29	39
Nord-Trøndelag	26	38	38
Oppland	39	39	39
Oslo & Akershus	39	39	39
Østfold	39	39	39
Rogaland	10	36	39
Sogn og Fjordane	0	2	39
Sør-Trøndelag	14	38	38
Telemark	35	39	39
Vest-Agder	4	32	39
Vestfold	39	39	39

2-4. Climate data

In general, the growing season for annual crops is defined as the end of planting until the start of harvesting time (Najafi et al., 2018, Jensen et al., 2021). In this study, I selected May, June, July, and August for the growing season of wheat, barley, and potato based on average county-wide crop calendars, which is a common approach in these types of studies (Zhu et al., 2019, Lobell and Asseng, 2017). The important limitation in collecting climate data from the Norwegian Meteorological Institute (Norsk-Klimaservicesenter, 2020) was the lack of data in some years. Therefore, I chose meteorological stations with a record of at least 35 years and considered additional criteria such as closeness to the agricultural area and station elevations below 200 m (maximum elevation for agricultural production). Considering the lack of precipitation or temperature data in some stations, I had three sets of stations: stations with both temperature and precipitation data, stations with just precipitation data, and stations with just temperature data. All attempts were made to ensure that each county had at least 4 sets of data for temperature and precipitation to reflect the whole county's climatic condition (Appendix 1).

From each station, I collected daily minimum and maximum temperature and precipitation of the four months. As average temperature data was not available in some stations, I calculated it as ave = (min + max)/2, (min and max are the minimum and maximum daily temperature, respectively). When utilizing statistical approaches in modelling climate change, it is typical to employ growing season mean temperature and cumulative precipitation (Lobell and Burke, 2010). Hence, I calculated the mean of minimum, maximum, and average temperature of the growing season for each station and then utilized the mean values of all stations in the county for a given year. For precipitation, I calculated the sum of precipitation of each station during these four months and then used the mean of all the stations for the final precipitation data of each county.

I also required monthly climate data for each month (May, June, July, August). Therefore, I calculated monthly mean temperature variables and cumulative precipitation in the same way as described for seasonal climate variables and used the mean of all stations as representative data of the county.

2-5. Model approach

The approach of this study was using linear regression to model yield against climate variables which has become more prevalent in recent years as data on climate and crops has been more available (Lobell and Asseng, 2017). Some other studies used panel regression or ANCOVA for such assessment, including County or State as a fixed factor (Gornott and Wechsung, 2016, Gammans et al., 2017). However, unlike these studies, the climate and crop yield trends were so different in Norway at the county level, making it difficult to generalize across counties. Therefore, I decided that it would be more efficient to model the counties individually rather than together in a single model. In addition, the transparency with which statistical models analyze model uncertainty is one of their advantages. For instance, if a model fails to depict crop yield responses to climate change accurately, it will have a low coefficient of determination (R^2), and model coefficients will have large confidence intervals (Lobell and Burke, 2010).

Linear regression was based on the equation, $Y = \alpha + \beta x$, in which Y was the response variable, x the explanatory variable, β regression coefficient, and α was the intercept. The coefficient of determination (R^2) was computed to assess the predictive power of each model. Moreover, the validity of models was checked graphically for linear regression assumptions of normally distributed residuals, an equal amount of variance across fitted values (homoskedasticity), and data independence. In the time series analysis case, the independence assumption is typically violated because data close together in time are more likely to be correlated than data further apart. However, my detrending procedure (detailed below) removed the temporal autocorrelation from the residuals, as shown via a visual inspection of auto-correlation function plots. Throughout this study, the significant variables had a probability of less than 5% ($p < 0.05$), and the R programming environment was used for all analysis (R-Core-Team, 2019).

2-5-1. Climate variables and crop yield time series

In order to assess the trend of the climate variables over time in each county, I modeled each climate variable (minimum, maximum, and average temperature and precipitation) against year using linear regression. The regression coefficient in this equation depicted the changes in climate variables per year, with a negative coefficient indicating a decrease and a positive coefficient indicating an increase in climate variables measured in degrees Celsius (˚C) for temperature and millimetres (mm) for precipitation. Furthermore, the yield of each crop was modeled against year to analyze the trends in wheat, barley, and potato yield during 1980–2018, and the coefficient in this model revealed the changes in crop yield (kg/decare) per year.

2-5-2. Effect of growing season climate variables on crop yield

Crop yield changes over time may result from a combination of climate variations, changes in management practices, new technologies, or adaptation measures (Lobell and Field, 2007). Thus, the first recommended step in analyzing climate-yield relationships is to exclude the time trend in order to remove the assumed impacts of technological advances on crop yield. Detrending is the process of eliminating the effects of the temporal trend from a data series, leaving just the deviations that can be used to identify cyclical and other patterns (Gail et al., 2008). Typically, when both the response and predictor terms of a regression are time series, more reliable models are achieved by detrending both variables (Shumway and Stoffer, 2016). As a result, I had to detrend both crop yield and climatic variables (minimum, maximum, and average temperature and precipitation) in the appropriate ways.

In general, there are four methods commonly used for detrending data (Gail et al., 2008):

1) Using first difference data: the difference between each value and the value in the year before.
2) Removal of a linear trend by extracting the residuals from a linear regression of yield versus year series and interpreting the residuals as time-adjusted yield values.
3) Removal of a cubic-spline trend by extracting the residuals from an additive model of yield versus year, with a cubic-spline smoother applied to year. This is typically used if the time series exhibits a non-linear trend.
4) Inclusion of “year” as a covariate in the regression between (non-detrended) yields and climate data.

Selecting one of these methods depends on the result of three tests to determine the nature of the trend and the stationarity of the time series. Stationarity is a common assumption of many time series analysis techniques and refers to the variability of the data over time. A series is stationary when the variance of the series is equal through time, and there is no remaining trend. For my analyses, I require the data to be stationary, and this was assessed as below:

1) Plotting crop yield versus year and checking the time series visually for any linear or non-linear trend.
2) Kwiatkowski–Phillips–Schmidt–Shin test (KPSS) to evaluate two types of stationarity. First, if a time series is stationary around a mean or linear trend, it is "level stationary". Alternatively, the time series may only be "trend stationary" or stationary around a trend. In both cases, if $p > 0.05$, I accepted the null hypothesis, and the series was level/trend stationary.
3) Phillips-Perron test (PP-test) is a further test to look for a unit root in time series. The existence of unit root in a time series shows a systematic pattern that is unpredictable, and the unit root causes the non-stationarity of time series. The null hypothesis of the PP-test is that there is a unit root; therefore, the series is non-stationary. If $p < 0.05$, then I rejected the null hypothesis and accepted the alternative (there is no unit root, the series is stationary).

In all cases, the trends appeared to be linear, ruling out the need for detrending method 3 (cubic spline regression). After conducting the above tests, there were three solutions to select the detrending method:

a) If there was a unit root (PP-test, $p > 0.05$), I chose to use the first difference data.
b) If there was no unit root (PP-test, $p < 0.05$) and there was trend stationarity (KPSS test, $p > 0.05$), I chose to use the residuals of the linear regression on time.
c) If there was no unit root (PP-test, $p < 0.05$) and the data were not trend stationary (KPSS test, $p < 0.05$), I chose to use log-transformed data.

The result of tests for crop yields time series and growing season climate variables showed that there was no unit root (PP-test, $p < 0.05$), and the trends were stationary (KPSS test, $p > 0.05$). Therefore, I applied the residuals of the linear regression on time to detrend both crop yield data and climate variable data (method 2).

In the final exploratory analysis, I checked that the detrended data did not exhibit auto-correlation by using Auto-Correlation Function (ACF). Auto-correlation is a feature of data that shows the degree of similarity among the values of the same variables across subsequent time intervals (Gail et al., 2008). If there is a pattern in the time series that values in the series can be anticipated based on previous values, there is an auto-correlation in the data, and the resulting regression model will not be valid. ACF gives us the auto-correlation values of time series with its lagged values, and it plots these values along with a confidence band. An auto-correlation of +1 is a perfect positive, whereas an auto-correlation of -1 is a perfect negative correlation, but the criterion for my assessment was the commonly used values of between -0.3 and +0.3 for all lags. In all detrended variables, there was no remaining auto-correlation, and I also checked the residuals of regressions for auto-correlation, and it did not exist too.

In summary, in the equation for these linear regression models, Y represents the detrended crop yield (kg/decare), α is the intercept, x is detrended temperature and precipitation variables, and β is the coefficient that implies the amount of deviation in crop yield (kg/decare) from the trend by each degree (or mm) of deviation from the trend in temperature (or precipitation). This interpretation of the regression coefficients is rather difficult to comprehend. However, as discussed by Lobell et al. (2007), the interpretation of the regression coefficients from these types of models is that positive (or negative) coefficients indicate a positive (or negative) impact of climate on crop yield.

2-5-3. Effect of monthly climate variables on crop yield

In the last stage of analysis, to test the importance of the intra-seasonal variation of climate, the growing season temperature and precipitation variables in the equations were replaced with the detrended monthly precipitation and temperature, and new regressions were computed.

As monthly climate variables might be highly correlated with each other, the following model selection procedure was employed to avoid collinearity. The first step in developing these models was to select the best monthly climate variables for each county as the explanatory variable. Running models for every month would have been very time-consuming and increased the risk of making a Type I error. There was also the chance that temperature from one month and precipitation from another was a better predictor. Therefore, I used the Pearson Correlation Coefficient test to select the best monthly climate variables and used them as the model's explanatory variables. The criterion for selection in each county was to have the highest correlation coefficient with crop yield, and in some cases, some monthly variables had the same coefficients, so I used them together. However, in each month, the minimum, maximum, and average temperature showed high collinearity, and I could not use them in the same model. Therefore, I developed models for them individually and chose the valid model with the highest R^2 as the best model.

I ran the KPSS test, PP-test, and ACF plot for each of the selected monthly variables, and they showed that there was no unit root (PP-test, $p < 0.05$), the trend was stationary (KPSS test, $p > 0.05$), and ACF plot showed no auto-correlation. Therefore, I applied the residuals of the linear regression on time for detrending monthly climate variables.

I had to develop the best model for each crop, so I started with the model that included all the selected detrended monthly variables (maximum three variables) as this equation, $Y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$. In this model, Y was the crop yield, β_1, β_2, and β_3 were the regression coefficient of the first, second, and third monthly climate variables (where applicable), and x_1, x_2, and x_3 were the selected monthly climate variables. Then I used backward stepwise selection, a process by which variables were sequentially removed from the model and the subsequent models compared with a log-likelihood test to determine if the variable should be retained in or removed from the model (Gail et al., 2008). The final "minimum adequate model" was then the one with only significant variables remaining.

It should be mentioned that in all models related to the effect of the growing season and monthly climate variables, I standardized climate variables before constructing the models to put the variable in units of standard deviations and plot them on the same graph, which made the comparison easier. This means that for each value, I subtracted the mean and divided by the standard deviation of the variable, so a value of 1 was 1 standard deviation above the mean.

3. Results

In this part, I firstly describe the result of the climate variables time series, then the results of the yield time series and the effect of the growing season and monthly climate variables will be described for each crop separately.

3-1. Climate variables time series

Over the growing season (May–August) during 1980–2018, the average temperature increased in all regions significantly except in Buskerud and Oslo & Akershus in the East region that had a non-significant increase (Figure 3). Nonetheless, the rate of increase was different in various regions, and there was not a consistent trend. Moreover, the scatterplots showed that some years were extreme years; in the East and South, the growing season of 1987 was very cold, whereas 2018 was very warm, and in the Mid and West, 2002 was extremely warm.

Precipitation increased in all regions except in the Mid that showed a decreasing trend (Figure 4). However, these changes were just significant in two counties in East, Oppland ($\beta = 0.35 \pm 0.15$ s.e., $p = 0.02$) and Oslo & Akershus ($\beta = 0.35 \pm 0.15$ s.e., $p = 0.02$). The scatterplots showed that precipitation was highly scattered in all regions, and 2018 was an extremely dry year in East and South (Appendix 2 and 3).

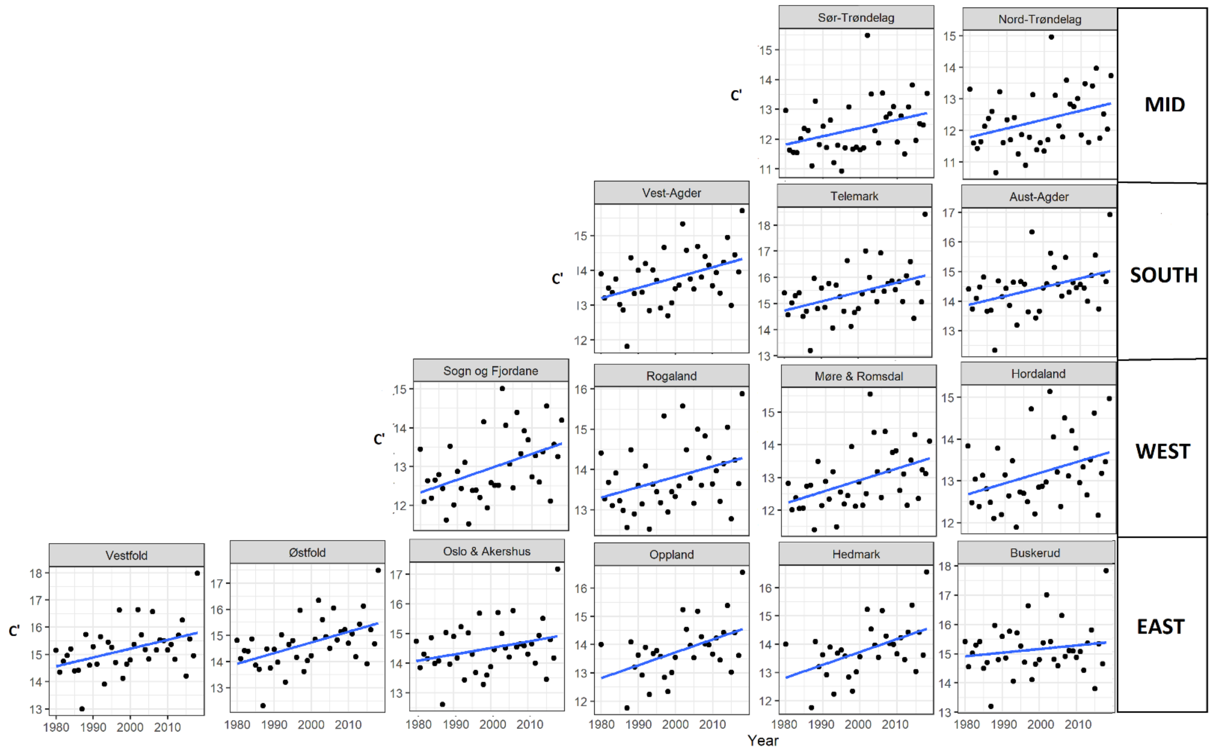

Figure 3. Scatterplots of average temperature change across the growing season (1980–2018) with the best-fit linear regression (blue line). Counties are organized by region (MID, SOUTH, WEST, EAST).

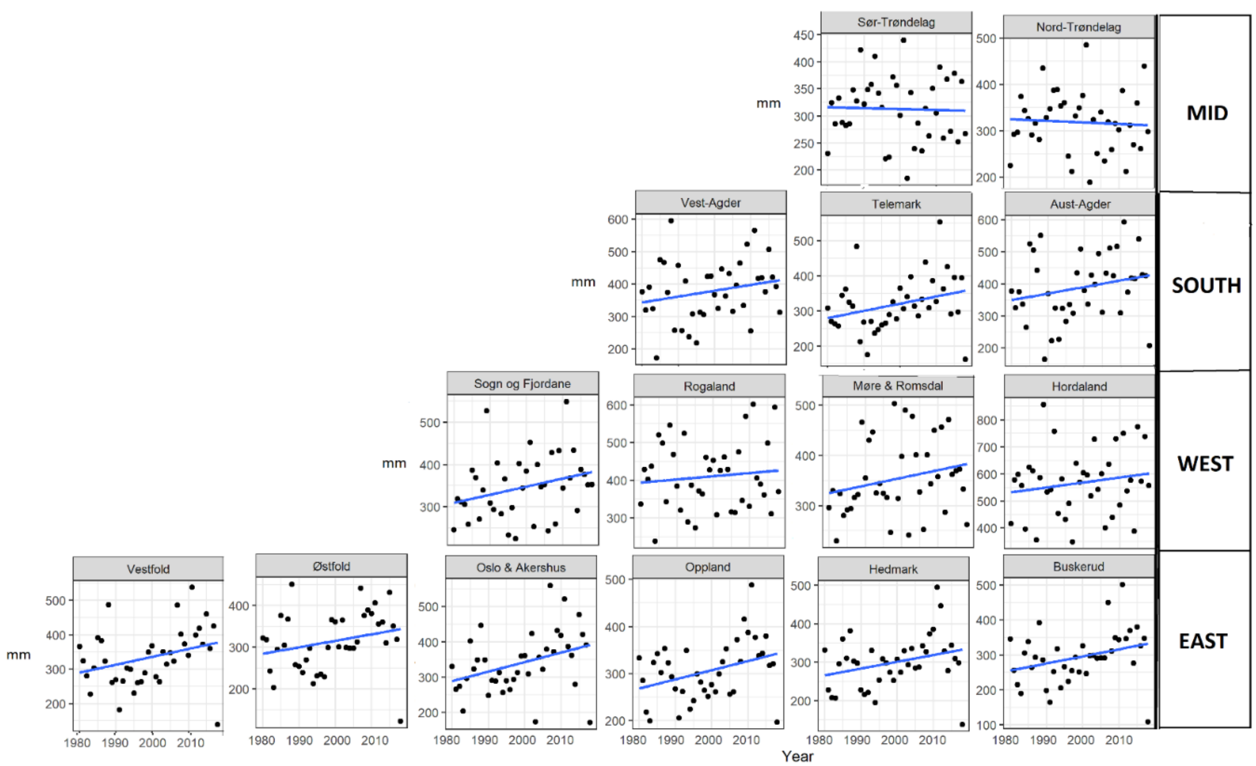

Figure 4. Scatterplots of precipitation change across the growing season (1980–2018) with the best-fit linear regression (blue line). Counties are organized by region (MID, SOUTH, WEST, EAST).

3-2. Crops

3-2-1. WHEAT

3-2-1-1. Wheat yield time series

Wheat yield varied considerably between years and between regions, but changes were not significant for any regions (Figure 5). However, the trends were decreasing in the Mid and South regions and both decreasing and increasing in the East. Wheat yield time series was highly scattered in all regions; East had the least wheat yield in 2018 while South experienced the least yield in 1993 and 2018. Therefore, I excluded 2018 as an extreme year, and while this could improve the model performance and lead to the increasing trend in the East and South, the trend was still not significant (Appendix 4 and 5).

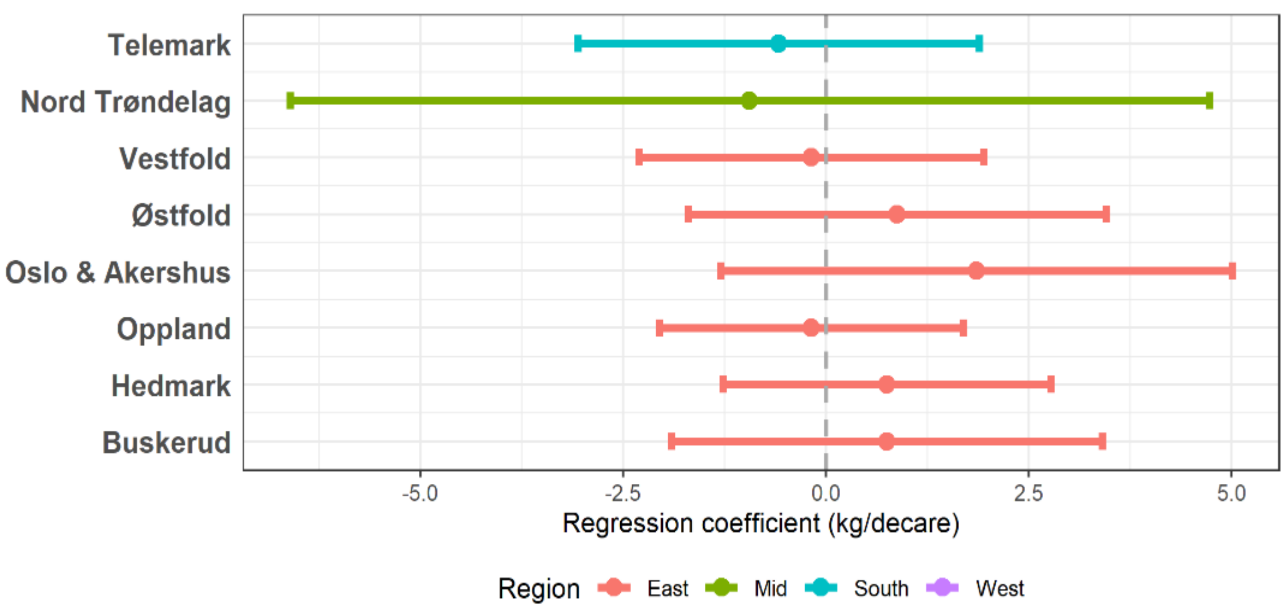

Figure 5. Regression coefficients and 95% confidence intervals from individual linear models of annual wheat yield against year (1980–2018) for the main wheat-growing regions in Norway. Coefficients are colored according to Region for comparison with other results.

3-2-1-2. Effect of growing season climate variables on wheat yield

Wheat yield was affected negatively in all regions by increasing temperature during the growing season, but this negative effect was just significant in some of the East counties, i.e., Buskerud and Oppland (Figure 6). The highest significant reduction belonged to the average temperature in Buskerud ($\beta = -0.38 \pm 0.16$ s.e., $p = 0.02$). Considering the standardized coefficient (β), by each unit increase in average temperature anomaly, yield anomaly was likely to decrease by 0.38 standard deviations. Precipitation had no significant effect in any of the regions; however, the trend was positive in the Mid and negative in the South, whereas East counties showed both trends (Appendix 6).

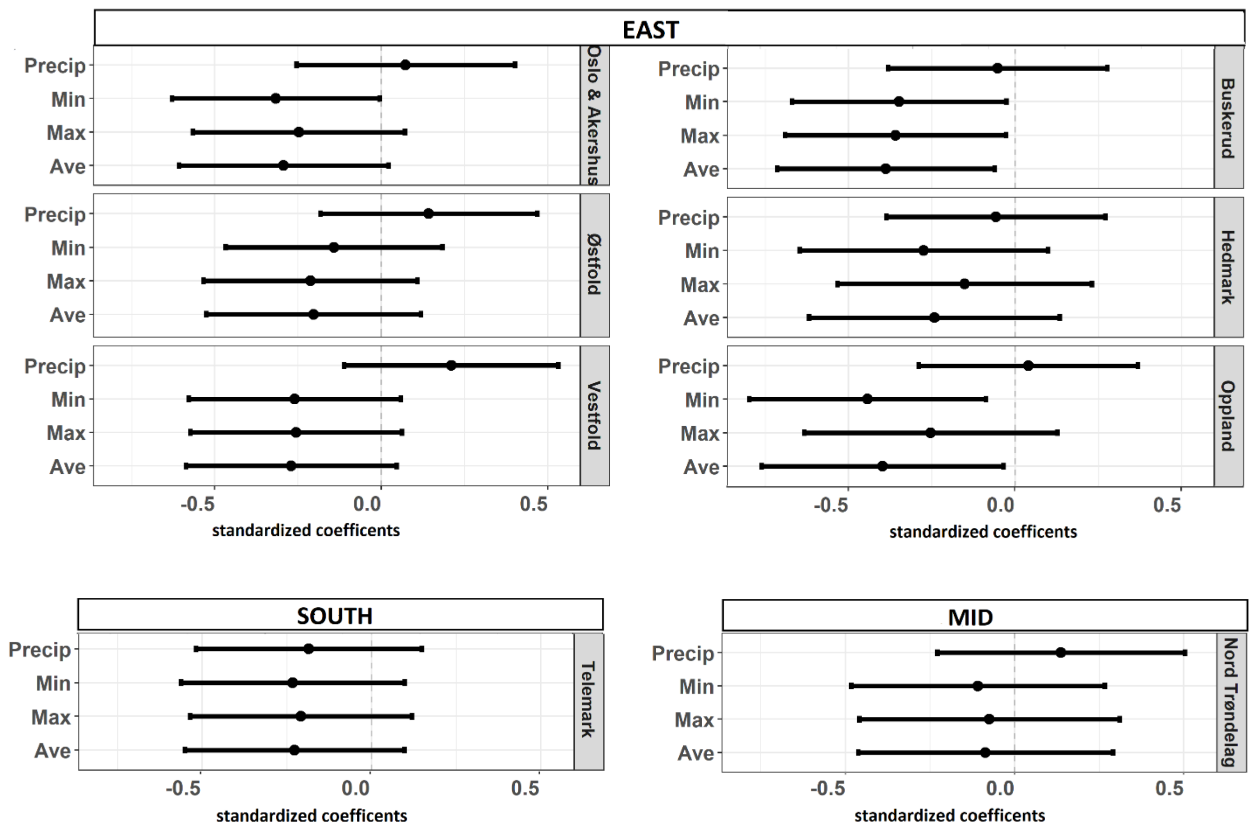

Figure 6. Standardized regression coefficients and 95% confidence intervals of individual linear regression models between detrended wheat yield and detrended growing season climate variables (Precip: precipitation, Min: minimum temperature, Max: maximum temperature, Ave: average temperature). Coefficients are standardised (y – mean/sd) in order to compare precipitation and temperature on the same plot. Counties are organized by Region for comparison with other results.

3-2-1-3. Effect of monthly climate variables on wheat yield

Monthly temperature variables with the highest Pearson correlation coefficients (Appendix 7) showed more significant effects on wheat yield than those of the whole growing season in East and South (Figure 7). Monthly temperatures improved the R^2 of the models with smaller confidence intervals compared to the growing season models. May was a critical month for wheat, and the increasing temperature in May had a significant negative effect in both East and South. However, there were different significant coefficients for the minimum and average temperatures, and the biggest significant negative effect was in the South (β = -0.66 ± 0.13 s.e., $p < 0.001$). It's worth noting that none of the monthly precipitation variables were highly correlated with wheat yield; hence they weren't used as explanatory variables in the models (Appendix 8).

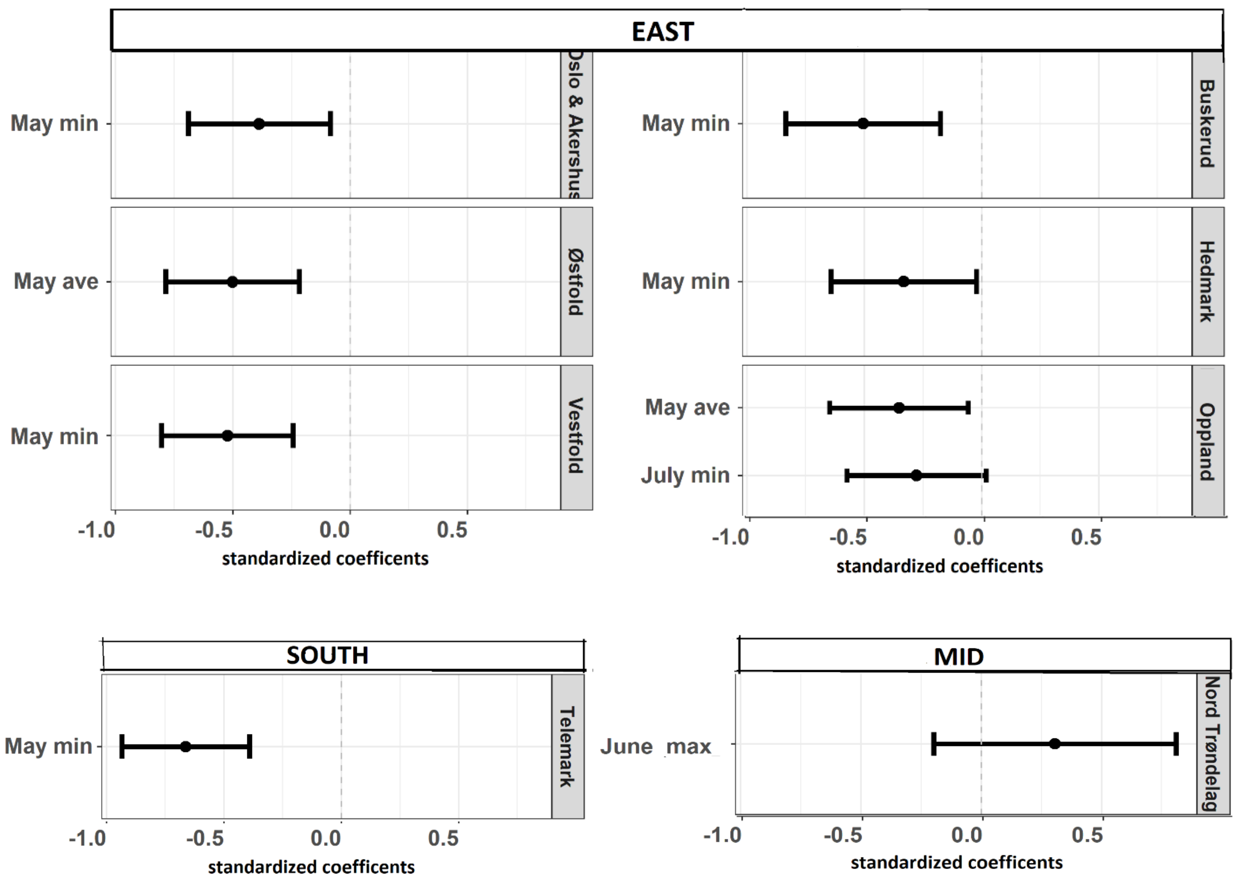

Figure 7. Standardized regression coefficients and 95% confidence intervals of individual linear regression models between detrended wheat yield and detrended monthly climate variables (min: minimum temperature, max: maximum temperature, ave: average temperature).

3-2-2. BARLEY

3-2-2-1. Barley yield time series

Barley yield time series showed a significant positive trend in Mid and negative in the South, while in other regions, the trends were not consistent and mostly non-significant (Figure 8). The highest significant increase was in the Mid, Nord-Trøndelag (β = 2.20 ± 0.60 s.e., p = 0.001) and the highest significant decrease was in the South, Vest-Agder (β = -2.62 ± 1.22 s.e., p = 0.04). Barley in the East and West regions had the lowest yield in 2018, and it was an extreme year. Therefore, excluding 2018 from the model changed the yield trend in some regions; it resulted in an increasing trend in the West (in Rogaland), increased the coefficients toward a more positive trend and smaller confidence intervals in the East region, and led to the significant increase in Oppland (Appendix 9 and 10).

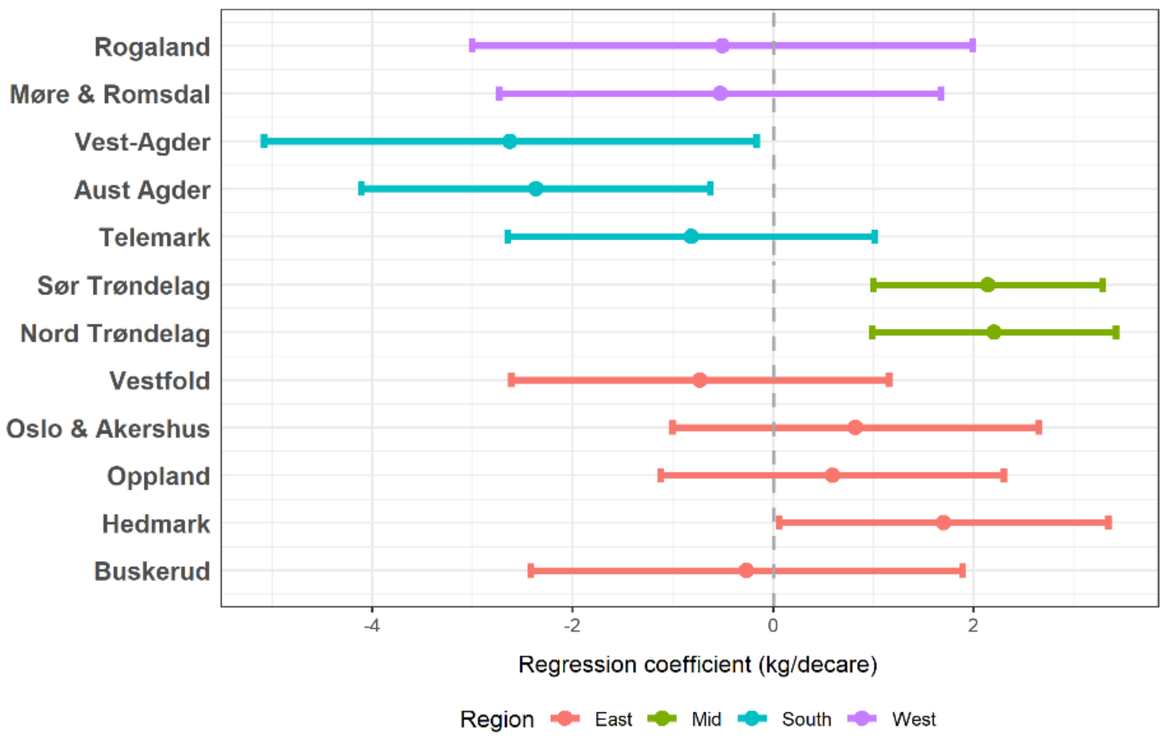

Figure 8. Regression coefficients and 95% confidence intervals from individual linear models of annual barley yield against year (1980–2018) for the main barley growing regions in Norway. Coefficients are colored according to Region for comparison with other results.

3-2-2-2. Effect of growing season climate variables on barley yield

Barley yield response to increasing growing season temperature was mostly non-significant, but the general trend was positive in the Mid and West and negative in the East and South (Figure 9). The only significant negative effect belonged to the average temperature in three counties in East as Buskerud, Hedmark, and Oppland, which had the highest rate ($\beta = -0.43 \pm 0.18$ s.e., $p = 0.02$). Moreover, the significant positive effect was in Sør-Trøndelag of Mid region for maximum temperature ($\beta = 0.36 \pm 0.15$ s.e., $p = 0.02$) and average temperature ($\beta = 0.34 \pm 0.15$ s.e., $p = 0.03$). Precipitation increase had a significant negative effect in Mid region and one county in South, Telemark, with the highest rate ($\beta = - 0.37 \pm 0.16$ s.e., $p = 0.02$; Appendix 11).

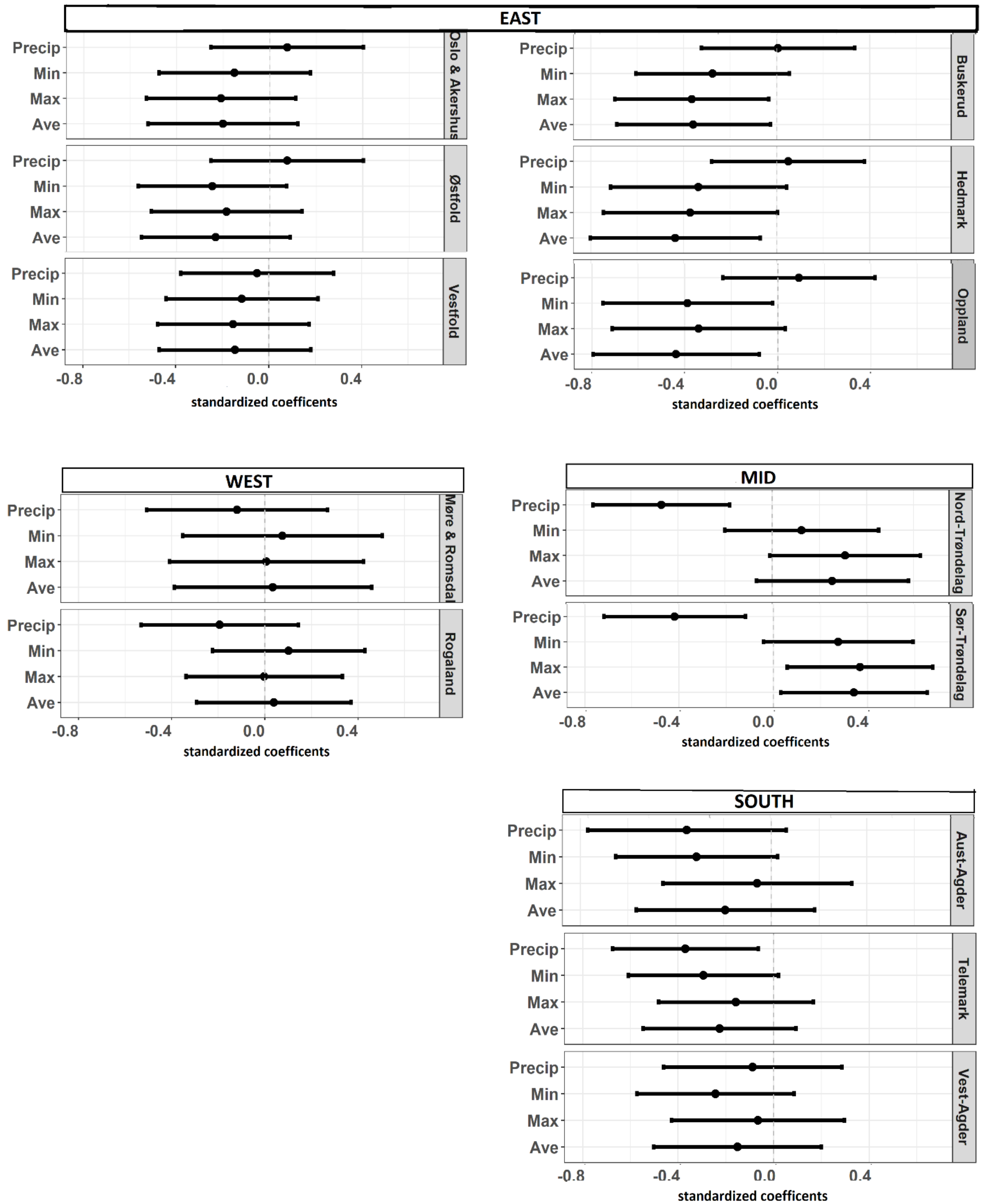

Figure 9. Standardized regression coefficients and 95% confidence intervals of individual linear regression models between detrended barley yield and detrended growing season climate variables (Precip: precipitation, Min: minimum temperature, Max: maximum temperature, Ave: average temperature).

3-2-2-3. Effect of monthly climate variables on barley yield

The monthly temperature variables (Appendix 12) showed a positive effect in the Mid and West and a negative effect in the East and South regions, and monthly precipitations exhibited a negative trend in all regions (Figure 10). However, each region had different significant monthly variables, in the Mid region, the significant effect belonged to June precipitation ($\beta = -0.30 \pm 0.10$ s.e., $p = 0.03$) and July maximum temperature ($\beta = 0.37 \pm 0.14$ s.e., $p = 0.03$), while in the West, June precipitation ($\beta = -0.34 \pm 0.16$ s.e., $p = 0.04$) and May average temperature ($\beta = 0.32 \pm 0.15$ s.e., $p = 0.04$) were significant. In the South and East, increasing May temperature and May precipitation showed significant negative effects with different rates. Regression models with monthly climate variables had higher R^2 and smaller confidence intervals than growing season climate variables (Appendix 13).

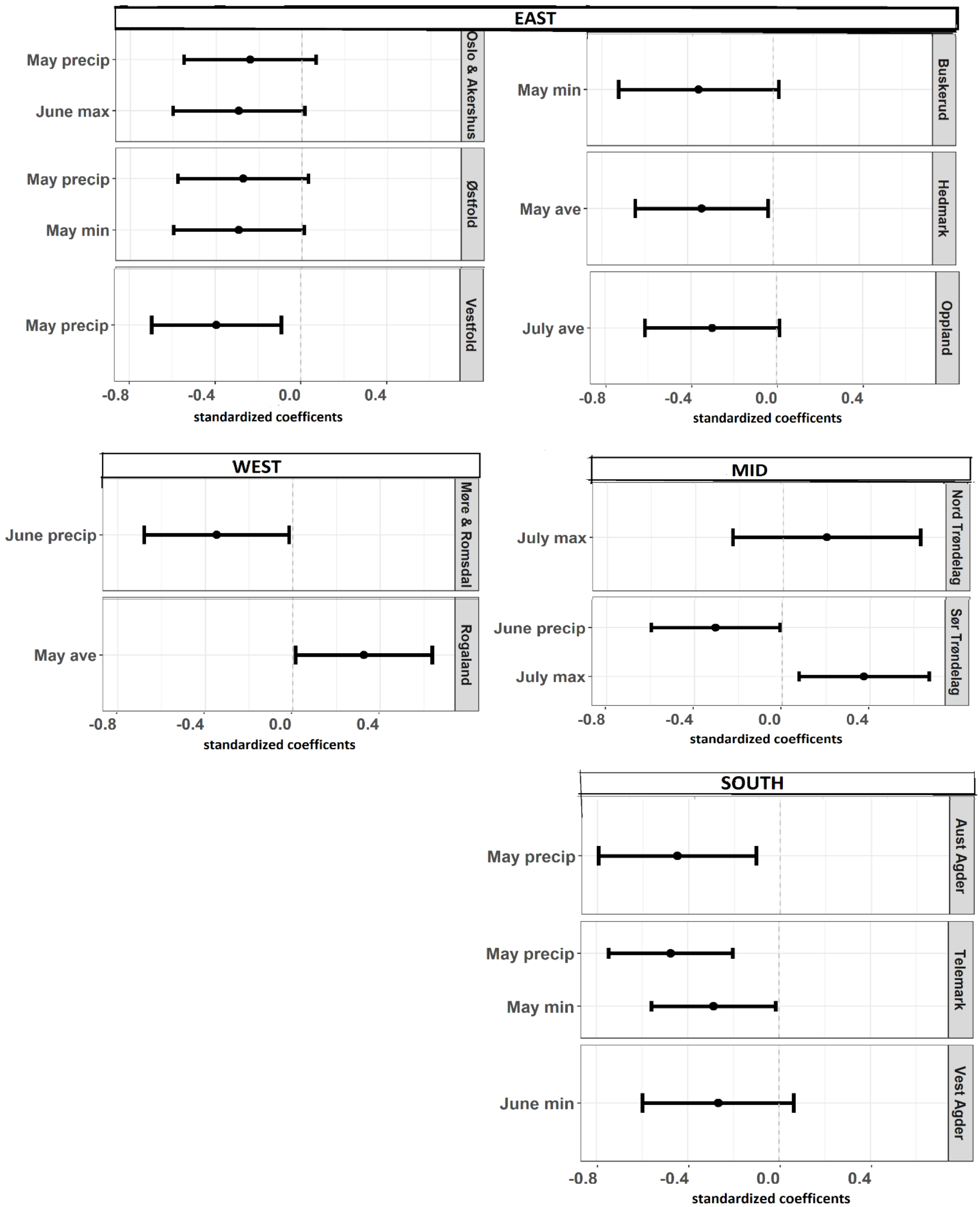

Figure 10. Standardized regression coefficients and 95% confidence intervals of individual linear regression models between detrended barley yield and detrended monthly climate variables (precip: precipitation, min: minimum temperature, max: maximum temperature, ave: average temperature).

3-2-3. POTATO

3-2-3-1. Potato yield time series

Potato yield showed diverse trends across regions; the West region had a significant reduction in Hordaland and a significant increase in Møre og Romsdal, and the East had a significant increase in Oslo & Akershus, Hedmark, and Buskerud. The trend in South and Mid was increasing, but it was non-significant (Figure 11). However, the highest rate of change was in Hordaland (β = -20.22 ± 6.2 s.e., $p = 0.002$) and Møre og Romsdal (β = 25.62 ± 5 s.e., $p < 0.001$). The potato yield trend was more scattered than the other two crops during these 39 years, and most of the regions did not include the extreme year. Therefore, excluding 2018 yield data, which was an extreme year for wheat and barley, did not considerably change the potato yield trend (Appendix 14 and 15).

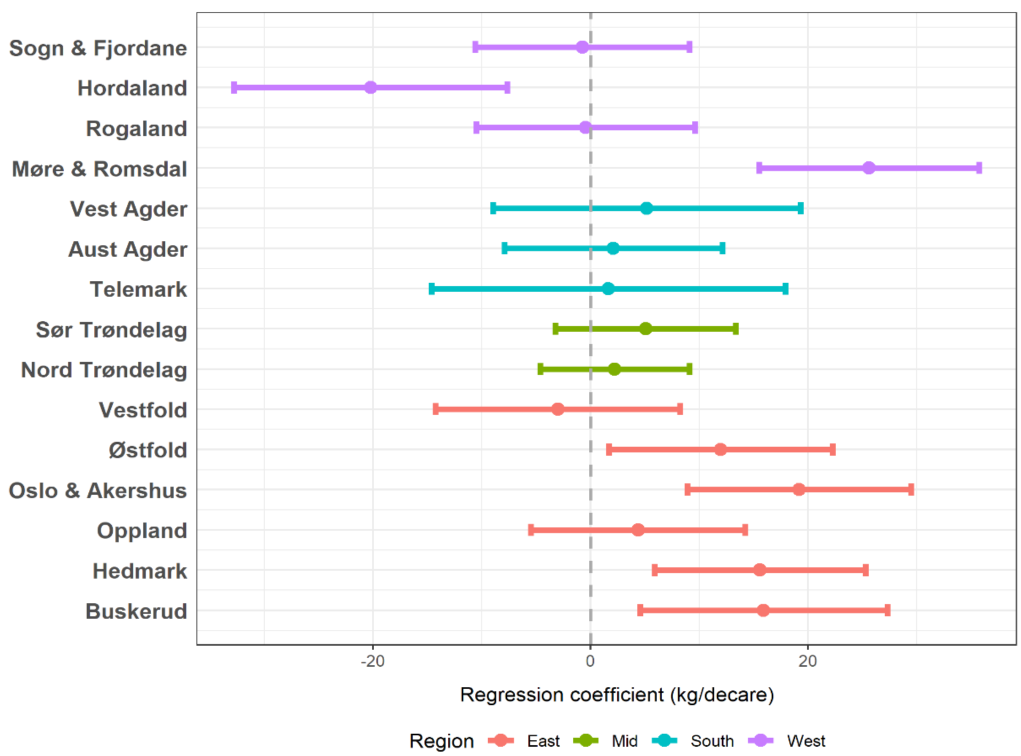

Figure 11. Regression coefficients and 95% confidence intervals from individual linear models of annual potato yield against year (1980–2018) for the main potato growing regions in Norway. Coefficients are colored according to Region for comparison with other results.

3-2-3-2. Effect of growing season climate variables on potato yield

Potato yield was affected positively by increasing the growing season temperature in the Mid and West and negatively in the East and South (Figure 12). However, this effect was just significant in East for minimum temperature in Østfold (β = -0.35 ± 0.15 s.e., p = 0.02) and maximum temperature in Oppland (β = 0.36 ± 0.17 s.e., p = 0.04), which was the highest rate of change in all regions. The general effect of increasing precipitation during the growing season was negative in all regions, but the significant effect was just in the West, Sogn of Fjordane (β = -0.39 ± 0.15 s.e., p = 0.01) and in the South, Telemark (β = -0.43 ± 0.14 s.e., p = 0.005; Appendix 16).

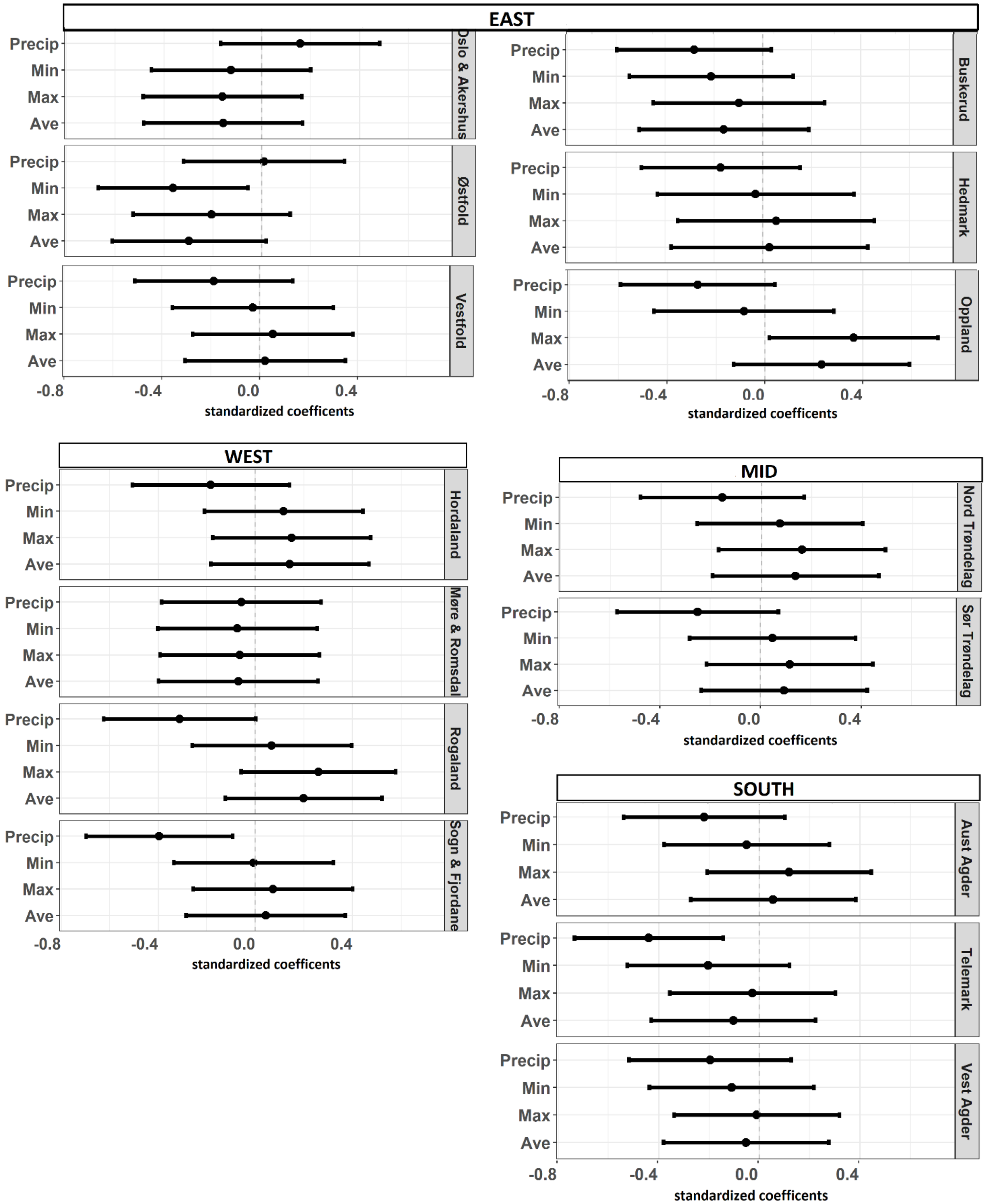

Figure 12. Standardized regression coefficients and 95% confidence intervals of individual linear regression models between detrended potato yield and detrended growing season climate variables (Precip: precipitation, Min: minimum temperature, Max: maximum temperature, Ave: average temperature).

3-2-3-3. Effect of monthly climate variables on potato yield

The monthly climate variables with the highest correlation coefficients with potato yield (Appendix 17) were mostly precipitation in all regions and negatively affected yield (Figure 13). The Mid region did not include any significant variable, but increasing May precipitation had a significant negative effect in the West, East, and South, along with July precipitation in the South. The highest rate of May precipitation effect was in West, Rogaland ($\beta = -0.53 \pm 0.13$ s.e., $p < 0.001$). The limited monthly temperature variables showed an inconsistent trend in regions, the significant negative effect belonged to June average temperature in West region, Møre og Romsdal ($\beta = -0.44 \pm 0.14$ s.e., $p = 0.003$) and July minimum temperature in East, Østfold ($\beta = -0.36 \pm 0.15$ s.e., $p = 0.02$) while there was a positive effect for May maximum temperature in East, Oppland ($\beta = 0.45 \pm 0.15$ s.e., $p = 0.004$; Appendix 18).

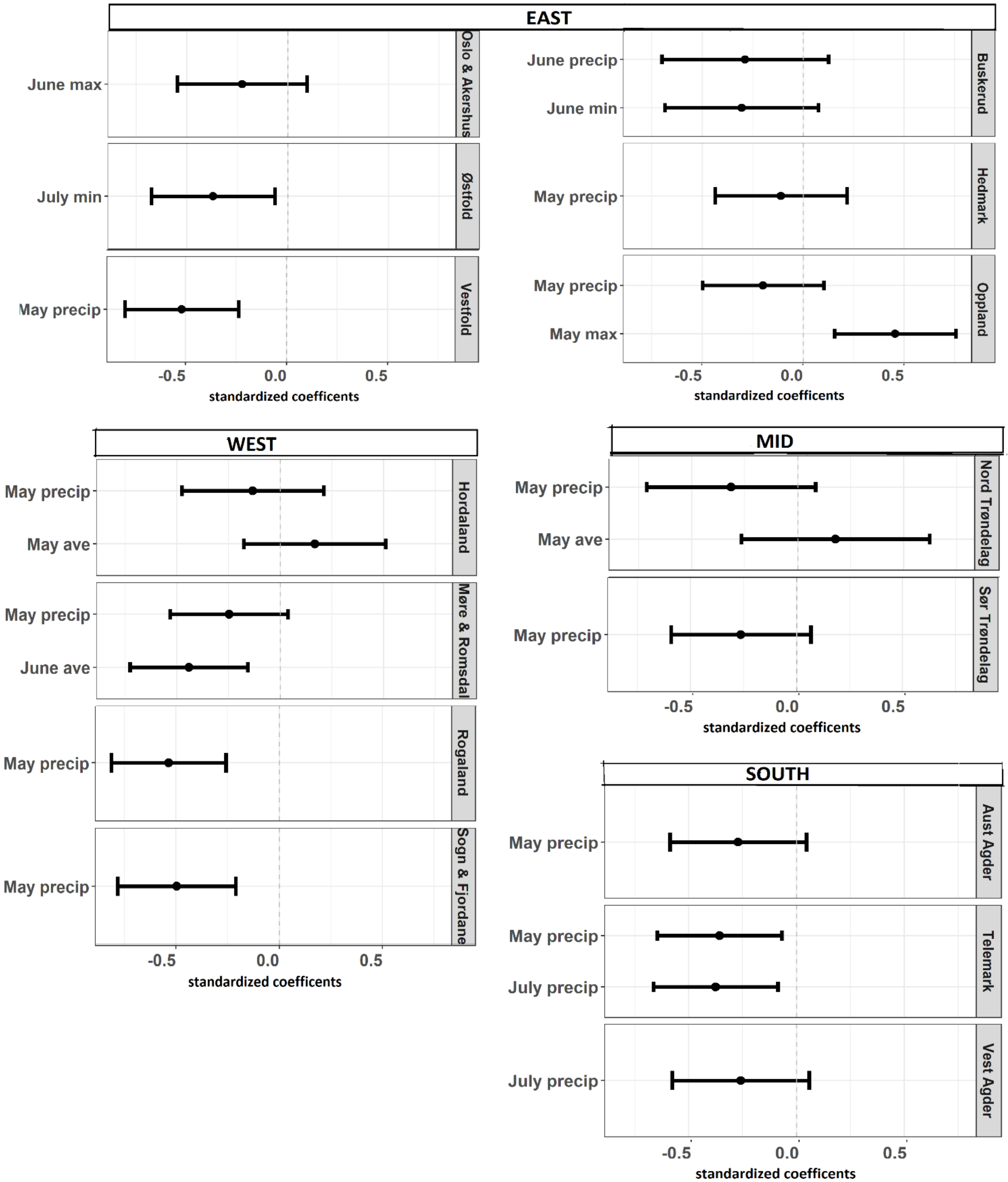

Figure 13. Standardized regression coefficients and 95% confidence intervals of individual linear regression models between detrended potato yield and detrended monthly climate variables (precip: precipitation, min: minimum temperature, max: maximum temperature, ave: average temperature).

4. Discussion

This study analysed 39 years of wheat, barley, and potato yield against climate data for the first time in Norway to assess the yield trend and effect of climate change on the yield. It demonstrated patterns that were not consistent throughout the country; while temperature and precipitation increased across Norway since 1980, all three crop yields exhibited different trends in various regions. Furthermore, I showed that climate variables, seasonally and monthly, did not allow the prediction of the yield in all counties equally.

Increasing temperature and precipitation of the growing season during 1980–2018 was in line with the evaluation of the Norwegian Climate Service Centre (Hanssen-Bauer et al., 2017). A more continental climate in the East region may explain the prevalence of heat records and the highest temperature increase among all regions studied (Moen, 1999). The Norwegian Climate Service Centre evaluation (Hanssen-Bauer et al., 2017) reported statistically significant positive precipitation trends in all regions, while during these four months, there was a great variation from year to year and non-significant changes. In this study, the temperature and precipitation time series were used to confirm the expected increase in these climate variables; hence they are discussed more precisely in the context of climate change effects on crops. Moreover, the results of the yield series and the effect of the growing season and monthly climate variables will be discussed for each crop separately.

4-1. WHEAT

Wheat yield in Norway has remained relatively constant over the previous 39 years, despite improvements in crop varieties, agricultural inputs (fertilizers, insecticides, herbicides, and fungicides), and mechanization that should, in theory, result in a significant increase (Ortiz, 2019, Troy et al., 2015). In fact, this expectation is for potential yield, and harvested yield data in Norway did not show a significant positive trend, and there was a 190 kg/decare yield gap, which is the difference between potential yield and average yields harvested on the farms (Seehusen and Uhlen, 2020).

Wheat yield was stagnating since the 1990s in other countries as well, such as France, Denmark, Sweden, and Portugal (Michel and Makowski, 2013). Although it is beyond the scope of this study to determine the exact limiting causes in each Norwegian region, some general trends throughout Norway can help explain the situation. My results showed that climate change might account for 11–25% of the trend, but other agricultural policies and regulations might account for the remainder. From mid-1980, changes in Norwegian agricultural policy, including subsidies reductions, resulted in farmers exerting less effort to optimize yield. Besides this, wheat production profitability diminished due to lower wheat grain prices and higher input and machinery prices (Hoel et al., 2013, Stabbetorp, 2017). In addition, due to environmental concerns, the use of chemical fertilizers and plant protection as effective elements in improving yield was restricted in Norway over the previous two decades (Seehusen and Uhlen, 2020). The introduction of new varieties likely had a relatively minimal impact on the wheat yield because the highest yield belonged to Zebra, which was launched in 2002, and the later varieties showed only tiny yield improvements (Seehusen and Uhlen, 2020). Therefore, policies and regulations played a more critical role in the stagnated wheat yield trend than climate change.

Increasing growing season temperature had little effect on wheat yield except in several counties in the East, where the temperature increase made them the warmest region in Norway. In other European countries, increasing temperatures since 1980 led to a considerable yield decrease (Zhu et al., 2019). In Austria, for example, the wheat yield was reduced by 6% for each degree of high temperature (Ebrahimi et al., 2016), and in Denmark, an increase of 1˚C reduced the wheat dry matter yield by 3.5% (Børgesen and Olesen, 2011, Kristensen et al., 2010, Ozturk et al., 2017). A key reason that Norway did not follow this pattern of wheat yield decrease is that temperatures in Norway were rarely higher than the wheat optimal temperature of 16–22˚C (Thaler et al., 2012), compared to countries in southern Europe with a sharper and more consistent temperature increase (Trnka et al., 2015, Dong et al., 2017). However, 2018 was an exceptional year in Norway, when the maximum temperatures in the East region exceeded 23–25˚C and resulted in a yield decline. Furthermore, spring wheat, the most widely cultivated type in Norway, is less vulnerable to rising temperatures than winter wheat which is often used further south (Liu et al., 2016).

Despite a lack of countrywide effects of growing season temperature on wheat yields, monthly temperature changes were more critical in some counties. Wheat yield was impacted mainly by high temperatures in May, while wheat is in the emergence and stem elongation stage. At this time, high temperatures cause membrane thermo-instability, lower leaf chlorophyll concentration, and reduced photosynthesis, resulting in wheat growth reduction and crop dieback (Dong et al., 2017, Harkness et al., 2020, Ortiz et al., 2008). Temperatures in other months and growth stages are important to wheat yield (Semenov et al., 2014, Roberts et al., 2017), but the lack of significant effects for these months in this study suggests that temperature changes in Norway during these periods have not yet reached threshold levels.

The lack of growing season and monthly precipitation effects on wheat yields is supported by findings in other studies about the low sensitivity of wheat to precipitation and high sensitivity to drought conditions (Lobell and Asseng, 2017, Zhu et al., 2019, Semenov and Shewry, 2011). In Norway, wheat is a rainfed crop, but farmers have good access to water, and they can irrigate in dry conditions, so that water is not a limiting factor as in southern European countries (Jensen et al., 2021). Furthermore, Norwegian wheat is mainly grown in the East region, where soil varies greatly, ranging from heavy clay to light sand, with varying soil rooting depths and precipitation responses (Persson and Kværnø, 2017, Persson et al., 2015). In my study, I employed average yield data for each county and across a mix of soils; therefore, the sensitivity of crop yield to precipitation would diminish, and we cannot expect to get a significant effect of precipitation in the East for any of the three crops. Lobell and Burke (2010) also examined this effect and showed reduced sensitivity of crop yield to precipitation by aggregating yield across multiple soil types.

4-2. BARLEY

The diverse and mostly non-significant trends in barley yields during the study period are comparable with findings from another Norwegian study, which revealed that barley yield variation was not considerable since the 1990s and reported a 30–32% yield gap (Flø et al., 2017). During this time, this yield gap in Finland, Denmark, and Sweden were 38%, 27%, and 25%, respectively (Seehusen and Uhlen, 2020). The following factors are likely to influence barley yield over the study period negatively: (a) applied inputs not being cost-effective and (b) restrictions imposed by fertilizer and chemical plant protection regulations, and (c) variable weather conditions, which could account for 10–25% of these changes in this study. A likely response by farmers to these conditions was less intensive production at many farms and yield stagnation, especially since the 1990s (Lillemo et al., 2010).

Introduced varieties, on the other hand, had a favorable impact on barley yield in Norway, as for other Nordic countries, which had gains of 23% from new barley varieties (Seehusen and Uhlen, 2020). Norwegian reports mentioned the various contribution of new varieties, such as 0.4–0.6% of annual yield increase during 1985–2015 (Seehusen and Uhlen, 2020) or 50% of the total yield increase during 1980–2008 in the Mid region (Lillemo et al., 2010). Furthermore, a quarter of the yield increase over the study period was reported as the result of using resistant varieties to diseases such as scald, net blotch, and ramularia leaf spot (Wonneberger et al., 2017). These assessments indicate that the barley yield stagnation from the 1990s was not due to an absence of yield increase in new varieties.

This study corroborated my hypothesis that rising temperature in Norway had a contradictory effect on barley in various regions, albeit it was not severe. The positive effect in Mid and West regions is supported by other Norwegian studies that revealed a favorable link between temperature and barley production in these regions and claimed that recent warming improved the possibility of producing barley there (Lillemo et al., 2010, Martin et al., 2017). After sowing, the number of degree days during the season has the greatest impact on barley production, and rising temperature in the colder parts of Norway boosted degree days, resulting in a 100 kg/decare increase in barley yield for every 100 degree days (Martin et al., 2018). Evidence from other countries also supports the positive effect of temperature in northern climates. For example, in Finland, a 1˚C increase resulted in a 10-day increase in the growing season, less frost danger, and increased the rate of barley growth and development (Peltonen-Sainio and Jauhiainen, 2014, Peltonen-Sainio et al., 2009, Kleemola et al., 1995). In the northern part of Canada, climate change resulted in a higher barley yield due to the extension of the growing season and developing the cultivation of varieties with a longer maturity time (An and Carew, 2014). Therefore, temperature changes provided an opportunity for barley in the Mid and West regions of Norway.

The negative effects of rising temperature in the East and South were also pronounced in other Nordic countries, as well as temperate and Mediterranean areas. According to the Danish study, the expected yield increase in northern Europe due to increased temperature might not hold owing to the interactions between the biotic and abiotic factors (Clausen et al., 2011). In the southern part of Finland, even with adjusted earlier sowing, increasing temperature reduced barley yield considerably because the positive effects of climate warming may reverse as it passes the threshold (Rötter et al., 2011). Moreover, the temperature rises in southern European countries such as Italy and Spain reduced average barley yields by 3.8% (Soussana et al., 2012, Moore and Lobell, 2015, Cammarano et al., 2019). Broadly speaking, temperatures in the range of 24–28˚C cause a slight drop in spring barley yield, which is followed by a severe fall in yield at temperatures above 30˚C (Gammans et al., 2017). In my study, just three counties in the East region experienced temperatures above 25˚C in some years (especially 2018), and it is likely that a 1˚C increase in temperature resulted in a 2.8–3.8% barley yield reduction (An and Carew, 2014).

Effects of precipitation on barley were also assessed in another Norwegian study that could lead to a decline in the quantity and quality of harvested barley (Seehusen and Uhlen, 2020). Barley lacks a physiological mechanism to deal with excess moisture (Cattivelli et al., 2011); thus, excessive rainfall and anaerobiosis soil conditions can reduce yield by 12–20% (Hura, 2020). Moreover, more disease infestations in the humid climate often challenged barley, and it reduces grain size and grain yield (Seehusen and Uhlen, 2020).

The mechanism of temperature and precipitation effect on barley production may be analysed more precisely by considering the monthly climate variables and sensitive barley growth stages. Higher temperatures at the beginning and later part of the growing season (May and July) in the Mid and West regions can help extend the growing season and allow using late maturity and higher-yielding varieties (Martin et al., 2018). Furthermore, raising the temperature in May reduces the risk of late frosts following emergence, whereas in July enhances grain filling rate, which correlates positively with grain weight (Olesen et al., 2011). On the other hand, the detrimental effect of warm May (germination to double ridge stage) in the East and South regions has been replicated in numerous studies (Abiko et al., 2005, Gammans et al., 2017, Ahmed et al., 2016, Hossain et al., 2012). High temperatures in this stage disrupt barley developmental processes and diminish plant height, dry matter accumulation, and grain production (Jensen et al., 2021, Dijkman et al., 2017), although Norwegian barley grew more resistant to heat stress in later growth stages.

Increasing precipitation and high soil water content in May necessitates waiting for some soil drying, and farmers' capacity to take advantage of better spring temperatures and earlier planting may be limited (Aurbacher et al., 2013). Moreover, delayed sowing may generate a cascade of change during the rest of the growing season and increases the probability of exposure to high temperature at more critical stages, especially in the East and South regions (Eitzinger et al., 2013, Kolberg et al., 2019). Besides this, June in Norway is typically the month of anthesis or flowering stage, and high precipitation in this stage may impair barley fertility in the Mid and West regions (Hura, 2020), although statistical models cannot determine the exact mechanisms. A study in Denmark reported that very wet springs impeded barley root development in loamy soils, while it did not happen in the sandy soils, and barley suffered less yield decline (Dijkman et al., 2017). Therefore, increasing precipitation may interact with more fine-scale factors such as a soil type, suggesting that yield modelling at finer scales may be required in Norway to provide a better overview of precipitation's effect on barley yield.

4-3. POTATO

The potato yield data revealed a wide range of trends in different regions as well as significant year-to-year fluctuation, particularly in the Mid and South. Changes in temperature and precipitation were responsible for 10–40% of the changes, while national and local factors also played a role. During 1980–2018, the potato industry in Norway profited from introducing new varieties, which expanded from 20 to 45 varieties (Krogsti, 2021). Throughout the 1980s, Norwegian-bred varieties were planted on 50% of potato-growing land in Norway, but this fell to 25% over time as farmers favored varieties from the Netherlands or Denmark that had higher yields (Møllerhagen, 2012).

Simultaneously, there was a remarkable structure change in growing potato in Norway; in the 1980s, potato was harvested by hand, and many farmers had small potato acreages. Over time, specialized machines were introduced for potato, farms became larger, and the production was concentrated where potato factories existed and in regions where potato harvesting with machines was most efficient (Hermansen et al., 2012). Hordaland experienced a large yield loss over time as it shifted to private/gardening potato cultivation, and commercial high-yield farming was no longer possible. On the other hand, Møre og Romsdal took the opposite path and boasted one of Norway's most efficient and high-quality potato productions. In Vestfold, most farmers specialized in salad/baby potato, which had a lower yield in terms of weight than processing potato, resulting in a negative yield trend (Statistics Norway, 2020). The spread of pests and diseases also affected the potato trend considerably; in the South region, potato leaf hopper and aphids significantly lowered yields, and the Mid region was affected harshly by the spread of late blight (Hermansen et al., 2018, Klingen et al., 2012, Nærstad et al., 2012).

The potato's adaptability and tolerance to a wide range of temperatures possibly explain why increasing temperature had no considerable effect on potato yield in this study, which is in line with other studies' results (Hermansen et al., 2012, Raymundo et al., 2018, Rabia et al., 2018, Zhou et al., 2017). However, my findings provide useful insights for further research on the impact of climate change on potato. Increasing temperature in the East and South adversely affected potato yield trend as 1˚C increase of temperature higher than the optimum (13–24˚C) can cause 6 –10 % potato yield loss, and it becomes severe when the maximum temperature approaches 30˚C (Fleisher et al., 2017, Zhou et al., 2017). High temperatures promote leaf senescence, a decrease in net photosynthetic assimilation rates, and a decrease in carbohydrate synthesis that delayed the onset of tuber growth (Raymundo et al., 2018, Pulatov et al., 2015). Meanwhile, increased minimum temperature slows or inhibits tuberization and tuber bulking (Rabia et al., 2018, Haverkort et al., 2013), which probably explains the significant yield reduction in Østfold with the highest rate of increasing minimum temperature during the study period. Moreover, the increasing temperature can indirectly affect potato yield by promoting the spread of pests and diseases, particularly late blight, which has a higher probability of spreading, and the outbreak begins 2– 4 weeks sooner as the temperature rises (Martinelli et al., 2015).

The exception to the majority of temperature effects in the East region was in Oppland, where increasing maximum temperature led to a significant yield increase, and this was exemplified by the data from 2018 when Oppland had the highest potato yield in the hottest and driest year of the 39 year study period. This promising effect of temperature also appeared in the Mid and West regions, where mild temperature increases can result in extended frost-free growing seasons, sub-optimal temperatures becoming optimal, and frost damage in late spring being reduced (Borus, 2017, Rabia et al., 2018, Raymundo et al., 2018). When considering the base value of 12 tubers per plant at 13˚C average temperature, a moderate rise of temperature increases the number of tubers per plant by 1.68 tubers by every 1˚C rise (Haverkort & Verhagen, 2008).

The negative impacts of increasing precipitation in all regions align with other studies that reported the highest tuber yield loss in years with excess rainfall (Fageria et al., 2010, Fleisher et al., 2013, Saue and Kadaja, 2010). Potato is more susceptible to water stress than most crops due to a relatively shallow rooting system and inefficient system to transport water from roots (Haverkort and Struik, 2015). This sensitivity also appeared in monthly variables, as most of the highly correlated monthly variables with potato yield were precipitation, and it had a greater negative impact than monthly temperatures.

The adverse effect of precipitation was more pronounced in sprouting (May), except in Telemark that sprouting and tuber bulking (July) were the most sensitive ones. Other studies also singled out wet start and end of the potato growing season as critical weather extremes that explain yield anomalies (Levy and Coleman, 2014, Borus, 2017, Van Oort et al., 2012). Excess soil moisture in May delays cultivation, which is problematic, especially in the Mid and West regions, because the growing season is restricted in those regions, and farmers lose several days of this period due to late planting. Furthermore, regular cultivation causes the potato seeds to rot and stop sprouting because high soil water content depletes soil oxygen and restricts respiration (Borus, 2017). Tuberization (June) and tuber bulking (July) were the only times that monthly temperature had a substantially detrimental effect. Developing tubers are the primary sink for nutrients and carbohydrates during tuberization and tuber bulking, but high temperature boosts foliage growth, and larger amounts of carbohydrates are allocated to vegetative growth, resulting in fewer and light tubers (Borus, 2017, Raymundo et al., 2018).

5. Conclusion

Understanding the effect of climate change on crop yields is critical for achieving food security goals, as well as for policymakers developing food production programs, agricultural development initiatives, and climate-related adaptation measures (Najafi et al., 2018). This study showed that using a single set of climate predictors for the entire country of Norway is challenging, and the impacts of climate variables on wheat, barley, and potato vary by county. Meanwhile, some counties should focus on climate change during specific crucial months that correspond with certain crop growth stages. Moreover, it seems that these crops are not under immediate threat from climate change in Norway, and other factors such as policies, management practices, and crop varieties selection had a more significant impact on crop yield during the last 39 years. However, given the projected increase of temperature and precipitation in Norway until 2100 and the observed crop yield trend in this study, climate change may be a credible threat to wheat, barley, and potato productivity in some counties of Norway in the future.

According to this study, climate change may present opportunities in eastern and southern parts of Norway to grow crops that require higher temperatures and opportunities in the mid and western areas to grow more barley and potato. The impacts of climate change on yield trends since 1980 were variable among these three crops, demonstrating the diversity of climatic variables' importance for various crops. This result suggests that the diversity of Norway's agriculture may help to reduce the impact of climate change on the agricultural industry, with reductions in some crops potentially compensated by increases in others. Furthermore, the different reactions of these crops in different counties necessitates devising any strategies and adaptation measures crop-specific and county-specific, and offering a plan at the national level cannot be an option for Norway.

5-1. Limitations of the study

1) The statistical model used in this study did not explicitly account for management practices or other factors that could influence the effect of climate on yields, and it was unable to pinpoint the particular mechanisms of climate impacts. Furthermore, farmers may have taken modest adaptation steps, and they may have mitigated the effects of climate change, but statistical models based on detrended data cannot capture such subtle changes. As a result, the yield change attributed to climate trends in this study can be seen as the effect in the absence of adaptation during the study period.
2) In this study, I compared all counties using a static crop calendar, which may impact the results, notably for monthly climate variables. It's possible that using the exact crop schedule for each county or region improves the outcome.
3) Described models in this study cannot be used to predict the effect of climate change in the future because it was based on finite historical observations. The stated models would no longer be viable if future temperature and precipitation exceeded the extremes of the historical record used to build them.

5-2. Recommendations for future research

1) A typical flaw in statistical models is that they do not consider the impacts of CO_2 increase accompanying climate change warming. The effects of rising CO_2 levels on the growth and development of numerous crops have been widely documented (Kumari et al., 2015, Fleisher et al., 2017, Ozturk et al., 2017). Therefore, employing other crop modelling methods to determine the effect of CO_2 fertilization on these three crops can be a topic of future research.
2) Other indices to assess climate change effects are frost/chill days, growing degree days, heat days, and the length of the growing season (Borus, 2017, Molahlehi et al., 2013, Pulatov et al., 2015), which are entirely dependent on data availability. Consequently, improving climate data collection in Norway can path the way to conduct further research on these crops by using these indices.
3) In order to design adaptation measures, it is vital to project the impact of climate change on these crops for different warming levels. To the best of my knowledge, such research has only been carried out in a few parts of Norway (Kolberg et al., 2019, Uleberg et al., 2014).
4) This study showed that various factors might affect crop yield trends in various counties, necessitating more studies at the finer scales. This fine-scale assessment can employ process-based crop models that incorporate information from agronomy, physiology, and agrometeorology to explain the link between crop characteristics and climate variables, as well as the mechanisms underlying the processes depicted (Shi and Zhang, 2013).
5) One of the key reasons for the lack of agreement in research on the effects of climate change is the diversity of modelling methods and their structural and functional variations (Ozturk et al., 2017, Hawkins et al., 2013, Lobell and Asseng, 2017). Meanwhile, the combined model (Roberts et al., 2017) can predict the outcomes slightly better than single models and provides a more reliable result.

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7. Appendix

Appendix 1. Meteorological stations' information

Table 1. Information of the selected meteorological stations for climate data in each county.

County	Station with temperature and precipitation data		Station with precipitation data		Station with temperature data	
	Name	**Number**	**Name**	**Number**	**Name**	**Number**
Østfold	Rygge	SN17150	Strømsfoss	SN1650		
			Fløter	SN17500		
Oslo & Akershus	Blindern	SN18700	Skedsmo	SN4260		
	Ås	SN17850	Eidsvoll Verk	SN11120		
	Asker	SN19710				
Buskerud	Kongsberg	SN28380	Hole	SN20250		
	Blindern	SN18700				
Hedmark	Kise	SN12550	Nord-odal	SN5350		
Oppland	Kise	SN12550	Biri	SN11900		
Vestfold	Melsom	SN27450	Sandefjord	SN27600		
	Blindern	SN18700	Hedrum	SN27800		
			Notodden	SN30530		
			Høidalen I	SN32780		
			Kviteseid	SN32850		
Aust-Agder	Nelaug	SN36560	Eikeland	SN35090		
	Landvik	SN38140				
Vest-Agder	Kjevik	SN39040	Tonstad	SN42810		
	Lista Fyr	SN42160				
Telemark	Nelaug	SN36560	Eikeland	SN35090		
	Landvik	SN38140				
Rogaland	Sola	SN44560	Egersund	SN43360		
	Sauda	SN46610	Karmøy	SN47240		
Hordaland	Sauda	SN46610	Hatlestrand	SN50150	Flesland	SN50500
	Takle	SN52860	Eikemo	SN47820		
Sogn og Fjordane	Takle	SN52860	Aurland	SN53700		
	Sandane	SN58070	Vik I Sogn Iii	SN53070		
Møre og Romsdal	Fiskåbygd	SN59610	Sunndalsøra Iii	SN63420		
	Tafjord	SN60500	Sæbø	SN59900		
	Vigra	SN60990				
Sør-Trøndelag	Værnes	SN69100	Løksmyr	SN68270	Sula	SN65940
	Ørland Iii	SN71550				
Nord-Trøndelag	Værnes	SN69100	Otterøy	SN75020		
	Snåsa - Ki	SN70850	Buran	SN69960		

Appendix 2. Climate variables scatterplots

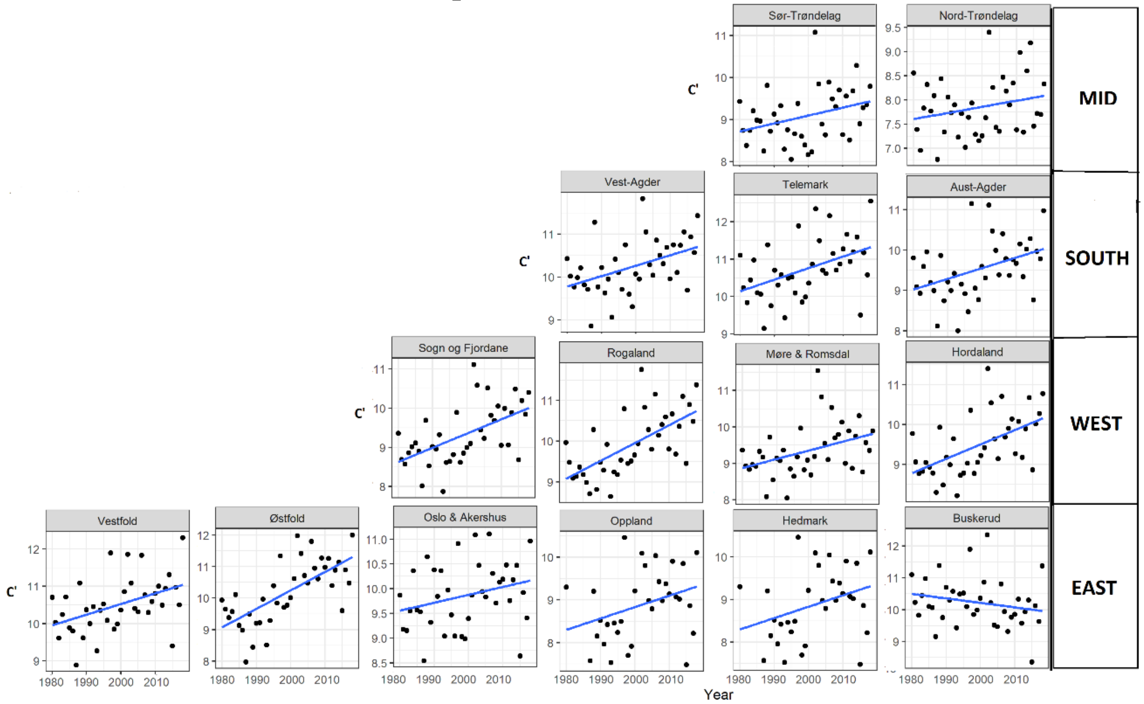

Figure 1. Scatter plots of minimum temperature along with best-fit linear regression (blue line). Counties are organized by region (MID, SOUTH, WEST, EAST).

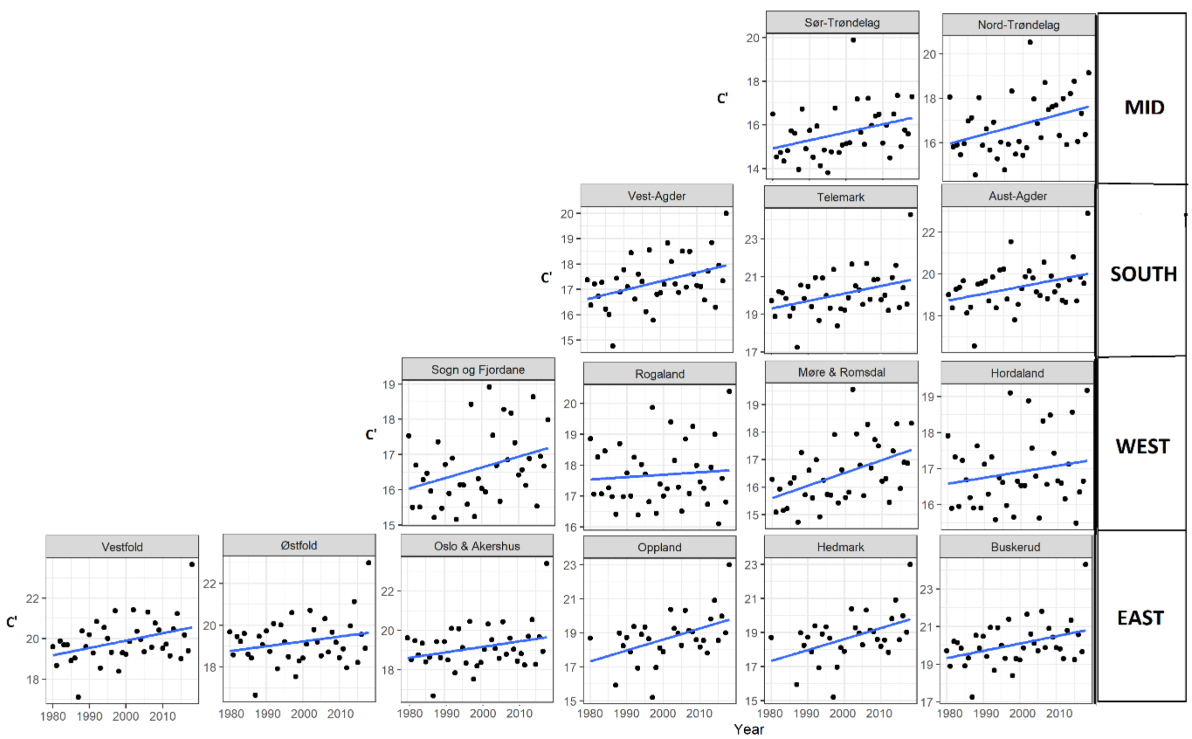

Figure 2. Scatter plots of maximum temperature along with best-fit linear regression (blue line). Counties are organized by region (MID, SOUTH, WEST, EAST).

Appendix 3. Summary statistics of climate variables time series. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 2. Summary statistics of regression models of growing season average temperature time series modeled against Year.

Region	*County*	*Average temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.344	0.154	2.230	0.032	0.119
	Sør-Trøndelag	0.351	0.153	2.280	0.028	0.123
WEST	Møre og Romsdal	0.456	0.146	3.124	0.209	0.003
	Rogaland	0.357	0.153	2.331	0.025	0.128
	Hordaland	0.360	0.153	2.353	0.024	0.130
	Sogn og Fjordane	0.450	0.146	3.069	0.004	0.203
EAST	Buskerud	0.167	0.162	1.030	0.310	0.028
	Hedmark	0.542	0.179	3.033	0.005	0.235
	Oppland	0.542	0.179	3.033	0.005	0.235
	Oslo & Akershus	0.302	0.156	1.931	0.061	0.092
	Østfold	0.498	0.142	3.500	0.001	0.249
	Vestfold	0.422	0.149	2.837	0.007	0.179
SOUTH	Telemark	0.434	0.148	2.932	0.006	0.189
	Aust-Agder	0.412	0.149	2.751	0.009	0.170
	Vest-Agder	0.442	0.147	3.001	0.005	0.196

Table 3. Summary statistics of regression models of growing season precipitation time series modeled against Year.

Region	*County*	*Precipitation*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	-0.591	0.164	-0.360	0.721	0.003
	Sør-Trøndelag	-0.320	0.164	-0.195	0.847	0.001
WEST	Møre og Romsdal	0.232	0.159	1.451	0.155	0.054
	Rogaland	0.100	0.163	0.651	0.519	0.011
	Hordaland	0.170	0.162	1.055	0.298	0.029
	Sogn og Fjordane	0.288	0.157	1.830	0.075	0.083
EAST	Buskerud	0.310	0.156	1.988	0.054	0.096
	Hedmark	0.292	0.157	1.860	0.071	0.086
	Oppland	0.356	0.153	2.317	0.026	0.127
	Oslo & Akershus	0.359	0.153	2.340	0.025	0.129
	Østfold	0.250	0.159	1.571	0.125	0.063
	Vestfold	0.312	0.156	1.999	0.053	0.097
SOUTH	Telemark	0.299	0.156	1.910	0.064	0.090
	Aust-Agder	0.226	0.160	1.417	0.165	0.051
	Vest-Agder	0.219	0.160	1.368	0.180	0.048

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Appendix 4. Wheat yield scatterplot and model

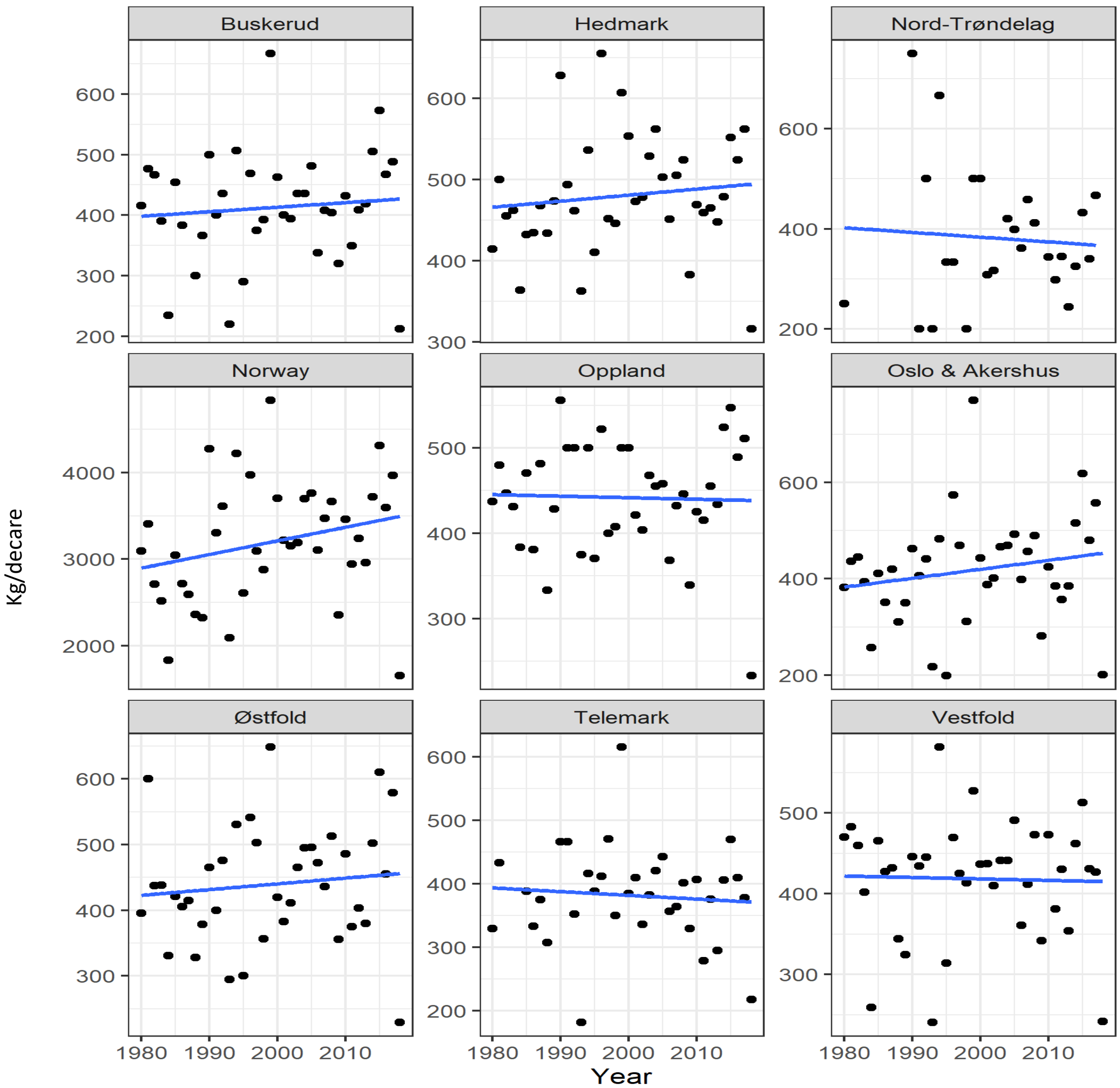

Figure 3. Scatter plots of wheat yield time series along with best-fit linear regression (blue line).

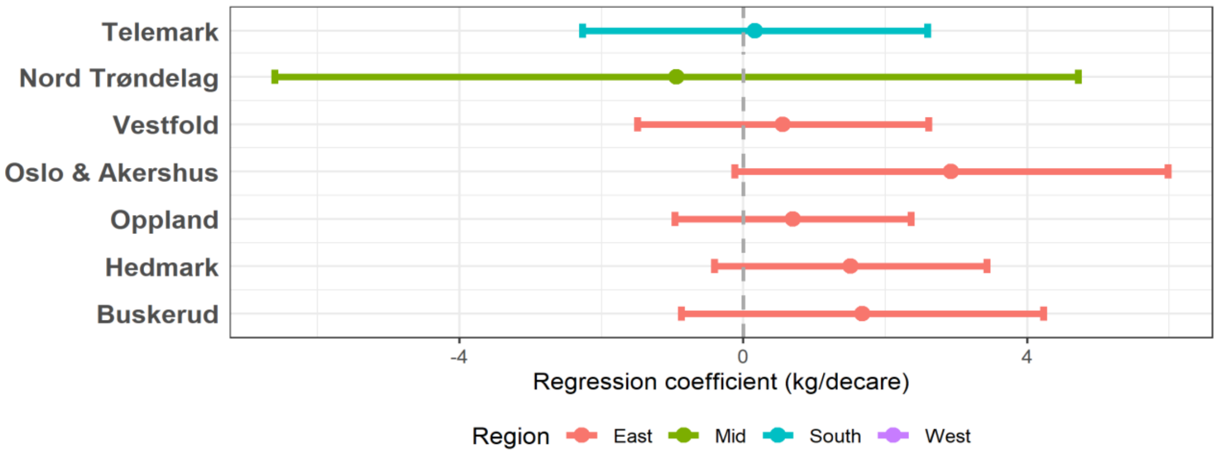

Figure 4. Regression coefficients and 95% confidence intervals from individual linear models of annual wheat yield against year (1980–2017) for the main wheat-growing regions in Norway. Coefficients are colored according to Region for comparison with other results. In this model 2018 that was an extreme year was excluded.

Appendix 5. Wheat yield time series summary statistics. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 4. Summary statistics of regression models of wheat yield time series.

Region	*County*	*Regression coefficient*	*Std.Error*	*t-value*	*p-value*	R^2
MID	Nord-Trøndelag	-0.943	2.830	-0.333	0.741	0.004
EAST	Buskerud	0.750	1.327	0.565	0.575	0.008
	Hedmark	0.749	1.010	0.741	0.463	0.014
	Oppland	-0.179	0.937	-0.191	0.849	0.001
	Oslo & Akershus	1.853	1.576	1.176	0.247	0.036
	Østfold	0.874	1.288	0.678	0.501	0.012
	Vestfold	-0.180	1.061	-0.170	0.865	0.001
SOUTH	Telemark	-0.584	1.234	-0.473	0.639	0.006

Appendix 6. Summary statistics of the effect of growing season climate variables on wheat yield. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 5. Summary statistics of regression models between detrended wheat yield and detrended minimum temperature during growing season.

Region	*County*	*Minimum temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	-0.108	0.187	-0.581	0.566	0.013
EAST	Buskerud	-0.348	0.161	-2.167	0.036	0.115
	Hedmark	-0.274	0.186	-1.471	0.151	0.067
	Oppland	-0.443	0.177	-2.491	0.018	0.171
	Oslo & Akershus	-0.317	0.155	-2.036	0.048	0.100
	Østfold	-0.142	0.163	-0.874	0.387	0.020
	Vestfold	-0.260	0.158	-1.641	0.109	0.067
SOUTH	Telemark	-0.232	0.164	-1.411	0.167	0.057

Table 6. Summary statistics of regression models between detrended wheat yield and detrended maximum temperature during growing season.

Region	*County*	*Maximum temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	-0.075	0.192	-0.388	0.701	0.006
EAST	Buskerud	-0.360	0.166	-2.169	0.037	0.116
	Hedmark	-0.152	0.191	-0.795	0.433	0.021
	Oppland	-0.254	0.190	-1.338	0.191	0.056
	Oslo & Akershus	-0.248	0.159	-1.558	0.128	0.062
	Østfold	-0.213	0.161	-1.326	0.193	0.045
	Vestfold	-0.256	0.159	-1.613	0.115	0.066
SOUTH	Telemark	-0.209	0.164	-1.277	0.211	0.047

Table 7. Summary statistics of regression models between detrended wheat yield and detrended average temperature during growing season.

Region	*County*	*Average temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	-0.087	0.188	-0.461	0.649	0.008
EAST	Buskerud	-0.389	0.163	-2.380	0.023	0.135
	Hedmark	-0.243	0.188	-1.291	0.206	0.052
	Oppland	-0.398	0.181	-2.196	0.035	0.138
	Oslo & Akershus	-0.294	0.157	-1.869	0.069	0.086
	Østfold	-0.203	0.161	-1.264	0.214	0.041
	Vestfold	-0.271	0.158	-1.711	0.095	0.073
SOUTH	Telemark	-0.228	0.162	-1.406	0.168	0.056

Table 8. Summary statistics of regression models between detrended wheat yield and precipitation during growing season.

Region	*County*	*Precipitation*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.137	0.183	0.748	0.461	0.022
EAST	Buskerud	-0.053	0.164	-0.320	0.751	0.002
	Hedmark	-0.058	0.164	-0.354	0.725	0.003
	Oppland	0.039	0.164	0.238	0.813	0.001
	Oslo & Akershus	0.073	0.164	0.443	0.660	0.005
	Østfold	0.142	0.163	0.874	0.387	0.020
	Vestfold	0.210	0.161	1.304	0.200	0.043
SOUTH	Telemark	-0.185	0.166	-1.114	0.274	0.036

Appendix 7. Wheat Pearson correlation coefficients

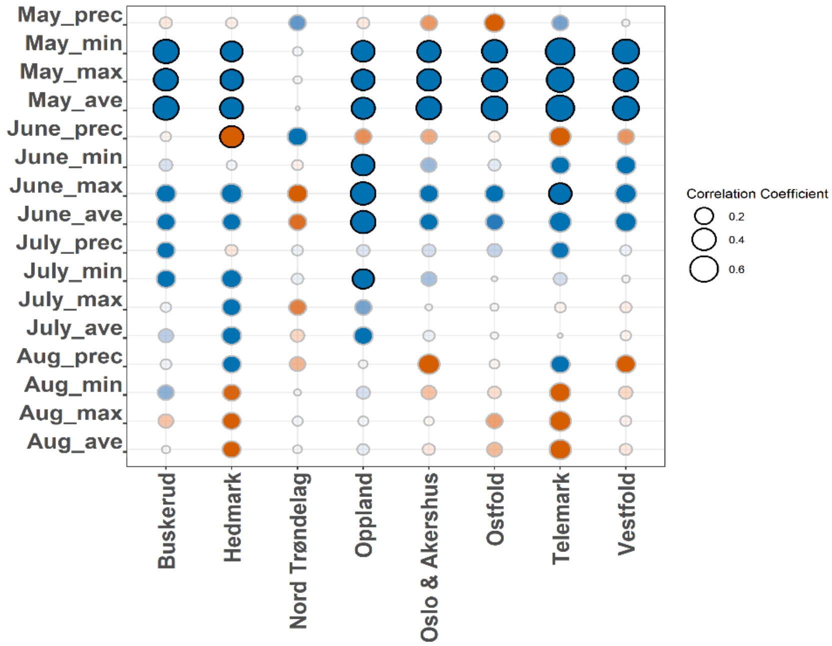

Figure 5. Pearson correlation coefficients between detrended monthly variables and detrended wheat yield in each county. The size of circles indicates the size of coefficients, black outlines around circles indicate significant correlations, blue circles are negative and red circles are positive coefficients. max: maximum temperature, min: minimum temperature, ave: average temperature, prec: precipitation.

Appendix 8. Summary statistics of the effect of monthly climate variables on wheat yield. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 9. Summary statistics of regression models between detrended wheat yield and detrended monthly climate variables (max: maximum temperature, min: minimum temperature, ave: average temperature). Models with two monthly variables have one R^2.

Region	*County*	*Monthly variables*	*Regression coefficient*	*Std.Error*	*t-value*	*p-value*	*R^2*
MID	Nord-Trøndelag	June max	0.306	0.251	1.216	0.236	0.062
EAST	Buskerud	May min	-0.505	0.164	-3.070	0.004	0.245
	Hedmark	May min	-0.332	0.155	-2.143	0.038	0.110
	Oppland	May ave	-0.352	0.147	-2.383	0.022	0.223
		July min	-0.210	0.147	-1.875	0.069	
	Oslo & Akershus	May min	-0.388	0.151	-2.561	0.014	0.150
	Østfold	May ave	-0.501	0.142	-3.521	0.001	0.251
	Vestfold	May min	-0.523	0.140	-3.736	0.001	0.273
SOUTH	Telemark	May min	-0.662	0.135	-4.878	0.001	0.419

Appendix 9. Barley yield scatterplot and model

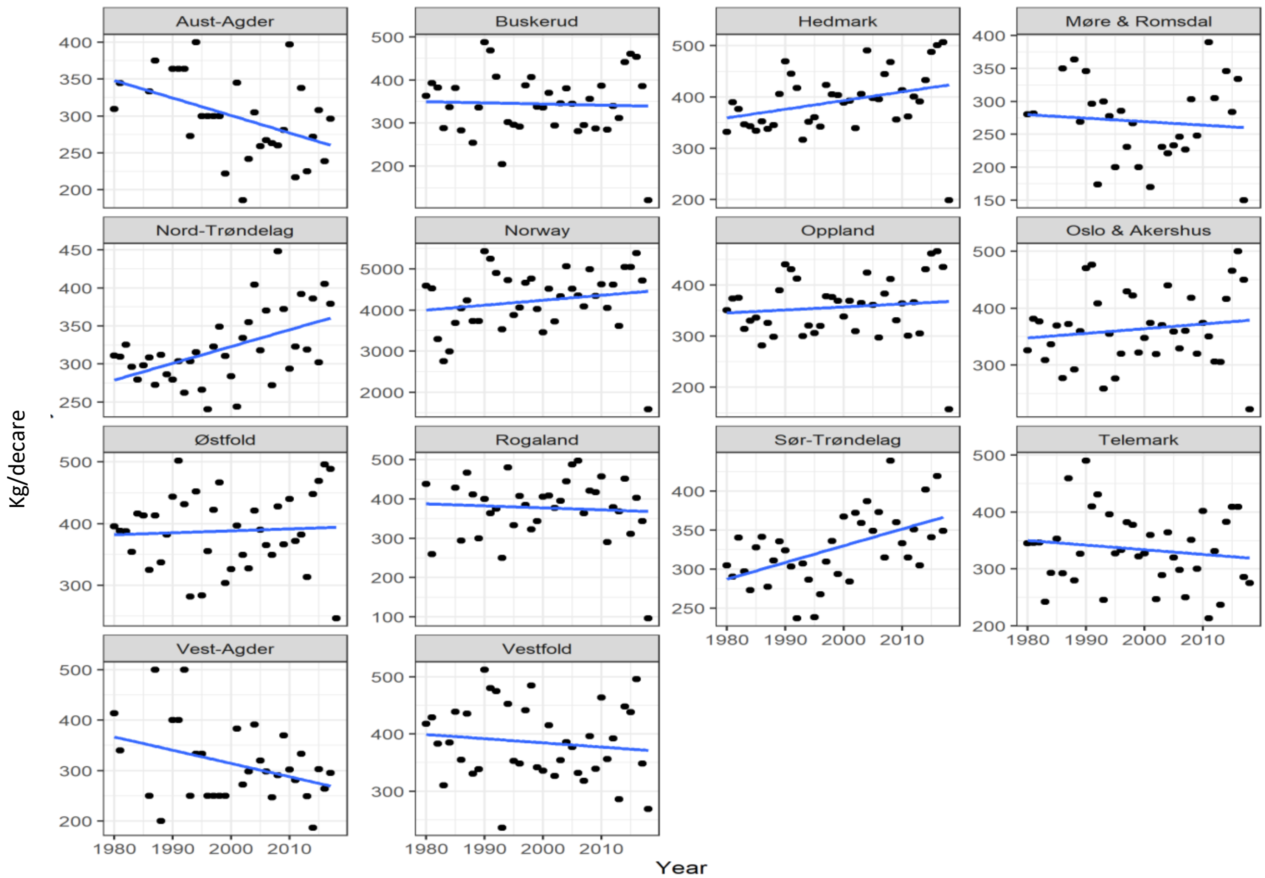

Figure 6. Scatter plots of barley yield time series along with best-fit linear regression (blue line).

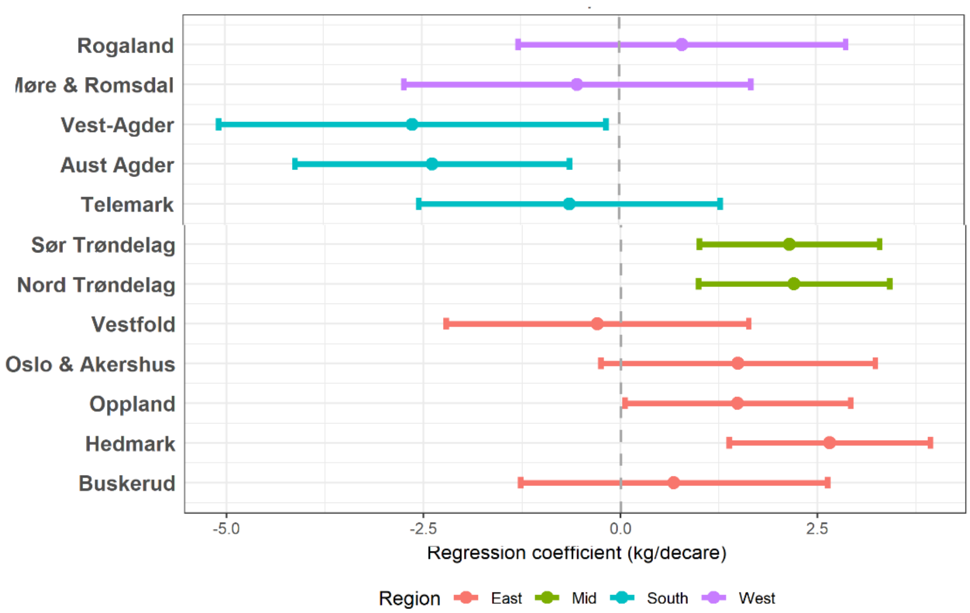

Figure 7. Regression coefficients and 95% confidence intervals from individual linear models of annual barley yield against year (1980–2017) for the main barley-growing regions in Norway. Coefficients are colored according to Region for comparison with other results. In this model 2018 that was an extreme year was excluded.

Appendix 10. Barley yield time series summary statistics. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 10. Summary statistics of regression models of barley yield time series.

Region	*County*	*Regression coefficient*	*Std.Error*	*t-value*	*p-value*	*R^2*
MID	Nord-Trøndelag	2.202	0.607	3.624	0.001	0.267
	Sør-Trøndelag	2.141	0.571	3.747	0.001	0.280
WEST	Møre og Romsdal	-0.530	1.102	-0.481	0.634	0.008
	Rogaland	-0.507	1.248	-0.406	0.687	0.004
EAST	Buskerud	-0.266	1.077	-0.248	0.805	0.001
	Hedmark	1.697	0.821	2.067	0.045	0.103
	Oppland	0.588	0.855	0.688	0.495	0.012
	Oslo & Akershus	0.821	0.912	0.900	0.374	0.021
	Østfold	0.320	0.890	0.359	0.721	0.003
	Vestfold	-0.731	0.944	-0.774	0.443	0.015
SOUTH	Telemark	-0.816	0.915	-0.892	0.378	0.021
	Aust-Agder	-2.370	0.870	-2.721	0.010	0.203
	Vest-Agder	-2.626	1.229	-2.136	0.040	0.132

Appendix 11. Summary statistics of the effect of growing season climate variables on barley yield. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 11. Summary statistics of regression models between detrended barley yield and detrended minimum temperature during growing season.

Region	*County*	*Minimum temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.124	0.164	0.759	0.452	0.015
	Sør-Trøndelag	0.275	0.159	1.733	0.091	0.076
WEST	Møre og Romsdal	0.075	0.214	0.349	0.729	0.004
	Rogaland	0.102	0.164	0.626	0.535	0.011
EAST	Buskerud	-0.276	0.165	-1.678	0.102	0.072
	Hedmark	-0.337	0.190	-1.776	0.085	0.095
	Oppland	-0.389	0.183	-2.126	0.041	0.131
	Oslo & Akershus	-0.152	0.163	-0.935	0.355	0.023
	Østfold	-0.247	0.159	-1.553	0.128	0.061
	Vestfold	-0.116	0.163	-0.712	0.480	0.013
SOUTH	Telemark	-0.294	0.157	-1.872	0.069	0.086
	Aust-Agder	-0.314	0.170	-1.849	0.074	0.105
	Vest-Agder	-0.244	0.164	-1.483	0.148	0.068

Table 12. Summary statistics of regression models between detrended barley yield and detrended maximum temperature during growing season.

Region	*County*	*Maximum temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.309	0.160	1.931	0.061	0.094
	Sør-Trøndelag	0.368	0.154	2.383	0.023	0.136
WEST	Møre og Romsdal	0.006	0.208	0.030	0.976	3.31E-05
	Rogaland	-0.004	0.168	-0.022	0.982	1.47E-05
EAST	Buskerud	-0.366	0.165	-2.211	0.034	0.120
	Hedmark	-0.372	0.187	-1.986	0.056	0.116
	Oppland	-0.341	0.186	-1.835	0.076	0.101
	Oslo & Akershus	-0.210	0.161	-1.305	0.200	0.044
	Østfold	-0.186	0.162	-1.152	0.257	0.035
	Vestfold	-0.153	0.163	-0.943	0.352	0.023
SOUTH	Telemark	-0.158	0.162	-0.973	0.337	0.025
	Aust-Agder	-0.059	0.198	-0.299	0.767	0.003
	Vest-Agder	-0.066	0.181	-0.364	0.718	0.004

Table 13. Summary statistics of regression models between detrended barley yield and detrended average temperature during growing season.

Region	*County*	*Average temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.254	0.161	1.576	0.123	0.064
	Sør-Trøndelag	0.342	0.156	2.197	0.034	0.118
WEST	Møre og Romsdal	0.034	0.212	0.160	0.874	0.001
	Rogaland	0.038	0.166	0.230	0.819	0.001
EAST	Buskerud	-0.359	0.165	-2.173	0.036	0.116
	Hedmark	-0.437	0.183	-2.393	0.023	0.160
	Oppland	-0.438	0.179	-2.448	0.020	0.166
	Oslo & Akershus	0.161	-0.201	-1.250	0.219	0.040
	Østfold	-0.233	0.160	-1.456	0.153	0.054
	Vestfold	-0.146	0.163	-0.894	0.376	0.021
SOUTH	Telemark	-0.226	0.160	-1.412	0.166	0.051
	Aust-Agder	-0.193	0.187	-1.028	0.312	0.035
	Vest-Agder	-0.151	0.175	-0.862	0.395	0.024

Table 14. Summary statistics of regression models between detrended barley yield and detrended precipitation during growing season.

Region	*County*	*Precipitation*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	-0.471	0.145	-3.258	0.002	0.227
	Sør-Trøndelag	-0.420	0.150	-2.796	0.008	0.178
WEST	Møre og Romsdal	-0.120	0.194	-0.618	0.542	0.013
	Rogaland	-0.195	0.169	-1.151	0.257	0.037
EAST	Buskerud	0.005	0.164	0.030	0.976	2.48E-05
	Hedmark	0.049	0.164	0.298	0.767	0.002
	Oppland	0.091	0.164	0.555	0.582	0.008
	Oslo & Akershus	0.075	0.164	0.456	0.651	0.005
	Østfold	0.075	0.164	0.459	0.648	0.005
	Vestfold	-0.051	0.163	-0.894	0.759	0.002
SOUTH	Telemark	-0.370	0.164	-0.308	0.020	0.137
	Aust-Agder	-0.354	0.208	-1.703	0.099	0.090
	Vest-Agder	-0.088	0.187	-0.470	0.642	0.007

Appendix 12. Barley Pearson correlation coefficients

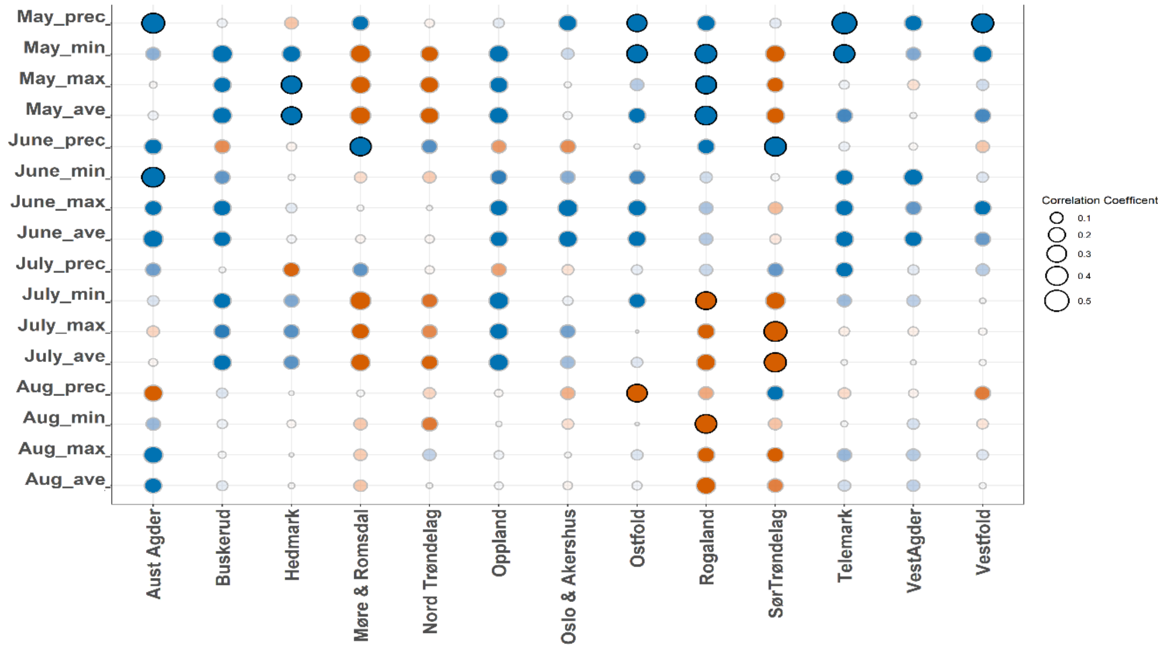

Figure 8. Pearson correlation coefficients between detrended monthly variables and detrended barley yield in each county. The size of circles indicates the size of coefficients, black outlines around circles indicate significant correlations, blue circles are negative and red circles are positive coefficients. max: maximum temperature, min: minimum temperature, ave: average temperature, prec: precipitation.

Appendix 13. Summary statistics of the effect of monthly climate variables on barley yield. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 15. Summary statistics of regression models between detrended barley yield and detrended monthly climate variables (max: maximum temperature, min: minimum temperature, ave: average temperature, precip: precipitation). Models with two monthly variables have one R^2.

Region	*County*	*Monthly variables*	*Regression coefficient*	*Std.Error*	*t-value*	*p-value*	*R^2*
MID	Nord-Trøndelag	July max	0.197	0.213	0.924	0.363	0.029
	Sør-Trøndelag	June precip	-0.303	0.146	-2.074	0.003	0.281
		July max	0.371	0.148	2.509	0.003	
WEST	Møre og Romsdal	June precip	-0.348	0.165	-2.101	0.045	0.140
	Rogaland	May ave	0.324	0.156	2.078	0.004	0.279
EAST	Buskerud	May min	0.186	0.186	-1.872	0.071	0.107
	Hedmark	May ave	-0.334	0.154	-2.161	0.037	0.112
	Oppland	July ave	-0.301	0.156	-1.923	0.062	0.090
	Oslo & Akershus	June max	-0.294	0.153	-1.917	0.050	0.153
		May precip	-0.242	0.153	-1.575	0.058	
	Østfold	May min	-0.294	0.152	-1.939	0.060	0.187
		May precip	-0.274	0.152	-1.804	0.061	
	Vestfold	May precip	-0.394	0.151	-2.608	0.013	0.155
SOUTH	Telemark	May min	-0.287	0.136	-2.113	0.001	0.352
		May precip	-0.474	0.136	-3.488	0.001	
	Aust-Agder	May precip	-0.450	0.172	-2.607	0.014	0.189
	Vest-Agder	June min	-0.266	0.165	-1.609	0.279	0.084

Appendix 14. Potato yield scatterplot and model

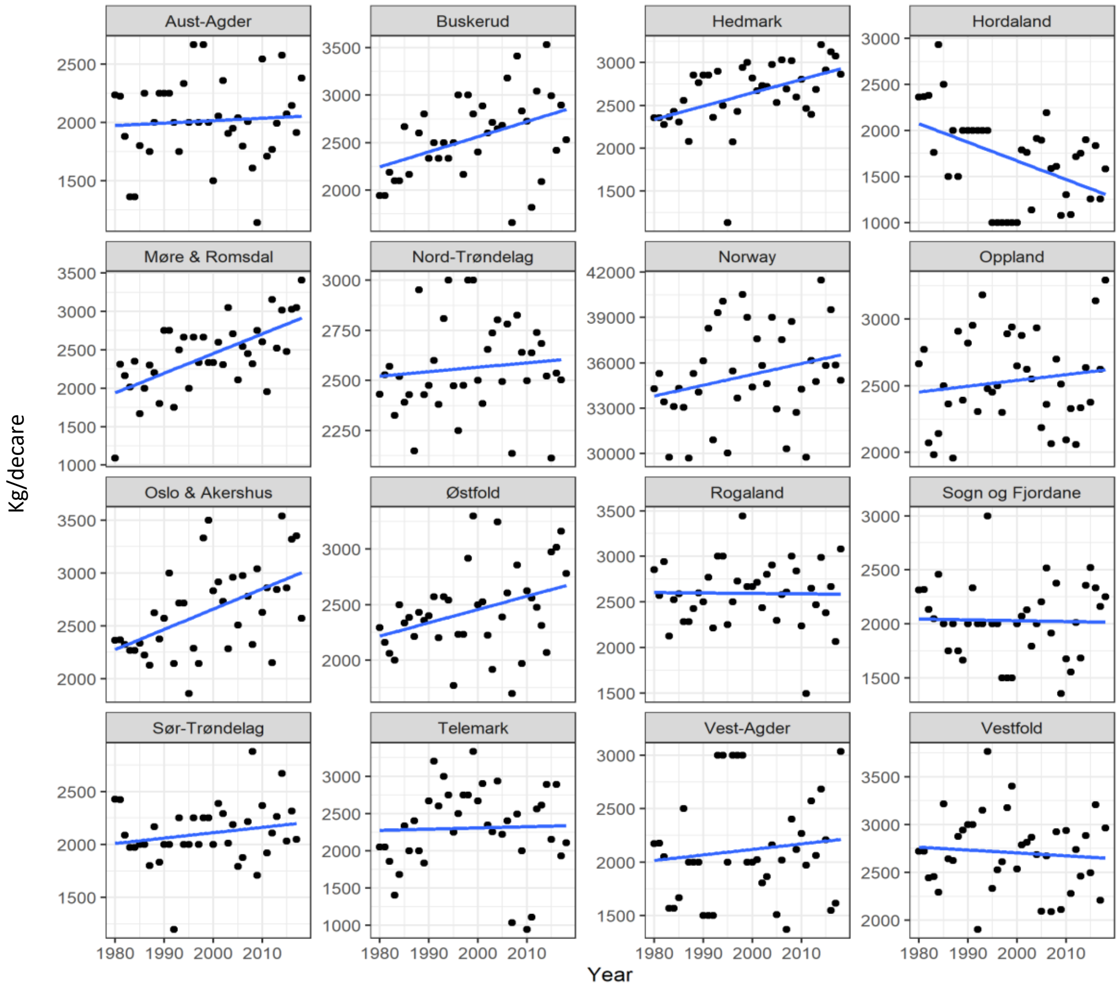

Figure 9. Scatter plots of potato yield time series along with best-fit linear regression (blue line).

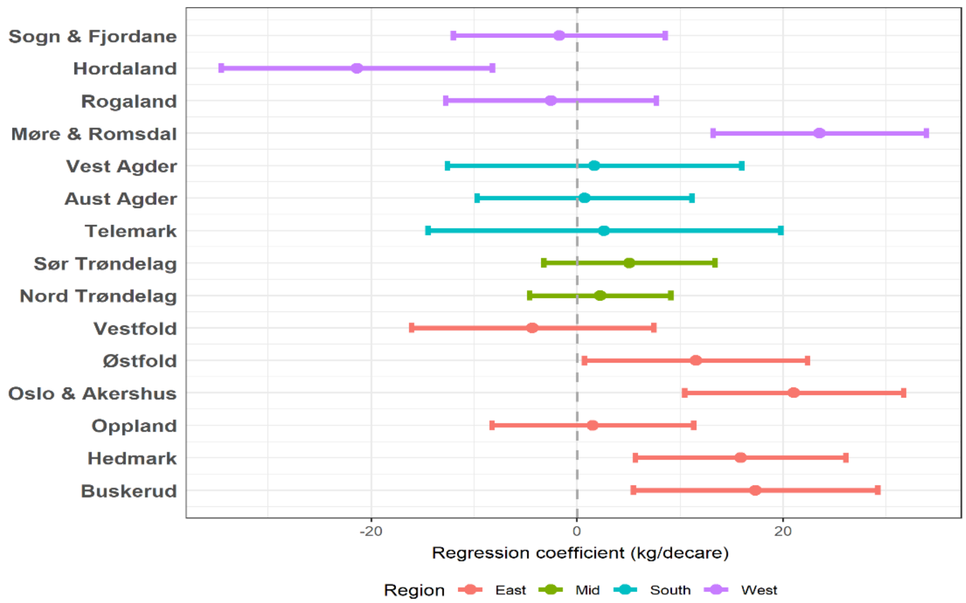

Figure 10. Regression coefficients and 95% confidence intervals from individual linear models of annual potato yield against year (1980–2017) for the main potato-growing regions in Norway. Coefficients are colored according to Region for comparison with other results. In this model 2018 that was an extreme year was excluded.

Appendix 15. Potato yield time series statistics. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 16. Summary statistics of regression models of potato yield time series.

Region	*County*	*Regression coefficient*	*Std.Error*	*t-value*	*p-value*	*R^2*
MID	Nord-Trøndelag	2.219	3.430	0.647	0.521	0.011
	Sør-Trøndelag	5.068	4.152	1.221	0.230	0.039
WEST	Møre og Romsdal	25.625	5.057	5.067	1.15E-05	0.409
	Rogaland	-0.451	5.011	-0.090	0.928	0.001
	Hordaland	-20.221	6.283	-3.218	0.002	0.218
	Sogn og Fjordane	-0.751	4.924	-0.153	0.879	0.001
EAST	Buskerud	15.921	5.684	2.801	0.008	0.179
	Hedmark	15.580	4.846	3.215	0.002	0.218
	Oppland	4.379	4.931	0.888	0.380	0.020
	Oslo & Akershus	19.182	5.147	3.727	0.001	0.272
	Østfold	11.981	5.144	2.329	0.025	0.127
	Vestfold	-3.005	5.631	-0.534	0.596	0.007
SOUTH	Telemark	1.641	8.142	0.202	0.841	0.001
	Aust-Agder	2.104	5.015	0.420	0.677	0.004
	Vest-Agder	5.166	7.075	0.730	0.469	0.014

Appendix 16. Summary statistics of the effect of growing season climate variables on potato.

Table 17. Summary statistics of regression models between detrended potato yield and detrended minimum temperature during growing season.

Region	*County*	*Minimum temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.072	0.164	0.440	0.662	0.005
	Sør-Trøndelag	0.047	0.165	0.291	0.773	0.002
WEST	Møre og Romsdal	-0.074	0.163	-0.453	0.653	0.005
	Rogaland	0.067	0.164	0.411	0.683	0.004
	Hordaland	0.116	0.163	0.711	0.481	0.013
	Sogn og Fjordane	-0.007	0.164	-0.043	0.965	0.001
EAST	Buskerud	-0.211	0.167	-1.261	0.215	0.042
	Hedmark	-0.029	0.201	-0.147	0.884	0.001
	Oppland	-0.086	0.184	-0.469	0.642	0.007
	Oslo & Akershus	-0.126	0.163	-0.774	0.444	0.015
	Østfold	-0.363	0.153	-2.372	0.022	0.132
	Vestfold	-0.027	0.164	-0.169	0.866	0.001
SOUTH	Telemark	-0.202	0.161	-1.260	0.215	0.041
	Aust-Agder	-0.050	0.164	-0.307	0.760	0.002
	Vest-Agder	-0.109	0.163	-0.673	0.505	0.012

Table 18. Summary statistics of regression models between detrended potato yield and detrended maximum temperature during growing season.

Region	*county*	*Maximum temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.160	0.165	0.966	0.340	0.025
	Sør-Trøndelag	0.115	0.165	0.702	0.487	0.013
WEST	Møre og Romsdal	-0.064	0.164	-0.392	0.697	0.004
	Rogaland	0.259	0.158	1.635	0.110	0.067
	Hordaland	0.149	0.162	0.917	0.364	0.022
	Sogn og Fjordane	0.072	0.164	0.442	0.660	0.005
EAST	Buskerud	-0.097	0.175	-0.557	0.581	0.008
	Hedmark	0.054	0.201	0.269	0.789	0.002
	Oppland	0.362	0.172	2.100	0.044	0.120
	Oslo & Akershus	-0.160	0.162	-0.991	0.328	0.025
	Østfold	-0.205	0.160	-1.277	0.209	0.042
	Vestfold	0.054	0.164	0.330	0.743	0.002
SOUTH	Telemark	-0.027	0.164	-0.165	0.870	0.001
	Aust-Agder	0.118	0.163	0.726	0.472	0.014
	Vest-Agder	-0.010	0.164	-0.065	0.948	0.001

Table 19. Summary statistics of regression models between detrended potato yield and detrended average temperature during growing season.

Region	*County*	*Average temperature*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	0.134	0.165	0.814	0.420	0.018
	Sør-Trøndelag	0.093	0.165	0.567	0.574	0.008
WEST	Møre og Romsdal	-0.070	0.164	-0.428	0.671	0.004
	Rogaland	0.198	0.161	1.231	0.226	0.039
	Hordaland	0.141	0.162	0.871	0.389	0.020
	Sogn og Fjordane	0.042	0.164	0.260	0.796	0.001
EAST	Buskerud	-0.159	0.173	-0.919	0.364	0.022
	Hedmark	0.026	0.201	0.133	0.895	0.001
	Oppland	0.231	0.179	1.286	0.208	0.052
	Oslo & Akershus	-0.158	0.162	-0.975	0.336	0.025
	Østfold	-0.297	0.157	-1.896	0.065	0.088
	Vestfold	0.022	0.164	0.139	0.890	0.001
SOUTH	Telemark	-0.103	0.163	-0.632	0.531	0.010
	Aust-Agder	0.054	0.164	0.334	0.740	0.003
	Vest-Agder	-0.052	0.164	-0.321	0.750	0.002

Table 20. Summary statistics of regression models between detrended potato yield and detrended precipitation during growing season.

Region	*County*	*Precipitation*				
		Regression coefficient	Std.Error	t-value	p-value	R^2
MID	Nord-Trøndelag	-0.156	0.162	-0.964	0.341	0.025
	Sør-Trøndelag	-0.250	0.160	-1.560	0.127	0.063
WEST	Møre og Romsdal	-0.057	0.164	-0.351	0.727	0.003
	Rogaland	-0.312	0.156	-1.997	0.053	0.097
	Hordaland	-0.183	0.161	-1.135	0.263	0.033
	Sogn og Fjordane	-0.395	0.151	-2.623	0.012	0.156
EAST	Buskerud	-0.281	0.157	-1.782	0.083	0.081
	Hedmark	-0.172	0.161	-1.065	0.293	0.029
	Oppland	-0.275	0.158	-1.743	0.089	0.075
	Oslo & Akershus	0.157	0.162	0.969	0.339	0.024
	Østfold	0.008	0.164	0.051	0.959	0.001
	Vestfold	-0.187	0.161	-1.158	0.254	0.035
SOUTH	Telemark	-0.439	0.147	-2.973	0.005	0.192
	Aust-Agder	-0.219	0.160	-1.369	0.179	0.048
	Vest-Agder	-0.195	0.161	-1.215	0.232	0.038

Appendix 17. Potato Pearson correlation coefficients

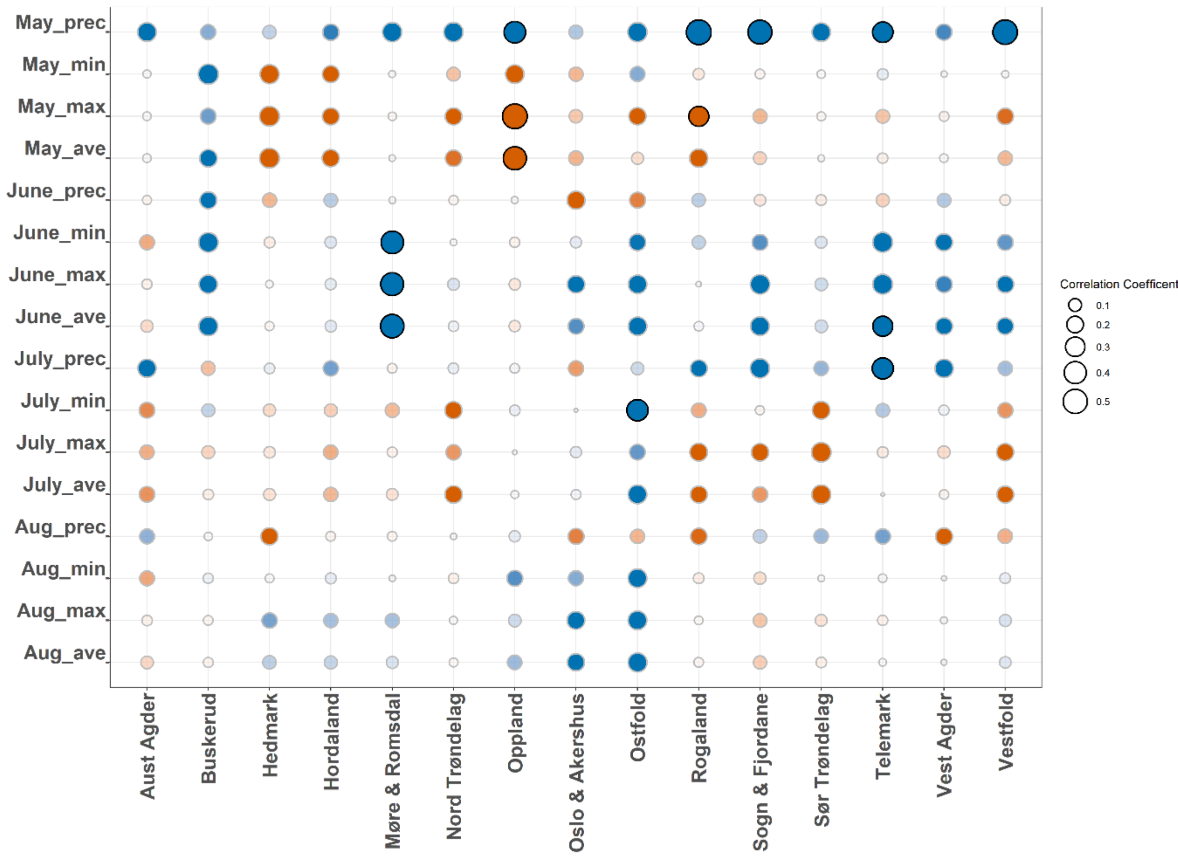

Figure 11. Pearson correlation coefficients between detrended monthly variables and detrended potato yield in each county. The size of circles indicates the size of coefficients, black outlines around circles indicate significant correlations, blue circles are negative and red circles are positive coefficients. max: maximum temperature, min: minimum temperature, ave: average temperature, prec: precipitation.

Appendix 18. Summary statistics of the effect of monthly climate variables on potato. Each county was modeled separately. Note that intercepts have not been included for brevity.

Table 21. Summary statistics of regression models between detrended potato yield and detrended monthly climate variables (max: maximum temperature, min: minimum temperature, ave: average temperature, precip: precipitation). Models with two monthly variables have one R^2.

Region	*county*	*Monthly variables*	*Regression coefficient*	*Std.Error*	*t-value*	*p-value*	R^2
MID	Nord-Trøndelag	May precip	-0.314	0.199	-1.577	0.126	0.114
		May ave	0.177	0.221	0.801	0.430	
	Sør-Trøndelag	May precip	-0.262	0.164	-1.593	0.119	0.065
WEST	Møre og Romsdal	May precip	-0.248	0.142	-1.743	0.060	0.274
		June ave	-0.442	0.142	-3.107	0.003	
	Rogaland	May precip	-0.534	0.138	-3.849	0.001	0.285
	Hordaland	May precip	-0.133	0.171	-0.778	0.442	0.060
		May ave	0.166	0.171	0.969	0.339	
	Sogn og Fjordane	May precip	-0.495	0.142	-3.471	0.001	0.245
EAST	Buskerud	June precip	-0.287	0.206	-1.394	0.175	0.149
		June min	-0.304	0.189	-1.604	0.120	
	Hedmark	May precip	-0.110	0.163	-0.674	0.504	0.012
	Oppland	May max	0.455	0.150	3.033	0.004	0.319
		May precip	-0.198	0.150	-1.323	0.194	
	Oslo & Akershus	June max	-0.225	0.160	-1.406	0.168	0.050
	Østfold	July min	-0.369	0.152	-2.418	0.020	0.136
	Vestfold	May precip	-0.519	0.140	-3.694	0.001	0.269
SOUTH	Telemark	May precip	-0.357	0.144	-2.479	0.018	0.253
		July precip	-0.375	0.144	-2.605	0.013	
	Aust-Agder	May precip	-0.270	0.158	-1.710	0.095	0.073
	Vest-Agder	July precip	-0.259	0.158	-1.634	0.110	0.042