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Impact of climate change on Swedish agriculture: Growing season rain deficit and irrigation need

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ABSTRACT

Over 90% of Swedish agriculture is rainfed, and thus future climate change can pose a risk to agricultural production in coming decades. An overall increase in annual precipitation is predicted for northern Europe, but Sweden could still face an increasing need for irrigation, as shown by the drought summer of 2018. Adaptation of Swedish agriculture to include irrigated agriculture should thus be considered. To evaluate the theoretical need for irrigation, calculations were performed for different locations in Sweden, and for different soil-crop pairs at each location. *In-situ* weather data from a projected climate dataset created by the Swedish Meteorological and Hydrological Institute were used to evaluate changes in irrigation need over the period 1981–2050. The results showed an increasing need for irrigation of cereal crops during the early season (May–June), for two main reasons: i) A shift to an earlier start of the cropping period, leading to an earlier need for irrigation; and ii) a higher probability of dry spring weather, substantially increasing the irrigation requirement in dry years. Crops for which the growing season starts later (e.g., potatoes) showed an increasing need for irrigation during July. Crop development stages were predicted to occur earlier, leading to earlier harvesting, reducing the irrigation requirement in August. However, the calculation approach developed for this study may have underestimated the need for irrigation, which could be higher than reported here.

1. Introduction

The occurrence of global climate change and its predicted continuation over the coming century are now largely accepted (Cook et al., 2016). This global climate imbalance will have impacts on atmospheric components, affecting e.g., temperature and precipitation patterns (Kovats et al., 2014; Putnam and Broecker, 2017; Stagge et al., 2015; Vautard et al., 2013). This will have a direct impact on human societies, because changes in temperature and precipitation can cause substantial changes to the terrestrial water cycle (Grusson et al., 2018; Hartmann et al., 2013; Held and Soden, 2006; Jiménez Cisneros et al., 2014). For instance, such changes have been shown to affect evapotranspiration demand (Cook et al., 2014; McCabe and Wolock, 2015; Mishra et al., 2017) and soil water content (Destouni and Verrot, 2014; Verrot and Destouni, 2016). Alterations in hydrological variables can also affect agriculture and food production, posing risks to this strategic economic sector. Adaptation of agricultural practices and mitigation of climate change impacts to secure food production is a major concern for stakeholders and scientists. On a global scale, it has been shown that climate change can disrupt the cropping calendar, destroy harvests, or trigger soil erosion (Savo et al., 2016), placing food production systems under pressure (Tripathi et al., 2016). These potential impacts should be carefully investigated regionally and locally, in order to adapt practices and polices efficiently.

In northern Europe, the drought summer of 2018 provided an example of the vulnerability of agricultural systems (JRC, 2018). For example, Sweden experienced cereal yield reductions of up to 50% and livestock numbers were reduced due to lack of affordable fodder and feed (Statistiska-Meddelanden, 2018). In the Scandinavian region, average precipitation amounts and temperatures are predicted to increase over the coming century (Jacob et al., 2014; Strandberg et al., 2015). Beyond those average variations, the distribution of precipitation throughout the year and the pattern of precipitation within each month could change, with impacts on the balance between rainfall and evapotranspiration, and therefore on water management for agriculture. An early study by the Swedish Meteorological and Hydrological Institute (SMHI) estimated that the increase in precipitation in northern Europe foreseen in global projections might be concentrated mainly in autumn

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and winter, while spring and summer could face decreases in precipitation (Rummukainen et al., 2004). In Sweden, the vast majority of agricultural production is rainfed, and there is a lack of data on irrigation because it has not been a major research focus in the past. Depending on sources and years, only 1.7% (EuroSTAT, 2016) to 3.8% (Windfäll et al., 2010) of Swedish arable land is irrigated. Most of the water used for irrigation is consumed in southern counties of Sweden (Statistics-Sweden, 2015), but future changes in rainfall pattern could have serious implications for food production and agricultural practices. Substantial loss of agricultural production due to drought could be avoided by the use of supplementary irrigation. However, very few studies have investigated the implications of climate change for soil water balance and irrigation practices in Sweden, despite the fact that systemic adaptation of Nordic agriculture appears inevitable (Juhola et al., 2017). In a review on the topic, Wiréhn (2018) located only 35 peer-reviewed papers exploring the impact of climate change on Nordic agriculture, and found that most of those papers focused on crop phenology and life cycle (Eckersten et al., 2012; Kristensen et al., 2011; Olesen, 2005; Ozturk et al., 2017; Pulatov et al., 2015) or on system vulnerability (Juhola et al., 2017; Kvalvik et al., 2011). Very few studies have examined the soil-water relationship or the impact of climate change on agro-hydrological systems. The only published paper on irrigation and water circulation in Swedish agricultural production focused on the previous drought summer of 2013, and noted the benefit that irrigation could bring in drought management in Sweden (Campana et al., 2018). A Swedish government report pointed out the vulnerability of the Swedish agricultural system to dry years in the period 1965–2014, when most years with low yield were associated with above-average dry or wet periods (De Toro et al., 2015).

The few previous studies highlighting the vulnerability of Swedish agriculture to changes in temperature and precipitation did not quantify the future change in terms of irrigation need induced by water deficits. Considering the severity of the 2018 drought, it is crucial to determine whether summer droughts will become more frequent in Sweden and whether the need for irrigation will increase substantially in the coming century. The aim of the present study was thus to assess the future need for irrigation at different agriculture-dominated locations in Sweden, using simple modeling of rain deficit-irrigation need. At each selected location, the rain deficit and the theoretical need for irrigation were calculated for a past and a future period, for several crops, and for several types of soil, in order to assess whether: i) the projected increase in precipitation will compensate for the increase of temperature; and ii) the current rainfed model in Swedish agriculture is resilient to projected climate change.

2. Materials and methods

Seven different locations in Sweden were selected for the study, encompassing different climate regions throughout the country (Fig. 1). Differences in agricultural production in the selected counties are described in detail in Supplementary Materials (Table S1). For each location, two 30-year periods were considered: a recent past period (1989–2018), for which calculations were performed based on observed weather data, and a future period (2021–2050), for which climate projections were used. At each location, the rain deficit and the potential irrigation requirement in the past and future periods were compared.

2.1. Rain deficit and potential irrigation need

In the first step of the analysis, daily potential rain deficit was calculated for each location, using the formula:

$$RD_{day} = R_{day} - PET_{day} \quad (1)$$

where RD_{day} is rain deficit on a particular day, R_{day} is rainfall on that day, and PET_{day} is potential evapotranspiration on that day.

Fig. 1. Location of the seven different locations in Sweden for which rain deficit and potential irrigation requirements in past and future periods were calculated.

Potential evapotranspiration (PET) was calculated using the Hargreaves formula (Hargreaves and Samani, 1985) based on temperature and latitude. The choice of this method was driven by limited availability of climate parameters within the projected dataset, which includes only temperature and precipitation.

Following rain deficit calculation for each day of the growing season, the irrigation need for different crops and different soils was calculated at each location. In this calculation, the soil was considered a homogenous reservoir from which crops could take up water to supply evapotranspiration. For each crop, a development schedule was devised, based on a fixed number of days for each crop development stage and a daily crop factor (K_c). The development schedule of each crop is described in Fig. S1 in Supplementary Materials. The starting date of the cropping period changes between years, based on climate conditions. In the calculations in the present study, the starting date for crop development was constrained by a minimum date and a minimum daily average temperature over 7 days. From the minimum date in each year, the average temperature on each day in the previous seven-day period had to be higher than the defined minimum temperature. If this temperature condition was fulfilled, the crop was assumed to start developing. If at least one of the days had an average temperature lower than the threshold, the starting growing date was considered to be the subsequent day and the temperature threshold verification operation was repeated. When the seven previous days had a temperature higher than the minimum threshold temperature, the crop was assumed to start growing and daily actual evapotranspiration was calculated. The starting date for crop growth was also recorded and saved for every year, in order to monitor possible changes induced by the future climate. From the starting date of crop development, daily evapotranspiration (ET) volume was calculated based on the Hargreaves equation and a daily crop factor (K_c):

$$ET_{day} = PET_{day} \times K_c \quad (2)$$

Soil water content (SWC) for the day was then calculated as:

$$SWC_{day} = SWC_{day-1} - ET_{day} + R_{day} \tag{3}$$

If the soil water content of the day reached the available water capacity (AWC), the remaining rainfall on the day was considered to be lost through runoff and was not taken into consideration. The point at which the crop was under hydric stress, and thus required irrigation, was determined by a threshold, expressed as fraction (α) of the AWC at which the crop was considered unable to take up water from the soil at a rate sufficient to support optimum evapotranspiration. If the soil water content fell below this threshold, irrigation was assumed to be performed during the day:

If

$$SWC_{day} < (AWC \times \alpha) \tag{4}$$

Then

$$SWC\_adj_{day} = SWC_{day} + Irrigation_{day} \tag{5}$$

The volume of irrigation applied to adjust (adj) soil water content was taken to be the volume necessary to increase the soil water content up to the soil water threshold level:

$$Irrigation_{day} = (AWC \times \alpha) - SWC_{day} \tag{6}$$

Irrigation was assumed to be performed when needed throughout the cropping season, up to a plant development stage at which irrigation was stopped regardless of hydrological conditions (see Section 2.2 and Table 1).

The equations described above were implemented automatically, using a specially designed MatLab® code. The overall procedure is schematized in Fig. 2. The different parameters affecting the calculation (minimum date, minimum temperature, AWC, and α factor) are described in Section 2.2. The volume of water used for irrigation was recorded and was taken as the theoretical volume of irrigation needed to maintain the soil in perfect hydric conditions for crop development.

2.2. Data and parameters

2.2.1. Crops and soils

The calculation procedure described above was performed for four different crops: winter cereal, spring cereal, grass ley, and potatoes. As shown in Table S2 in Supplementary Materials, the four types of crops selected for this study are the main crops cultivated in the different locations. Each crop has a particular development schedule and associated daily crop factor (K_c). In each year, the starting development date based on temperature was determined using a minimum temperature for crop development based on published data (Allen et al., 1998; Peña, 2002; Tribouillois et al., 2016), or taken from the FAO database (http://www.fao.org/land-water/databases-and-software/crop-information/en/).
The daily crop factor K_c associated with each crop was calculated from the equation proposed by Allen et al. (1998). The length of development stages for each crop were based on Allen et al. (1998) and the FAO database. All crop parameters were adapted for Swedish conditions, through author knowledge and through careful examination of the germination dates and harvesting dates resulting from the calculation method (Section 2.1) for the past 30-year period. In the development schedule, a specific day was set at which no more irrigation was performed because the crop had reached maturity and needed to dry before harvesting. Crop development parameters can be found in Table 1 and more details of each crop development period and associated K_c value are provided in Fig. S1 in Supplementary Materials.

Table 1
Values of model parameters used for the four selected crops studied.

	Minimum date for development start	Minimum average temperature in the preceding 7-day period to start development	Maturation day, after which no irrigation is applied regardless of hydrological conditions
Winter cereal	1 March	5 °C	106
Spring cereal	1 April	5 °C	85
Grass ley	1 April	5 °C	105
Potatoes	8 May	9 °C	95

Four soil types, categorized in the official Swedish agricultural soil classification based on clay content (Eriksson, 1999), were considered for the four selected crops. In soil type selection, the crops were associated with soils on which they are commonly cultivated. The soil types were: medium clay soil (MCS; *mellanlera* in Swedish classification), light clay soil (LCS; *lättlera* in the Swedish classification), clayey sandy soil (CSS; *lerig sand* in the Swedish classification), and slightly clayey sandy soil (SCSS; *svagt lerig sand* in the Swedish classification). Each crop was associated with two different soils, as shown in Table 2.

Hydrological parameters associated with each soil (Table 3) were derived from several soil characterizations performed at the Swedish University of Agricultural Sciences (SLU) over recent decades. The AWC of each soil was calculated assuming the maximum root depth of the crop in that soil type. The soil/crop combinations assessed in this study can been seen as a theoretical and simplified representation of agricultural systems commonly found in southern Sweden.

2.2.2. Climate data

To perform the calculation for the past period (1989–2018), a dataset from in situ SMHI stations was obtained for each location. The stations considered for each of the seven locations included in the analysis are shown in Table S2 in Supplementary Materials.

Another set of data from SMHI were used in calculations for the future period (2021–2050) for two different scenarios: Representative Concentration Pathway (RCP) 4.5 and RCP 8.5. This dataset is based on different global circulation models (GCM) from the Euro-CORDEX project (Jacob et al., 2014). The SMHI regional climate model (RCA4) was used to downscale the different GCM for northern Europe, to produce a dataset comprising five climate models for each scenario. A bias correction step has been performed by SMHI. This dataset is projected on a 5 km grid and corrected against MESAN reanalysis (Häggmark et al., 2000), using the distribution-based scaling (DBS) method (Yang et al., 2010). For each location, the closest point in the grid to the SMHI station supplying the past weather dataset was selected. Table 4 lists the models used.

2.3. Analysis and Kolmogorov–Smirnov (KS) statistical test

An overall assessment of the variation in the projected climate parameters (precipitation and temperature) was first performed, in order to evaluate the intrinsic distribution of the model ensemble. The change in three hydro-agronomical variables (rain deficit, irrigation need, yearly starting date of crop development) between the past period (1989–2018) and the future period (2021–2050) was then calculated. For irrigation need, the change was investigated by comparing the overall 30-year periods, but also by comparing highest irrigation need (higher quartile) in each distribution. For each of those variables, Kolmogorov–Smirnov statistical hypothesis testing was performed, using the inbuilt Matlab® function *KStest2*, to assess the significance of the change between past and future periods. The Kolmogorov–Smirnov test is a non-parametric test used to challenge the equality and continuity of two distributions (Smirnov, 1939). Being non-parametric, it can be used with freely distributed samples of reduced size. The test involves comparing the distance between the cumulative distribution functions (CDF) of two distributions, and enables comparison of the overall distributions instead of a central value. The Kolmogorov–Smirnov test was used here for the rain deficit balance and for the volume of irrigation applied for each crop/soil combination tested. A trend was considered

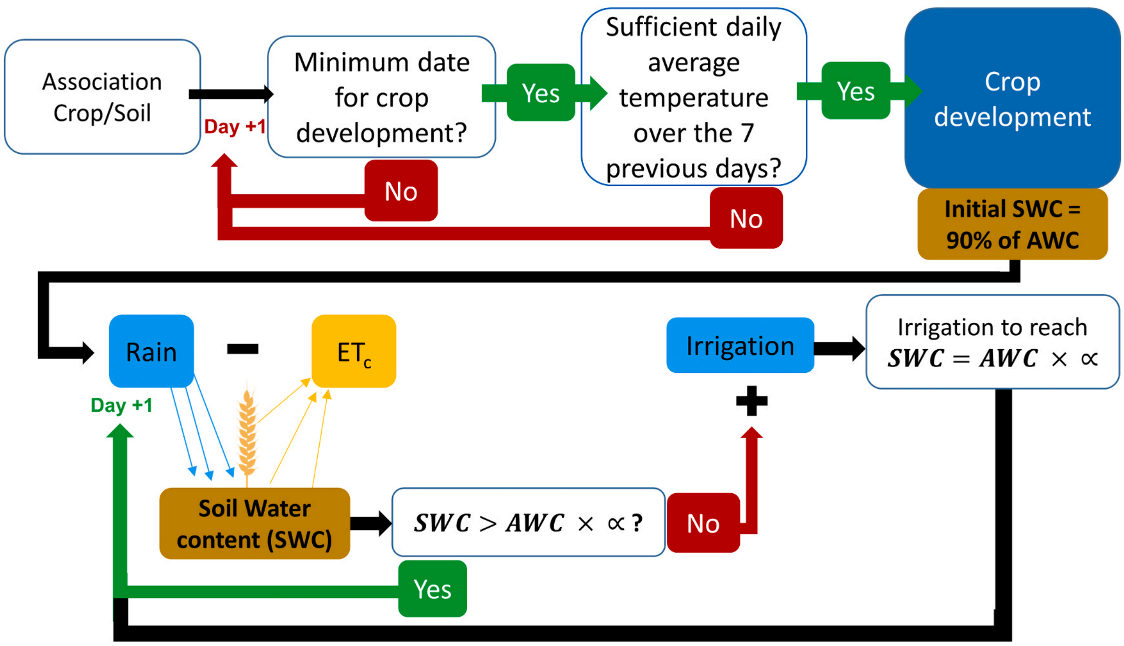

Fig. 2. Schematic illustration of calculation of irrigation need. For more information on date, temperature, and factor α, see Section 2.2. (AWC = available water capacity, ET_c = crop evapotranspiration).

Table 2
Combinations of crops and soils tested.

Crop Soil	Winter Cereal	Spring Cereal	Grass ley	Potatoes
Medium clay soil	X	X	X	
Light clay soil	X	X	X	
Clayey sandy soil				X
Slightly clayey sandy soil				X

Table 3
Clay content and available water parameters for the four soil types studied.

	Clay content (%)	Available water capacity (mm) – (AWC)	AWC consumed before irrigation is performed – (α)
Medium clay soil	25–40	185	0.5
Light clay soil	15–25	120	0.5
Clayey sandy soil	5–15	53	0.5
Slightly clayey sandy soil	2–5	92	0.8

Table 4
Climate models used for calculation of rain deficit in the future period (2021–2050) at each location.

Scenario abbrev.	Global circulation model, GCM	Regional climate model, RCM	Correction
RCP45-M1	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP45-M2	ICHEC-EC-EARTH	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP45-M3	IPSL-IPSL-CM5A-MR	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP45-M4	MOHC-HadGEM2-ES	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP45-M5	MPI-M-MPI-ESM-LR	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP85-M1	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP85-M2	ICHEC-EC-EARTH	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP85-M3	IPSL-IPSL-CM5A-MR	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP85-M4	MOHC-HadGEM2-ES	SMHI-RCA4	DBS43-MESAN-1989–2010
RCP85-M5	MPI-M-MPI-ESM-LR	SMHI-RCA4	DBS43-MESAN-1989–2010

significant at $p < 0.05$.

3. Results

3.1. Climate ensemble

In order to identify triggers of change in the hydro-agrological variable analyzed, but also to evaluate the dispersion of the climate ensemble, the future changes projected for the temperature and precipitation variables were first mapped for each location (Fig. 3).

The maximum and minimum daily temperature were considered separately and both were found to increase overall between the past and future periods. The only noteworthy exception was for model 1 (CNRM-CERFACS-CNRM-CM5/ SMHI-RCA4), which gave a decrease in maximum temperature for both scenarios and for all locations from May to September. For the minimum temperature, model 1 did not give a negative trend, but produced a visibly lower positive trend than most other models in the ensemble. The average of the ensemble was positive for all locations, all months, and both scenarios (RCP 4.5, RCP 8.5). Regarding the temporal re-partition of temperature change, June and July showed a slightly lower increasing trend in maximum temperature than other months (with presence of several null or negative values for both scenarios). It is interesting to note that the trend was similar for all locations except Östergötland, which showed a higher increasing trend in minimum temperature than the other locations. Regarding precipitation, the ensemble seemed to produce more homogenous results than for temperature, with no model giving a dissimilar trend from the rest of the ensemble. However, a temporal pattern emerged whereby if a global increase of precipitation was given by the ensemble, this increase appear

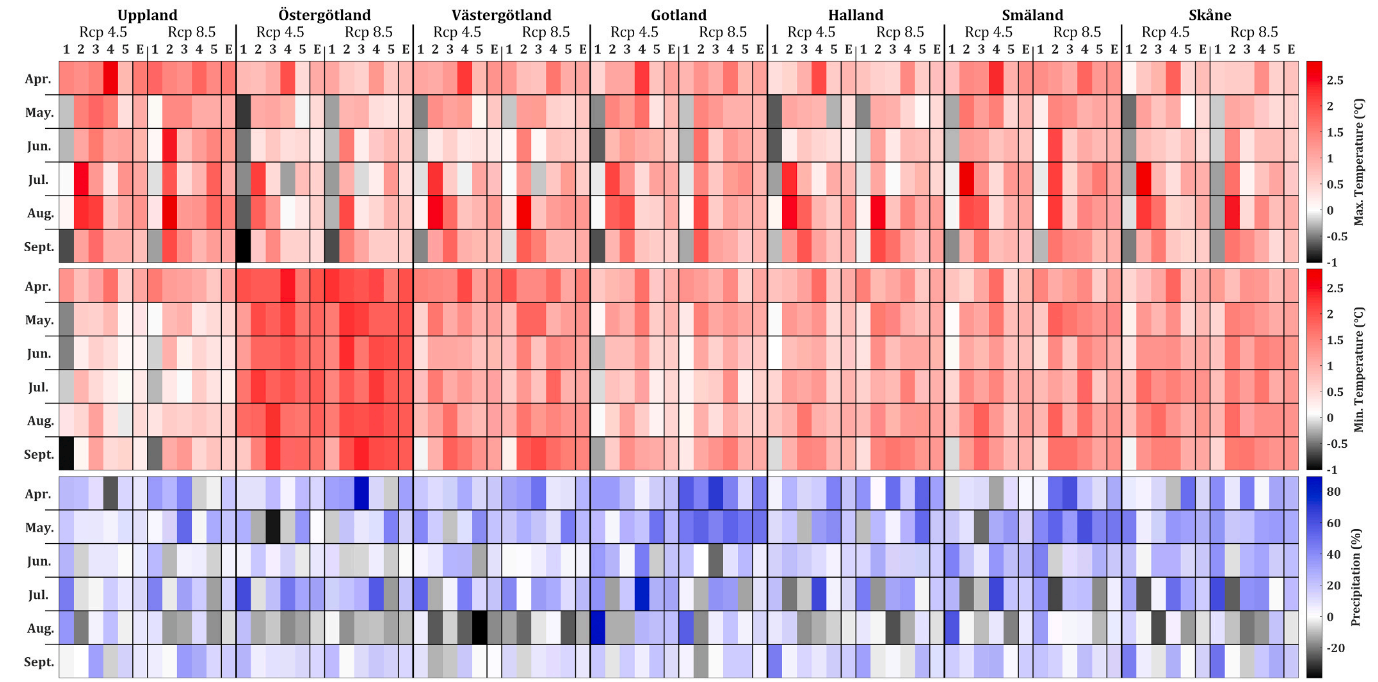

Fig. 3. Change in climate parameters (precipitation, maximum and minimum temperature) between the past period (1989–2018) and the future period (2021–2050) projected by each model of the ensemble (1–5 as listed in Table 4) and by the average of the ensemble (columns E) for each location and scenario. (Variation scale shown on the right-hand axis).

more pronounced during the early months of the cropping season (April–May), while August was clearly impacted by a decrease in precipitation and September by a very limited increasing trend in precipitation. In some few cases, the models gave a very high increase of precipitation (> 60%), but the ensemble average always showed a variation of ± 15%.

3.2. Rain deficit

The change in rain deficit between the past and future periods, calculated from the difference in daily rainfall and potential evapotranspiration (Eq. (1)) is presented in Fig. 4, where a positive value reflects an increase in rain compared with ETP (i.e. a decrease in the rain deficit). The difference observed between rainfall and evapotranspirative demand indicated that the rain deficit tend to decrease in the future period compared with the past period. However, a temporal pattern was detected (Fig. 4), where August seemed to be the only month in the cropping season with negative values, indicating an increasing rain deficit. This increase can be directly related to the decrease in precipitation projected by the ensemble for August, while the temperature was projected to increase, and thereby the potential evapotranspiration (see Fig. 3). Some models also gave an increasing rain deficit during July, but to a more limited extent than in August, and positive variations appeared to be more significant than negative variations. When comparing the different locations, spatial homogeneity was observed for all sites except Uppland, for which a markedly higher

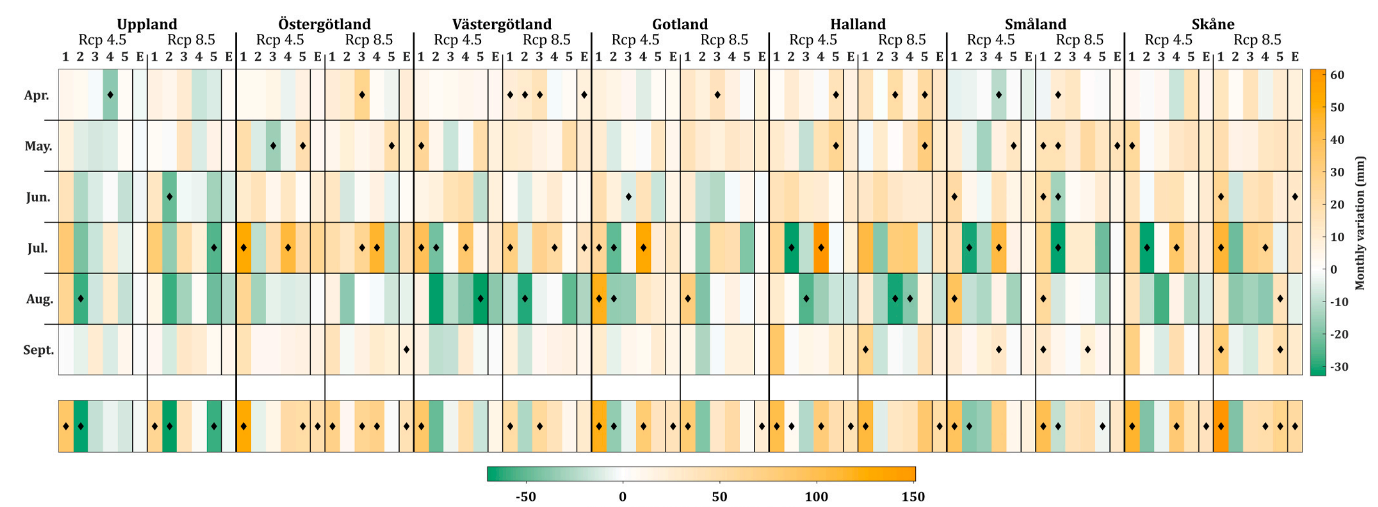

Fig. 4. Variation in rain deficit (Rainfall - Potential evapotranspiration) between the past period (1989–2018) and the future period (2021–2050) projected by each model of the ensemble (1–5 as listed in Table 4) and by the average of the ensemble (columns E) for each location and scenario. Black diamonds indicate a significant trend according to the Kolmogorov–Smirnov test ($p < 0.05$).

number of climate models gave an increase in the rain deficit. Independently of the location, the month or the scenario, the ensemble average (columns E in Fig. 4) showed very little variation.

As seen in the lower part of Fig. 4, the clustered distribution of the rain deficit over the entire cropping season showed little more significant variation than the monthly comparisons above. This is remarkable when considering the ensemble averages, which showed a significant decreasing trend in rain deficit for four locations: Östergötland, Gotland, Halland, and Skåne.

3.3. Irrigation needs

The changes in irrigation need between the past and future periods, calculated using the procedure shown in Fig. 2, reflected a double dichotomy: spatial and temporal (Fig. 5). From a spatial point of view, some locations (Västergötland, Halland, Skåne) seemed to be characterized by a decrease in irrigation need, with a dominance of green color in Fig. 5. This was consistent with the significant decreasing trend in rain deficit over the cropping season observed at these locations (Section 3.2). On the other hand, sites such as Uppland, Gotland, and Småland showed a more balanced pattern between increased and decreased irrigation need. At all locations, the pattern seemed to be rather similar for the same crop grown on different soils.

A temporal pattern was apparent, with an increase in irrigation need during the early cropping season (May–June) and a decreasing trend in July and, to a lesser extent, in August. This pattern was very clear for both cereal types studied (winter, spring), and to a lesser extent for grass ley. For potatoes, more models indicated a later impact in the season, with increasing irrigation need during July and August. Beyond these regional and temporal patterns, very few variations were noted for the different climate models.

In order to identify the driest years, in which irrigation is most necessary for the production, the analysis of changes between the two periods was repeated using the higher quartile of each distribution, which represented the years in which irrigation demand was highest (Fig. 6). The findings of this second analysis reinforced those of the previous analysis and emphasized the temporal dichotomy, with the future need for irrigation increasing in the first part of the cropping season. On analyzing the highest quartile, this trend emerged also for locations where it was not evident when considering the entire distribution, such as Östergötland, Västergötland, Halland, and Skåne. However, at those locations the early season increase was observed mainly for cereals (winter and spring), and not as much for grass ley or potato crops. The change was sharper for the locations where this temporal dichotomy was already visible for the entire distribution. The strong significance of the changes detected using the highest quartile of the distribution indicate the possibility of more intense extremes and their impact in increasing the overall need for irrigation during the first part of the season.

3.4. Date of crop development

The average date at which crop development started was also investigated, to see whether a future temperature increase induced a change in the starting date of crop development. The results clearly showed an earlier starting date of crop development during 2021–2050 compared with 1989–2018 (Fig. 7). This was particularly apparent for winter cereal, with a shift forward of between 10 and 20 days in the growing season, followed by spring cereal and grass ley, for which a forward shift of 5–10 days was seen. The potato season seemed to be much less impacted, probably because of the later starting date for this crop (8 May), by which time the minimum temperature was often already reached, even in the past period 1989–2018.

4. Discussion

A simple modeling scheme was applied to investigate how future climate change may affect the water deficit and irrigation need for different crops, on different soils, at different locations in Sweden. The climate variations projected by the model ensemble used in this study were consistent with those in other analyses for Sweden. For instance, Eklund et al. (2015) used nine climate models and found an average

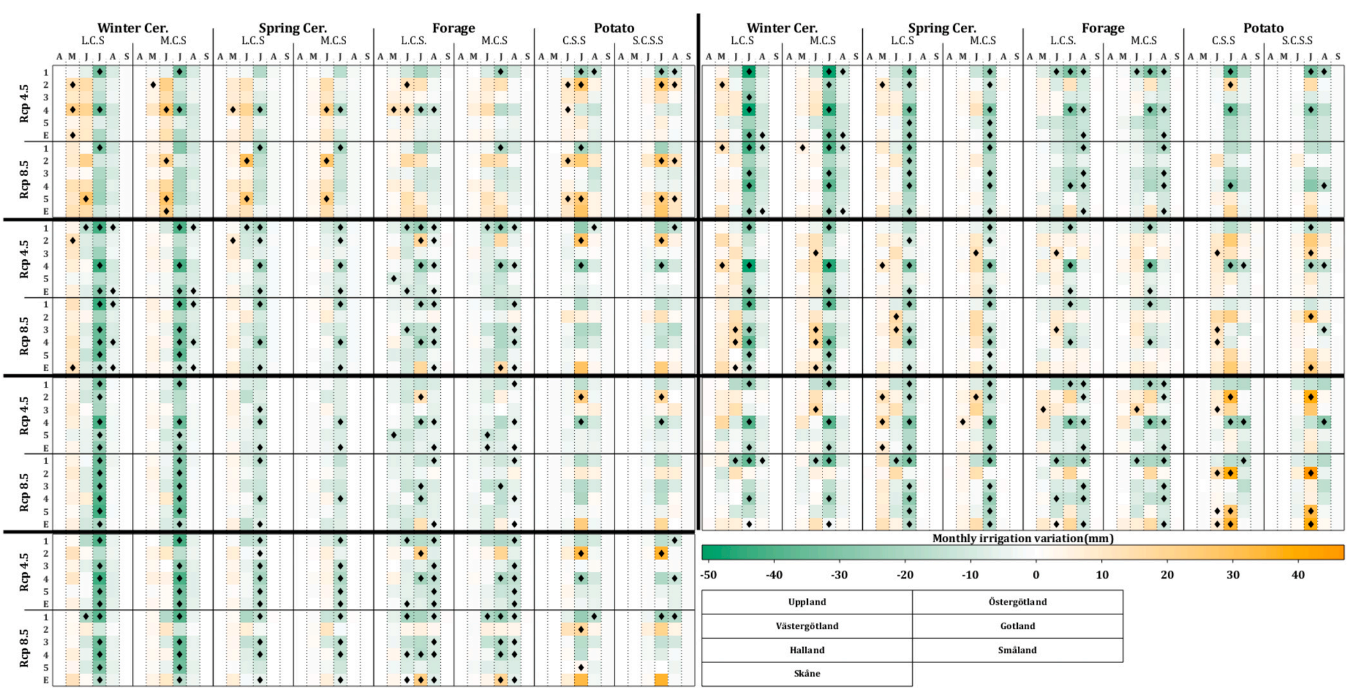

Fig. 5. Change in irrigation volume between the past period (1989–2018) and the future period (2021–2050) projected by each model of the ensemble (1–5 as listed in Table 5) and by the average of the ensemble (E) for each site, crop, soil, and scenario. Black diamonds indicate a significant trend according to the Kolmogorov–Smirnov test ($p < 0.05$).

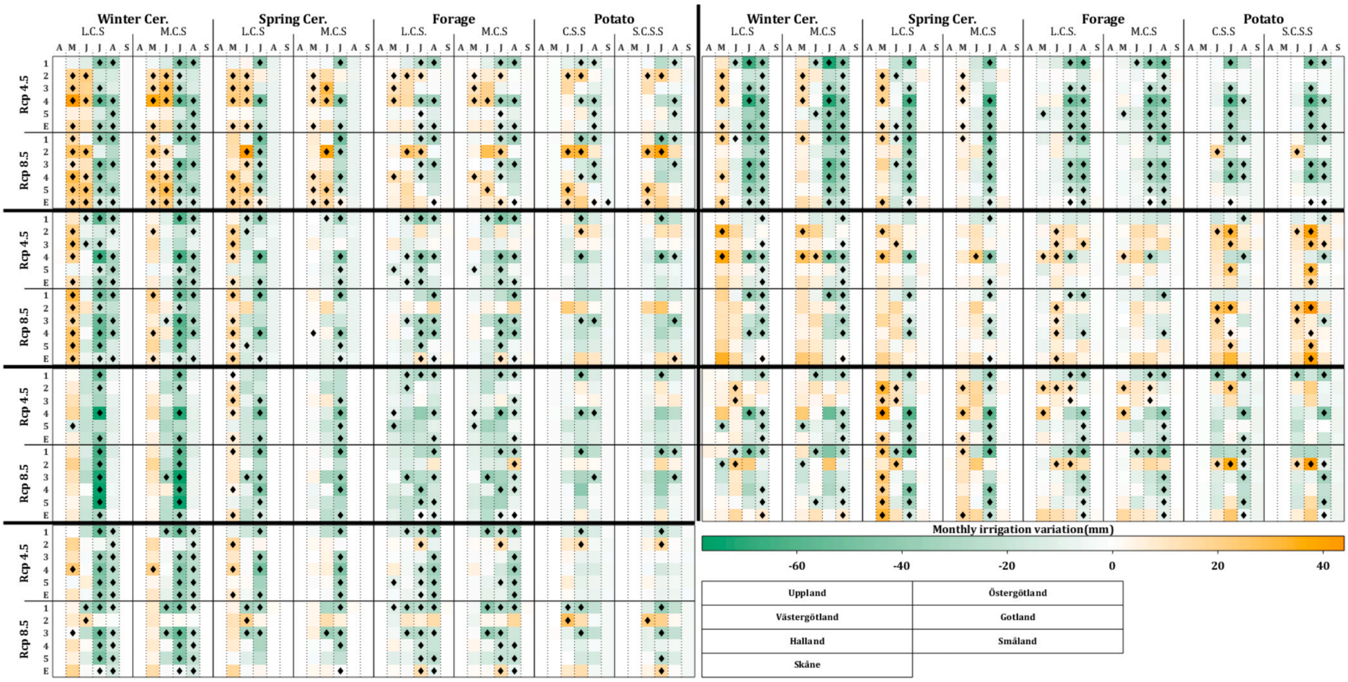

Fig. 6. Change in irrigation volume for the years in the highest quartile of the distribution between the past period (1989–2018) and the future period (2021–2050) projected by each model of the ensemble (1–5 as listed in Table 4) and by the average of the ensemble (E) for each location, crop, soil, and scenario. Black diamonds indicate a significant trend according to the Kolmogorov–Smirnov test ($p < 0.05$).

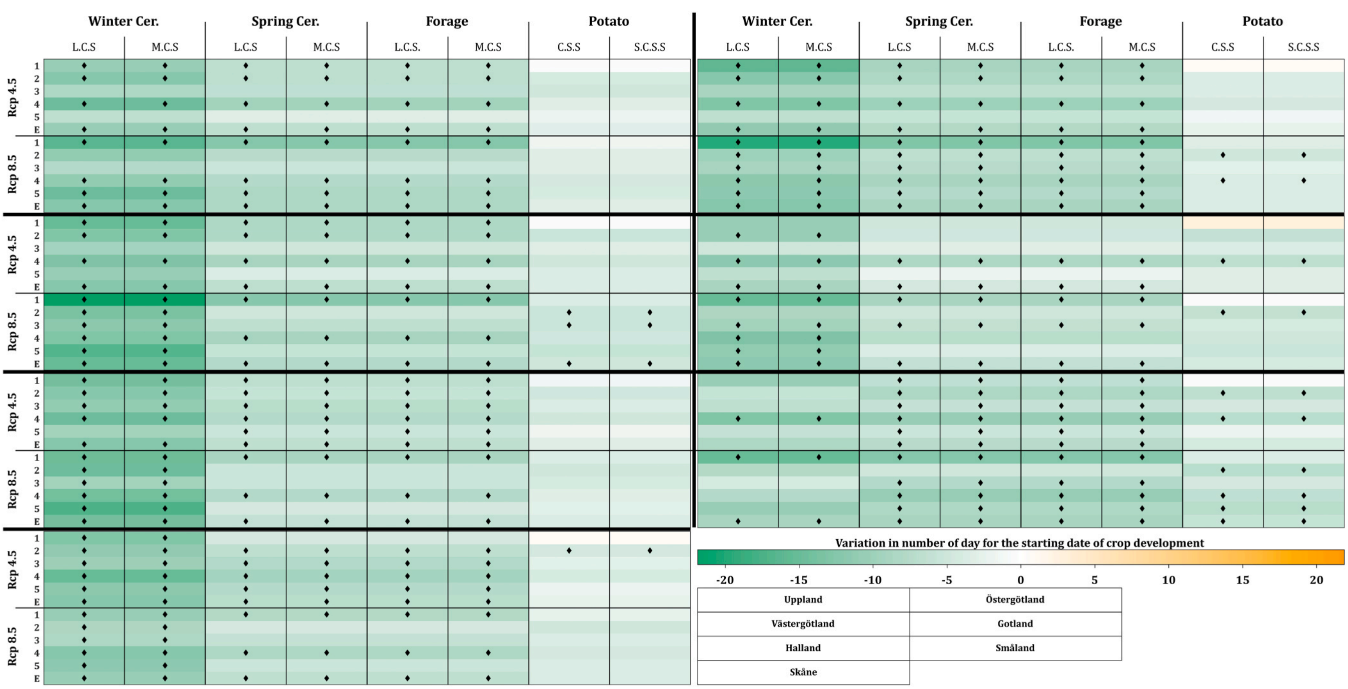

Fig. 7. Change in starting date for crop development projected by each model of the ensemble (1–5 as listed in Table 4) and by the average of the ensemble (E) for each location, crop, soil and scenario. Black diamonds indicate a significant trend according to the Kolmogorov–Smirnov test ($p < 0.05$).

change in summer rainfall of 8–28%, with the highest increase being around 50%, and a change in summer temperature of between 0 and 3 °C, with an ensemble average of 1–2 °C depending on the scenario and period considered. Similar ranges have been reported by Olsson et al. (2016) for southern Sweden (i.e., the Skåne site in this study), e.g., an ensemble change in yearly precipitation of 6.5–13.5%, depending on period, with minimum and maximum values ranging from − 35.9% to 25.2%. The good consistency between previous studies and the present study is understandable, considering that all were based on the same GCMs from the EURO-CORDEX program. They differed mainly in regionalization, downscaling processes, and the scale of the analysis. The model ensemble used in this study gave projections in the same range as other similar ensembles, despite the use of only one regional climate model (RCM). The calculation procedure developed in this study was inspired by the simple FAO-56 (Allen et al., 1998) calculation method for evapotranspiration. That simple method has limitations, but is still widely used to compute evapotranspiration and the input-output balance of soil water content (Pereira et al., 2015), using algorithms very similar to that developed in this study (e.g., Battude et al. (2017)). The approach developed here allowed us to build a tool which can be easily modified, transferred to other locations, and used with different crops and soils, unlike other more complex irrigation modeling tools, which are far more demanding in terms of input data and implementation time (Valipour et al., 2015). However, as in any attempt of hydrological modeling, simplification of processes had to be performed. The most important simplifications in the present study were the absence of water loss by direct evaporation from interception and surface runoff before infiltration. These simplifications meant that soil recharge was considered "perfect", i.e. all water applied to the fields (precipitation and irrigation) was assumed to recharge the soil reservoir. In reality, a part of this water does not reach the ground for infiltration. This simplification may have led to underestimation of the irrigation volume needed. Other important simplifications in the calculations concerned the fixed volume of soil considered and the available water capacity accessible to the plant. The accessible soil volume was set considering the maximum rooting depth, but in reality access increases as the roots grow. During the early season, even if some water is available deeper in the soil layers, the undeveloped roots would normally not be able to access this water, which would lead to a need for more frequent irrigation and a higher volume of water applied. Again, this approximation may have led to underestimation of the irrigation volume needed. The formulae and calculations presented in this study aimed more to investigate the relative variation in water deficit and the theoretical volume of irrigation needed to maintain perfect hydric conditions in the field. It is important to bear in mind that the bias regarding irrigation operations induced by the simplifications was the same over the past period and the future period, allowing comparison of the changes between the two periods.

Notwithstanding those limitations, some interesting results were obtained in the study. During the first part of the cropping season (May–June), rainfall amount appeared to increase but the rain deficit was found to be relatively stable. Despite this stability, a slight increase in irrigation need was found for this period. The crops with the greatest increase in irrigation need (cereals) were those projected to undergo the most important shift in the start date of plant development. The increase in irrigation need would then derive partly from extension of the irrigation period towards the beginning of the season. In May–June, the increase in future irrigation need appeared greater when considering only the higher part of the distribution, indicating a strong influence of dry years on the general increase in irrigation need. During July and August, the irrigation need appeared to decrease, but for different reasons. In July, future rainfall increased slightly, resulting in a decrease in the rain deficit despite the rise in temperature, and thus to a decrease in the irrigation need. During August, on the other hand, the future rainfall decreased and the rain deficit increased, but the irrigation need also decreased. As for the beginning of the cropping season, this finding is likely to be explained by the temporal shift forward of the cropping period. Through this, crop development tended to start earlier and maturity was reached earlier in the season, leading to a decrease in irrigation need in August (irrigation stopped a few days before maturity). This analysis is consistent with the few studies available over northern Europe, indicating an extension of the growing period. In a systematic review, Wiréhn (2018) identified this extension of the cropping period as one of the major challenges for Nordic agriculture in terms of crop selection and scheduling. The present study showed that this temporal shift will also have a substantial impact on irrigation need, with a shift toward the beginning of the season. However, in the calculations presented here, the length of the crop development cycle was fixed, whereas the vegetative period has also be shown to be shortened by climate change (Kristensen et al., 2011; Rötter et al., 2013). A balance needs to be found between the accelerated development and water needs of crops, to avoid loss of production due to water stress. Irrigation during the season could actually shift the harvest date and intensify the decreased irrigation need at the end of the season. In the absence of irrigation, there is a risk of loss of production due to water stress during the latter part of the season. For instance, during the dry summer of 2018 in Sweden, the growing season for experimental fields of rainfed wheat was shortened by 3–4 weeks due to water stress, but accompanied by lower yields. The increasing probability of dry spring weather, as also highlighted by other studies such as Rötter et al. (2012), Trnka et al. (2014), Wiréhn (2018), was shown here to be the second most influential factor for increased irrigation need during the beginning of the season. Considering the limitations with the calculations detailed above, this early-season increase could potentially be more important than shown in this study. In particular, the assumption that all water inputs infiltrated until maximum AWC was reached reduced the impact of increasing probability of high-intensity rainfall events (Chen et al., 2015; De Toro et al., 2015), which would create more runoff and reduce infiltration.

A spatial gradient was also seen in this study, with eastern Sweden (Uppland, Östergötland, Småland) and, to a lesser extent, the inland site of Västergötland seeming to be more impacted than the south-western sites of Skåne and Halland. This spatial gradient is somewhat consistent with the data from SMHI on projected future changes in temperature and precipitation, where the north of Sweden will be more impacted than the south, and the east than the west (Eklund et al., 2015). In addition, it is important to point out that for the northern regions, the need for irrigation to date has been very low, so a small increase upon that level gave a statistically significant variation.

In Sweden, individual farmers or groups of farmers do not receive any support for investments related to irrigation and must bear all costs. For this reason, the level of irrigation and willingness to invest in irrigation are relatively low. The typical irrigation system in Sweden consists of medium-high-pressure sprinklers with 300–600 m laterals. Yearly cost (investment plus running costs) for this type of system ranges from 300 to 650 Euros per ha. Irrigation water is withdrawn from groundwater, natural lakes, or streams in most cases. However, uptake is restricted by law, a license is needed, and the potential cost of obtaining this license may be 10,000–20,000 Euros. Because of these restrictions, farmers tend to invest in on-farm ponds, adding a cost for irrigation water of 2–3 Euros per m^3. Cost-benefit analysis based on the details in this study is relatively complicated, as yield differences were not calculated. A calculation was performed of the water needs for 'optimum yield', but not loss of yield in the absence of irrigation. More specific analyses on yield differences in rain-fed compared with irrigated agriculture should be performed. The results in the present study showed that the overall need for irrigation was highest in the beginning of the season and that irrigation seemed to influence yield most in the driest years. However, the number and intensity of summer drought episodes in Sweden have been increasing in the past decade, and this is expected to continue over the next century. Unless part of this problem can somehow be avoided by a shift in sowing date, there is a strong probability of yield losses. Sweden is currently less than 50% self-sufficient in crop production and a discussion on food strategies is ongoing. Irrigation could reduce Sweden's dependence on the international market for crop supplies during particularly dry years.

5. Conclusions

The results presented in this paper show that the future irrigation need in Sweden will increase during the beginning of the season (May–June), for two main reasons: i) A shift in the cropping period to earlier dates, leading to an earlier need for irrigation; and ii) higher probability of dry spring weather, substantially increasing the irrigation need during the driest years. These findings apply particularly for cereals and, to a lesser extent, for grass ley. Potatoes, which start to develop later in the season, showed a future increasing need for water during July. A shift in yearly crop development dates was projected, leading to earlier harvesting date and decreasing the future irrigation need during August. This decrease could be accentuated by the shorter future vegetative period predicted in the literature, which was not included in the calculations in this study. However, the infiltration-oriented calculation procedure developed for this study may have underestimated the need for irrigation, by considering all rainfall as effective water input to soil and by letting crops access the full water content of the soil from the start of their development. Modification of the approach, e.g., by excluding a percentage of water input to encompass interception and by simulating root growth over time, could improve the accuracy of the analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2021.106858.

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