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Assessing climate effects on wheat yield and water use in Finland using a super-ensemble-based probabilistic approach

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ABSTRACT: We adapted a large area crop model, MCWLA-Wheat, to winter wheat *Triticum aestivum* L. and spring wheat in Finland. We then applied Bayesian probability inversion and a Markov Chain Monte Carlo technique to analyze uncertainties in parameter estimations and to optimize parameters. Finally, a super-ensemble-based probabilistic projection system was updated and applied to project the effects of climate change on wheat productivity and water use in Finland. The system used 6 climate scenarios and 20 sets of crop model parameters. We projected spatiotemporal changes of wheat productivity and water use due to climate change/variability during 2021–2040, 2041–2070, and 2071–2100. The results indicate that with a high probability wheat yields will increase substantially in Finland under the tested climate change scenarios, and spring wheat can benefit more from climate change than winter wheat. Nevertheless, in some areas of southern Finland, wheat production will face increasing risk of high temperature and drought, which can offset the benefits of climate change on wheat yield, resulting in an increase in yield variability and about 30% probability of yield decrease for spring wheat. Compared with spring wheat, the development, photosynthesis, and consequently yield will be much less enhanced for winter wheat, which, together with the risk of extreme weather, will result in an up to 56% probability of yield decrease in eastern parts of Finland. Our study explicitly parameterized the effects of extreme temperature and drought stress on wheat yields, and accounted for a wide range of wheat cultivars with contrasting phenological characteristics and thermal requirements.

KEY WORDS: Adaptation · Drought · Evapotranspiration · Heat stress · Risk · Uncertainties

1. INTRODUCTION

The average temperature in Europe has continued to increase with regionally and seasonally different rates of warming, being greatest at high latitudes in northern Europe (IPCC 2014). Annual precipitation has increased in northern Europe by up to 70 mm decade^{-1} since 1950 and has decreased in parts of southern Europe (Haylock et al. 2008). In the future, the warming trend is projected to continue all over Europe, with strongest warming projected in southern Europe in summer and in northern Europe in winter. Precipitation trends are less clear in continental Europe, although it is most likely to increase in northern Europe and decrease in southern Europe (Ylhäisi et al. 2010, Lehtonen et al. 2014).

Global warming has generally been considered beneficial for agriculture in high-latitude regions such as northern Europe (e.g. Carter & Saarikko 1996, IPCC 2007, 2014, Bindi & Olesen 2011). Based on earlier studies, Bindi & Olesen (2011) suggested that positive yield changes combined with the expansion of climatically suitable areas could lead to crop production increases between 2.5 and 5.4°C

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regional warming. However, increased climatic variability would limit the expansion of winter crops (Peltonen-Sainio et al. 2011a) and at high latitudes could cause considerable risk of marked cereal yield loss without adaptation (Rötter et al. 2011a). Some recent studies have shown a higher proportion of negative expectations concerning the impacts of climate change on crops and crop production throughout Europe than in earlier studies, even in the cool temperate northern European countries (Trnka et al. 2011, 2014). These more negative expectations are in line with recent findings for the main cereals at a global scale (Challinor et al. 2014, IPCC 2014). Recently, IPCC AR5 concluded that climate change is likely to increase cereal yields in northern Europe (with medium confidence and disagreement) but will decrease yields in southern Europe (with high confidence). Compared to AR4, new projections regarding future yields in northern Europe are less consistent regarding the magnitude and sign of change (IPCC 2014).

Understanding the effects of climate change/variability on crop productivity in northern European countries has important implications for perspectives of global food security, since these countries are located at the northern limits of crop production globally. Insights into future crop productivity require more robust climate impact studies taking into account the uncertainties from emission scenarios, global circulation models (GCMs), and crop models (Rötter et al. 2012, Asseng et al. 2013). Crop models that can accurately simulate the impacts of mean climate change, extreme climate events, and fertilization effects of elevated CO_2 concentration are preferable, but many of them are not yet fully fit for this purpose (Rötter et al. 2011b). In addition, ensemble agricultural and climate modeling has been increasingly applied to project future productivity and to develop adaptation options as a result of its advantage in quantifying uncertainty in both climate and agriculture (Tao et al. 2009a,b, Asseng et al. 2013, Challinor et al. 2013).

The current study aimed at a detailed national assessment of climate change risks to wheat *Triticum aestivum* L. productivity and water use for Finland using an ensemble-based probabilistic approach, and comparing the results to previous studies that used different approaches. We intend to provide decision-making support to regional resource managers and policy makers by enhancing the understanding of the spatial and temporal changes of wheat productivity and water use due to climate change in the 21st century across Finland, as well as the underlying mechanisms.

2. MATERIALS AND METHODS

2.1. Description of the crop model MCWLA-Wheat

Details of MCWLA-Wheat model development, parameter optimization, and uncertainty analyses have been described by Tao et al. (2009a) and Tao & Zhang (2013). MCWLA-Wheat (Tao & Zhang 2013) was developed by adapting the MCWLA (Tao et al. 2009b) to simulate the growth, development, and productivity of wheat. MCWLA simulates crop growth and development at daily time-steps. It is designed to investigate the impacts of weather and climate variability (and change) on crop growth, development, and productivity for large areas. Air temperature converted into growing degree-days provides the driving force for the processes of canopy development, flowering, and maturity. The daily growth of the crop leaf area is simulated by temperature-dependent potential growth rate and stresses from water deficit or excess. Soil hydrology is modeled following the semi-empirical approach of Haxeltine & Prentice (1996a). MCWLA adopts the robust, process-based representation of the coupled CO_2 and H_2O exchanges in the Lund–Postdam–Jena (LPJ) dynamic global vegetation models (Haxeltine & Prentice 1996a,b, Sitch et al. 2003). Impacts on yield due to factors other than weather (e.g. pests, disease, and management factors like nitrogen fertilizer application) are modeled in a simplified way. Biomass is accumulated from photosynthesis and further transferred into crop yield by the harvest index. MCWLA has been extensively tested to simulate the impacts of climate variability and elevated CO_2 concentration on wheat growth and yields in China (Tao & Zhang 2013) and in other major production areas (Asseng et al. 2013), suggesting that it is also useful for impact assessment under future climate (Tao et al. 2009b).

2.2. Model modifications and calibration

For this study, the wheat development model by Streck et al. (2003) was incorporated and applied in MCWLA-Wheat to simulate the development of wheat under the effects of temperature, photoperiod, and vernalization. The wheat development model introduces a nonlinear vernalization function and divides the life cycle of the wheat crop into 3 phases, viz. 2 sub-phases of vegetative development (emergence to terminal spikelet initiation and terminal spikelet initiation to anthesis) and a reproductive phase (anthesis to physiological maturity) (Streck et al. 2003), based on Wang & Engel (1998), in which the impacts of extreme temperatures on wheat development are taken into account. In addition, the impacts of drought stress and waterlogging on root and leaf area development are simulated as described by Tao et al. (2009b). Heat stress limits leaf area development and flowering when daily maximum temperature is above 34°C. The impacts of extreme temperatures on wheat leaf area development and harvest index are simulated as suggested by Asseng et al. (2011) and Challinor et al. (2005), respectively.

2.3. Data

The MCWLA model requires daily weather inputs for maximum and minimum temperature, precipitation, vapor pressure (or relative humidity), wind speed, and solar radiation. In this study, the MCWLA-Wheat was run for each 10 × 10 km grid cell with a wheat cultivation fraction ≥0.01 across Finland (Monfreda et al. 2008) (Fig. 1). Daily weather data of maximum and minimum temperature, precipitation, vapor pressure, wind speed, and solar radiation in each 10 × 10 km grid for the period 1971–2010 were obtained from the Finnish Meteorological Institute (Venäläinen et al. 2005). The 6 future climate scenarios for 3 future periods, i.e. 2011–2040, 2041–2070, and 2071–2100, followed the selection of emission scenarios and climate models and utilized the climate scenario data generated by a national study on mapping shifts of agroclimate by Rötter et al. (2013). The climate scenarios consist of the combinations of 6 GCMs (BCCR, CCCMA, GISS, IPSL, MIROC, and CSIRO) and 3 emission scenarios (A2, A1B, and B1), namely BCCR_A2, CCCMA_A1B, GISS_B1, IPSL_A2, MIROC_A1B, CSIRO_B1. The climate scenarios were constructed and interpolated bi-linearly to the 10 × 10 km grid of the observed data. For each 10 km grid cell, linear interpolation of monthly changes to daily change estimates. The daily deltas were then added to the observed time-series 1971–2000 for each grid cell for the 3 future periods (Rötter et al. 2013, www.mtt.fi/modags).

Soil texture and hydrological properties data are based on the FAO soil data set (FAO 1991). Soil parameters include the soil-texture-dependent percolation rate (mm d^{-1}) at field capacity and available volumetric water holding capacity (i.e. the water holding capacity at field capacity minus water holding capacity at the wilting point, expressed as a fraction of soil layer depth). Yearly mean yields of spring wheat and winter wheat for Häme province from 1998 to 2009, and for all of Finland from 1971–2009, were obtained from the statistical yearbook of Finland (Matilda Agricultural Statistics 2014). Yearly mean sowing dates, flowering dates, and maturity dates for Häme province from 1998–2009 were estimated from MTT Official Variety Trials data (Peltonen-Sainio et al. 2011b).

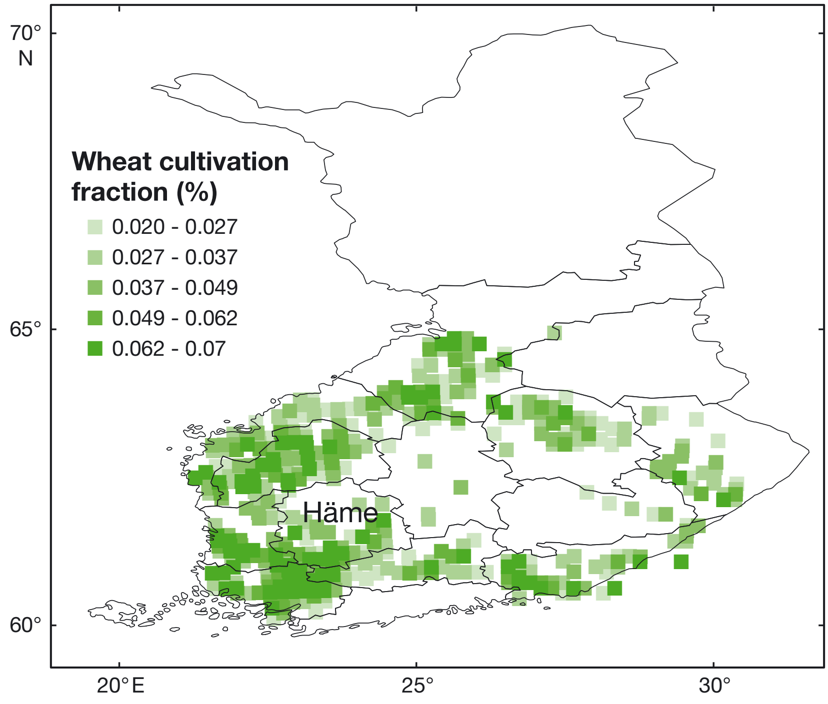

Fig. 1. Wheat *Triticum aestivum* cultivation fraction across Finland based on Monfreda et al. (2008)

2.4. Parameter uncertainty analyses and optimization using Bayesian probability inversion and MCMC

Parameter uncertainty analyses and optimization using Bayesian probability inversion and a Markov Chain Monte Carlo (MCMC) technique have been described by Tao et al. (2009b). Here, we applied the technique to inverse and optimize the 18 parameters of the MCWLA-Wheat for Häme province using the observed time series of data on sowing date, flowering date, maturity date and linearly de-trended yields, from 1998–2009. The de-trended yields series were used here to remove the influences of non-climatic factors. We made 3 parallel runs of the Metropolis–Hastings algorithm and then ran the MCWLA-Wheat using 20 000 sets of parameters sampled by the final run of the Metropolis–Hastings algorithm (Spall 2003) to investigate the uncertainties of the ensemble prediction and to optimize the parameters. From 20 000 sets of parameters, we further selected the optimal 20 sets of parameters that produce the minimum root mean-square error (RMSE) between modeled and detrended yield series for spring wheat (optimal 10 sets of parameters for winter wheat). The number of parameters sets is smaller for winter wheat because the 20 000 sets of parameters were more convergent for winter wheat than those for spring wheat.

2.5. Probabilistic assessment of climate impacts on wheat yield and water use using a super-ensemble-based probabilistic approach

Using the optimal 20 (10) sets of parameters for spring wheat (winter wheat), MCWLA-Wheat was driven by the baseline climate conditions (1971–2000) and the 6 future climate scenarios for the 2020s (2011–2040), 2050s (2041–2070), and 2080s (2071–2100), respectively, resulting in a super-ensemble-based projection. The super-ensemble-based projection approach not only accounts for the uncertainties from climate scenarios but also for the uncertainties from biophysical processes of crop models. Mean CO_2 concentration during 1971–2000 was set at 360 ppmv. It may reach levels of approximately 424.5–436.0 ppmv during the 2020s, 498.5–602.5 ppmv during the 2050s, and 541.0–842.0 ppmv during the 2080s (IPCC 2001). Finally, for each 1 × 1 km wheat cultivation grid, we generated 20 sets of parameters × 30 yr = 600 sets of simulation results for 1971–2000, and 20 sets of parameters × 30 yr × 6 climate scenarios = 3600 sets of simulation results for the future periods centered on the 2020s, 2050s, and 2080s, respectively. We calculated the changes of wheat productivity and evapotranspiration (ET) using every set of simulation result during the 2020s, 2050s, and 2080s, relative to the corresponding simulation during 1971–2000. We further derived histograms and cumulative distribution functions (CDFs) of wheat yields based on the large number of simulation results.

Since wheat is rainfed in Finland, simulations were conducted for conditions without irrigation. Simulations were conducted with and without CO_2 fertilization effects. A 1 wk sowing window was set to allow automatic planting once soil water content was above half of soil water capacity or sowing regardless at the end of the sowing window. A wide range of crop cultivars with contrasting phenological and thermal characteristics was taken into account in the simulations by using multiple sets of cultivar parameters, although the diversity of crop cultivars and management practices in the future are assumed to reflect conditions during the baseline period.

3. RESULTS

3.1. Calibration and validation of the MCWLA-Wheat model for large-area climate impact assessment

The selected model parameters' prior intervals, mean estimates, standard deviation, and intervals of the optimal 20 (10) sets of parameters for spring wheat (winter wheat) are listed in Tables S1 & S2 in the Supplement at www.int-res.com/articles/suppl/c065p023_supp.pdf. Using the optimal sets of parameters, ensemble hindcasts show that the MCWLA-Wheat can simulate both long-term time trends and inter-annual variability of wheat yield in Finland fairly well. For spring wheat, the correlation coefficient (r) and RMSE between the area-weighted mean simulated yields across all wheat cultivation grids and the observed mean yields for all of Finland from 1971 to 2009 is 0.52 ($p < 0.01$) and 706 kg ha^{-1}, respectively (Fig. 2a). The corresponding values for winter wheat are 0.60 ($p < 0.01$) and 698 kg ha^{-1}, respectively (Fig. 2b). The model overestimates winter wheat yield systematically before 1985. Among other things, the deviations between the simulated and observed yields can be ascribed to the influences of insects and diseases, changes in agronomic management practices, and variable wheat cultivation area in each grid during the study period, which are not taken into account in the simulations.

3.2. Projected climate change across wheat cultivation regions in Finland

Climate during 1971–2000 and in the future may differ in its spatially explicit pattern in Finland. Across the wheat cultivation grids, annual mean temperature during 1971–2000 ranged from 1.1°C in the northern part to 5.4°C in the southern part (Fig. 3a). It is projected to increase on average by 3.0°C in the

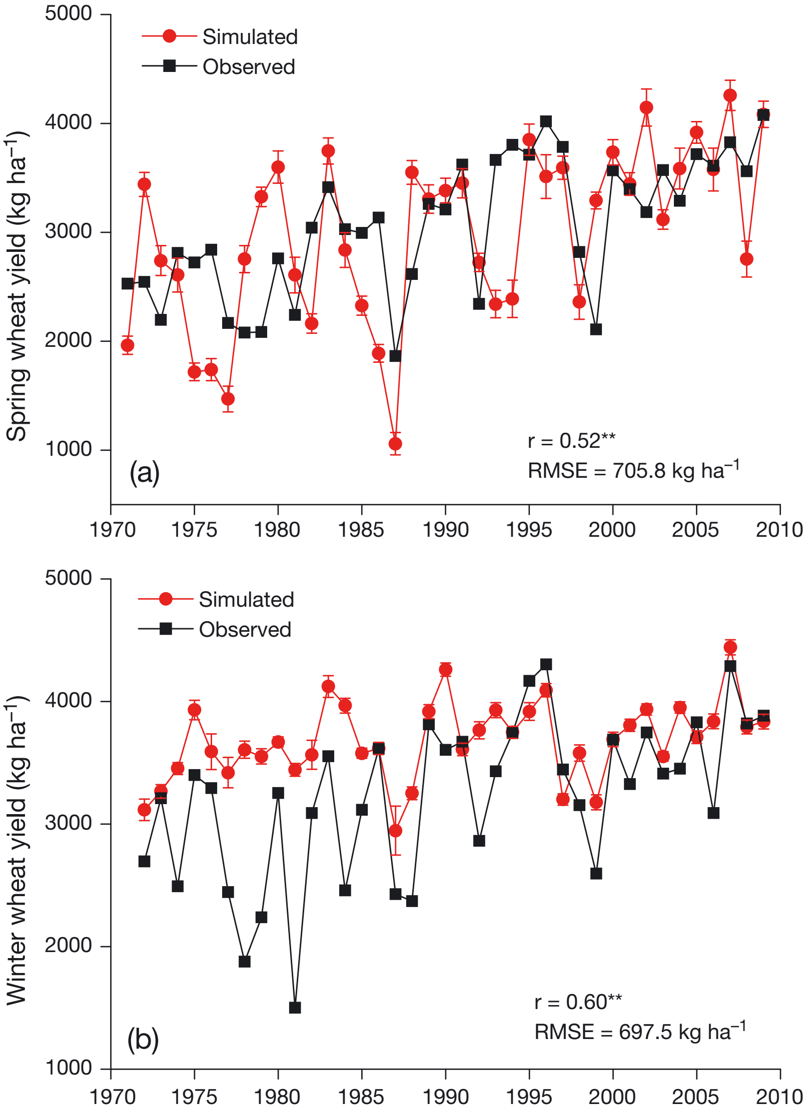

Fig. 2. Time series of observed and simulated wheat *Triticum aestivum* yield across Finland for (a) spring wheat and (b) winter wheat. Error bars represent standard deviation of simulated mean yields across the wheat cultivation grids in Finland with different parameter sets

southern part to 3.5°C in the northern part during the 2050s, based on the 6 climate scenarios (Fig. 3b). Annual mean precipitation during 1971–2000 ranged from 410.0 mm in the northwest to 640.0 mm in the south (Fig. 3c). It is projected to increase on average by 6.0 % in the west to 10.0 % in the east during the 2050s, based on the 6 climate scenarios (Fig. 3d). Annual mean solar radiation during 1971–2000 ranged from 8.0 MJ m^{-2} d^{-1} in the north to 9.6 MJ m^{-2} d^{-1} in the south (Fig. 3e). It is projected to increase on average by 0.1 % in the west to 0.9 % in the east during the 2050s, based on the 6 climate scenarios (Fig. 3f).

3.3. Probabilistic assessment of climate impacts on wheat yield in Finland

For spring wheat, across all wheat cultivation grids in Finland, yields ranged mostly from 2000 to 4000 kg ha^{-1} (Fig. 4a). The histograms and CDFs of wheat yield changes, based on the large number of super-ensemble simulations (486 grids × 20 sets of parameters × 30 yr × 6 scenarios = 1 749 600 simulations), show that spring wheat yields will increase with 86.3, 87.8, and 88.2 % probability during the 2020s, 2050s, and 2080s, respectively, relative to the 1971–2000 level, and with 50 % probability, spring wheat yields will increase by 27.6, 37.5, and 41.5 % during the 2020s, 2050s, and 2080s, respectively (Fig. 4b–d).

For winter wheat, across all wheat cultivation grids in Finland, yields ranged mostly from 3000 to 4500 kg ha^{-1} (Fig. S1a in the Supplement). The histograms and CDFs of wheat yield changes, based on the large number of super-ensemble simulations (486 grids × 10 sets of parameters × 29 yr × 6 scenarios = 845 640 simulations), show that yields will increase with 60.8, 67.8, and 60.0 % probability during the 2020s, 2050s, and 2080s, respectively, relative to the 1971–2000 level, and with 50 % probability, winter wheat yields will increase by 2.0, 4.7, and 3.1 % during the 2020s, 2050s, and 2080s, respectively (Fig. S1b–d).

3.4. Spatial and temporal changes in wheat yield and actual ET in Finland due to climate change

For spring wheat, yields ranged on average from less than 2200 kg ha^{-1} in the northwest to more than 3100 kg ha^{-1} in the south during 1971–2000 (Fig. 5a), and actual water use or ET during the wheat-growing period ranged on average from less than 130.0 mm in the northwest to more than 145.0 mm in the east and south (Fig. 5b). During the 2020s, wheat yields are projected to increase on average from ~30.0 % in the south to more than 50.0 % in the north

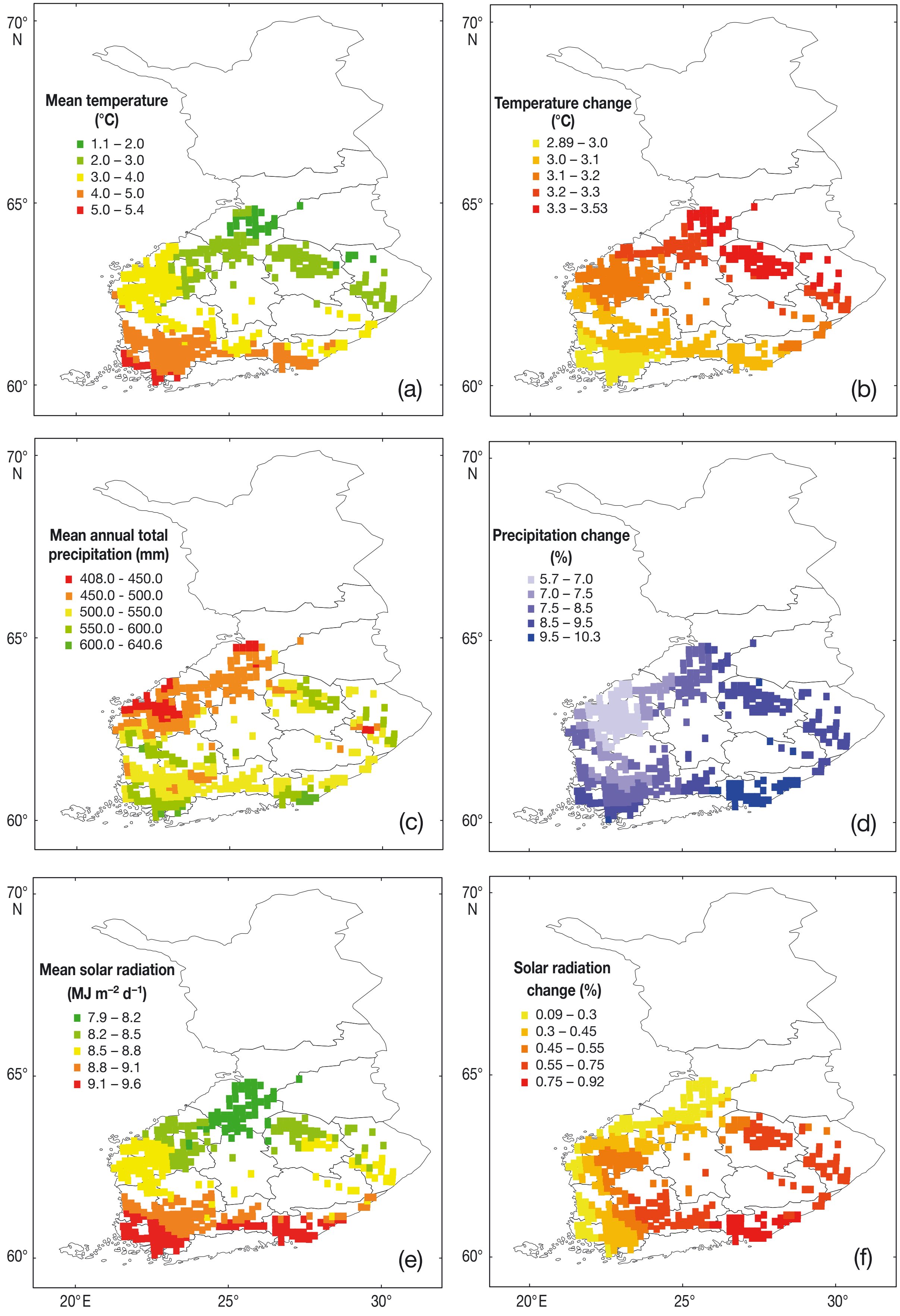

Fig. 3. Mean (a) temperature, (c) precipitation, and (e) solar radiation during 1971–2000, as well as the projected changes in mean (b) temperature, (d) precipitation, and (f) solar radiation during the 2050s

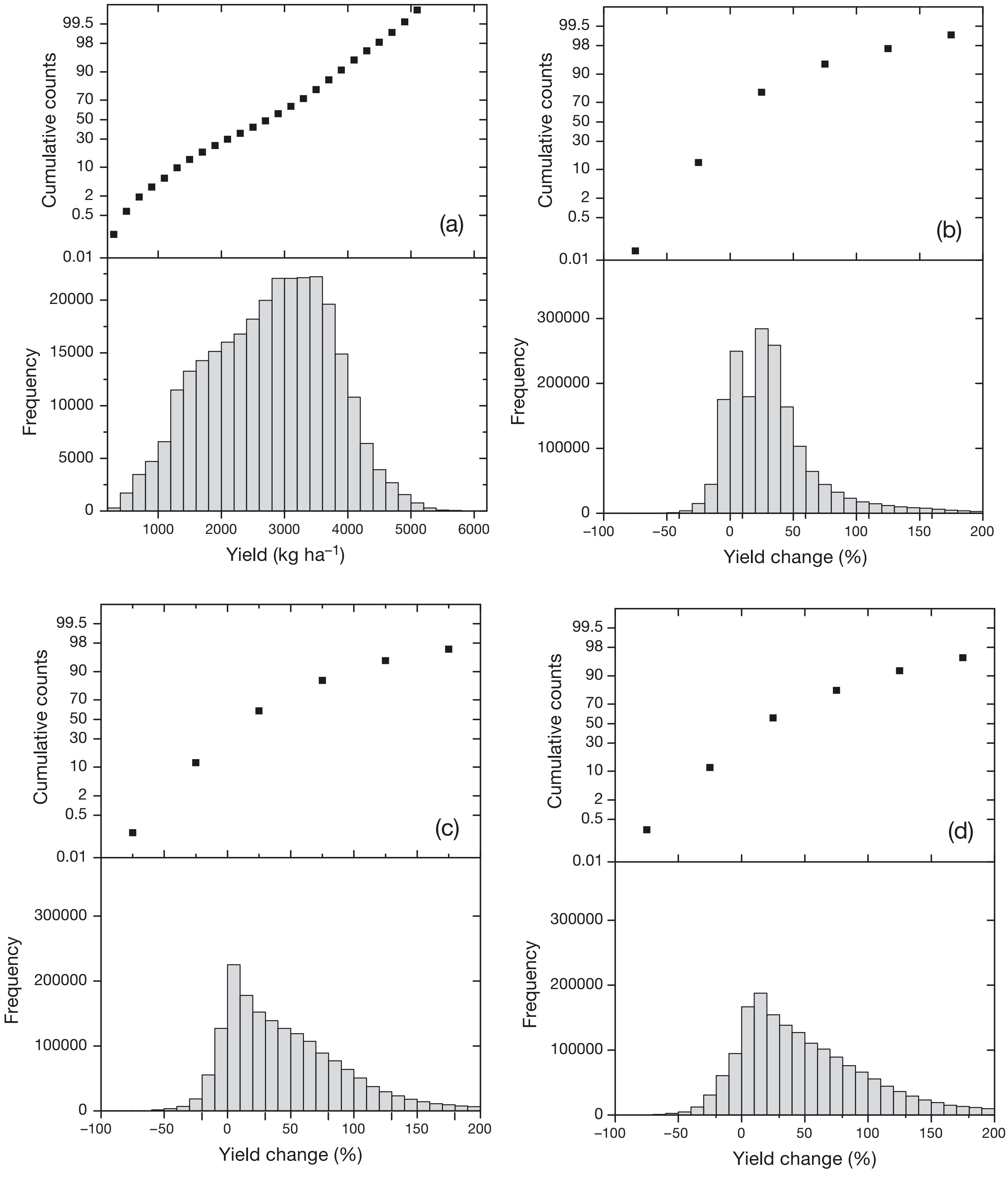

Fig. 4. Cumulative probability functions and histograms of spring wheat *Triticum aestivum* yield during (a) 1971–2000 and its changes during the (b) 2020s, (c) 2050s, and (d) 2080s across the wheat cultivation grids in Finland

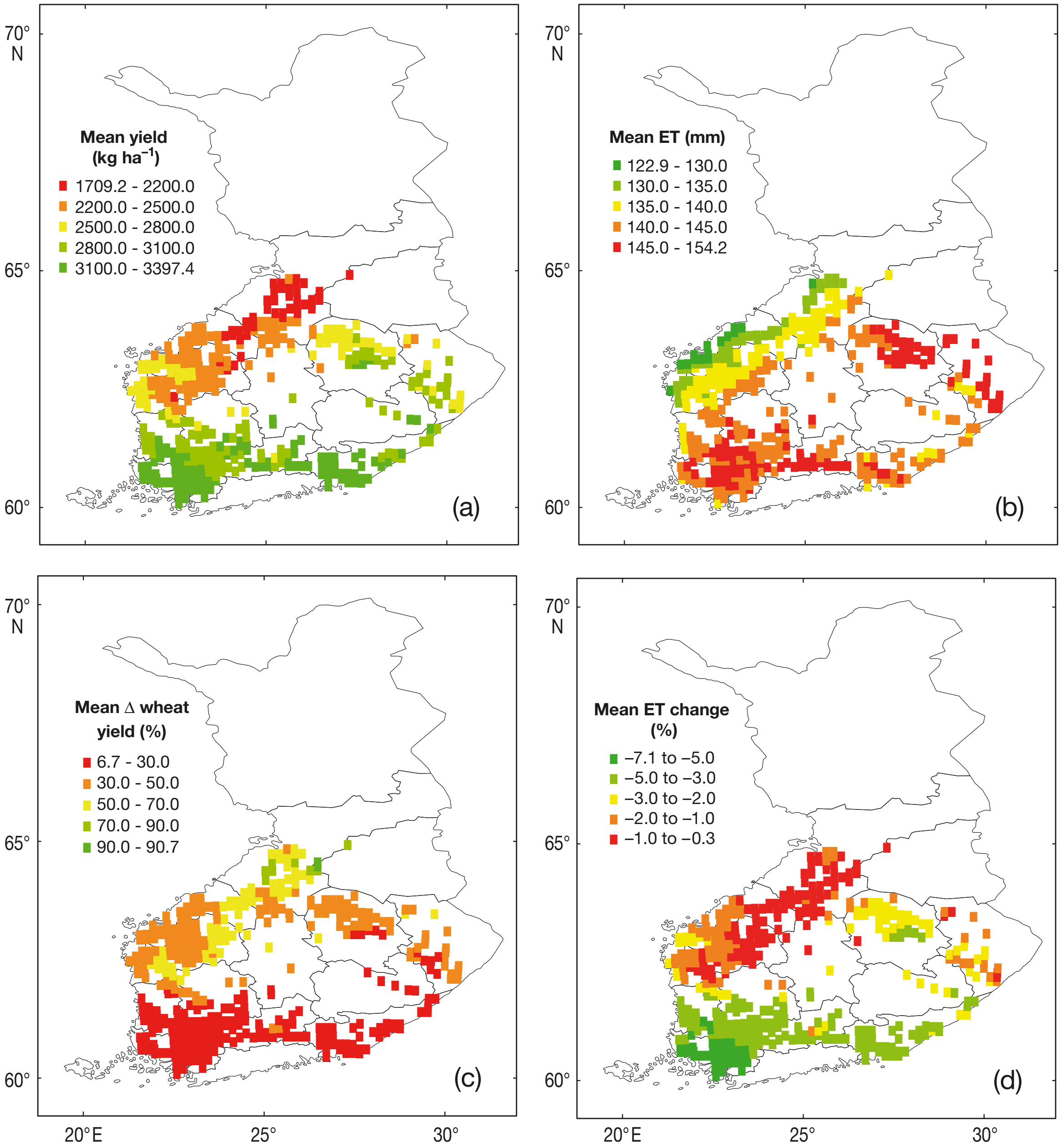

Fig. 5. Spatial patterns of spring wheat *Triticum aestivum* mean (a) yield and (b) evapotranspiration (ET) over wheat-growing period during 1971–2000, and the projected changes in mean (c,e,g) yield and (d,f,h) ET during the (c,d) 2020s, (e,f) 2050s, and (g,h) 2080s, respectively

(Fig. 5c), and ET is projected to decrease on average from 0.0% in the northwest to 7.0% in the south (Fig. 5d). During the 2050s, yield is projected to increase on average from ~30.0% in the south to over 70.0% in the northwest (Fig. 5e), and ET is projected to decrease on average from 3.0% in the northwest to 14.8% in the south (Fig. 5f). During the 2080s, yield is projected to increase on average from ~30.0% in the south to more than 70.0% in the northwest (Fig. 5g), and ET is projected to decrease on average from 7.7% in the northwest to 18.7% in the south (Fig. 5h). The patterns of yield changes are consistent with those of ET changes.

For winter wheat, yields range on average from ~3400 kg ha^{-1} in the northwest to more than 3700 kg ha^{-1} in the south during 1971–2000 (Fig. S2a in the Supplement), and ET during the wheat-growing period on average ranges from ~190.0 mm in the

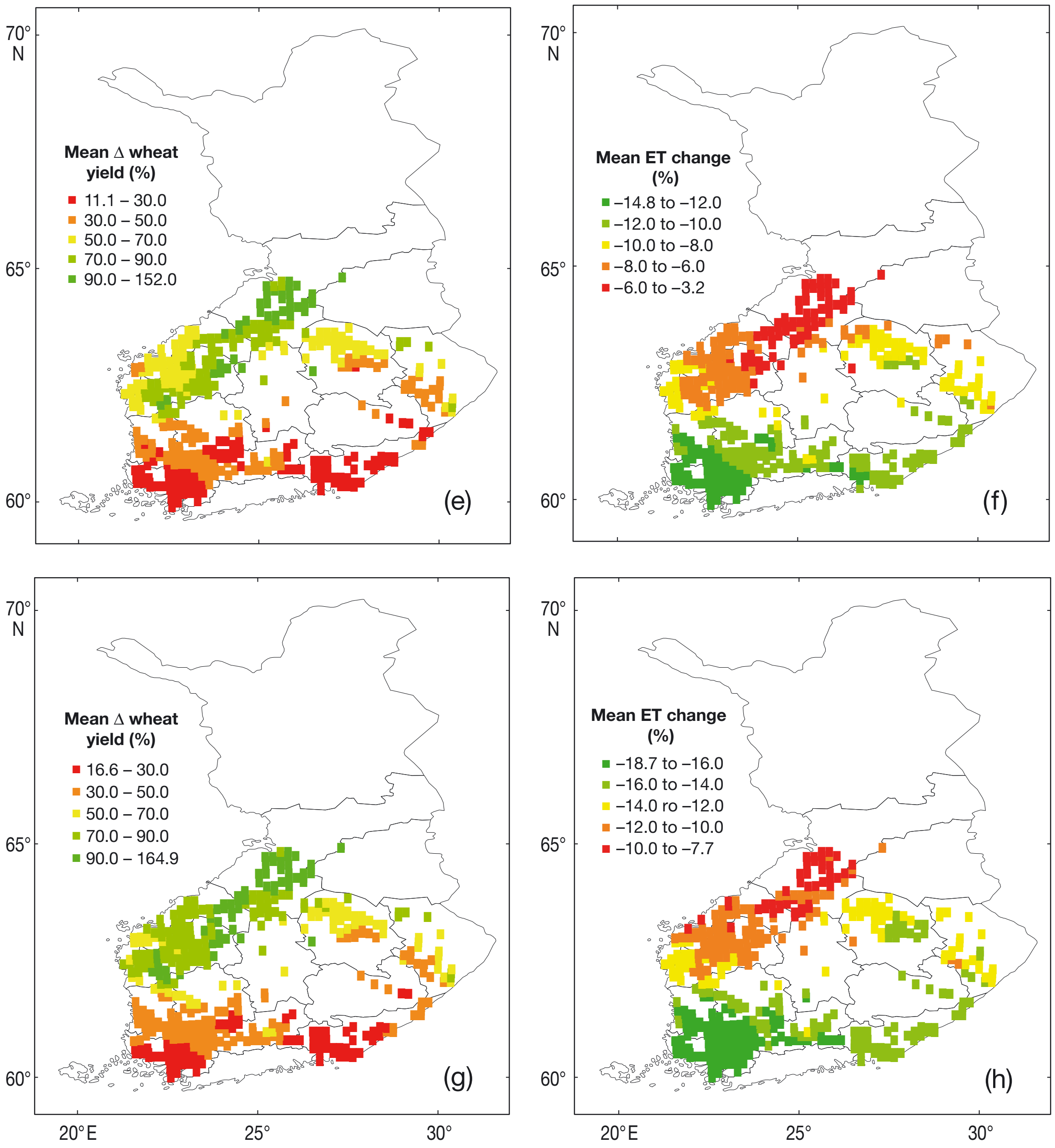

Fig. 5. (cont.)

west to >205.0 mm in the south (Fig. S2b). During the 2020s, yield is projected to increase on average from ~5.0% in the south and east to over 10.0% in the north (Fig. S2c), and ET is projected to decrease on average from 3.0% in the northwest to 14.0% in the south (Fig. S2d). During the 2050s, yield is projected to increase on average from ~5.0% in the south and east to more than 15.0% in the northwest (Fig. S2e), and ET is projected to decrease on average from 11.3% in the northwest to 25.0% in the south (Fig. S2f). During the 2080s, yield is projected to increase on average from ~5.0% in the south and east to more than 10.0% in the northwest (Fig. S2g), and ET is projected to decrease on average from 17.3% in the northwest to 34.4% in the south (Fig. S2h). Yield increases of winter wheat are modest and considerably lower than those of spring wheat.

3.5. Spatial and temporal pattern of yield decrease probability due to climate change

For spring wheat, during the 2020s, yield decrease probability will range from 0.0% in the northwestern

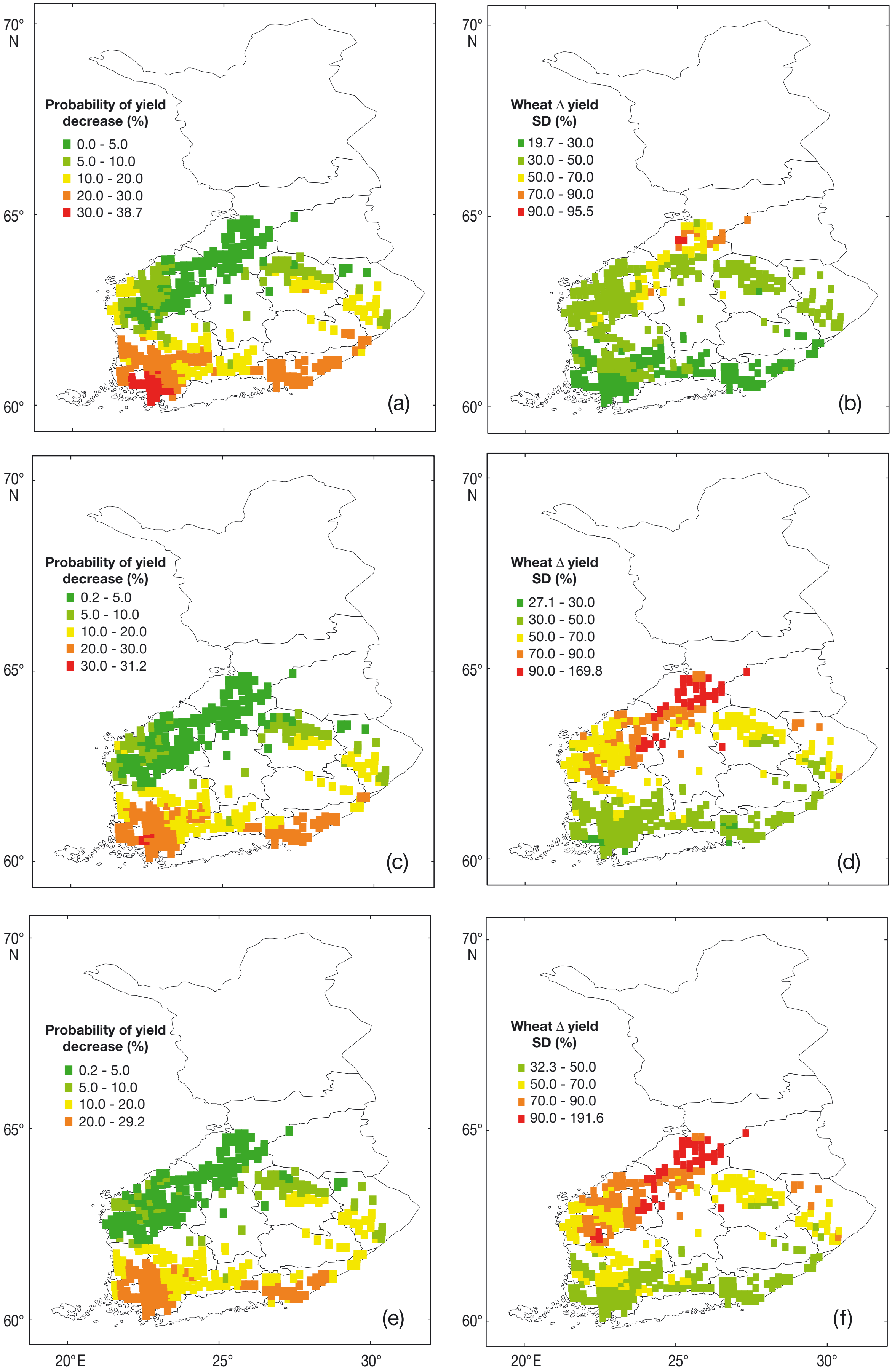

Fig. 6. Spatial patterns of (a,c,e) probability of yield decline and (b,d,f) standard deviation for yield change for spring wheat *Triticum aestivum* during the (a,b) 2020s, (c,d) 2050s, and (e,f) 2080s, across the wheat cultivation grids in Finland

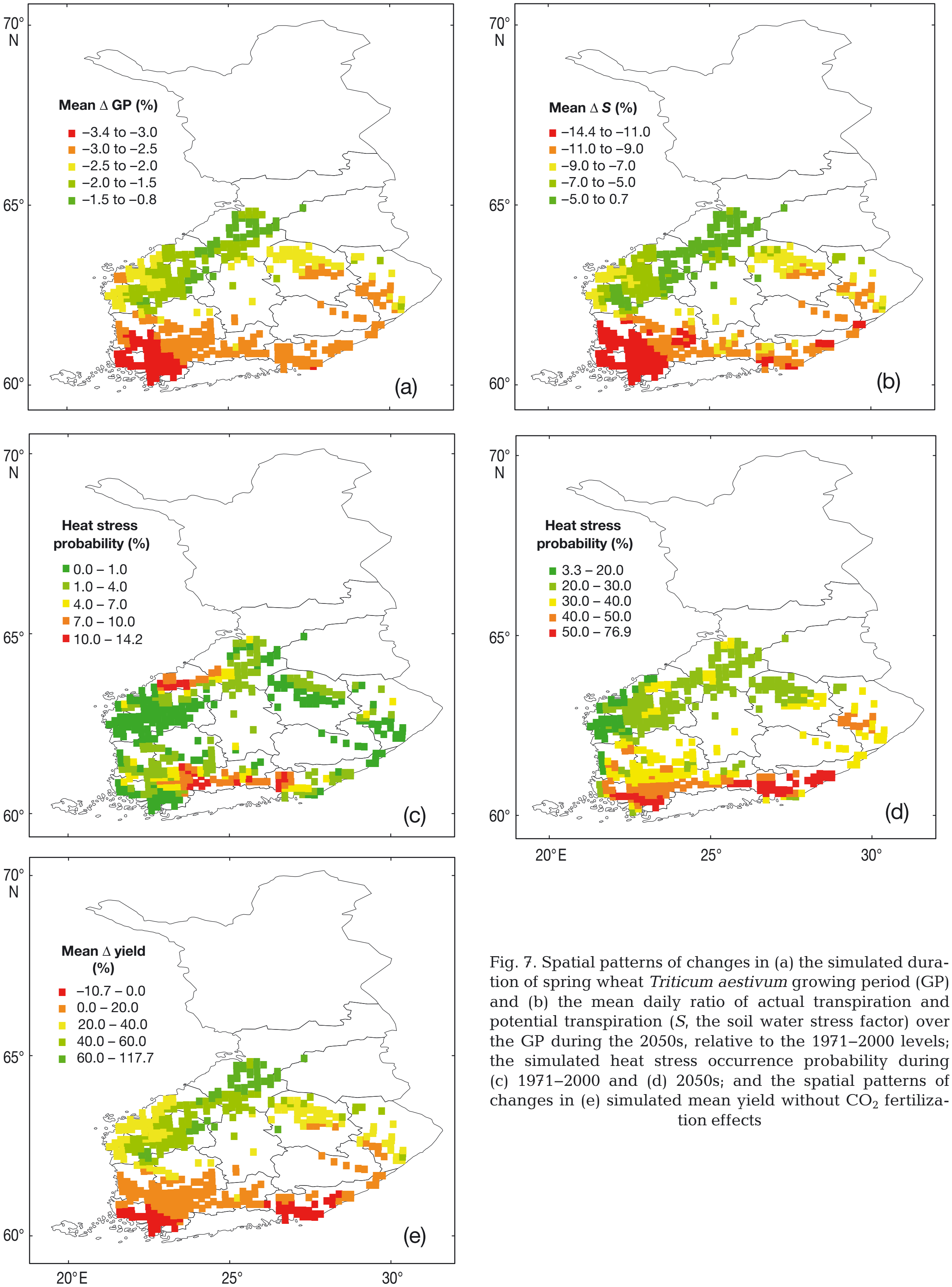

Fig. 7. Spatial patterns of changes in (a) the simulated duration of spring wheat *Triticum aestivum* growing period (GP) and (b) the mean daily ratio of actual transpiration and potential transpiration (*S*, the soil water stress factor) over the GP during the 2050s, relative to the 1971–2000 levels; the simulated heat stress occurrence probability during (c) 1971–2000 and (d) 2050s; and the spatial patterns of changes in (e) simulated mean yield without CO_2 fertilization effects

part to 38.7 % in the south (Fig. 6a), and yield standard deviation (SD) will increase from 19.7 % in the south to more than 50 % in the north, relative to 1971–2000 (Fig. 6b). During the 2050s, yield decrease probability will range from 0.2 % in the northwest to 31.2 % in the south (Fig. 6c), and yield SD will increase from 27.1 % in the south to more than 90.0 % in the north (Fig. 6d). During the 2080s, yield decrease probability will range from 0.2 % in the northwest to 29.2 % in the south (Fig. 6e), and yield SD will increase from 32.3 % in the south to over 90.0 % in the north (Fig. 6f).

For winter wheat, during the 2020s, yield decrease probability will range from 22.8 % in the west to 56.3 % in the east (Fig. S3a in the Supplement), and yield SD will increase from 5.2 % in the south to more than 20 % in the north relative to 1971–2000 (Fig. S3b). During the 2050s, yield decrease probability will range from 12.0 % in the west to 47.5 % in the east (Fig. S3c), and yield SD will increase from 7.2 % in the south to >30.0 % in the north (Fig. S3d). During the 2080s, yield decrease probability will range from 14.9 % in the west to 52.4 % in the east (Fig. S3e), and yield SD will increase from 9.1 % in the south to more than 30.0 % in the north (Fig. S3f).

4. DISCUSSION

4.1. Mechanisms underlying simulated changes in wheat yield and water use

Wheat yield is projected to increase notably with high probability due to climate change in Finland when assuming no change in climate variability. With spring wheat growing period temperature from 12.4 to 14.9°C, precipitation from 162.6 to 245.1 mm, mean solar radiation from 17.2 to 19.6 MJ m^{-2} d^{-1}, during 1971–2010, the temperature conditions are less than the optimal temperatures for wheat productivity (Porter & Gawith 1999). The projected increases in temperature, precipitation, and solar radiation in the future can better meet the optimal thermal and hydrological conditions for wheat, which, together with cultivar renewal and rising atmospheric CO_2 concentration, potentially can enhance wheat development, photosynthesis, and consequently yield substantially.

In addition, we found that climate change can reduce the duration of the wheat-growing period by ~3.4 % during the 2050s if the varieties are not changed, with the largest reduction in the south where the mean temperature will be relatively higher than in the north, where the wheat-growing period is projected to reduce slightly, i.e. by ~1.5 % (Fig. 7a). If wheat cultivars with longer growing durations will be cultivated in the future, the negative effects of temperature increase can be reduced to some extent. The soil water stress factor, S, is the ratio between actual and potential crop transpiration rate (water stress increases when the value of S becomes smaller). It will decrease most by 14.4 % in the south and change little in the north, suggesting that drought stress will increase notably in the south (Fig. 7b), although cumulative ET will decrease mainly due to the stomatal 'antitranspirant' response of plants to rising atmospheric CO_2 concentration and reduced growing duration. Simulated heat stress occurrence probability, which was less than 14.2 % across the study region during 1971–2000 (Fig. 7c), will rise to more than 50 % in the south during the 2050s (Fig. 7d). The fertilization effects of CO_2 are projected to increase yield most by ~30.0 % in the north, where the climatic conditions are relatively cooler and drier, and increase yield least by about 10.0 % in the south, where climatic conditions are hotter and wetter (Figs. 5e & 7e). If the fertilization effects of CO_2 are not taken into account, wheat yields are projected to decrease by up to 10.7 % in the south (Fig. 7e). The spatial patterns of changes in the wheat-growing period, drought stress, heat stress, and fertilization effects of CO_2 are consistent with those of projected yield change (Figs. 5e & 7a,b,d,e), suggesting that projected yield change can be ascribed to changes in the wheat-growing period, drought stress, heat stress, and fertilization effects of CO_2.

For winter wheat, the duration of the growing period will be reduced more (Fig. S4a), drought stress will be reduced substantially (Fig. S4b), and heat stress occurrence probability will also increase in future but with a lower probability than for spring wheat (Fig. S4c,d). Winter cereals are far better able to escape from drought due to a deep root system compared to spring cereals that are extremely vulnerable (Olesen et al. 2011). If the fertilization effects of CO_2 are not taken into account, wheat yield can decrease by up to 10.0 % in most of the study areas (Fig. S4e). These results suggest that photosynthesis of winter wheat will not be enhanced as high as that of spring wheat due to differences in seasonal climate change and its effects on leaf area index and root development. As a result, yield of winter wheat will increase much less than that of spring wheat in future.

4.2. Shortcomings, merits, and comparison of this study with previous work

This study has several shortcomings. For example, the climate scenario downscaling methods with baseline climate variability imposed on future climates may introduce uncertainties which may be too optimistic (Rötter et al. 2013, Lehtonen et al. 2014). The effects of extreme weather on wheat growth and productivity are not fully parameterized in the model; particularly, overwintering damage to crops needs to be further refined. Furthermore, some datasets such as crop cultivation fraction, soil properties, and climate change scenarios can be updated in further studies as new, more detailed information has become available.

In the previous studies, based on a set of qualitative and quantitative questionnaires, Olesen et al. (2011) showed that the expected impacts, both positive and negative, are just as large in northern Europe as in Mediterranean countries. Impacts are considered mostly negative in wide regions across Europe considering all effects of climate change and possibilities for adaptation. Based on agro-climatic indices, Trnka et al. (2011, 2014) showed a risk of an increasing number of extremely unfavorable years with droughts and heat waves, which might result in higher inter-annual yield variability. The occurrence of adverse conditions for 14 sites representing the main European wheat-growing areas might substantially increase by 2060 compared to the period 1981–2010. This is likely to result in more frequent crop failure across Europe. Rötter et al. (2011a) used the WOFOST crop growth simulation model to examine crop yield responses to a set of plausible scenarios of climate change, including changes in variability, for Finland up to 2100 at 2 Finnish locations, and concluded that the positive effects of climate warming and elevated CO_2 concentrations on cereal production at high latitudes are likely to be reversed at temperature increases exceeding 4°C, with a high risk of marked yield loss. Only enhanced plant breeding efforts aimed at increasing yield potential jointly with drought resistance and adjusted agronomic practices, such as sowing, and adequate nitrogen fertilizer management and plant protection, showed prospects of partly restoring yield levels and reducing the risks of yield shortfall. Rötter et al. (2013) developed the modeling tool NordicAgriCLIM for the automatic generation of indicators describing basic changes in agroclimatic conditions under climate change scenarios, and also applied WOFOST to simulate detailed crop responses (using spring barley as a test crop) to changes in climatic means at 4 representative locations. Their results showed that under the reference climate (1971–2000), the most risk-prone areas for spring cereals are in southwestern Finland, shifting to southeeastern Finland towards the end of this century. WOFOST simulation results suggest that CO_2 fertilization and adjusted sowing together can lead to small yield increases of current barley cultivars under most climate scenarios on favorable soils, but not under extremely unfavorable climate scenarios and poor soils.

The present study takes into account the adaptations to some extent using multiple cultivars with contrasting phenological and thermal characteristics and quantifies the risk of extreme weather stress and yield changes in a probabilistic framework. Yet, the climate scenarios that served as input did not include any with changes in climatic variability, although some recent studies suggest such variability also changes for northern Europe — e.g. more frequent high-intensity precipitation events (see Lehtonen et al. 2014). The MCWLA-Wheat model accounts for the key impact mechanisms of climate variability, simulates inter-annual yield variability reasonably well, and the super-ensemble-based projection accounts not only for the uncertainties from climate scenarios but also for the uncertainties from biophysical processes of crop models. Even under the given limitations described above, the resultant probabilistic projections can provide useful decision-making support to regional resource managers and policy makers that can be considered more robust than previous assessments.

4.3. Implication for wheat production under future climate in Finland

Our results suggest that wheat production in Finland could generally benefit from climate change in the future; nevertheless, the risk of drought stress, heat stress, and consequently yield variability can increase with climate change. The results are supported by previous studies; for example, some studies showed that high-temperature extremes have become more frequent while low-temperature extremes have become less frequent since 1950 in the study area (Peltonen-Sainio et al. 2011b, Rötter et al. 2013). There will be a marked increase in extremes in future, in particular, in heat waves, droughts, and heavy precipitation events (Rötter et al. 2013, Lehtonen et al. 2014, Trnka et al. 2014). In fact, early summer drought already severely limits yields in some years (Peltonen-Sainio et al. 2009, Rötter et al. 2013). Overwintering and damage caused by snow cover and overall winter conditions to crops is considered a major problem for winter wheat production in the study area (Hakala et al. 2012). Severity of overwintering damage, and associated yield penalties, fluctuate considerably on a year-to-year basis, and no reduction in variability was recorded during 1970–2006. The fluctuating conditions hampered overwintering, which may be an even harder challenge in future when weather variation is projected to increase and extreme weather events are projected to become more common (Peltonen-Sainio et al. 2011b). Therefore, how to improve crop varieties and agronomic management practices to take advantage of increases in temperature and realize the increased yield potential from climate change while protecting crops from increasing risk of droughts and heat stress, and risk of overwintering and damage, is the key point. Some studies have shown that autonomous adaptations by farmers, through the advancement of sowing and harvesting dates, the use of longer cycle varieties, and expansion of cropping areas (Howden et al. 2007, Moriondo et al. 2010, Olesen et al. 2011, Peltonen-Sainio & Jauhiainen 2014) can result in improvement of European wheat yields in future. This contradicts other studies which, for most regions in Europe, rather project yield penalties when using late-maturing cultivars for 2050 under high-end climate scenarios. Drought-tolerant and heat-tolerant varieties, intensive agronomic management such as water-conserving practices, as well as government economic incentives policy such as subsidies and agricultural insurance, should work effectively together to combat the negative effects of climate change and realize higher yield potentials without sacrificing yield stability.

5. CONCLUSION

An advanced super-ensemble-based probabilistic approach was applied to project the impacts of future climate change on the productivity and water use of spring wheat and winter wheat in Finland in a probabilistic framework. Our results show that wheat yields are projected to increase substantially with high probability under climate change in Finland, and spring wheat may benefit more from climate change than winter wheat. Nevertheless, in some parts of southern Finland, wheat production will face increasing risk of high temperatures and drought stress, which can offset the benefits of climate change on wheat yield resulting in an increase in yield variability and about 30% probability of yield decrease for spring wheat. Compared with spring wheat, the development, photosynthesis, and consequently yield will be much less enhanced for winter wheat, which, together with the risk for extreme weather, will result in an up to 56% probability of yield decrease in eastern parts of Finland. Our findings highlight that climate change will increase benefits and potential for crop production in Finland; nevertheless, the risks from climate extremes will increase. Effective adaptations should be adopted to take advantage of increases in temperature and realize the increased yield potential from climate change while protecting the crop from increasing risk of droughts and extreme temperature stress.

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