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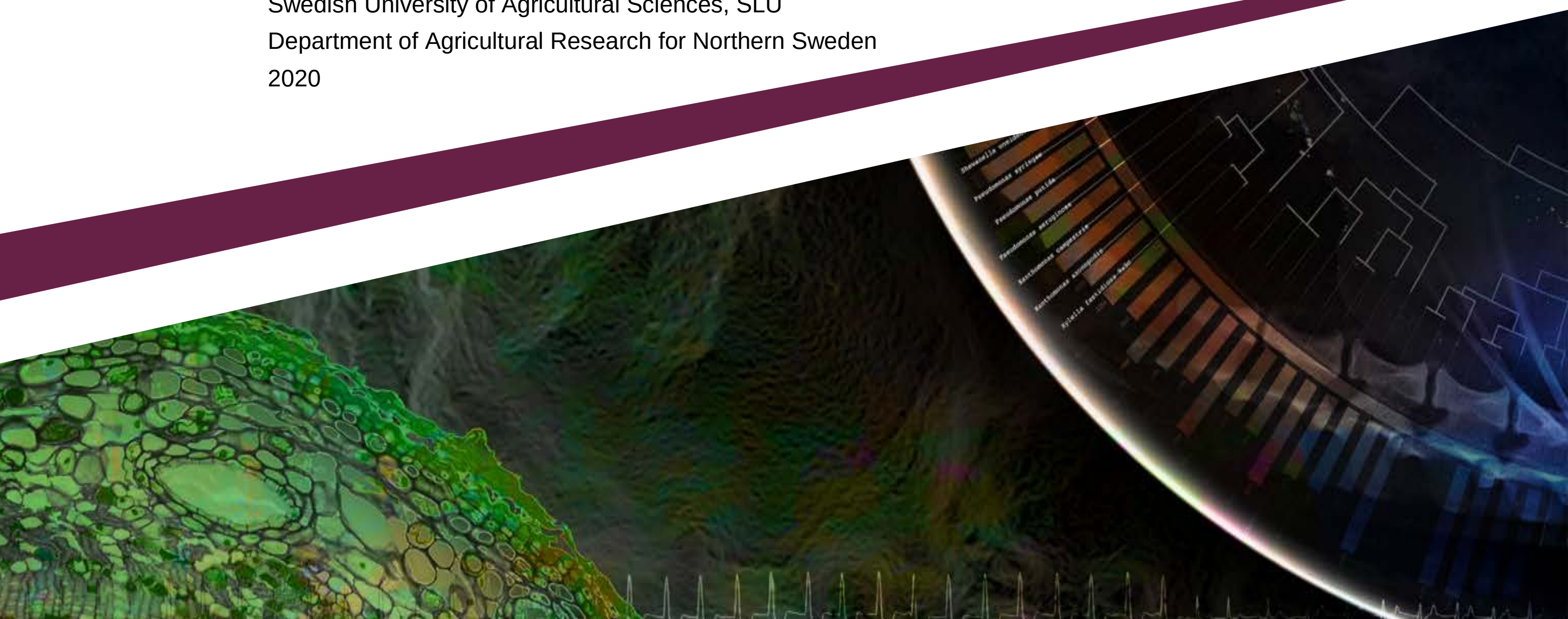

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Summary

We assessed the effects of temperature increase and variation in precipitation on the growth and development of four crops (barley, forage maize, oats and spring wheat) in five locations in Sweden (Kristianstad, Färjestaden, Lidköping, Uppsala and Umeå) using the process-based crop model APSIM. Baseline simulations were run for each crop and location, with weather data for 1980 to 2005 obtained from the CCAFS dataset. Synthetic climate data were defined using the baseline climate with (i) incremental increases in daily minimum and maximum temperatures and CO_2 concentrations, combined with (ii) incremental increases and decreases in daily precipitation. Future climate simulations were then run using 26 years of synthetic climate data and compared with baseline climate in terms of changes in (i) crop productivity (grain yield for barley, oats and spring wheat, aboveground dry matter yield for forage maize) and (ii) risk of crop failure.

Baseline results are consistent with the expected productivity in farmer fields for each crop. Considering the effects of climate change on the yield, the results suggest that crops will behave differently depending on the location and magnitude of changes in temperature. Barley and oats showed a maximum increase in yield with a 1°C increase in temperature. The same trend was observed for spring wheat, with the exception of Umeå, where the maximum yield was obtained for a 4°C increase in temperature. Forage maize showed better performances for greater temperature increases (2-3°C) in all locations, with the exception of Umeå, where the maximum simulated yield is reached for a 5°C increase. There is little effect of changes in precipitation on the productivity of the crops. Results suggest that, in the case of a high increase of temperature (+5° C) and decrease of precipitation (-20%), forage maize production should increase for all locations, whereas oats production should decrease for all locations. Barley and spring wheat should have a decrease in production, with the exception of Uppsala (barley) and Umeå (spring wheat). Risks of crop failure computed from simulations showed a different pattern, with all crops being little impacted by changes in climate, with the exception of Umeå where forage maize and, to a lesser extent, oats and spring wheat showed decreasing risk of failure with increasing temperatures.

Although some simplifications had to be made to parameterize the model and prepare the synthetic climate data, the current results provide a useful projection of potential trends in production of crops in Sweden, and are similar to results obtained in other studies in the Nordic region.

This study underlines several research questions that need to be addressed to better understand the effects of drought and, more generally, of climate change on annual crop production. Continual development of improved crop models (e.g. including a dynamic link between water use efficiency and CO_2 increases) is necessary to better understand the dynamics of crop production and increase prediction accuracy in changing climates. Effects of N-fertilization on mitigating the negative effects of temperature also need to be investigated. Finally, defining priority traits of ideal cultivars to reduce the negative effects of climate change is an important upcoming task.

Sammanfattning

Vi har utvärderat effekterna av ökande temperaturer och varierande nederbörd på tillväxt och utveckling av fyra grödor (korn, fodermajs, havre och fjädervete) för fem platser i Sverige (Kristianstad, Färjestaden, Lidköping, Uppsala and Umeå) med hjälp av den processbaserade grödmodellen APSIM. Baslinjesimuleringar kördes för varje område och gröda, med väderdata för åren 1980 till 2005 (data från CCAFS). De syntetiska väderdata definierades genom att använda samma väderdata som för baslinjesimuleringarna med (i) stegvisa ökningar av dagliga minimum och maximum temperaturer och CO2 koncentrationer och (ii) stegvisa ökningar och minskningar av daglig nederbörd. Framtidssimuleringar gjordes sedan med 26 års syntetisk väderinformation och jämfördes med körningarna med väder enligt baslinjen med avseende på förändringar i (i) grödproduktivitet (kärnavkastning av korn, havre och vårvete, skördad ovanjordisk biomassa av fodermajs) och (ii) risk för missväxt.

Resultatet av modellkörningarna enligt baslinjen överensstämde med den förväntade produktiviteten för samtliga grödor. De körningar som gjordes med framtida klimatscenarier indikerar att grödorna kommer att påverkas olika beroende på plats och storleken på temperaturökningen. Korn och havre hade störst ökning av avkastningen vid en temperaturökning på 1°C. Samma optimum observerades för vårvete, utom i Umeå, där nåddes maxavkastningen vid en temperaturökning på 4°C Fodermajs gynnades av större temperaturökningar, 2-3°C på samtliga platser utom Umeå där maxskörden nåddes vid +5°C. Enligt resultaten kommer förändringar i nederbördsmängder ha liten påverkan på avkastningen. Vid en stor temperaturökning (+ 5°C) och minskning av nederbörden (-20%) kommer fodermajsproduktionen öka sin avkastning på samtliga platser, medan havreproduktionen kommer att minska. Avkastningen av vårkorn och vårvete kommer enligt analysen att minska på alla platser utom Uppsala (vårkorn) och Umeå (vårvete). Risken för missväxt påverkades enligt simuleringarna enligt ett annat mönster än avkastningen. För samtliga grödor påverkades risken ganska lite av de testade förändringarna i väder, med undantag för Umeå där fodermajs och, i mindre utsträckning, havre och vårvete visade minskad risk för missväxt med ökande temperaturer.

Även om vissa förenklingar måste göras för att parametrera modellen och förbereda syntetiska väderdata, ger våra resultat en användbar bild av potentiella trender när det gäller förändringar i produktivitet hos jordbruksgrödor i Sverige. Resultaten överensstämmer i hög grad med resultat som erhållits i andra studier som utförts för de nordiska länderna.

Denna studie belyser flera forskningsfrågor som behöver besvaras för att bättre förstå effekterna av torka, och klimatförändringar generellt, på växtproduktionen. Det är viktigt med kontinuerlig utveckling och förbättring av grödmodeller, t.ex. koppling vattenanvändningseffektivitet och CO_2-koncentration, för att bättre förstå dynamiken i växtproduktionen och förbättra noggrannheten vid förutsägelser om effekten av klimatförändringar. Det kommer också att bli viktigt att undersöka hur N-gödsling kan användas för att mildra de negativa effekterna av ökande temperaturer. Slutligen är det viktigt att med hjälp av modelleringsverktyg identifiera prioriterade egenskaper hos sorter som ska klara ett förändrat klimat.

1. Introduction

The Swedish agricultural system is built to a large extent on rainfed crops, which makes it particularly dependent upon regular precipitation. This dependency has recently been highlighted with the extreme drought observed during the summer of 2018. Many farmers were not able to sow their crops, and even perennial forages were lower yielding than normal , resulting in the slaughtering of livestock. For annual crops, reduced yield and poor quality were obtained due to the combined effects of water stress and high temperatures. Since the frequency of drought events is expected to increase with climate change[1], it is necessary to quantify the impact of droughts on crops and explore ways to increase the resilience of the Swedish agriculture to water limitations. One way to perform such quantification is to use crop models and assess their response to various climate scenarios. Crop models can simulate the response of real crops to changing climate, soils, and farming practices, and can be a more efficient research tool compared with complex and costly field experiments.

The aims of this study are to (1) simulate potential trends of future crop production in Sweden using combined incremental changes in temperatures and precipitation, (2) identify the most resilient crops for each location compared to a historical baseline, and (3) identify key gaps in modelling knowledge and provide recommendations for further research.

We simulated the yield and risk of failure of four crops (barley, maize, oat and spring wheat) across five locations in Sweden. Two climate scenarios were considered, the first based on recorded historical weather data (from 1980 to 2005) and the second based on "synthetic" future climate data (Figure 1). The results of simulations were used to quantify the impact on yield and crop failure under a range of potential future climatic conditions.

2. Materials and methods

Simulations of plant growth and development were performed using the crop model APSIM. In order to take into account the spatial variability of soil and climate conditions, the simulations were performed for five different locations showing contrasting pedoclimatic contexts. Soil and weather data were organized for each location, along with farming practices for each crop, as inputs for APSIM. The general workflow of the project is presented in Figure 1.

2.1. An overview of the APSIM crop model

Mechanistic crop models can simulate crop growth and development as a function of soil, climate and agronomic management, providing information on interactions of genotype, environment and management (GxExM). Thereby, these models can be used to provide a comprehensive view of crop production at farm, regional and global scale. APSIM is one of the most commonly used models, with robust capacities to simulate the interactions of GxExM for crop yield and stability.

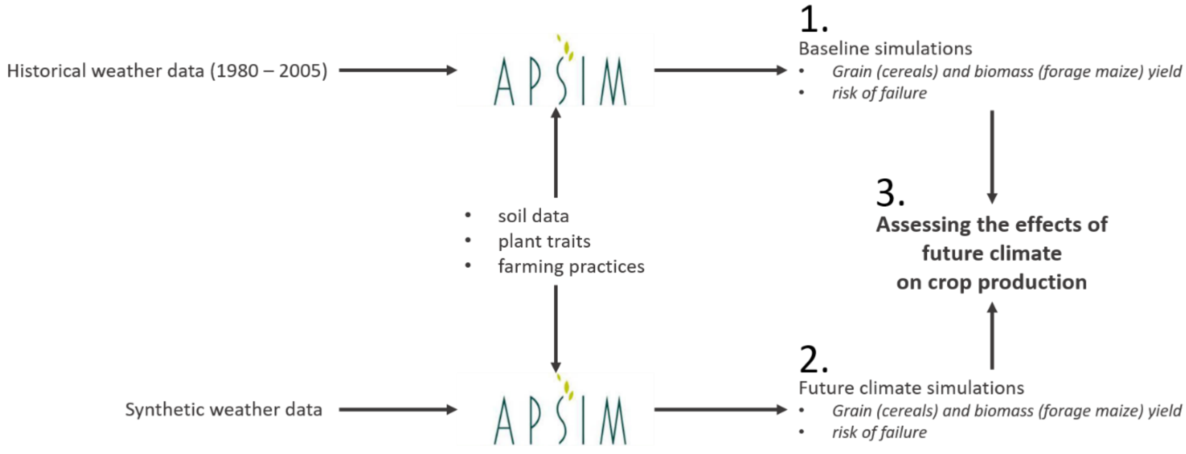

Figure 1. General workflow of the study. Using the APSIM crop model, the effects of future climate drought events are assessed by comparing the production and risk of failure for five crops based on (1) historical climate data and (2) synthetic climate data with higher temperatures and both increased and decreased precipitation.

APSIM[2,3] (version 7.10) simulates the growth and development of a homogeneous plot for a range of crops based on weather data, soil characteristics, plant traits and farming practices on a daily time step. The minimum weather information required to run APSIM includes daily precipitation, minimum and maximum air temperatures and solar radiation. Although having been rarely used for Nordic climates and high latitude conditions, APSIM is arguably the most widely used crop model around the world. It has the advantages of (1) having an open source code, (2) an active user and developer community, and, most importantly, (3) already includes useful submodules to simulate the crops assessed in this study and the effects of changes in precipitation and temperature on the phenology and yield of the crops.

2.2. Soil data

A precise description of the soil profile is critical for the model to correctly simulate the water and nutrient balances, which directly affect the growth of crops. For all locations except Uppsala, soil samples were directly acquired by the authors for 10 layers (Umeå) and 6 layers (Kristianstad, Lidköping and Färjestaden) to a depth of 120 cm. Soil water characteristics were measured using laboratory methods. For Uppsala, data from Wiklert et al. (1983)[4] were used to compute an estimation of the soil water characteristics using the SoilWat model[5].

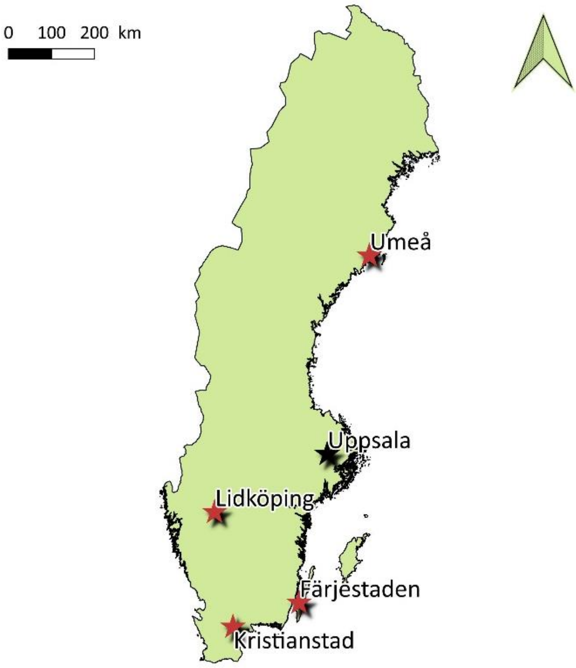

Figure 2. Locations used in the study. Red stars indicate locations with soil sampling performed by the authors. The black star shows the location for which soil data were acquired from a previous report[4].

2.3. Farming practices

Farming practices (including sowing dates, densities and depths) were defined for each crop based on expert knowledge. Farming practices were adjusted to ensure limited nitrogen stresses (less than 5%), to remove any potential influence of nitrogen-related stress on photosynthesis.

Sowing and cut-off harvest dates were defined based on usual practices for each crop whenever possible (Table 1). In the case of spring wheat and forage maize in Umeå, dates of sowing and harvest were estimated based on expert knowledge.

Table 1. Sowing and harvest dates for each crop and location of the study.

		Crop			
		Barley	*Maize*	*Oats*	*Spring wheat*
Location	*Kristianstad*	05/05, 15/10	05/05, 15/10	05/05, 15/10	05/05, 15/10
	Färjestaden	05/05, 15/10	05/05, 15/10	05/05, 15/10	05/05, 15/10
	Lidköping	05/05, 15/10	05/05, 15/10	05/05, 15/10	05/05, 15/10
	Uppsala	10/05, 15/10	10/05, 15/10	10/05, 15/10	10/05, 15/10
	Umeå	25/05, 01/10	01/06, 01/10	25/05, 01/10	01/06, 01/10

Synthetic cultivars were defined for each crop based on existing, calibrated cultivars and expert knowledge. Creation of barley and oats cultivars were categorized into northern and southern cultivars, based on the general crop growth and development in the regions. Northern cultivars in the model were calibrated to mature in around 100 days for barley and 110 days for oats, considering the shorter cropping duration in the region[6,7]. The days to complete maturity of southern cultivars were on average 15 days more than the northern cultivars. Synthetic cultivars were developed in APSIM to achieve a typical yield for farmer fields, i.e. 4.5 to 5.8 $t.ha^{-1}$ for barley and 4.3 to 5.4 $t.ha^{-1}$ for oats, based on crop production statistics from Jordbruksverket[8] (see reports JO 14 SM 1601, JO 14 SM 1701, JO 14 SM 1801, JO 14 SM 1901).

The synthetic cultivar of forage maize developed for this study was calibrated to flower around 80 days after sowing and reach approximately 12-14 $t.ha^{-1}$ of aboveground dry matter yield. These values have been determined using previous studies, including Eckersten et al. 2012[9], Nkurunziza et al. 2014[10] and Swensson et al. 2017[11]. Because forage maize has not been cultivated in northern Sweden, we used a single cultivar for both southern and northern locations.

The synthetic cultivar for spring wheat used in this study was calibrated to reach flowering around 60 days and achieve a grain yield of approximately 5.5 $t.ha^{-1}$, based on Wallach et al. 2018[12] and Swedish official field trials data[13]. As with forage maize, we used a single cultivar for northern and southern locations, due to the absence of high latitude cultivars.

2.4. Climate data

2.4.1. Historical weather data

In order to define a reliable baseline for crop production, it was necessary to run simulations over a period of historical weather data, to represent a climate. As weather station records of such data were not available for a period extending over a suitable time length (from 1st of January 1980 to 31st of December 2005), data used here were downloaded for each location from the CCAFS website[a]. A summary of the main climate indicators is provided in Table 2.

Table 2. Summary of the baseline climate for each location. GDD are accumulated growing degree days.

Location	Lat., Long. ° (WGS84)	GDD, base 5 °C	Precipitation $mm.yr^{-1}$	Mean annual temperature °C	Solar radiation $MJ.m^{-2}.y^{-1}$
Färjestaden	56.7, 16.5	1645	477	7.5	3966
Kristianstad	56.1, 14.0	1571	618	7.4	3806
Lidköping	58.4, 13.2	1444	625	6.4	3640
Umeå	63.8, 20.2	1048	613	2.8	3498
Uppsala	59.9, 17.6	1406	533	5.7	3614

2.4.2. Synthetic future climates

The projected increase in temperature for Sweden under the scenario with highest emissions (RCP8.5) is around 3°C by 2050 compared to the baseline 1961-1990 (https://www.smhi.se/en/climate/climate-scenarios). The prediction is higher in northern Sweden (around 5°C). Similarly, climate change is projected to increase precipitation by 10% in Sweden, and 20-25% in the northern region. The prediction for CO_2 concentration is between 450 to 600 ppm by 2050 depending on the emission scenario (IPCC AR5).

By the end of the century, the increases in temperature are predicted to be in the range of 3 to 6°C across the country compared to 1961-1990[14–16]. Higher changes will be observed in the north than in the south (https://www.smhi.se/en/climate/climate-scenarios).

[a] http://www.ccafs-climate.org/data_bias_correction/

With climate change, local weather anomalies might also be increased and intensified. One such event was observed in 2018 as an extremely hot and dry summer. The rise in temperature and long and intense dry period significantly impacted crop production.

Considering the predicted climate and anomalies, we evaluated the crops under different climate scenarios (Table 3) to represent different combinations of temperature and rainfall scenarios. Synthetic climate scenarios were created considering the RCPs of IPCC for 2020 to 2050 by adjusting historical daily maximum and minimum temperatures, and modifying precipitation values by a percentage change. The conditions of lower and higher increases in temperatures are similar to the low and high emission scenarios of the RCPs.

Table 3. Synthetic climate scenarios (scen.) for the study. The increase in maximum and minimum temperature are 1 to 5°C with corresponding CO_2 concentrations, in combinations with percentage increase or decrease in precipitation from the baseline climate.

	Temperatures and CO_2 concentrations increases					
Changes in precipitation	*0°C 350 ppm*	*1°C 440 ppm*	*2°C 450 ppm*	*3°C 480 ppm*	*4°C 520 ppm*	*5°C 560 ppm*
0%	Baseline	Scen. 1	Scen. 7	Scen. 13	Scen. 19	Scen. 25
-5%		Scen. 2	Scen. 8	Scen. 14	Scen. 20	Scen. 26
-10%		Scen. 3	Scen. 9	Scen. 15	Scen. 21	Scen. 27
-20%		Scen. 4	Scen. 10	Scen. 16	Scen. 22	Scen. 28
+5%		Scen. 5	Scen. 11	Scen. 17	Scen. 23	Scen. 29
+15%		Scen. 6	Scen. 12	Scen. 18	Scen. 24	Scen. 30

2.5. Analyzing APSIM outputs

APSIM output files were imported and analyzed with R 3.4.1 (R Core Team, 2017)[17]. The evolution of crop production was assessed using two indicators: yield change and yield variability.

Yield change (δ_y, expressed in %) is crop specific and was computed as

$$\delta_y = \frac{(m_y - r_y)}{r_y} \qquad 1$$

where m_y is the median yield of a given crop for a given climate scenario and r_y is the reference yield of the given crop, which was computed as

$$r_y = \frac{\sum_1^n b_n}{n} \qquad 2$$

where b_n is the median yield of a given crop under the baseline climate, for the n^{th} location.

Yield variability (υ_y, expressed in %) was calculated as the coefficient of variation of the yield of a given crop-location-climate scenario combination

$$\upsilon_y = \frac{\sigma_y}{\mu_y} \qquad 3$$

where σ_y and μ_y are respectively the standard deviation and the mean of the yields for a given crop-location-climate scenario combination.

Rules to consider a given crop as a failure were defined based on simulated phenological stages in APSIM. Forage maize was considered to be a failure if the grain filling process was less than half completed. For barley, oats and spring wheat, the crop was considered to be a failure if the phenological stage was not completed. Crop failure risk, was computed as the percentage of failures for a given crop-location-climate scenario combination.

3. Results

3.1. Impact on yield

The results presented in this section are relative values of yield (grain yield and aboveground dry matter yield for forage maize). Yield median values were first computed for every location, crop and climate scenario combination. Finally, the mean value of the baseline scenarios of a given crop for all locations was computed and used as a reference figure across locations.

Barley

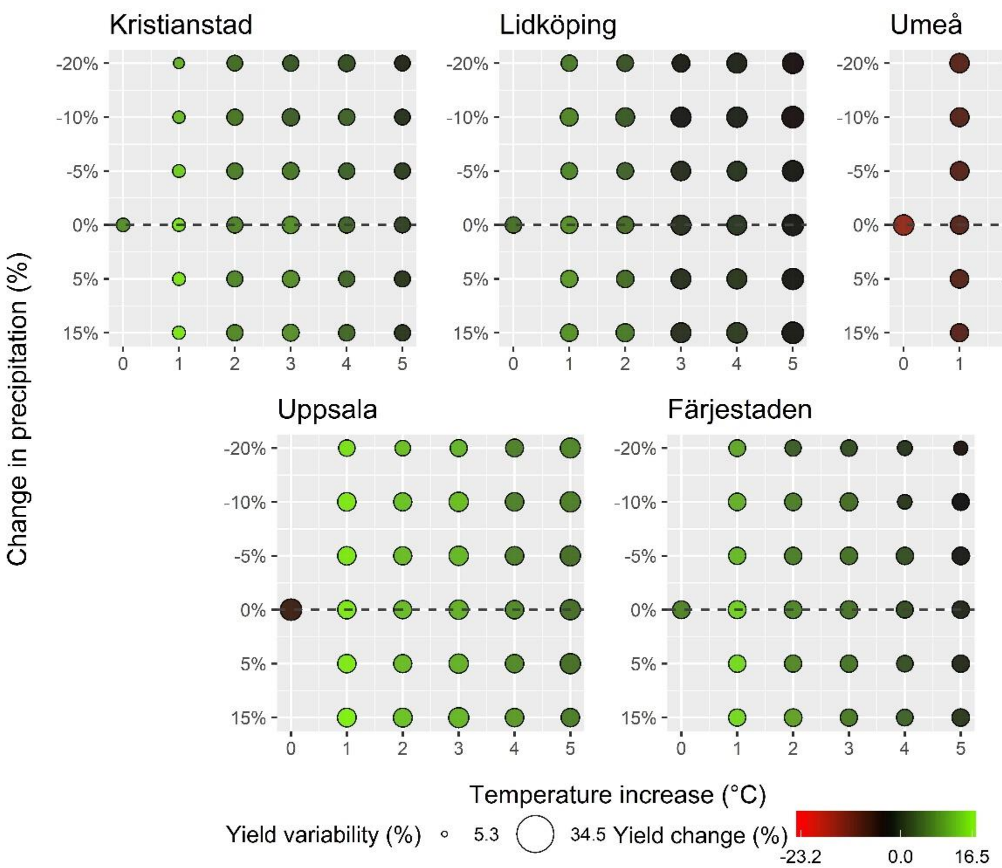

Figure 3. Changes in barley grain yields for the 5 locations of the study. Red colors indicate a decrease of yield while green colors indicate an increase of yield. The size of the points indicate the variability of the yield (coefficient of variation). The dashed line indicates a 0% change in precipitation. The yield reference value (0%) was computed as the mean of the baselines of the 5 locations (5.0 t.ha^{-1}).

In general, barley yields observed in Umeå were lower compared to the locations in southern Sweden (Figure 3). Yield variabilities, particularly with increasing temperature, were also higher in Umeå than for other locations. In all cases, increase in CO_2 fertilization did not negate the impact of temperature increase for synthetic climates. Barley yield in Umeå decreased with increasing temperatures. The productivity was not affected by changes in precipitation. In Uppsala, maximum yield was observed with a 1°C increase in temperature. Subsequent increases in temperature lead to a decreasing yield. Changes in precipitation did not affect the yield, irrespective of temperature increase. At Lidköping, simulated yields for the baseline climate were higher compared to Uppsala, whereas the increase of temperatures lead to a greater decrease in yield compared to Uppsala. Similar yields were observed for all climate scenarios with 3-5°C of temperatures increase. Yield variability was similar for all climate scenarios, including the baseline. At Färjestaden, the baseline yield was similar to Lidköping. The maximum yield was observed with a 1°C increase in temperature, although higher precipitation resulted in slightly higher yields. Subsequent increases in temperatures lead to a decrease in yield. The yield variability did not change significantly with the combinations of temperature and precipitation. At Kristianstad, the yields and yield variabilities of all combinations of temperature and precipitation were similar to Färjestaden, with a maximum yield obtained for a 1°C temperature increase and the minimum yield obtained for an increase of 5°C.

Maize

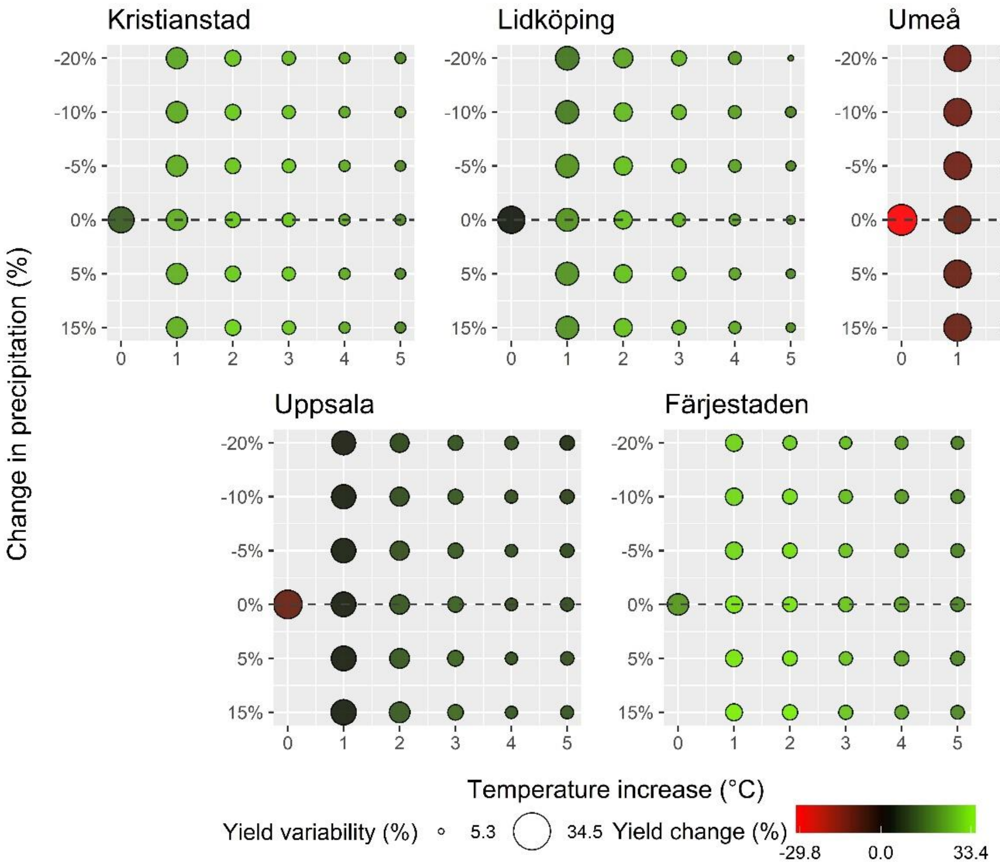

Figure 4. Changes in forage maize aboveground dry matter yield for the 5 locations of the study. Red colors indicate a decrease of yield while green colors indicate an increase of yield. The size of the points indicate the variability of the yield. The dashed line indicates a 0% change in precipitation. The yield reference value (0%) was computed as the mean of the baselines of the 5 locations (11.2 t.ha^{-1}).

The results suggest that maize should benefit from the expected increase of temperature, with higher yields and reduced variability observed for all locations (Figure 4). However, the optimal conditions tend to vary depending on the location. In Kristianstad, the simulations results showed that the aboveground dry matter yield of maize increased along with temperature when compared to baseline results, while the yield variability decreased. The maximum increase of yield was obtained for a temperature increase of 2-3°C. Precipitation variations didn't influence the biomass production. Results were similar in Lidköping, with an overall increase in yield and a decrease in variability, no influence of precipitation and a maximum yield increase corresponding to a 2-3°C increase. In Umeå, the baseline results showed a lower yield when compared to the mean of all baseline simulations. The increase in temperatures resulted in an increase of yield and, for scenarios with an increase of temperature higher than 3°C, a decrease in yield variability. Similarly, precipitation appeared to have no influence on the yield, like previous locations. In Uppsala, the baseline results were noticeably lower than the average of the baseline simulations for all locations, and the increase in temperature resulted in a progressive increase in yields, although the effects were less pronounced than in Umeå. Changes in precipitation did not affect the yield. In Färjestaden, the baseline results showed the highest yield and a slightly reduced variability, and the maximum increase of production was observed for a temperature increase of 1-2°C. Similarly to other locations, the variations in precipitation did not influence the yield.

Oats

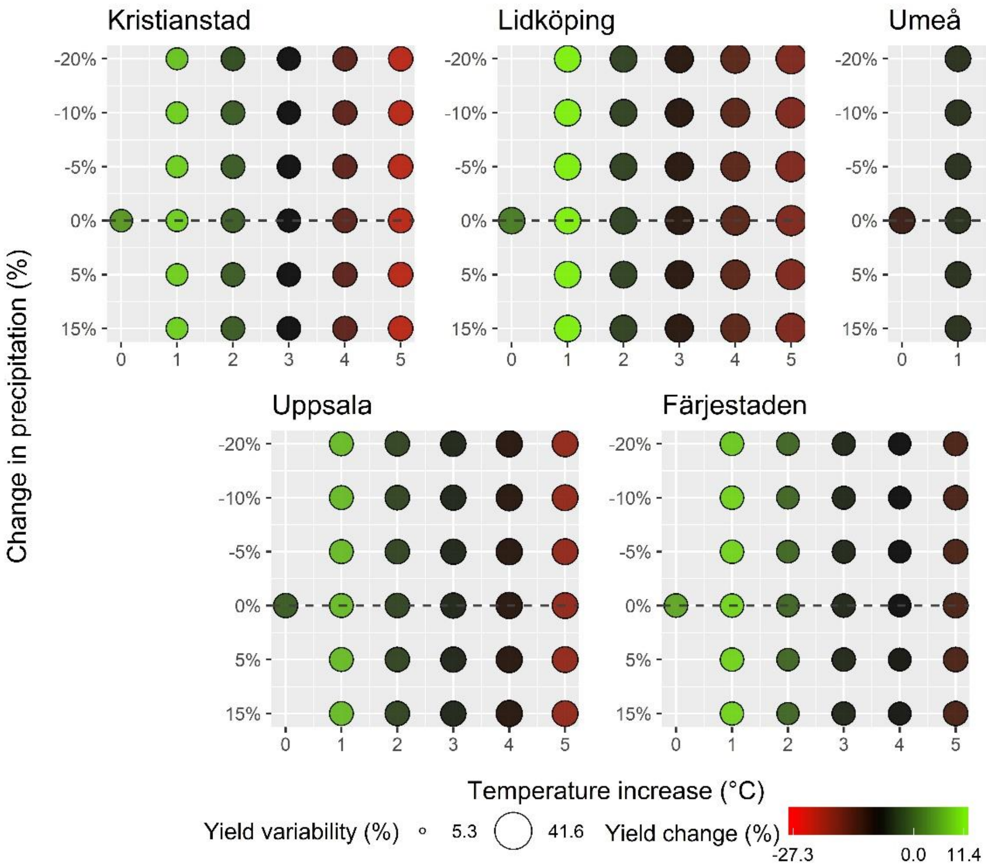

Figure 5. Changes in oats grain yield for the 5 locations of the study. Red colors indicate a decrease of yield while green colors indicate an increase of yield. The size of the points indicate the variability of the yield. The dashed line indicates a 0% change in precipitation. The yield reference value (0%) was computed as the mean of the baselines of the 5 locations (4.3 t.ha^{-1}).

In general, the greatest decreases in yields at higher temperature were observed at Umeå and Lidköping. At all locations, maximum yield was observed with a 1^{o}C increase in temperature (Figure 5). Above a 1^{o}C increase in temperature, the positive effect of CO_2, known as CO_2 fertilization, did not reduce the negative impact of increasing temperature on yield. At Umeå, maximum yield was observed with 1^{o}C increase in temperature with lowest yield variability. Subsequent increase in temperature induced a decreasing yield, with the highest decrease at 5^{o}C. Yield variabilities were similar from 2 to 5^{o}C temperature increases with all precipitation combinations. In Uppsala, the maximum yield was observed at 1°C increase in temperature, with precipitation slightly influencing the performances. Subsequent increases in temperatures induced a decrease in yield, the lowest one being obtained with 5°C of temperatures increases. The variability was similar for all climate scenarios. At Lidköping, similar to Uppsala, yields were higher at 1°C. Greater temperatures increases lead to a decreased yield and increased variability. The lowest yield was observed for a 5°C temperature increase with all combinations of precipitation. At Färjestaden and Kristianstad, similar to other southern locations, yield was maximum at 1°C and then decreased with further increasing temperature for all combinations of precipitation, the lowest yield being obtained with a 5°C increase of temperature. Yield variability was similar for all scenarios.

Wheat

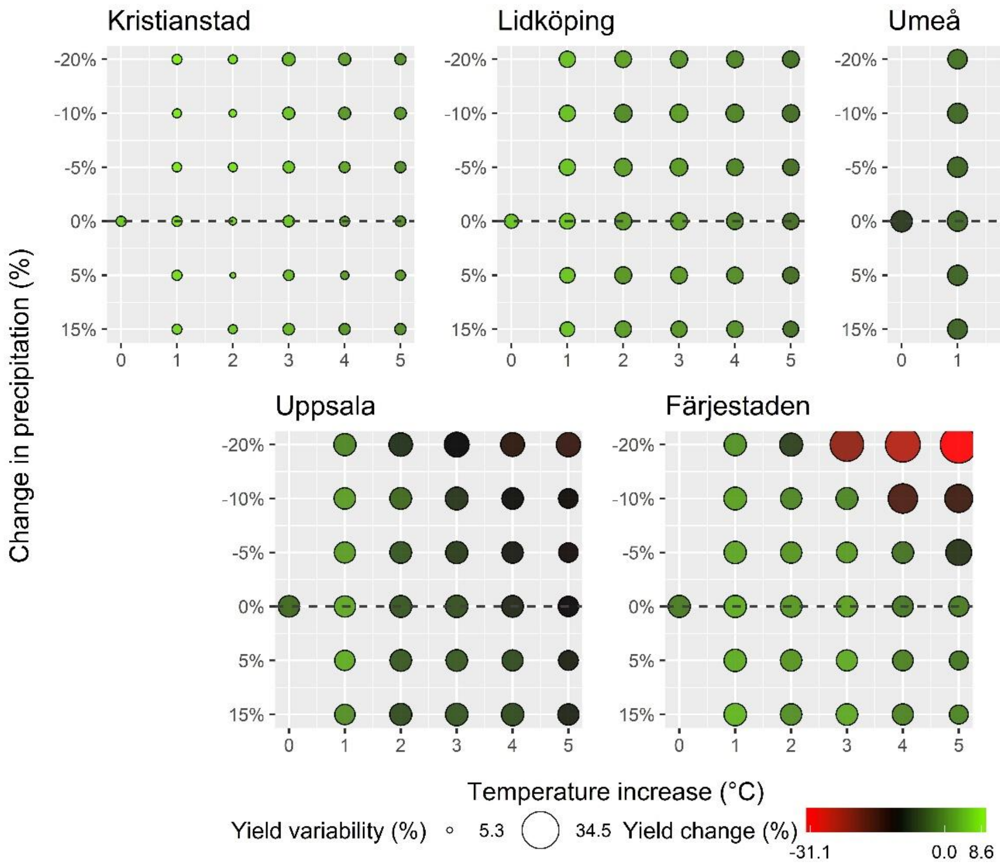

Figure 6. Changes in wheat grain yield for the 5 locations of the study. Red colors indicate a decrease of yield while green colors indicate an increase of yield. The size of the points indicate the variability of the yield. The dashed line indicates a 0% change in precipitation. The yield reference value (0%) was computed as the mean of the baselines of the 5 locations (5.3 t.ha^{-1}).

Wheat yield in Umeå increased with increased temperature. In contrast, wheat yields in Lidköping and Kristianstad decreased with increasing temperature. Wheat yields for Uppsala and Färjestaden decreased with decreased precipitation and increased temperature, accompanied by increasing yield variability at Färjestaden.

3.2. Risks of crop failures

Crop failure as presented here describes the risk of the crop not reaching a certain maturity stage. For the baseline scenarios, for Umeå the risk of failure was high (27% for spring wheat, 23% for barley and 21% for oats) when compared to other locations.

Simulation with increased temperatures showed no negative effects on the risk of failure. In the case of barley, oats and spring wheat, failure risk showed little to no variation depending on the location and climate scenario, and hence are not presented in the report.

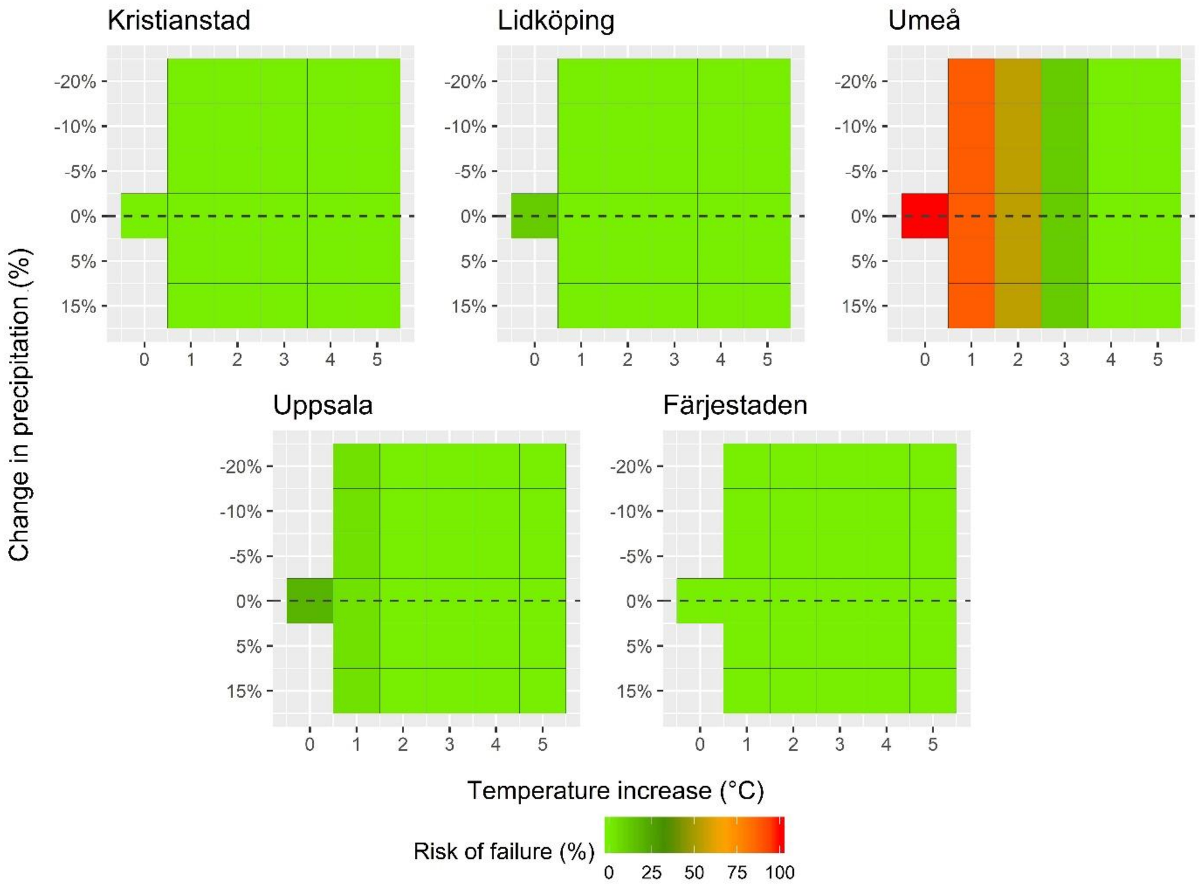

Figure 7. Risk of failure, expressed in %, for forage maize.

Results for maize showed a comparable, yet more pronounced dynamic (Figure 7). The risk of failure is very low for Kristianstad, Lidköping and Färjestaden. In Uppsala, the risk of failure for the baseline simulations is noticeably higher compared to synthetic climate simulations. In Umeå, the risk of failure for the baseline simulations is very high, with 0% of simulations reaching the maturity required for silage maize. The increases in temperatures rapidly led to a reduction of the risk of failure, with virtually no risk for scenarios with temperatures increased by 4 and 5°C.

3.3. Crops productions and failures risks with increased likeliness of drought

In order to simulate potential effects of increased droughts on the production of barley, forage maize, oats and spring wheat, we compared the results of the baseline simulations with those of the scenario #28 (Table 3) simulations, which corresponds to an increase of +5°C and a decrease in precipitation by 20%. Such conditions will increase the likeliness of droughts events during the growing season.

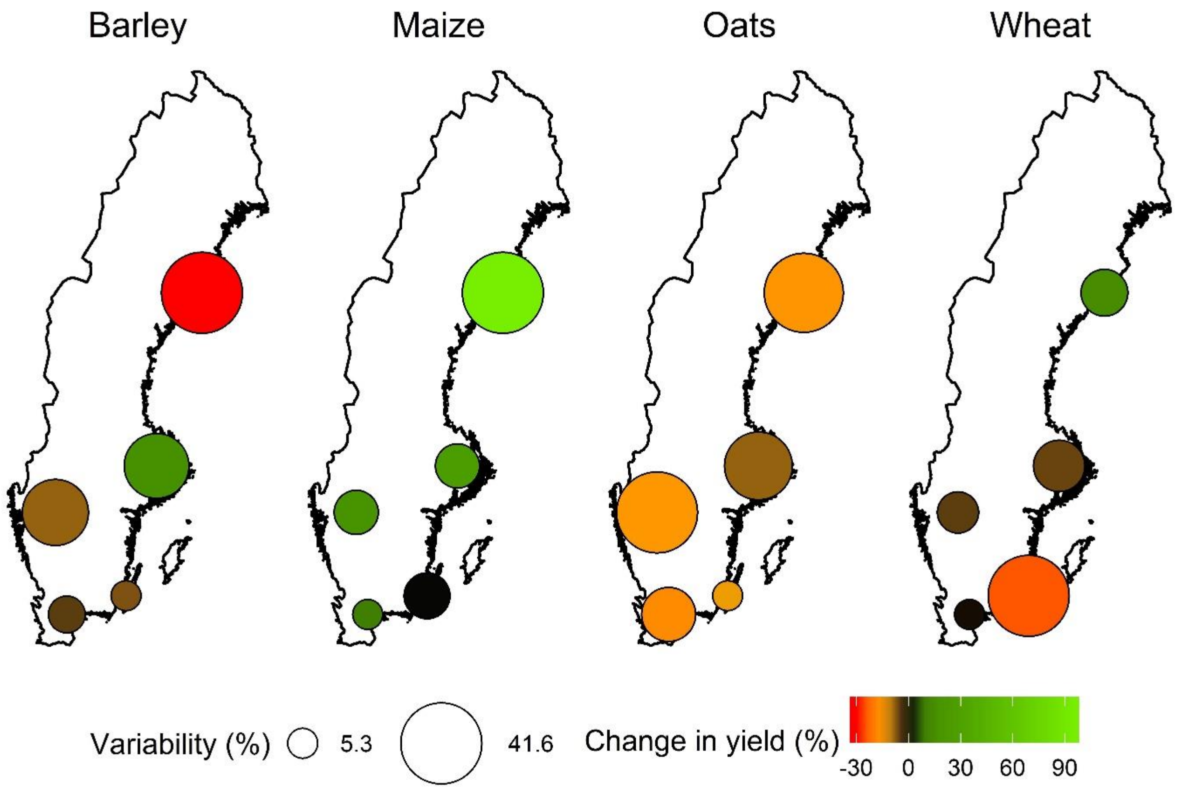

Figure 8. Expected variations of crop production for the five locations and four crops of the study for a scenario with increased risk of drought (increase of +5°C in temperatures and decrease of 20% of precipitation) compared to the baseline results.

Simulation results indicated that crops will perform differently: barley is projected to show a decrease in yield in all locations, with the exception of Uppsala. Maize, on the other hand, is projected to reach a higher yield in most of the locations. Oats showed the greatest decrease in production, with all locations negatively impacted by the effects of climate change. Finally, similar to barley, spring wheat is projected to decrease in yield at all locations except Umeå which had a slight increase in yield.

4. Discussion

Modelling natural processes is a delicate exercise of balancing the simplification of a set of complex phenomena while maintaining a high level of accuracy in the final output. In this study, we had to use simplifications and approximations to define some of the driving parameters of APSIM such as for example the sowing dates depending on the location and crop, or how to define a crop failure. Although the simplifications that we made can be modified, we consider the results obtained as (i) an acceptable first approximation of the potential trend of four important crops cultivated in Sweden in the incoming decades and (ii) an efficient way to point out the knowledge gaps that need to be further assessed to increase our understanding of what the future climate food production could be in Sweden and Nordic countries.

The method used here to define synthetic climate scenarios is also a simplification of a complex task – predicting climate change. The data used in this study account for a change in magnitude of the climate variables (warmer temperatures, more or less precipitation), but do not consider potential changes in the variability of the climate (e.g. distribution of precipitation), thus might not represent the current forecasted climate for the incoming decades. However, it is expected that a factorial combination of increased temperatures and both increased and decreased precipitation would be an interesting tool to assess the respective effects of temperature and precipitation on the development and growth of the crops.

All crops showed an increase of yield concomitant with temperatures increases, although the optimal range of temperatures for increases varies from one crop and locations combination to another. This increase in productivity has been reported in previous studies. Carter et al. (1996)[18] described a yield increase in Finland when assessing potential productivity of, among other crops, barley, grain maize, oats and spring wheat under climate change. Similar results were observed by Peltonen-Sainio et al. (2009)[19]. From the perspective of risk of failure, the results obtained here suggest that there is no negative effects of climate change on the risk of failure. This is consistent with expectations as the increase of temperatures induces a reduction of the days required to reach grain maturity, provided that no or little water stress was computed by the model. This might be linked to the fact that changes in precipitation appear to have limited influence on the productivity of the crops. This could be explained by the fact that increased CO_2 levels can compensate for droughts effects, as reported in previous studies, as for example Manderscheid et al. (2007)[20] or Robredo et al. (2007)[21]. However, this question needs to be further assessed in order to develop a better understanding of the physiological processes that link CO_2 concentrations, water use efficiency and stresses affecting the plant.

Simulated yields for high increase of temperatures and high decrease of precipitation suggest that maize will perform better than other crops in conditions with increased risk of drought. This is consistent with what has been observed in 2018, where losses were less important for forage maize compared to barley, oats and spring wheat[22]. This can be explained by the fact that maize, as a C4 plant, is expected to perform better with warmer temperatures compared to the typical temperatures of Nordic countries. Another reason for that is that the root system of maize can penetrate soil deeper compared to other crops, which would limit the effects of low surface moisture levels.

5. Conclusions

We used the APSIM crop model to simulate the growth of four crops in five locations in Sweden under various climate scenarios. Baseline climate (1980 to 2005) simulations were run and compared with synthetic climate data scenarios, with incremental increases in temperatures and both increases and decreases in precipitation. The results suggested that crops will perform differently depending on locations and climate scenarios: although all crops should benefit from an increase in temperatures, the maximum yield will often be reached with a small (1°C) temperature increases for barley, oats and spring wheat, whereas forage maize can benefit from greater temperatures increases. Changes in temperature did not dramatically affect the risk of failure, with the exception of maize in Umeå, where risk decreased with increasing temperature. Changes in precipitation showed limited influence on both productivity and risk of failure of crops. In the case of a high increase of temperatures and decrease in precipitation, oats was the most negatively affected compared to the baseline simulations, whereas forage maize showed the highest increase in production.

6. Knowledge gaps and perspectives

Methodological knowledge gaps

This study underlines several knowledge gaps related to the use of APSIM that limit the accurateness of the presented results.

Currently, APSIM does not include the effect of temperatures and water stresses on the sterilization of spikelets. Including such an effect would affect the current results, with a potential reduction of the gains in grain yield as simulated here.

One other relation that needs to be assessed by the model is the effects of CO_2 concentrations on the water use efficiency of the crop. Indeed, such a relation is critical to simulate with higher accuracy the trends of crop production for the incoming decades.

Perspectives

The structure of APSIM is complex and requires fine tuning of many parameters which heavily influence the final outputs of the model. This task is particularly hard when simulating crop production for various locations with different farming practices and soils. Different methods, including e.g. Bayesian statistics or satellite remote sensing should be tested, with the expectation of a reduced uncertainty on some of the most critical parameters of APSIM.

In this study, fixed sowing dates were used for each crop and location to simulate the growth of the plants. Using sowing windows with relevant sowing rules should make our results more representative of actual conditions. Similarly, simulations were set up in such a way that the nitrogen stress was kept low. Testing the effect of fertilization rates on the development and growth of crop might provide good farming strategies to mitigate the effects of increased water and temperature stresses.

We also stress that this was an impact study using current management. Future adaptation studies can assess the opportunities for different adaptation options, such as breeding cultivars that take advantage of the extended growing season.

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Additional information and acknowledgments

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All codes and data used in this study are available upon request.

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