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CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

Impact of projected mid-21st century climate and soil extrapolation on simulated spring wheat grain yield in Southeastern Norway

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SUMMARY

The effects of soil variability on regional crop yield under projected climate change are largely unknown. In Southeastern Norway, increased temperature and precipitation are projected for the mid-21st century. Crop simulation models in combination with scaling techniques can be used to determine the regional pattern of crop yield. In the present paper, the CSM-CROPSIM-CERES-Wheat model was applied to simulate regional spring wheat yield for Akershus and Østfold counties in Southeastern Norway. Prior to the simulations, parameters in the CSM-CROPSIM-CERES-Wheat model were calibrated for the spring wheat cvars Zebra, Demonstrant and Bjarne, using cultivar trial data from Southeastern Norway and site-specific weather and soil information. Weather input data for regional yield simulations represented the climate in 1961–1990 and projections of the climate in 2046–2065. The latter were based on four Global Climate Models and greenhouse gas emission scenario A1B in the IPCC 4th Assessment Report. Data on regional soil particle size distribution, water-holding characteristics and organic matter data were obtained from a database. To determine the simulated grain yield sensitivity to soil input, the number of soil profiles used to describe the soilscape in the region varied from 76 to 16, 5 and 1. The soils in the different descriptions were selected by arranging them into groups according to similarities in physical characteristics and taking the soil in each group occupying the largest area in the region to represent other soils in that group. The simulated grain yields were higher under all four projected future climate scenarios than the corresponding average yields in the baseline conditions. On average across the region, there were mostly non-significant differences in grain yield between the soil extrapolations for all cultivars and climate projections. However, for sub-regions grain yield varied by up to 20% between soil extrapolations. These results indicate how projected climate change could affect spring wheat yield given the assumed simulated conditions for a region with similar climate and soil conditions to many other cereal production regions in Northern Europe. The results also provide useful information about how soil input data could be handled in regional crop yield determinations under these conditions.

INTRODUCTION

Regional crop yield depends largely on spatial and temporal variability in ambient weather conditions (Rosenzweig *et al.* 2001, 2014; Lobell *et al.* 2011) and soil conditions (Hallett & Bengough 2013). Various studies have assessed the impact of weather, climate (Semenov & Porter 1995; Hansen & Jones 2000; Parry *et al.* 2004) and soil variability (Wassenaar *et al.* 1999; Gaiser *et al.* 2013; Angulo *et al.* 2014) on crop production. Lately, there has been a strong focus on assessing the impact of projected climate change on crop production (Tubiello *et al.* 2007; Soussana *et al.* 2010; White *et al.* 2011; Asseng *et al.* 2013; Eitzinger *et al.* 2013). For Europe, such analyses indicate a possible future northward shift in the production of many agricultural crops due to less favourable conditions, including increased heat and drought stress, especially in southern regions of the continent. However, the projected increased temperature and longer growing season in Northern Europe would generally entail more favourable

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production conditions than under the current climate (Olesen & Bindi 2002; Bindi & Olesen 2011; Rötter *et al.* 2012). Such a shift, together with projections showing more adverse conditions for crop production on many other continents (Fuhrer 2003; Soussana *et al.* 2010), imply that Northern Europe may become relatively more important for global food supply (Rötter *et al.* 2012). A few specific analyses conducted to date show higher forage grass yields in this region under climate change scenarios (Höglind *et al.* 2013; Persson *et al.* 2015). However, Eckersten *et al.* (2012) found no increase in simulated forage maize yield under climate change conditions in Sweden. Spatial heterogeneity in soil properties, such as water-holding capacity, soil organic matter (SOM) content and plant nutrients, can also have a large impact on crop productivity in many regions. Thus, adequate handling of soil factors and their impact on crop growth is crucial for predicting potential climate change impacts on regional crop yield levels and variability. However, the ways in which regional soil variability will affect cereal crop production potential under future conditions have not been thoroughly investigated for Northern Europe or other production regions.

Mechanistic simulation models that describe the growth, development and yield of a crop as a function of weather, soil, management practices and genetic factors have been widely developed and applied to determine the yield and other production aspects of major agricultural crops under existing and hypothetical production scenarios (Brisson *et al.* 2003; Jones *et al.* 2003; Stöckle *et al.* 2003). The output from these crop models is valid for a specific point with the specific weather, soil and management used as model input. In order to use crop models in assessments of regional yield levels and variability, it is necessary to apply methods that scale up point-based yield data to regions (Adam *et al.* 2011; Ewert *et al.* 2011). Such scaling methods for model yield output data include extrapolation and interpolation of point values to represent larger regions, aggregation of model input and output data, and development and use of meta-models (Ewert *et al.* 2011). In the methods applied, the region for which crop yield or other variables related to crop production is being determined is divided into grids of a defined size. In each grid, the most frequently occurring soil and representative weather and management conditions are extrapolated and used as model input to simulate the crop. By comparing crop yield and other simulation outputs for grids of different sizes, the effect of spatial resolution of soil and weather and other factors on the simulated crop can be determined. The gain in accuracy obtained from using detailed data compared with less detailed data has been exploited in studies conducted for a number of different crops and regions (Easterling *et al.* 1998; Folberth *et al.* 2012; Angulo *et al.* 2014). However, this grid-based approach does not explicitly take into account model sensitivity to regional variability in soil input variables, which makes it difficult to justify the use of one grid resolution for another region with different soil or weather variability from that for which it was tested. If groups of soil profiles that differ in terms of a range of soil characteristics, e.g. texture, water-holding capacity, organic matter and nutrient content, are compared using one soil in each group to cover the others, it is possible to analyse the importance of accurate description of regional soil characteristics. This method was used by Persson *et al.* (2015) to determine the sensitivity to soil input accuracy in simulations of regional yield of timothy grass, a forage crop, under different climate scenarios for Southeastern Norway. However, this method has rarely, if ever, been used previously to determine the importance of soil input accuracy in simulations of regional grain yield of wheat or other cereals under different climate scenarios. The CSM-CROPSIM-CERES-Wheat model, which is included in the Decision Support System for Agrotechnology Transfer (DSSAT) v. 4.5 software (Hoogenboom *et al.* 2010), has been widely applied to simulate wheat production in different regions in Europe (Bannayan *et al.* 2003; Langensiepen *et al.* 2008) and other major wheat-producing regions of the world (Timsina *et al.* 2008; Xiong *et al.* 2008; Persson *et al.* 2010; Thorp *et al.* 2010). These simulations with the CSM-CROPSIM-CERES-Wheat model include scaling studies of weather and soil data to determine regional crop yields (Gijsman *et al.* 2002; Thornton *et al.* 2009).

Southeastern Norway is currently characterized by a humid cold-temperate climate. However, projections on future climate conditions for this region include an increase in mean summer and winter air temperature and increased annual precipitation, the latter as a result of increased spring, autumn and winter precipitation. Summer precipitation is expected to decrease (Hanssen-Bauer *et al.* 2009). The soilscape in Southeastern Norway is highly variable, with soils ranging from heavy clay soils to light sandy soils (Norwegian Forest and Landscape

Institute 2014). Wheat and other cereal crops are frequently grown on most of these soil types. There are also large variations in the wheat acreage, including both a long-term increase from 9200 ha in 1959 to 74 000 ha in 2011 and year-to-year changes in this region (Rognstad & Steinset 2013). Possible future changes in wheat acreage could include a shift in the soil types on which wheat is grown in this region. An increased understanding of the sensitivity of wheat yield simulations to projected future climate change and to different characterizations of the regional soilscape would help determine the need for accuracy in weather and soil data and thus the feasibility of assessing the regional wheat yield potential and variability in this region under different production and climate scenarios. Such knowledge could be obtained by comparing wheat yield from simulations where different regional soil characterizations are combined with weather data representing current and future climate scenarios. The climate, geographical and agronomic characteristics in Southeastern Norway are similar to those in other major cereal production regions in Northern Europe, notably regions in Finland and Sweden (Eurostat 2015). Thus, results from studies focusing on Southeastern Norway could be relevant for larger regions in Northern Europe.

In order to determine the sensitivity of regional wheat yield levels and variability to soil input data under different climate scenarios, comparisons of simulated wheat yield in which different regional soil characterizations are used as model input, combined with weather data that represent different climate scenarios, could be conducted. The wheat grain yield outputs from these simulations would give a clear indication of the need for spatial detail in soil input data for crop simulation models to determine regional wheat yield under different climate scenarios. The aim of the present study was thus to determine the impact of projected mid-21st century climate on regional spring wheat yields in Akershus and Østfold counties in Southeastern Norway. Simulated wheat production for four contrasting projections of the mid-21st century climate and baseline climate conditions for the period 1961–1990 were evaluated. In simulations using the CSM-CROPSIM-CERES-Wheat model, weather data based on these projections were combined with descriptions of regional soil characteristics to evaluate the effect of spatial details in the soil under different climate scenarios.

Fig. 1. Location of Akershus and Østfold counties in Southeastern Norway.

MATERIALS AND METHODS

Spring wheat grain yield as simulated under different combinations of regional soil characterizations and climate scenarios was determined. The present study was confined to Akershus and Østfold counties in Southeastern Norway (Fig. 1). Weather data in addition to soil, crop genetic and management data were used as input to the crop model CSM-CROPSIM-CERES-Wheat (Ritchie *et al.* 1998). It simulates wheat growth, development and yield as a function of weather, soil and crop management, and is included in the Decision Support System for Agrotechnology (DSSAT) v 4.5 software (Hoogenboom *et al.* 2010). The methods used for obtaining soil, weather and crop input data for the simulations, the simulation settings and the upscaling of simulated spring wheat yield are described below.

Description of the study region

Akershus and Østfold counties comprise an area of 9100 km^2, with altitude ranging from 0 to 812 m asl.

The climate within this region is characterized as humid cold-temperate (Köppen climate types Dfb and Dfc). Mean annual air temperature in the region varies between 1 and 7 °C and mean annual precipitation between 600 and 1100 mm (data obtained from the Norwegian Meteorological Institute, http://www.met.no). Arable land, which is dominated by cereal cropping, covers 0·17 of the total land area. The remaining land area in the two counties is mainly covered with forest and, to a smaller extent, built-up area.

CSM-CROPSIM-CERES-Wheat input data

Soil data

Soil physical and chemical data used as input to the spring wheat simulations were derived by linking digital soil maps (http://www.skogoglandskap.no/kart/kilden) to soil profile data from the national soil survey database of the Norwegian Forest and Landscape Institute (2014) for the two counties included in the study. The scale of the soil map was 1:5000 and map units represented local soil series with associated representative soil profiles in the soil survey database. For each soil horizon of the representative profiles, data on soil properties, including particle size distribution, organic carbon content, coarse fragment class and chemical properties, were available. In Akershus and Østfold counties, approximately 900 local soil series were identified. The differences between many of these 900 soil profiles were not sufficiently large to result in marked differences between profiles in soil hydraulic characteristics, one of the factors by which crop growth is affected by the soil in the CSM-CROPSIM-CERES-Wheat model. The selection procedure and development of pedotransfer functions to obtain soil input data to crop simulations have been described previously by Persson *et al.* (2015), who used the same soils as considered in the current paper in simulations of timothy grass yields. In brief, the approximately 900 mapped soil types were divided into 'soil groups' by simplifying the layering to three layers of standard thicknesses and classifying the basic soil properties of SOM and particle size distribution based on Sveistrup & Njøs (1984):

- Layer simplification: Topsoil at 0–25 cm depth (representing lower boundaries varying from 15 to 40 cm depth); Subsoil 1 at 25–60 cm (representing lower boundaries varying from 40 to 80 cm); Subsoil 2 at 60–100 cm.
- Soil organic matter classes (fraction organic carbon content): Very low: 0–0·01; Low: 0·01–0·03; Moderate: 0·03–0·06; High: 0·06–0·12; Very high: 0·12–0·20; Organic: >0·20.
- Classes for particle size distribution, including coarse fragments: 'Coarse sand': Gravel and coarse sand; 'Sand': Fine and medium sand, loamy fine and medium sand; 'Silt': Silt, sandy silt; 'Loam': Loam, sandy loam; 'Silt loam': Silt loam; 'Clay': Clay loam, silty clay loam, heavy clay.

From each group, the soil type covering the largest area was selected to represent the other soil types within the same group. If the representative soil type in a group covered <10 ha arable land, that soil group was eliminated and the soil type moved to another soil group containing soils with similar properties. As a result of this extrapolation, the 900 soil types were reduced to 76 representative soil types. From this base set of 76 soil types, three sets with less detailed soil information were formed. These were:

- A 16 soil-type set, with an even more simplified classification of SOM, texture and layering.
- A five soil-type set, representing four major soil groups ('Clay', 'Silt', '60 cm silt over clay' and 'Sand' with moderate SOM) and one organic soil.
- A single soil-type set consisting of the soil type covering the largest area in the study region, i.e. a Luvic Stagnosol (Siltic) developed on marine clay deposits, with a silty clay loam texture throughout the profile and a topsoil organic carbon content of 0·026.

The CSM-CROPSIM-CERES-Wheat model required input data on soil bulk density, water content at saturation, field capacity (matric potential 100 hPa) and wilting point (matric potential 15 000 hPa). Such data were not available in the national soil survey database and were therefore calculated from class pedotransfer functions developed from Norwegian data in the EU-HYDI database. This database includes data on particle size distribution, bulk density and water content at saturation, field capacity and wilting point for a wide range of soils (Kværnø *et al.* 2013).

Weather data

Daily weather input data on solar radiation, maximum and minimum air temperature and precipitation for the CSM-CROPSIM-CERES-Wheat simulations were generated for climate scenarios representing Southeastern Norway in two periods, 1961–90 and 2046–65, using the Long Ashton Research Station Weather Generator (LARS-WG) tool (Semenov 2008). For the future period, the weather data represented the Special Report on Emission Scenarios (SRES) intermediate greenhouse gas emission scenario A1B (Nakicenovic *et al.* 2000) and four Global Climate Models (GCM): Bergen Climate Model version 2 (BCM2.0), Commonwealth Scientific and Industrial Research Organisation M.k3.0 (CSIRO-M.k3.0), Goddard Institute for Space Studies Atmosphere-Ocean Model (GISS-AOM) and Hadley Centre Coupled Model, version 3 (HadCM3), which were all included in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (Pachauri & Reisinger 2007). The same weather data as used by Persson *et al.* (2015) to simulate timothy grass under climate change conditions were used in the current paper and a detailed description of the generation of weather data can be found in Persson *et al.* (2015). In a previous study (Höglind *et al.* 2013), weather data representing these four GCM resulted in forage grass yields in the lower, centre and upper sections of the yield range that was simulated with weather data representing all 15 GCM in the IPCC 4th Assessment Report for the Nordic region in Europe and the period 2046–65. Therefore, it was assumed that the weather data from these GCM would cover the full range of spring cereal yields simulated using weather data associated with all GCM included in the IPCC 4th Assessment Report, and that inclusion of weather datasets generated from other GCM would not disclose more of the potential climate change effects on spring wheat under the SRES emission scenario A1B.

Wheat cultivar characteristics

To determine crop parameter values in CSM-CROPSIM-CERES-Wheat that are representative of the region, the model was calibrated and tested against data from spring wheat cultivar trials at six locations in Southeastern Norway: Apelsvoll (60°42′N; 10°52′E; 298 m a.s.l.), Ås (59°41′N; 10°47′E; 109 m a.s.l.), Kråkstad (59°42′N; 10°53′E; 113 m a.s.l.), Øsaker (59°19′N; 11°02′E; 46 m a.s.l.), Skjeberg (59°12′N; 11°13′E; 43 m a.s.l.) and Tjodalyng (59°03′N; 10°11′E; 4 m a.s.l.). Observed daily data on solar radiation, maximum and minimum air temperature and precipitation were obtained from nearby stations within the Weather Station Network of the Norwegian Institute for Agricultural and Environmental Research and used as input to the calibrations of the CSM-CROPSIM-CERES-Wheat model. These weather variables were the same as those generated with the LARS-WG tool and used later in the simulations with the calibrated model. The spring wheat cultivars Bjarne, Demonstrant and Zebra were selected for calibration because they were among the most commonly grown spring wheat cultivars in Norway during the previous few years. To calibrate parameters in CSM-CROPSIM-CERES-Wheat that represented these cultivars, version 2 of the Genotype Coefficient Calculator (GenCalc) tool (Hunt *et al.* 1993), which is included in DSSAT v 4.5, was used. First, parameters determining phenological development were calibrated against observations at Apelsvoll in 2007, 2009 and 2011 and tested against observations at the same location in 2008, 2010 and 2012. Second, parameters that determined the thousand-kernel weight and grain yield were calibrated against all years from 2007 to 2012 at Apelsvoll and then tested against the observations from the field cultivar trials at the other locations. The reason for this division of the observed field trial data into calibration and testing datasets was that there were no observations of phenology during the growing season at locations other than Apelsvoll. The calibration principles described by Hunt *et al.* (1993) and Boote (1999) were followed. For each step in the calibration, an iterative process was used where a set of different parameter combinations was tested. The starting point of the calibration was set to represent the wheat ECOTYPE CAWH0001 and the cultivar type Manitou, which are included in the CERES wheat ecotype and cultivar input files, respectively, of the DSSAT software v. 4.5. First, parameters P1, P2 and P3 in the ECOTYPE input file, which determine the phenological development until anthesis (growth stage (GS) 65 according to the Zadoks *et al.* (1974) scale), were adjusted (see Table 1 for a definition of all parameters). The next step in the calibration comprised adjustment of parameter P5 in the cultivar input file to minimize the difference between simulated maturity and observed day of maturation. After setting the phenology parameter values, parameter G2 was set at a fixed value so that it matched the highest thousand-kernel weight observed for each of the cultivars during the 6 years of trials in Apelsvoll. The G1, G3 and PHINT parameters were then changed to minimize the difference between

Table 1. *Parameters calibrated in the CSM-CROPSIM-CERES-Wheat model in the present study*

Parameter symbol	Units	Description	Input file in DSSAT
P1	°C days	Duration of phase end juvenile to terminal spikelet	Ecotype
P2	°C days	Duration of phase terminal spikelet to end leaf growth	Ecotype
P3	°C days	Duration of phase end leaf growth to end spike growth	Ecotype
PARUE	g dry matter/m^2	Photosynthetically active radiation conversion to dry matter ratio before last leaf stage	Ecotype
PARU2	g dry matter/m^2	PAR conversion to dry matter ratio, after last leaf stage	Ecotype
P5	°C days	Grain filling (excluding lag) phase duration	Cultivar
G1	no/g	Kernel number per unit canopy weight at anthesis	Cultivar
G2	mg	Standard kernel size under optimum conditions	Cultivar
G3	g dry matter	Standard, non-stressed mature tiller weight (incl. grain)	Cultivar
PHINT	°C days	Interval between successive leaf tip appearances (phyllochron)	Cultivar

simulated and observed grain yield and thousand-kernel weight. However, since these calibrations resulted in large under-prediction of grain yield (<70% of observed yield), the PARUE and PARU2 values in ECOTYPE were increased to match the observed grain yield. Then G1, G3 and PHINT were re-calibrated with the new PARUE and PARU2 values against the grain yield and thousand-kernel weight until parameter changes did not improve the grain yield predictions. Finally, the new parameter sets for the three cultivars were evaluated against grain yield data and harvest days in cultivar trials 2009–12 at the five other locations.

Wheat simulations

Wheat simulations in the CSM-CROPSIM-CERES-Wheat model were carried out with all combinations of the 76 soil profiles, weather data representing the four climate projections for the period 2046-65 and the baseline climate, and crop parameters for the three cultivars. For each climate dataset and cultivar, 100 years of simulations were conducted with different weather data for each year. The atmospheric carbon dioxide (CO_2) concentration in the simulations was set to 380 ppm in the climate scenario for the period 1961–90 and to 532 ppm in the projections for the period 2046–65, the latter in accordance with the A1B scenario from the IPCC 4th Assessment Report. The simulated management represented normal practices for the region. The planting date was set to 3 May for the period 1961–90 and 19 April for the period 2046–65, with 3 May representing the normal planting date under historical conditions. Mean daily temperature in the weather data representing all four GCM at 19 April under the 2046–65 climate conditions was equal to mean daily temperature on 3 May under the 1961–90 climate conditions. The nitrogen fertilizer rate was set to 132 kg/ha and all nitrogen was applied at planting in all simulations. Harvest date was set at the point when the crop reached maturity (GS 91).

Statistical analysis

The simulated wheat grain dry matter yield associated with each soil profile was weighted according to the fraction of total area of agricultural soil that profile occupied within Akershus and Østfold counties, within soil extrapolations, climate projections and cultivars. To assess statistically significant differences in mean wheat grain yield between the soil extrapolations, climate projections and cultivars, analyses of variance (ANOVA) and least significant difference (LSD) tests were conducted with PROC GLM in SAS v.9.2 (SAS Institute 2008), using individual years as replicates.

RESULTS

Weather data generated for the five climates

Mean daily air temperature from planting to harvest date was between 0·1 and 1·6 °C higher for the 2046–65 climate projections than for the 1961–90 climate. Mean accumulated precipitation during the growing season was lower in three out of four projections for the 2046–65 period than for 1961–90. Mean daily global radiation was between 3·1 and 4·0 MJ/m^2 higher in the HadCM3 projection than in the other projections of the

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Table 2. *Monthly generated average mean daily air temperature and accumulated precipitation from the date of planting to the date of harvest for the five climate projections included in the present study*

	Baseline	BCM2.0	CSIRO-M.k3.0	GISS-AOM	HadCM3
Mean daily air temperature (°C)					
May	10	13	12	11	13
June	15	16	16	15	17
July	16	17	17	17	19
August	15	16	16	16	18
Mean	14	16	15	15	17
Mean accumulated precipitation (mm)					
May	61	63	58	75	64
June	69	69	64	64	61
July	87	93	89	91	80
August	76	79	84	87	81
Sum	293	304	295	317	286

Table 3. *Calibrated parameter values in the CSM-CROPSIM-CERES-Wheat model for the three spring wheat cultivars included in simulations (see Table 1 for definition of parameters)*

Cultivar	P1	P2	P3	PARUE	PARU2	P5	G1	G2	G3	PHINT
Bjarne	335	239	191	3·0	3·0	771·5	19	40	1·50	123·6
Demonstrant	335	239	191	3·3	3·3	771·5	18	44	1·50	118·6
Zebra	335	239	191	3·3	3·3	771·5	12·5	47	1·546	85·4

2046–65 climate and the 1961–90 climate. Mean monthly temperature and accumulated precipitation during the growing season are presented in Table 2.

Model calibration and validation

The cultivar coefficients that resulted from model calibration are presented in Table 3. In the model evaluation, on average across the five locations and the three cultivars, the simulated grain yield (5126 kg/ha) was overpredicted compared with the observed grain yield (4126 kg/ha) (Fig. 2). Mean simulated thousand-kernel weight (36·9 g) was also over-predicted across the locations and cultivars (34·5 g) (Fig. 3).

Regional spring wheat grain yield

Effect of climate scenarios

For the most detailed soil extrapolation (76 soil types), the area-weighted grain yield for the baseline climate varied between 4600 and 5500 kg/ha for the three simulated wheat cultivars, being highest for Zebra and lowest for Bjarne. Mean grain yield was significantly higher (5–21%) ($P < 0·05$) for all four projections of the 2046–65 climate than for the baseline climate, for all four soil extrapolations and three cultivars (Tables 4 and 5). The range of yield differences between individual soil types was 5–25%. The climate dataset generated with the GCM HadCM3 resulted in significantly higher ($P < 0·05$) grain yields than the weather dataset generated using the other three GCMs for the period 2046–65. In addition, for the five-soil extrapolation, the average yields related to the GCM GISS-AOM and CSIRO-M.k3·0 were also significantly higher than the one related to the GCM BCM2·0 (Tables 4 and 5).

The yield variation between simulations was higher within the baseline scenario than in the simulations with weather data associated with the BCM2·0, CSIRO-M.K3·0 and GISS-AOM projections, but lower than in the simulations with weather data based on the HadCM3 yield projections within all extrapolations and cultivars. As shown for the cultivar Zebra for the 76-soil extrapolation in Fig. 4, there were regional variations in climate impact on grain yield. These regional yield variations followed the same patterns for the other two cultivars (data not shown).

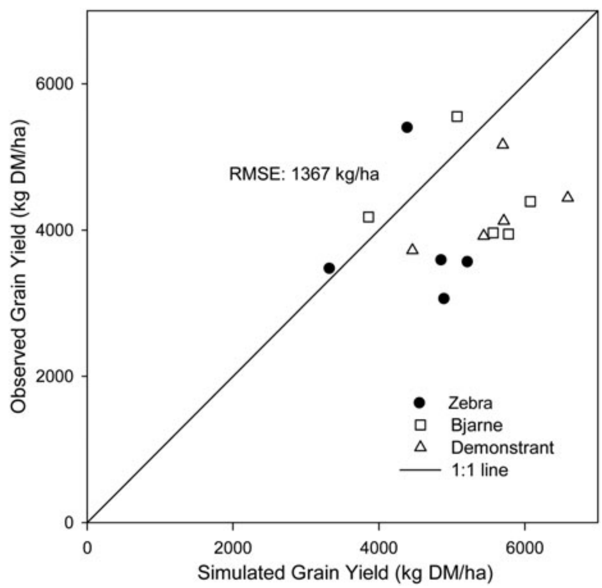

Fig. 2. Simulated *v.* observed spring wheat grain yield in cultivar trials in the seasons 2009–12 at five locations in Southeastern Norway.

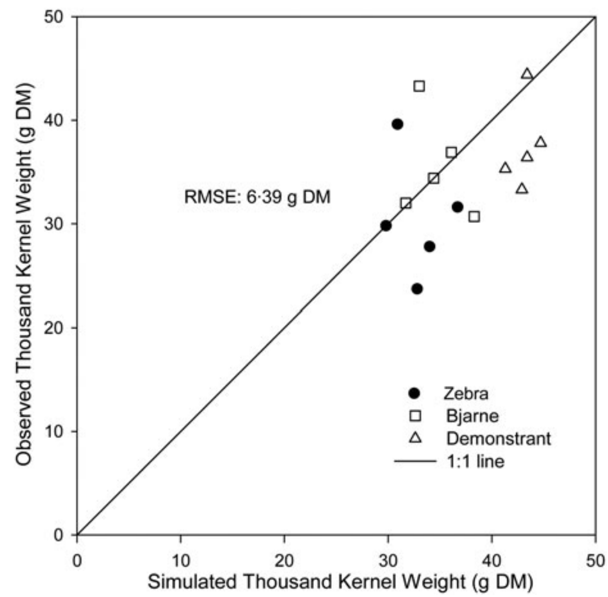

Fig. 3. Simulated *v.* observed thousand-kernel weight in cultivar trials in the seasons 2009–12 at five locations in Southeastern Norway.

Effects of soil extrapolations

Overall, the effects of the different soil extrapolations on mean regional grain yield were small. There were no statistically significant differences between the extrapolations within climate scenarios and cultivars except for: significantly higher ($P < 0{\cdot}05$) yield for the 16-soil extrapolation than for the single soil extrapolation for the weather dataset associated with GCM HadCM3 and the cultivar Zebra; and significantly higher ($P < 0{\cdot}05$) grain yield for Bjarne in the five-soil regionalization than for this cultivar in the other extrapolations within GCM BCM2·0 (Table 5). Nevertheless, for smaller regions within the two counties there were differences of up to 20% between the soil extrapolations. An example of these differences is shown in Fig. 5 for the cultivar Zebra under 1961–90 climate conditions. The grain yield differences between soil extrapolations followed the same spatial patterns for the other cultivars and the climate projections for the period 2046–65.

Relationship between soil extrapolations, soil water-holding capacity and grain yield

The reasons for the small, but in some sub-regions significant ($P < 0{\cdot}05$), grain yield differences between the soil extrapolations were further investigated by analysing the relationship between soil water-holding capacity for the different soil profiles and grain yield. These analyses showed a clear relationship between available water capacity (AWC) for the different soil profiles and grain yield. As shown in Fig. 6 for the baseline 1961–90 climate conditions, there was a tendency for a yield increase when AWC in the soil profile from 0 to 100 cm depth increased from approximately 100–200 mm, whereas increases in AWC above 200 mm did not affect yield levels substantially. These tendencies were similar for all three cultivars, but with some variation among the five climate scenarios. For GCM HadCM3, the yield increase with higher AWC was steeper than for the other climates. As shown for cultivar Zebra in Fig. 7, there was a clear positive relationship between yield increase compared with the baseline climate scenario and AWC up to 200 mm. For the other three GCMs, there was a slight negative relationship between yield increase and AWC up to 100–200 mm. For AWC > 200 mm, there were small differences in climate impact between soil types for all GCM (Fig. 7).

Differences in grain yield between wheat cultivars

Grain yield of the cultivar Bjarne was significantly lower ($P < 0{\cdot}05$) than that of the other two cultivars in the baseline scenario and the 2046–65 climate projections. Moreover, grain yield of the cultivar Zebra was higher than grain yield of the cultivar Demonstrant across climate scenarios. Among these two cultivars, the grain yield difference also tended

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Table 4. *Difference (%) in regional area-weighted mean grain yield in three spring wheat cultivars between the 2046–65 climate projections and the 1961–90 climate, and minimum and maximum yield difference considering the individual 76 soil types*

Cultivar	BCM2.0	CSIRO-M.k3.0	GISS-AOM	HadCM3
Bjarne				
Mean	7	7	7	21
Min	5	5	5	15
Max	11	10	11	23
Demonstrant				
Mean	7	7	6	21
Min	5	5	5	14
Max	11	10	11	23
Zebra				
Mean	9	10	8	20
Min	7	9	5	11
Max	14	14	15	25

Table 5. *Mean dry matter grain yield of three spring wheat cultivars under 1961–90 climate conditions and projected climate conditions for the period 2046–65*

	Zebra	Demonstrant	Bjarne
	76 soils		
Baseline	5518	5301	4584
BCM2·0	6055	5687	4925
GISS-AOM	6042	5677	4918
HadCM3	6634	6418	5569
CSIRO-M.k3·0	6096	5672	4914
	16 soils		
Baseline	5583	5352	4628
BCM2·0	6113	5725	4958
GISS-AOM	6050	5674	4914
HadCM3	6731	6489	5629
CSIRO-M.k3·0	6160	5715	4952
	5 soils		
Baseline	5522	5297	4578
BCM2·0	6039	5764	5124
GISS-AOM	6082	5689	4926
HadCM3	6637	6414	5567
CSIRO-M.k3·0	6120	5680	4923
	1 soil		
Baseline	5459	5251	4538
BCM2·0	6071	5684	4923
GISS-AOM	6063	5669	4910
HadCM3	6530	6342	5511
CSIRO-M.k3·0	6081	5652	4902

($P < 0{\cdot}05$) to be higher for most of the 2046–65 projections than for the baseline 1961–90 climate across soil extrapolations. Intra-regional soil-related differences followed the same pattern for all three cultivars. These differences were naturally most detailed for the 76 soil regionalization, as shown in Fig. 8 for the baseline scenarios. The intra-regional yield patterns for the three cultivars were similar

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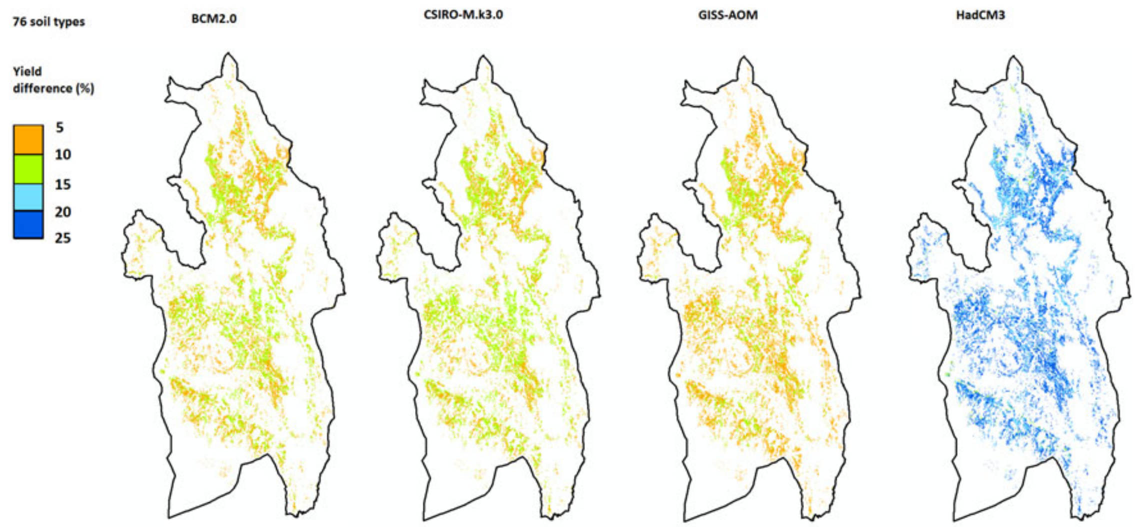

Fig. 4. Grain yield differences in spring wheat (cvar Zebra) between the 2046–65 climate projections and the 1961–90 climate when 76 profiles were used to describe the soil characteristics in Akershus and Østfold counties in Southeastern Norway.

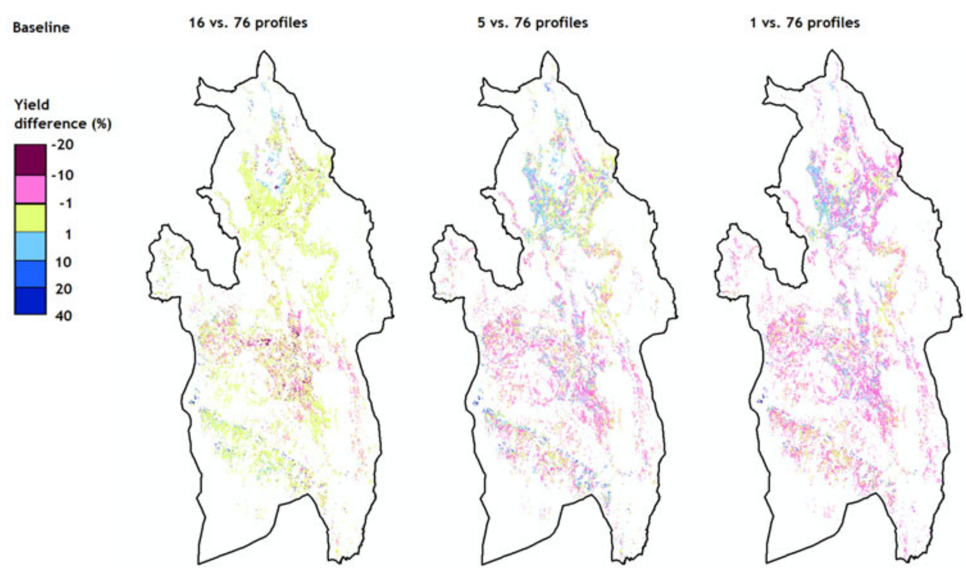

Fig. 5. Regional grain yield differences in spring wheat (cvar Zebra) under baseline 1961–90 climate scenarios between the 76 soil extrapolation and the coarser soil extrapolations.

under the projected 2046–65 climate conditions (data not shown).

DISCUSSION

The results of the present study, showing large differences in mean wheat grain yield between the baseline climate scenario and climate projections for the period 2046–65, indicate that future climate change will be favourable for spring wheat production in Southeastern Norway. These results agree with previous reports of positive climate change yield increases in forage grasses (Höglind *et al*. 2013; Persson & Höglind 2014; Persson *et al*. 2015), but contradict the lack of positive climate change effect on forage maize yield found by Eckersten *et al*. (2012) in Northern Europe. Similar types of simulation studies on spring cereal production in this region or other regions in Northern Europe appear to be lacking. For the region investigated in the present study, the

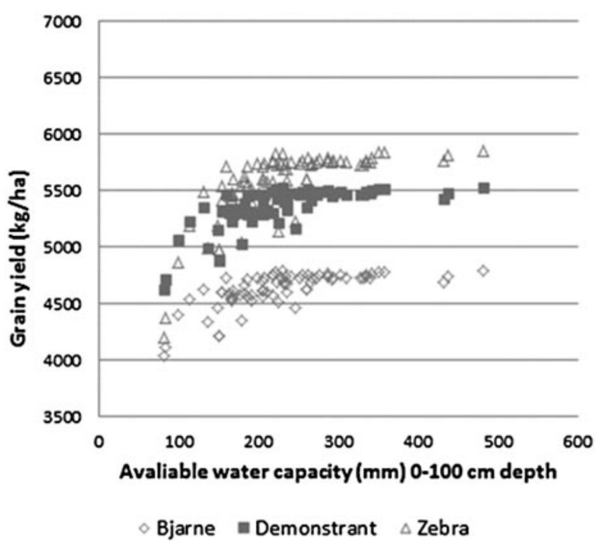

Fig. 6. Relationship between the available water capacity from 0 to 100 cm depth and grain yield for three spring wheat cultivars (available on *x*-axis) under 1961–90 climate conditions.

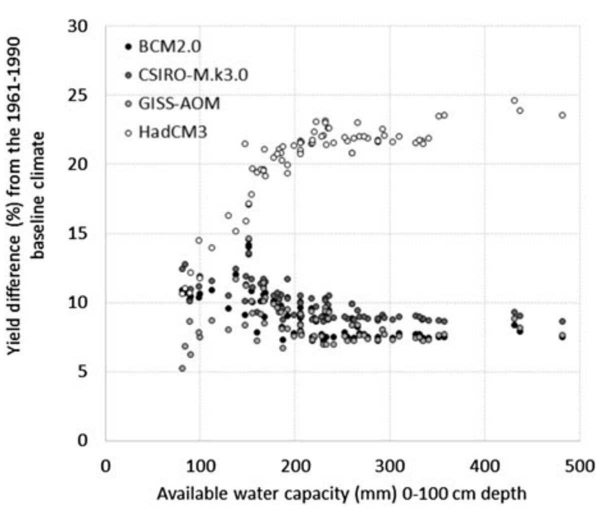

Fig. 7. Grain yield differences for the spring wheat cultivar Zebra between projected 2046–65 climate conditions and baseline 1961–90 climate conditions for soils with different available water capacity.

climate projections, including temperature increases and changes in precipitation patterns, are similar to climate projections for other main cereal-producing regions in Northern Europe, such as Southcentral Sweden and Southern Finland (Rötter *et al.* 2012). Moreover, the soils in those regions are to some extent similar to those studied in the present study (e.g. large areas of clay soils). In total, these similarities suggest that the positive effects of projected climate change on spring wheat yield found for Southeastern Norway in the present study could also apply to other Northern European regions. The results are in line with other types of analyses of crop yield performance, which point at more favourable production conditions for cereals in Northern Europe (Bindi & Olesen 2011; Rötter *et al.* 2012) and in wet and cool upland regions in central and Eastern Europe (Eitzinger *et al.* 2013) under projected climate change. These positive effects of climate change on grain yield could be due to the combined effect of changed precipitation and temperature patterns, the extended growing season due to the earlier planting date and the increased atmospheric CO_2 concentration. Since all these factors interact during the growing season, it was not possible to determine whether any one was more important for yield increases than the others under the conditions studied in the present work. However, further analyses of the sensitivity of grain yield to each of these factors could possibly disclose more information about their importance for the overall grain yield increase. The positive effects of climate change on cereal yields in the study region are in contrast to the expected negative impacts of climate change on crop production in regions such as Southern and Central Europe (Olesen & Bindi 2002; Bindi & Olesen 2011; Soussana *et al.* 2012; Thaler *et al.* 2012), large areas of Asia and North America (Teixeira *et al.* 2013) and Australia (Ejaz Qureshi *et al.* 2013), effects which are mostly attributable to heat and drought stress. In this context, the results of the present study are a further indication that northern Europe could become a relatively more important global cereal-producing region than under current conditions.

There are some uncertainties associated with the results of the present study that deserve to be discussed. The first source of uncertainty is related to the representations of the climate-crop systems in the climate and crop models on which the output yield depends. The large yield differences between and within climate projections based on the four different GCM indicate large uncertainty in how climate change will affect spring wheat yield. Nevertheless, the fact that all GCM showed increased grain yield compared with that under the baseline climate indicates that the effect of climate change on simulated wheat grain yield is rather robust within the A1B greenhouse gas emissions scenario in the IPCC 4th Assessment Report. This is further indicated by the fact that the GCM used in the present study were selected from among the larger ensemble of GCM included in the IPCC 4th Assessment Report,

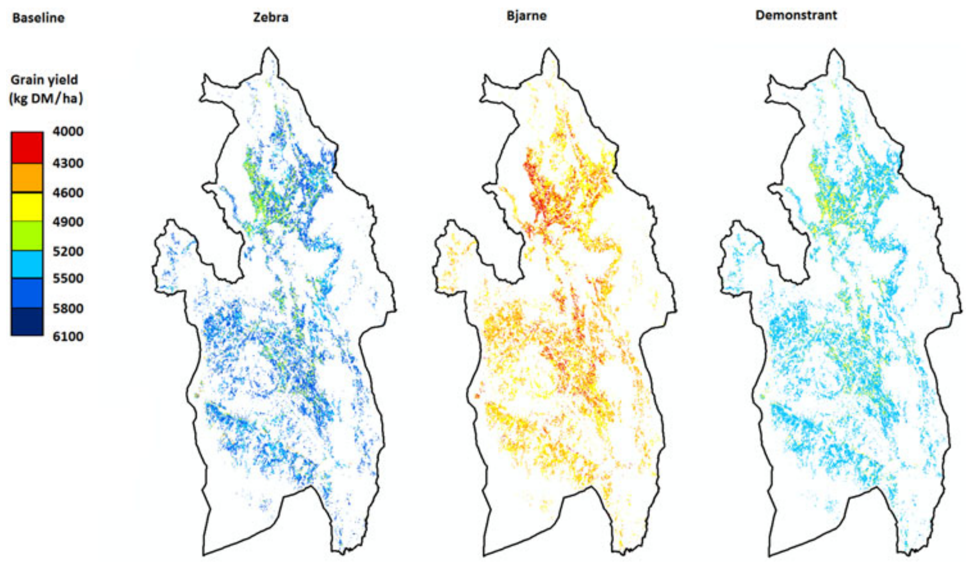

Fig. 8. Intra-regional grain yield differences in Akershus and Østfold counties, Norway, for the three spring wheat cultivars under 1961–90 climate conditions.

based on how weather data generated from these GCM affected crop yield in Northern Europe in a previous study (Höglind *et al*. 2013). Other greenhouse gas emission scenarios than the A1B scenario, for example one of those included in the IPCC 5th Assessment Report (Stocker *et al*. 2013), might have resulted in other grain yield differences between the projected climate scenarios and the baseline climate. However, since most studies of climate change effects on crop production are based on scenarios from the IPCC 4th assessment report, using other scenarios would have risked making it more difficult to compare the results from the present study with those published previously. A different crop simulation model than the CSM-CROPSIM-CERES-Wheat model would possibly also have generated other results. There is large variation in simulated wheat yield between crop models under current (Palosuo *et al*. 2011; Rötter *et al*. 2011) and projected future climate scenarios (Asseng *et al*. 2013). However, a model ensemble study of climate and soil impact of wheat yield in Northern Europe or elsewhere would probably benefit from a pre-selection of models based on how they handle soil input data to avoid excessive workload.

A second source of uncertainty is that air temperature was the only criterion used for selecting planting date. Notably, the simulations did not take into account how soil moisture conditions and precipitation events could limit trafficability and workability of the soil. Given the increased spring and autumn precipitation shown by the climate change projections, there is a considerable risk that increased soil moisture content and more frequent rainfall events could delay seedbed preparation, planting, harvest and application of fertilizers and pesticides, as well as increasing the risk of lodging, fungal infections, wheel traffic damage and soil compaction (Aurbacher *et al*. 2013). The study region has experienced years (e.g. 2011 and 2012) with such unfavourable weather conditions during the growing season, resulting in reduced yield quantity and quality (Wågbø & Hjukse 2012; Terefe *et al.* 2013). The effects of soil water conditions may also be misrepresented in the CSM-CROPSIM-CERES-Wheat simulation, because it omits simulation of artificial drainage systems, which are common on arable land in Akershus and Østfold counties. Field trials on clay soil in Akershus county (Hove 1981) and adjacent regions in Western Sweden (Berglund *et al*. 1976*a*, *b*) showed positive relationships between soil water management by artificial drainage, planting date and yield level. In line with this reasoning about misrepresentation of the effects of increased precipitation and soil water content, Trnka *et al*. (2014) highlighted the increased risk of adverse conditions such as lodging and waterlogging for winter wheat in a few other western and Northern European locations based on an analysis of projected climate change in 2060 compared with the period 1980–2010. Thus, the yield increases shown in the present study under projected future climate conditions should be regarded as potential yield gains, given that possible increased adverse effects of increased precipitation and soil water content on spring cereal production could be handled, e.g. by improved machinery operations and other management practices.

A third source of uncertainty concerns the handling of regional soil conditions (Folberth *et al.* 2012; Angulo *et al.* 2014). To determine the regional spring wheat grain yield in the present study, four different descriptions of the regional soil variability were applied. The rather small impact of soil regionalization on grain yield suggests that other factors are more important than the details in the descriptions of regional soil characteristics when estimating regional crop yields. Thus, given the current model assumptions, a rough description of the regional soil characteristics should be sufficient in simulations of average regional grain yields under the conditions used in the present study. Other possible variability, e.g. in nutrient content, or in the regional soil characteristics, that was not well accounted for could possibly also affect the regional wheat yield variability. Moreover, it should be noted that the use of class pedotransfer functions for estimating soil properties tends to smooth the variation between and within soil types. Using measured data instead of pedotransfer estimates could potentially have resulted in different conclusions, but measured data were not available for most of the soil types in the region. Nevertheless, the results reported here and the conclusions drawn largely agree with those from a previous study showing a rather small impact of regional soil extrapolation when assessing regional yield of the forage grass timothy for the same region as included in the present study (Persson *et al.* 2015). Likewise, previous studies show little impact of soil resolution on simulated winter wheat yield and growing season evapotranspiration in seven counties in the state of North-Rhine Westphalia in Germany (Angulo *et al.* 2014) and on maize yields in the USA (Folberth *et al.* 2012).

A fourth source of uncertainty was that wheat production in the mid-21st century will naturally take advantage of breeding advances from now on, which were not accounted for in the present study. Here, the genetic diversity in wheat was handled by calibrating cultivar-specific coefficients in the CSM-CROPSIM-CERES-Wheat model against three currently grown wheat cultivars and comparing the performance of these cultivars under the different combinations of climate and soil descriptions investigated. Besides, the results of the cultivar-specific calibration were poor, which is probably attributable to the lack of in-season data on leaf area and other crop components, and phenological stages in field trials that were used for model calibration, which adds further uncertainty to the cultivar effects. More thorough analyses including additional calibration data or techniques and the effects of possible future crop breeding advances could include evaluation of the performance of cultivars with theoretical crop model coefficients, still within what is realistic given the existing gene pool of wheat, as suggested by Semenov & Halford (2009) as an integrated step in wheat breeding programmes. One way of taking into account future cultivars would be to apply dynamic cultivar coefficients that change according to trends in crop yield, as applied by Parker *et al.* (2016). An analysis of the effects of warming on wheat varieties released in different decades revealed a more positive effect of a warmer climate on post-anthesis biomass and thousand-kernel weight in varieties that were released more recently than for those released earlier, suggesting that adaptation to a warmer climate has been taken into account in wheat breeding (Zheng *et al.* 2015). If this adaptation to a changing climate is a general trend in wheat breeding, the application of dynamic cultivar coefficients would thus probably enhance the positive climate change effects on yield.

Further analyses to follow up the present study could include adjusting planting date according to the prevailing season- and site-specific precipitation and soil moisture conditions, e.g. by including artificial drainage, and thus analysing the integrated effect of planting conditions and the conditions for plant growth and development. Moreover, a wider range of cultivar characteristics, including hypothetical future cultivars, could be included in such studies to encompass the effects of potential breeding advances on crop yield under future scenarios. Methodologically, the approach used in the current work for determining the impact of the level of detail in regional variability in soil texture and water-holding capacity on spring wheat growth and yield could serve as a base for such studies, and could be used to determine the need for soil input data when soil moisture impact on planting and harvest is also taken into account for a wide range of cultivars.

CONCLUSIONS

The present study showed increased regional spring wheat yield under projected climate change

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conditions in Southeastern Norway compared with historical baseline conditions for three different spring wheat cultivars. The effects on wheat yield of differing level of detail in description of regional soil characteristics were small on average across the region for all climate projections and cultivars. However, there were substantial intra-regional differences in the effects of different soil extrapolations. In total, these results of soil regionalization analysis suggest that for soil and climate conditions and simulation methods similar to those included in this study, little accuracy is gained from using fine-scaled descriptions of regional soil characteristics. However, coarse descriptions of soil conditions could mask intra-regional differences in grain yield.

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