

Modeling water demand for crop irrigation in Sweden under climate change

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ABSTRACT

Study region: The study encompasses Sweden (450 000 km²) located on the Scandinavian Peninsula in northern Europe.

Study focus: We quantified the future crop-water demand and water-irrigation needs of 30,000 km² arable land across Sweden to prepare for climate adaptation. We applied a spatially distributed catchment-scale (40,000 sub-basins) hydrological model with an irrigation routine according to FAO guidelines. The model was forced with an extensive ensemble of bias adjusted regional climate-model data to explore climate impact.

New hydrological insights for the region: Compared to the rest of the world, Scandinavia is a region with sparse irrigation and lack of data on crop-water demand, despite the rising concerns among practitioners. For the first time, we quantified the needed increase in irrigation water to preserve current crop cultivation under climate change. End-of-century projections indicate average annual irrigation-water demand of 905 and 1239 million m³ under the mid- and high-emission scenarios, corresponding to 38% and 52% of Sweden's current freshwater use which is a significant increase from 3% today. The driest years were not found significantly drier but rather more frequent, and at worst, an average year might become as dry as the driest year in 1981–2010. Hence, because of global warming, Sweden may shift from rainfed to more irrigated crop production. This would increase agricultural production but also reduce water availability for competing sectors and ecological flows.

1. Introduction

During times of water scarcity, one of the first consequences is water stress reducing plant growth and potentially leading to agricultural production losses (Tallaksen and Van Lanen, 2004). In Sweden the crop production is generally rainfed in contrast to most areas of the world, where irrigation is indispensable to increase crop yield and mitigate the impacts of agricultural droughts (e.g. Bruinsma, 2009; Siebert and Döll, 2010; Yan et al., 2022). On the global scale, the agricultural sector is the world's largest consumer of freshwater, with irrigation accounting for 70% of the freshwater extraction globally (OECD n.d.). In Sweden, however, agriculture currently only accounts for 3% of the total Swedish water allocation, although in the most southern parts of Sweden, which are

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dominated by agricultural areas, it exceeds 10% when water used for livestock is included (Eklund et al., 2020; The Swedish Board of Agriculture, 2022).

The country of Sweden covers 450 000 km² in Northern Europe and is mainly covered by Boreal-forest. The northern parts of the country have a subarctic climate while the central parts have a humid continental climate with more ocean influence in the coastal south. Agriculture is mainly dominant in the southern, south-eastern and south-western parts of the study region and along the coast of the Baltic Sea. In 2024, agricultural land covered about 30,000 km², of which 85% was arable land and 15% pasture and meadow (Swedish Board of Agriculture, 2024). In 2015 less than 100,000 ha were irrigated in Sweden, which is less than 3.5% of the total agricultural area used for cultivation (Wesström, 2017). However, similar to climate-change impact on agriculture at the global scale (Savo et al., 2016), the need for irrigation due to global warming is likely to increase also in Sweden (Swedish Agency for Marine and Water Management, 2022) but how much is yet unknown.

In Sweden irrigation is mostly done with mobile irrigation sprinklers (Mattsson et al., 2018). The recommended irrigation amount per irrigation event in Sweden varies between 15 and 30 mm depending on how much water the soil can retain (Malm and Berglund, 2018). The most commonly irrigated crops in Sweden are fruits and berries, vegetables and potatoes (Swedish Board of Agriculture, 2024). Additionally, after the dry summer of 2018 the interest among dairy farmers to irrigate ley used as fodder for livestock is growing to ensure a stable production of food for the animals (Berglund, 2019). Surface water is the most common source for irrigation water, however, in some regions it is more common to use ground water for irrigation (Swedish Board of Agriculture, 2024).

Irrigation water demand (IWD) is projected to increase at the global scale (e.g. Haile et al., 2024; Wada et al., 2013) and for Europe, Busschaert et al. (2022) reported an increase in mean IWD, estimating around 13 mm per month (+18%) under a low emission scenario and 22 or 26 mm per month (+30% or +35%) under two high emission scenarios by the end of the century. To the authors' knowledge there is only one study focusing on the IWD change in Sweden (Grusson et al., 2021). They estimated the trends in IWD patterns, but without quantifying absolute IWD demands, by calculating rain deficit and irrigation requirement at seven locations in Sweden for the period 2021–2050. Their findings highlighted an increase in IWD for cereals and, to a lesser extent, ley during May–June due to earlier start of the growth season and a higher likelihood of dry periods in spring. For potatoes, which start growing later in the season, the IWD increased in July. Due to predicted earlier crop development stages, IWD decreased in August as a result of earlier harvesting.

This previous study by Grusson et al. (2021) provided valuable insights into irrigation demand in Sweden. However, it simplified some hydrological processes, such as the absence of water losses from interception and surface runoff, i.e. all the water applied as both precipitation and irrigation reached the soil, thus overestimating the plant-available water. The accessible water content was assumed to extend to the maximum root depth during the entire growth period when in reality the root depth increases as the roots grow. These simplifications probably lead to underestimates of the IWD. Furthermore, the previous study did not cover the entire country.

There is a general lack of information regarding irrigation in Sweden expressed both by experts and users, with very few and old reports on the subject (e.g. Johansson and Klingspor, 1977). Although it is assumed that the IWD will probably increase, no peer-reviewed studies have examined this in Sweden apart from Grusson et al. (2021). Hence, with our study we aim to follow up by a more thorough hydrological analysis and spatial coverage across the entire country of Sweden, focusing on the total yearly water usage necessary for crop cultivation.

The primary research question of the current study is: “What IWD values could we expect in Sweden as a result of global warming?”. To answer this research question, we also needed to analyze how climate change affects the growth start of different crops and crop water demand, focusing on the number of days during which different crops experienced water stress. Answering the research question will increase the understanding of climate-change impact and necessarily adaptation measures at the catchment scale. The findings will guide decision-makers in the equitable allocation of water resources during times of scarcity, addressing the needs of various stakeholders sharing the water resources, for instance farmers, industries, and municipalities in the region.

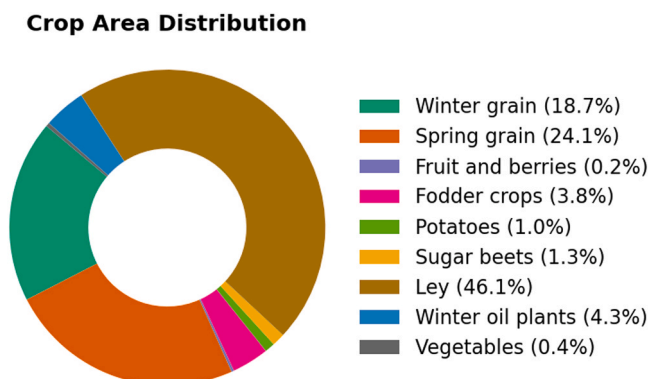


Fig. 1. The crop area distribution in Sweden for the nine crop groups used in this study. The total area for each crop is: winter grain 436 856 ha, spring grain 565 027 ha, fruit and berries 5 772 ha, fodder crops 89 134 ha, potatoes 24 150 ha, sugar beets 30 677 ha, ley 1 080 013 ha, winter oil plants 101 269 ha and vegetables 8 957 ha.

2. Methods

2.1. Crop and soil data

For the present study, farmland areas for 48 different crop classes in Sweden for the year 2016 were used. This data was provided by the Swedish Board of Agriculture as field block data, containing geospatial information on the crop classes, which are used to monitor agricultural land and to administer agricultural subsidies in Sweden. For the purpose of this study, these crop classes were combined into nine crop groups (Fig. 1) based on the expertise of water resource specialists at the Swedish Board of Agriculture. The areas for each crop class are available at [Zenodo.org](https://zenodo.org/doi/10.5281/zenodo.14778227) DOI:10.5281/zenodo.14778227 along with the rest of the data in this study. Crops were grouped based on similar irrigation demand according to crop coefficient, K_{CB} , values in the FAO Irrigation and Drainage Paper (Allen et al., 1998). Details on which crop classes are included in each crop group are provided in the Appendix (Table A.1). The field block data were combined with soil type maps covering Sweden provided by the Geological Survey of Sweden, always using the map with the highest resolution for a given area, to determine the distribution of crops across different soil types (sandy soils, loam, silt, silty clay loam and heavy clay) which are used as input to create agricultural land use classes for the hydrological model (see section 2.2.1 below).

2.2. Hydrological modeling

The HYPE model

IWD was calculated on a daily basis using the hydrological model HYPE (Lindström et al., 2010) developed by the Swedish Meteorological and Hydrological Institute (SMHI) twenty years ago. The model is open source and has been shared internationally ever since (see Hypeweb at <https://hypeweb.smhi.se/model-water/>). It is applied across the world in scales ranging from urban (e.g. Tanouchi et al., 2019) to global (e.g. Arheimer et al., 2020) in order to predict water resources (e.g. Andersson et al., 2017) and water quality (e.g. Bartosova et al., 2019) as well as for operational forecasts or assessments of ecological flows (e.g. Arheimer et al., 2018) and climate-change impact on water systems (e.g. MacDonald et al., 2018).

The model is semi-distributed and describes the water balance and flow paths including precipitation, evapotranspiration, groundwater, streams, lakes and rivers in nested catchments. HYPE accounts for losses by interception, surface and subsurface runoff, and tile drainage in agricultural soils. The soil-runoff part is calculated in sub-basins, for individual classes based on soil and land use. The soil is divided in two or three layers and in the Swedish setup of HYPE (i.e. S-HYPE; Strömqvist et al., 2012) all agricultural soils are assumed to have three soil layers, which are 0.25, 1 and 2 m deep, respectively. In each layer the model thus computes soil wetness for each crop and soil combination.

The simulations are performed with a daily timestep at a sub-basin scale, where each combination of soil type and land-use class constitutes an independent calculation unit, or hydrological response unit. The model parameters are either global, or valid for certain regions within the model domain, or coupled to the different soil types or land uses depending on the type of parameter. Information about parameter options can be found in the HYPE wiki (<http://hype.smhi.net/wiki/doku.php>). For a more in-depth model description see the Appendix. The S-HYPE model is repeatedly calibrated and evaluated against observed data, as part of documentation of the continuous model development (e.g. Arheimer et al., 2011; Arheimer and Lindström, 2013; Fuentes-Andino et al., 2022; Lindström, 2016; Strömqvist et al., 2012).

In this study, the S-HYPE version 2016g was used, in which Sweden is divided into almost 40,000 sub-basins based on the Swedish Water Archive (Abdoush et al., 2024). The sub-basins size ranges from $< 1 \text{ km}^2$ to $> 1000 \text{ km}^2$ (the largest is 4067 km^2) with an average of 13 km^2 (median 6.5 km^2) and calculations are made on a daily timestep.

The irrigation routine in HYPE

The irrigation module in S-HYPE calculates the daily irrigation demand based on soil and crop specific coefficients, soil water content and temperature. The applied irrigation water can be abstracted from lakes, streams or deep aquifers, or from unlimited sources outside the model area. Losses in the irrigation system, caused by e.g. evaporation or wind drift, are accounted for by removing a percentage of the irrigation water before it reaches the soil (Swedish Meteorological and Hydrological Institute, n.d.), the IWD thus represents the gross irrigation demand. In this study, the losses were assumed to be 15% of the abstracted water and are included in the IWD. When using irrigation sprinklers, the losses rarely exceed 10–15% in Sweden (Mattsson et al., 2018), we choose the upper limit so as to not underestimate the IWD. After the irrigation water has been applied to the soil it is subjected to further losses through subsurface runoff and tile drainage. In the S-HYPE model all agricultural lands are assumed to have subsurface drainage systems unless they are naturally well drained (see A.1.3.5 Drainage in the Appendix).

The water demand in the model is then determined by the potential evapotranspiration, which is calculated with a daily timestep in the model. In HYPE the potential evapotranspiration occurs when the air temperature (t_{AIR}) is above a threshold temperature (t_{tmp}) which depends on land use. To determine the reference crop evapotranspiration (ET_0), we avoid using the term potential evapotranspiration as FAO discourages its use due to the ambiguity of the term (Allen et al., 1998), we use a temperature-based function following Wisser et al. (2008) adjusted for daylength (or global radiation) and humidity based on Hamon (1963). The equation used to estimate ET_0 incorporates air temperature (t_{AIR}), a seasonal adjustment factor (c_{season}) and a rate parameter ($cevp$) which also is landuse dependent (Lindström et al., 2010) (Eq. 1).

$$ET_0 = (cevp \times c_{season}) \times (t_{AIR} - t_{tmp}) \quad (1)$$

The seasonal adjustment factor is used to make the evapotranspiration rate higher in the spring when the global radiation is higher and the air is often dry, and lower in autumn when the global radiation is lower and the air is often more humid. The crop evapotranspiration is then calculated with crop specific coefficients (K_{CB}) (Strömqvist et al., 2020) using the dual crop coefficient method where soil evaporation and crop transpiration is managed by two separate coefficients (Allen et al., 1998). The K_{CB} values, which depends on the plant development stage and vary during the growing season, which is divided into four stages (initial, development, mid-season and late season), were obtained by connecting the crop groups used in HYPE to similar crops in table 11 in Allen et al. (1998).

During the development stage the K_{CB} value is a linear interpolation between the K_{CB} value in the initial stage and the K_{CB} value in the mid stage. The lengths of the growing stages were adjusted to Swedish conditions using a scaling factor. This factor was calculated by dividing the entire growing season, which is both crop- and latitude-specific (Johnsson et al., 2019), by the growing season for a representative crop in Allen et al. (1998) for each crop group. The factor was then applied to rescale each growth stage to the regional Swedish conditions (Strömqvist et al., 2020). This means that the length of the growth season varies depending on the latitude with shorter growth seasons in northern Sweden and longer growth seasons in southern Sweden.

For forage crops, which are harvested at several occasions during a season, the K_{CB} value has a sawtooth-shaped curve for an individual field, where the K_{CB} value returns to its initial level after each harvest. Since the model is not able to handle the cyclic pattern that occurs when a crop goes through multiple growth cycles, a constant value—the average over the period—was assumed instead. In a sub-basin containing many fields, this averaging may also occur in reality, which justifies the modeling assumption. The K_{CB} values and the lengths of the growing stages can be found in Table 1.

For each timestep, for each agricultural soil and land use-class in all the different sub-basins, the model compares the simulated soil water content in the top two soil layers, with a dynamic threshold value representing plant water stress. If the soil water content is below this threshold, irrigation water is added if available (as mentioned there is also a model option to take the irrigation water from an unlimited source). The amount of water to be added can be set to a percentage of the field capacity, a fraction of the stress threshold or as a predefined constant amount in mm.

The threshold for water stress (S_{SW}), which varies with the potential evapotranspiration, is set to a fraction of the maximum plant available water (AWC), i.e. the sum of the water between the wilting point and field capacity in the two topmost soil layers. S_{SW} depends on the crop type and the crop evapotranspiration under standard conditions (ET_C) and varies from day to day (Eq. 2) because under hot dry weather conditions when the evaporative power is higher the plants start to experience water stress at higher soil water contents (Allen et al., 1998). ET_C depends on K_{CB} and the reference potential crop evapotranspiration (ET_0) (Eq. 3).

$$S_{sw} = 1 - \left(DL_{ref} + 0.04 \times \left(5 - \frac{ET_C}{0.95} \right) \right) \quad (2)$$

$$ET_C = K_{CB} \times ET_0 \quad (3)$$

DL_{ref} is a crop-type specific reference depletion level (essentially the fraction of AWC that can be depleted before stress occurs). DL_{ref} values were obtained from Allen et al. (1998). The irrigation need is assessed by comparing the water stress threshold (S_{SW}) with the current soil water content (H) (Eq. 4).

$$\text{if } H < (S_{sw} \times P_{SSWCORR} \times AWC) \rightarrow \text{irrigate} \quad (4)$$

where $P_{SSWCORR}$ is a correction parameter. In our study $P_{SSWCORR}$ was set to 1. Below S_{SW} the crops experience water stress creating a need for irrigation. Eq. (3) is a slightly modified form of the original FAO-56 equation (Allen et al., 1998) with only ET_C used to calculate S_{SW} .

Table 1

Crop groups used in the irrigation module and the length of the different growth stages, the respective KCB value for each stage (for the development stage the KCB value is a linear interpolation between the KCB values in the initial stage and the mid stage), the total growth season, and the threshold temperature for start of growth for each crop used in the study.

Crop group	Initial stage		Development stage	Mid stage		Late stage		Growth season length	Threshold temperature
	Days	K_{CB}	Days	Days	K_{CB}	Days	K_{CB}	Days	°C
Winter grain	144–168	0.15	68–79	68–79	1.1	23–26	0.15	303–352	-
Spring grain	27–43	0.15	20–32	27–43	1.1	14–21	0.15	88–139	5
Fruit and berries	8–13	0.3	29–46	38–60	0.8	13–20	0.7	88–139	5
Fodder crops (maize + protein crops)	21–30	0.15	28–40	34–51	1.15	34–51	0.15	117–172	9
Potatoes	24–34	0.15	28–40	40–57	1.1	24–34	0.65	116–163	9
Sugar beets	41–54	0.15	33–44	41–54	1.15	33–44	0.5	148–194	5
Ley (forage crops)	12–17	0.3	19–26	93–130	0.8	44–61	0.8	168–234	5
Winter oil plants	160–161	0.15	76	76	0.95	25–26	0.25	337–338	-
Vegetables	18–28	0.15	23–37	35–56	0.95	12–19	0.85	88–139	5

Regional adaptation of growth start in the HYPE irrigation routine

As described above (section 2.2.2), the irrigation routine in HYPE includes some static and empirical information about crop growth that needed adaptation to regional conditions for this study on climate-change impact. The Swedish agricultural land is classified into 18 regions with similar natural agricultural characteristics, for instance the times for sowing and harvesting (Johnsson et al., 2019). This information is used when calculating crop growth in HYPE and whenever one of the S-HYPE crop groups did not exactly match the crops in Johnsson et al. (2019) the values were obtained by comparing similar crop groups based on parameter values. However, such dates may shift with climate change and therefore we further developed the HYPE model to dynamically determine the plant day for spring sown crops by air temperature using a method proposed by Grusson et al. (2021). This is a new functionality added to the HYPE code as a part of this study in order to study how the starting date of crop growth will change as a result of climate change.

Each crop is attributed with an earliest possible starting date and a threshold temperature (Table 1). After the earliest possible starting day, the model checks whether or not the daily mean temperature is above the threshold for the last 7 consecutive days, when that condition is fulfilled plant growth is initiated and the irrigation routine is activated which checks if irrigation is needed or not. The threshold temperatures for spring grain, ley and potatoes were taken from Grusson et al. (2021) and these threshold temperatures were also used for fruit and berries, fodder crops, sugar beets and vegetables, by comparing crop similarities in the work by Johnsson et al. (2019). Since this condition for a dynamic growth start (i.e. based on a daily mean temperature above a threshold temperature) is not applicable to crops sown in the autumn, the winter grain and winter oil plants still have a fixed start of growth date in S-HYPE.

Evaluating the irrigation routine

The HYPE irrigation routine was initially evaluated for S-HYPE in a pilot study conducted in the Vramså catchment area in Skåne in southern Sweden (Strömqvist et al., 2020). The Swedish Board of Agriculture had conducted an interview survey with local farmers in this area to estimate irrigation withdrawals. The collected data were used to validate the assumptions and parameterization of the irrigation routine in the S-HYPE model. The results indicated that both the frequency and intensity of irrigation across different crops were generally well represented, and that the simulated irrigation volumes were of the correct order of magnitude.

Additionally, regionally modeled irrigation volumes from S-HYPE were compared to independent irrigation estimates derived from a national survey conducted by The Swedish Board of Agriculture in 2016 (Fig. 2). In the survey, farmers were asked which crops and how large area they irrigated, and farmers known to own irrigation equipment were additionally asked to estimate the volume of water applied during the 2016 growing season. This data can be found in Table A.3 in the Appendix. The S-HYPE model was therefore used to estimate irrigation volumes based on the irrigated areas reported by farmers, and the resulting estimates were compared with the irrigation volumes reported by the farmers. It is important to note that this survey dataset only provides an estimate of total irrigated volumes per production region, without crop-specific details. Nevertheless, these estimates show good agreement, particularly considering that the underlying estimates of irrigated area differ slightly between the two sources, as they originate from separate

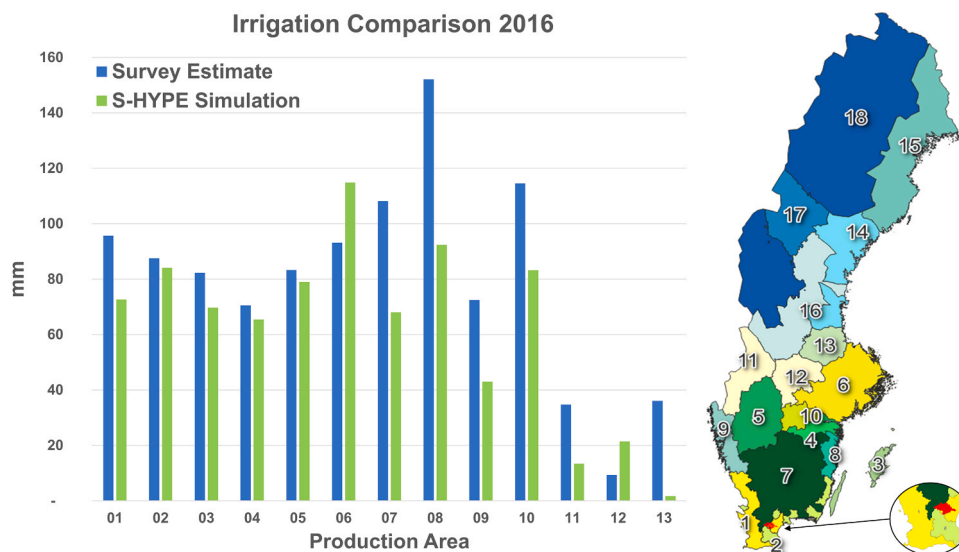


Fig. 2. Comparison of irrigation volumes estimated by the S-HYPE model and reported in an interview survey across 18 agricultural production areas (18 regions with similar natural agricultural characteristics) in 2016, the red area marks the Vramså catchment area where the local evaluation of the irrigation routine was conducted. 1 - Skåne–Halland Plain Region, 2 - South Swedish Transitional Region, 3- Öland and Gotland, 4 - Östergötland Plain, 5 - Vänern Plain, 6 - Mälaren and Hjälmaren Region, 7 - South Swedish Highlands, 8 – East Swedish Valley Region, 9 - West Swedish Valley Region, 10 - Southern Bergslagen, 11- West Swedish Lake and Valley Area, 12 - Northern Bergslagen, 13 - Eastern Dalarna–Gästrikland, 14 - Coastal Region of Southern Norrland, 15 - Coastal Region of Northern Norrland, 16 - North Swedish Transitional Region, 17 - Jämtland Silurian Region, 18 - Mountain and Moraine Region.

surveys. In production areas 14–18, the irrigated areas were negligible, and thus no irrigation was considered there for the purpose of this evaluation. These areas are however included in the rest of this study.

2.3. Scenarios, model setup and indicators of change

In order to answer our research question, we employed the S-HYPE model to simulate three key indicators: (i) the starting date for growth, (ii) the number of days per year with plant water deficit (i.e. the number of days when the water demand of the different crops surpasses the available soil water if no irrigation water is applied) (PLWD-days), and (iii) the IWD. In order to study both the PLWD-days and IWD two sets of simulations were performed:

1. The first simulation (S1) was conducted without any irrigation by setting the applied irrigation to 0 mm, allowing us to examine the PLWD-days.
2. The second simulation (S2) was performed incorporating irrigation to see how the IWD changes assuming 20 mm irrigation water applied per irrigation event. This scenario assumes universal access to irrigation equipment among farmers, with the commitment to irrigate all farmland planted with the crops listed in Table 1 whenever the need for irrigation arises.

Two scenarios were needed as adding irrigation in S1 would reduce the impact of the climate signal. S2 investigates future irrigation needs for all farmland where crops that potentially require irrigation are grown. The choice to calculate the IWD for all farmland in Sweden was made to simulate the irrigation needs, including areas that are not irrigated today.

For S2, the model option to add a predefined amount was used. This value, 20 mm, determined from expert judgements at The Swedish Board of Agriculture, mirrors the most common irrigation practices among Swedish farmers. With this model option the model applies 20 mm of water whenever the criteria for irrigation is fulfilled (Eq. 4) for a certain crop group. This water is drawn from an unlimited source to ensure that water availability does not restrict the theoretical IWD. The 20 mm is the water applied to the soil after taking into account the 15% losses within the irrigation system. To perform a sensitivity test we also ran two simulations identical to S2 but with 15 respectively 30 mm as the irrigation load applied to the soil.

Both simulations, S1 and S2, were run using a bias-corrected ensemble of 17 Euro-CORDEX regional climate forcing data (Strandberg et al., 2024, 2026) for three different Representative Concentration Pathways (RCP), namely 2.6, 4.5 and 8.5, applied in the hydrological climate-impact modeling of Sweden at SMHI (see Climate Change Scenario Tool 2025 at <https://www.smhi.se/en/climate/tools-and-inspiration/climate-change-scenario/climate-change-scenario-tool>). The model ensemble contains combinations between five global climate models (GCMs) and nine regional circulation models (RCMs) and two different model initializations for the different GCMs (see Table A.2 in the Appendix). The forcing data is bias adjusted using a multi-scale bias adjustment method (Berg et al., 2022). The simulations spanned over the period from 1981 to 2100, with a daily timestep, and the results were segmented into four 30-year intervals. The reference period, 1981–2010, served as a benchmark against which the subsequent periods (2011–2040, 2041–2070, and 2071–2100) were evaluated. The reference period is the same for the different RCP scenarios. To start the simulations the model was initiated with a 10 year spin up period from 1971.

The climate model ensemble under different RCP scenarios is used to increase robustness and account for the uncertainty regarding future climates. The probability for each RCP can be discussed and should be considered when drawing conclusions from our results, which show a wide range between the RCPs applied. The temperature increase given by RCP 2.6 has passed or will occur within the first half of this century (IPCC, 2018) but serves as a good lower limit of change, indicating what could be achieved by human actions from the global community. The RCP 4.5 is likely to occur at the end of the century following current actions. The emissions in RCP 8.5 are less likely, but the temperature increase could potentially occur should the climate system be more sensitive to changes in greenhouse gases than expected, unknown and misleading reporting of sources appear, or in the absence of climate change policy (e.g. Riahi et al., 2011). Hence, RCP 8.5 is used as an upper limit of what is probable, although it has been designated as unrealistic by the end of the century (Huard et al., 2022).

To evaluate the results from the two simulations, the ensemble median across the 17 RCMs for two different indicators were used based on PLWD-days and IWD. We also tested using the ensemble mean which gave almost identical results as the median. These were calculated in each catchment for each 30-year period both for an average year, the mean year for each 30-year period, and for the driest years, the year with the highest value for each 30-year period. Hence the years with the most PLWD-days/IWD does not have to be the same year for two different sub-basins. The PLWD-days were analyzed separately for each of the nine crop groups. The IWD was analyzed both as the sum of all the irrigation water applied to all the crop groups present in each catchment, and separately for each crop. Also, the change in growth start, in days, was analyzed for each crop group except winter grain and winter oil plants as these are sown during the autumn.

Evaluating the climate-signal robustness

Following the recommendations by Nikulin et al. (2018), results were considered robust if the climate-model ensemble signal met the following two criteria:

- At least 80% of the models in the ensemble indicated the same direction of the change (i.e. increasing or decreasing).
- The ratio of the ensemble mean divided by the standard deviation (i.e. the signal to noise ratio) was greater than or equal to 1.

3. Results

3.1. Irrigation water demand in a future climate

We found that already in the current climate irrigation would benefit crop production in nearly all agricultural areas of Sweden (Fig. 3.); particularly during the driest years with about 100 mm of irrigation water needed per year in southern Sweden (see total

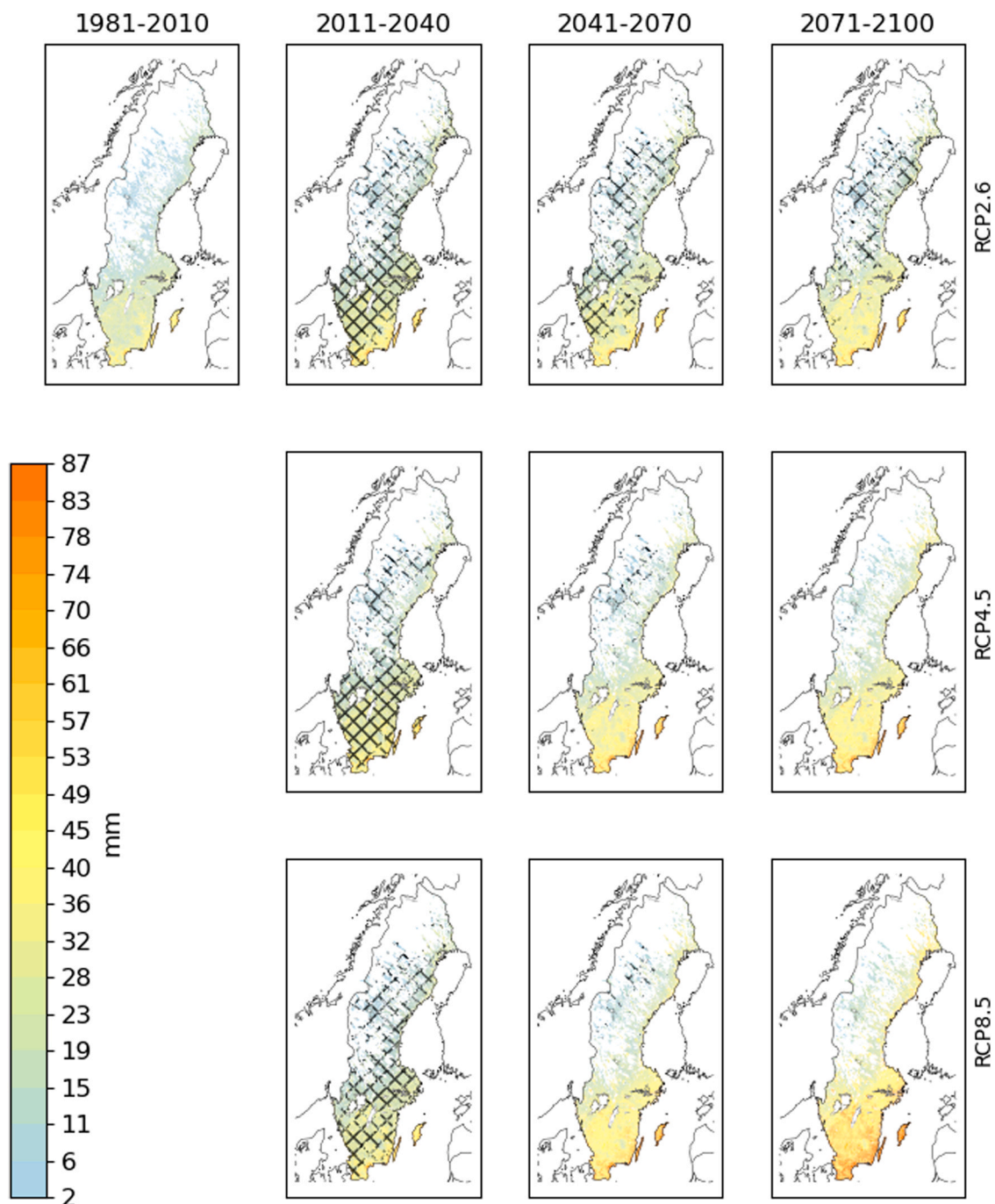


Fig. 3. Yearly irrigation water demand in mm for an average year in each catchment across three 30-year periods for three different RCP scenarios, RCP 2.6, RCP 4.5 and RCP 8.5. 1981–2010 acts as reference period. The cross-hatch pattern is where the results did not meet our robustness criteria. The yearly irrigation water demand was calculated for nine different crops in Sweden and summed for each catchment. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

values for the reference period 1981–2010 in Fig. 4). At the national scale, this corresponds to irrigation requirements of 573 million m³ in an average year and 1878 million m³ in the driest year under the reference period. However, this demand is largely unmet as less than 3.5% of Sweden's agricultural land was irrigated as of 2015 (Wesström, 2017).

The results for future scenarios in Fig. 3 show that the projected change of IWD will increase most in southeastern Sweden. This is the driest part of the country in the sense that it has the highest ratio of evaporation to precipitation (Persson, 2015) and it is also here that the change in growth periods is largest. The relative increase in IWD compared to the reference period will be larger for an average

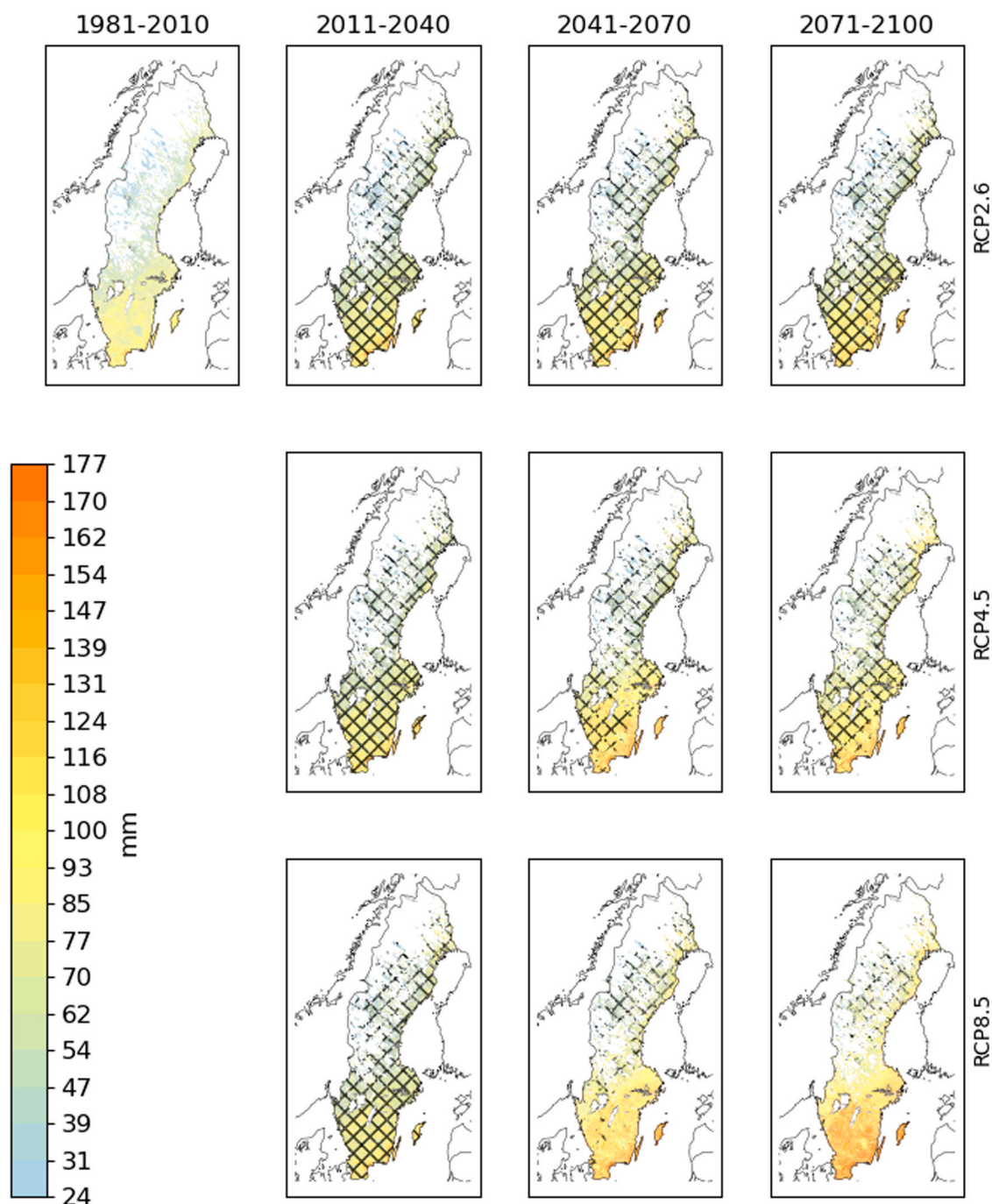


Fig. 4. Yearly irrigation water demand in mm for the driest year in each catchment across three 30-year periods for three different RCP scenarios, RCP 2.6, RCP 4.5 and RCP 8.5. 1981–2010 acts as reference period. The cross-hatch pattern is where the results did not meet our robustness criteria. The yearly irrigation water demand was calculated for nine different crops in Sweden and summed for each catchment. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

year than for the driest years. Under RCP 8.5, the IWD for an average year is projected to more than double by the end of the century. The largest increase is expected in southern Sweden, but there will also be a significant increase along the northern coastal regions. For the driest years, the increase follows the same spatial pattern, with the IWD reaching up towards 180 mm by the end of the century along the southeastern coast, including Öland and Gotland for RCP 8.5 (Fig. 4). Although the absolute change in millimeters is greater during the driest years, the percentage change compared to the reference period is smaller than for an average year. By the end of the century, under RCP 8.5, the IWD for an average year will be nearly equivalent to the IWD during the driest years of the reference period. Under the RCP 2.6 scenario, the IWD will increase minimally, about 5–10 mm for an average year by the end of the century in southern Sweden, and there are almost no significant changes during the driest years.

Under RCP 4.5, the IWD is projected to increase by about 50% in all of Sweden compared to the reference period during an average year by the end of the century. For the driest years, the percentage change is smaller compared to the reference period, and the results are less robust. Interannual variability was also assessed for each time period; however, because the minimum IWD was close to zero, the calculated range effectively represented the maximum IWD values, corresponding to the driest years.

The modeled climate-change impacts were not found to be sensitive to the assumption on irrigation load. Regardless of the amount of water applied to the soil as irrigation, the relative changes compared to the reference period remained basically the same, the largest difference was 5%, for each time period and RCP. The total IWD was about 16–20% lower in total for the different time periods and RCPs when applying 15 mm as irrigation load compared to 20 mm. When increasing the irrigation load to 30 mm the total IWD increased by 42–46% compared to the scenario when 20 mm was applied.

3.2. Shift in crop-growth start and water stress

By the end of the century, the start of the growing season for most crops in Sweden is projected to occur earlier due to climate change, with greater shifts under higher emission scenarios. Geographic variation is notable, with the largest advances in south and south eastern Sweden and smaller shifts in northern inland regions. Spring cereals, fruits, berries, potatoes, vegetables, ley, and sugar beets all show earlier growth starts (ranging from a few days under RCP 2.6 to over two weeks under RCP 8.5) while the start of growth for autumn-sown crops (winter grains and winter oil plants) remains unchanged (in line with the assumptions of the model concept, see section 2.2.3). More details and maps showing the change of start of the growing season for the different crops can be found in the [supplementary material](#).

We found that by the end of the century, the number of PLWD-days (i.e. days with water stress for plants) are expected to increase in Sweden, particularly under higher emission scenarios. The rise in water stress is most pronounced in southeastern coastal regions, while northern and western areas see smaller changes. On average, PLWD-days may increase by 10–20 days under RCP 4.5 and up to 20–35 days under RCP 8.5 in the southeast of Sweden, while much smaller increases—just a few days—are projected for northern and western Sweden. During the driest years the increase in PLWD-days ranges from almost one month to over two months depending on the scenario and geographic locations with the largest increases in PLWD-days for winter grain, winter oil plants and vegetables in southeastern Sweden under RCP 8.5. Winter oil plants may face more PLWD-days especially during dry years, while fruits, berries, and

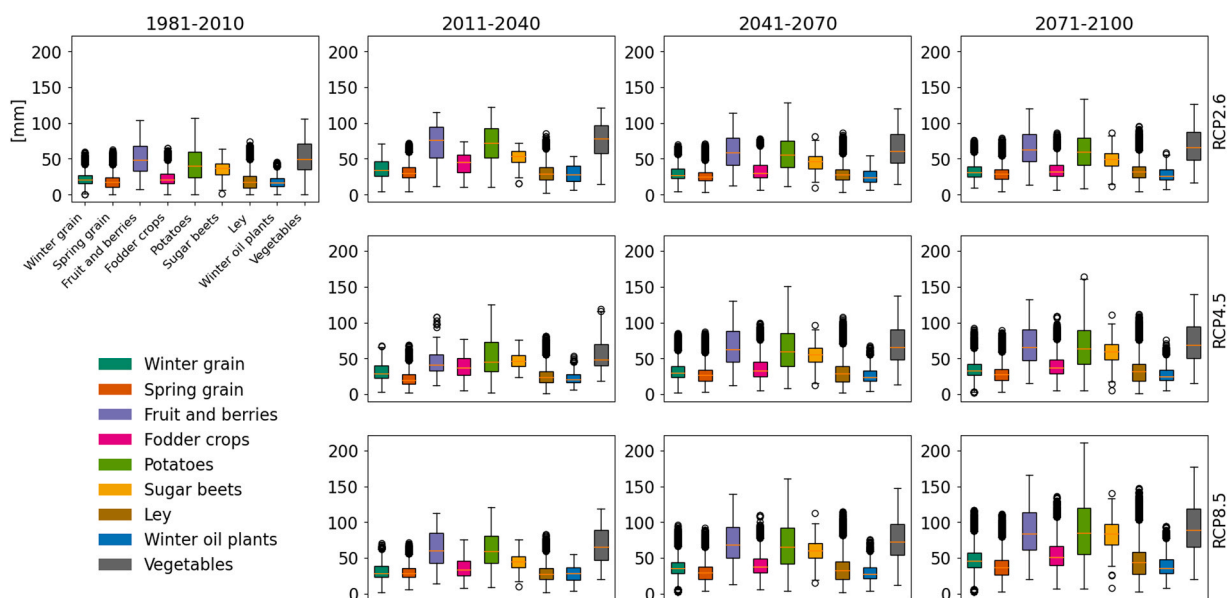


Fig. 5. Yearly irrigation water demand in mm for an average year for each of the nine different crop groups across three 30-year periods for three different RCP scenarios, RCP 2.6, RCP 4.5 and RCP 8.5. 1981–2010 acts as reference period. The boxes extend from the first quartile to the third quartile of the data, the median is marked with a line. The whiskers extend from the boxes to the farthest data point lying within 1.5 times the interquartile range from the boxes and the flier points are those outside of the whiskers.

vegetables show relatively smaller increases although they already experience quite many PLWD-days under the reference period (two to three weeks during an average year, and almost two months during the driest years). Under RCP 2.6 the results of the model ensemble are mostly too ambiguous to see any significant changes in PLWD-days, especially during the driest years, but also on average; only the areas in southern and southeastern Sweden exhibit some increases of up to 10 more PLWD-days by the end of the century.

3.3. Variable irrigation-water demand between crop groups

The IWD varies quite substantially between the different crop groups (Fig. 5), with some crops such as potatoes, sugar beets, vegetables and fruit and berries having a much larger IWD compared to the other crops. However, when expressed in total volumes, the crops with the largest IWD are those that are most widely cultivated, such as grains and ley (Table 2). Hence, the total IWD for arable land in the region is very much dependent on crop area and crop composition in the rotation. For winter grain and winter oil crops the IWD remained zero during the dormant period.

3.4. Future irrigation water demand in relation to Sweden's total water use

By the end of the century, the average IWD for the region is estimated in total volumes to 790 million m³ under RCP 2.6, 905 million m³ under RCP 4.5 and 1239 million m³ under RCP 8.5 (Table 3). The current total freshwater consumption in Sweden amounts to about 2400 million m³ (Statistics Sweden, 2022). Table 3 shows that even during an average year, the IWD equals a significant portion of Sweden's freshwater consumption and is projected to increase towards the end of the century, assuming that the total freshwater water consumption stays constant. Under the RCP 8.5 scenario, meeting the IWD during an average year would double the water use by the end of the century compared to the reference period.

During the driest years estimated for the past period, the IWD equals almost 80% of Sweden's current freshwater consumption. For RCP 8.5, the demand during the driest years would exceed Sweden's current freshwater consumption by mid-century. This indicates that if irrigation equipment is installed at large scale in the region, it must be preceded by local water accounting and allocation regulation to ensure water availability for other users and ecology to avoid conflicts.

4. Discussion

4.1. Climate impact modeling

The variability in projected increases of IWD across different climate-change scenarios underscores the need to use an ensemble of climate models as a basis to prepare society for climate adaptation. Even though we find that the future will bring significantly higher irrigation demands than today, the quantification of IWD differs considerably due to assumptions behind the different climate models and the RCPs. For the time period 2011–2040, we found little to no significant change in IWD, which is in line with results for the whole of Europe (Schaldach et al., 2012). It should be noted that the RCP 8.5 scenario by the second half of the century has been considered unlikely (Huard et al., 2022; Strandberg et al., 2024) but with the current political direction and less commitment to the Paris agreement by several high emitting countries this scenario becomes more plausible. Additionally, our findings of IWD with RCP 8.5 by mid-century shows similar patterns as RCP 4.5 by end-century, so it might be a matter of timing and pace in climate warming.

The consistent change in IWD relative to the reference period across all RCPs, regardless of the irrigation amount applied, suggests that uncertainties in assumed irrigation efficiency or application rates have little influence on the relative change in the projections; this strengthens the confidence in the overall climate impact assessment. However, with a 15 mm irrigation load, the total water use was considerably lower than for higher loads, indicating that applying smaller amounts more frequently is more efficient than applying larger amounts less often. This is probably due to more efficient crop uptake and reduced loss by evaporation and runoff. Additionally,

Table 2

IWD during a mean year for the nine crop groups in million m³ for the historical reference period and by the end of the century for RCP 4.5 and RCP 8.5.

	1981–2010		2071–2100			
	-		RCP 4.5		RCP 8.5	
	Mean yr	Dry yr	Mean yr	Dry yr	Mean yr	Dry yr
Winter grain	109	355	171	442	236	581
Spring grain	123	425	184	511	246	652
Fruit and berries	4	8	5	10	6	12
Fodder crops	24	79	41	100	56	128
Potatoes	15	37	24	48	32	58
Sugar beets	12	33	19	43	27	55
Ley	257	870	419	1102	583	1412
Winter oil plants	21	74	32	90	45	119
Vegetables	7	14	9	17	11	20

Table 3

IWD during a mean year and IWD during the driest year in million m³ and as a percentage of the freshwater usage in Sweden 2020, i.e. 2400 million m³ (Statistics Sweden, 2022). Note that the reference period is the same for the different RCP scenarios.

	1981–2010		2011–2040		2041–2070		2071–2100	
	Mean yr	Dry yr	Mean yr	Dry yr	Mean yr	Dry yr	Mean yr	Dry yr
RCP 2.6	573 (24%)	1878 (78%)	672 (28%)	1917 (80%)	696 (29%)	2077 (87%)	790 (33%)	2099 (87%)
RCP 4.5	-	-	693 (29%)	2004 (84%)	839 (35%)	2407 (100%)	905 (38%)	2330 (97%)
RCP 8.5	-	-	675 (28%)	1955 (81%)	953 (40%)	2611 (109%)	1239 (52%)	3005 (125%)

in regions with a fair amount of rainfall, heavy rain events can complement irrigation more effectively when smaller irrigation doses are applied, further improving water use efficiency.

4.2. Confirming changes in growth start

The observed changes in starting date of growth for the various crop groups confirms an extension of the growing season, which has already been suggested as one of the major agricultural shifts in the Nordic countries due to climate change (Wiréhn, 2018). Our results show trends similar to those reported by Grusson et al. (2021), although we found a larger shift especially by the end of the century, while their study only considered changes until 2050. A prolonged growth season could lead to an increased demand for irrigation. However, while a longer growing season implies potential for increased agricultural production (mainly in the southern and eastern parts of the country where these trends are strongest) this is also determined by other factors, such as the amount of daylight and soil conditions (e.g. sufficiently dry to allow for sowing). Thus, relying solely on temperature as an indicator for sowing conditions might lead to an oversimplification of the complexity of the factors involved.

4.3. Future irrigation needs

Our results indicate that the IWD in the region will increase under future climate conditions, with crops experiencing varying increases in PLWD-days. Water-sensitive crops such as potatoes and sugar beets are projected to face the largest increases in water stress, potentially raising irrigation needs or even threatening viability if profitability remains low. Variations in climatic response across crop groups likely reflect disparities in growth periods, regional cultivation patterns, and the timing of water-sensitive stages. The projected variability in PLWD-days suggests that a shift toward more drought-resilient crops should be considered as part of climate-change adaptation. In addition, investments in irrigation equipment and the construction of irrigation ponds may be required to reduce the risk of production losses. However, it is important to note that the most effective irrigation strategy may not be to maximize yield per area, but rather per the volume of water applied, particularly under water-scarce conditions. In this context deficit irrigation, where irrigation volumes are intentionally kept below the crop's full water demand, may become increasingly relevant in Sweden as competition for water intensifies across sectors.

The total IWD in each catchment is averaged for all crops present and since grain and ley are dominating area wise they have a larger effect on the IWD compared to more water demanding crops. The values, both the total and crop specific IWD in mm, are supported by the few reports available (Johansson and Klingspor, 1977; Malm and Berglund, 2018) and dialogues with farmers show that our results on crop specific IWD are of realistic magnitude for this region.

In the drought year of 2018, which was attributed to global warming according to Holmgren and Kjellström (2024), irrigation could probably have reduced the PLWD. The Swedish neighbor country of Denmark experienced relatively lower harvest losses during the drought, probably because of a higher degree of irrigation equipment; 11% vs 3% irrigation and 30% cereal loss vs 45% (Swedish Board of Agriculture, 2019; Statistics Denmark n.d.) Accordingly, increasing irrigation capacity in Sweden could help mitigate production losses during drought periods now and in the future. Such resilient food production chains have been identified as a cornerstone of food sovereignty, strategic autonomy, and economic resilience within the EU (European Commission, 2024). Additionally, the Swedish government has emphasized the importance of securing national food production as a key component of the civil defense preparedness (Government Offices of Sweden, 2023). If Sweden and the EU aim to become more self-sufficient and autonomous in food production, the agricultural sector in the region will need to become more resilient and capable of withstanding even the driest years without suffering significant losses in production.

4.4. Limitations with the IWD modeling

A considerable portion of the IWD results was under detection limit for our robustness criteria during the time period 2011–2040. This highlights the uncertainty surrounding IWD changes until mid-century, even when using a large ensemble of regional climate forcing data. This uncertainty in projected IWD changes until mid-century is also evident in the study by Grusson et al. (2021).

The lack of measured irrigation data to calibrate and validate the model is one limiting factor in this study. However, we have used the best available irrigation data derived from farmer interviews to validate the irrigation routine. Although the lack of measured data introduces some uncertainty, we believe the approach remains valid for assessing relative changes and patterns in irrigation demand and relating them to the water usage in Sweden.

Another limitation of our study was the assumption that all soil water above the wilting point in the top two layers is available to

the plants, despite variations in root depth across crop stages. This simplification likely overestimated plant-available water, leading to a slight underestimation of the IWD. However, as we assume a 15% loss in the irrigation system—at the higher end of reported values for sprinkler systems in Sweden—it is likely that we have overestimated these losses. Additionally, the S-HYPE model assumes that all agricultural land is equipped with subsurface drainage systems if not sufficiently naturally drained, while only about 50% of agricultural land is artificially subsurface-drained. Therefore, more water may be available to plants. Consequently, it is hard to judge whether we have underestimated or overestimated the actual increase in IWD without having more measured data on plant available water for different soils and plant combinations in Sweden. Another limitation was that the crop data used in the simulations was static, based on the farmland areas from 2016. Since the HYPE model is not set-up to handle dynamic land use, and continuous farmland data was not available, we opted to use crop data from a specific year. Keeping the crop distribution constant also made it easier to compare how the irrigation conditions will change in the future relative to our reference period. However, it is reasonable to assume that changing crops would be one of the key adaptations that agriculture could adopt to mitigate the impacts of climate change and increased IWD.

In this study we opted to use the RCP scenarios instead of the Shared Socioeconomic Pathways (SSP) scenarios as at the time of this analysis, only RCP-based scenarios were available for the regional climate model ensemble used in this study. The choice of these scenarios was therefore constrained by the availability of high-resolution, regionally downscaled data. However, the SSPs include assumptions about socioeconomic development and land use, which also substantially influence components of the hydrological cycle (Bartosova et al., 2019). These aspects were not included in our study but would be valuable to address in future studies. We recognize that socio-economic drivers also have a large impact on the future irrigation demand (Schaldach et al., 2012), but nevertheless, our findings and limitations show that there is a pressing need for additional research to comprehensively assess the water availability and climate-change impact on agricultural water demand at the regional scale.

To further improve this study, one option would be to use growing degree days instead of calendar days to represent crop development. In addition, similar to using an ensemble of climate models, employing an ensemble of hydrological models would further enhance the robustness of the results. Lastly, investigating how IWD responds to variation in soil type would provide an additional dimension for future research.

4.5. Modeled IWD vs actual irrigation

We found that the IWD during the reference period, as a percentage of Sweden's total freshwater consumption in 2020, is much higher than the actual water usage in the agricultural sector. This discrepancy stems from the fact that most agricultural land in Sweden is not irrigated. In 2015, less than 3.5% of this land was irrigated and even if irrigation increased slightly after the dry summer of 2018, it still remains low. If all agricultural land were to be irrigated according to crop water requirements today this would equal about 25% of the freshwater consumption in the region during an average year. This discrepancy between what is irrigated today and what could be irrigated can be attributed to several factors; many farmers not having invested in irrigation equipment, the financial gains of irrigating not compensating for the costs, or just a tradition of not irrigating.

The Swedish Board of Agriculture also highlighted this gap between actual irrigation and the total irrigation demand in a comparison of irrigated and total arable land in 2016 (Mattsson et al., 2018). They applied generalized irrigation need values for different crops, showing a total water requirement of 377 million m³, while only 133 million m³ was actually used for irrigation. Our results confirm the existence of this gap but suggest that it is significantly larger than their estimates, with a mean annual irrigation requirement of 672 million m³ for the period 2011–2040 for RCP 2.6. It should be noted that the estimations by Mattsson et al. (2018) are relatively coarse, as they are based on a general millimeter-per-year figure for four crop types across three regions in southern Sweden.

Sweden's agricultural sector witnessed significant production and monetary losses owing to agricultural droughts and water scarcity during 2016 and 2018 (Government Offices of Sweden, 2019; Stensen et al., 2019). The income loss for one year can be compensated for by farmers but not a general decrease. Hence, the change in IWD for an average year being equal or larger than for the worst years, probably makes it more worthwhile to invest in irrigation equipment and water storage facilities, rather than if only the worst years would have become drier. However, peak irrigation demand coincides with the driest periods, exacerbating challenges with water-scarcity also for other societal sectors.

With Sweden anticipating an extended vegetation season due to climate shifts, not only crops but also other plants will increase their water uptake. This may reduce the volume of water reaching streams, lakes, and groundwater and thus affecting the overall water availability. Increased water usage in the agricultural sector will thus have an impact on other stakeholders, including the hydropower, industry and municipalities. It could also affect specific ecosystem services and biodiversity that are sensitive to prolonged low-flow periods or which are disrupted when flows fall below critical thresholds (Rideout et al., 2022). Hence, better and more accurate knowledge on irrigation demand must pave the way for both climate adaptation of the agriculture in the region and for water management planning and water allocation at the catchment level.

5. Conclusions

The following key points summarize the major findings in this study on climate-change impact on crop cultivation and irrigation water demand in Sweden:

- By the end of the century, climate change is projected to alter agro-hydrological conditions in Sweden. The growing season is expected to start earlier across most of the country, with the largest advances occurring in southern and southeastern regions and smaller shifts in northern inland areas, under RCP 8.5 up to two weeks earlier. At the same time, plant water stress is projected to increase, with the number of PLWD-days rising markedly under RCP 4.5 and especially RCP 8.5. The strongest increases occur in southeastern Sweden with 10–35 days more with plant water stress depending on the emission scenario.
- The region can expect that the crop-irrigation need will increase with global warming by the end of the century, between 5 and 45 mm per year for an average year or 10–70 mm per year for the driest years, respectively, depending on region, crop-types cultivated and emissions of greenhouse gases. This equals to 905–1239 million m³ in total irrigation water demand for an average year and 2330–3005 million m³ for the driest years for the whole region for the mid- and high-emission scenarios, respectively. This is a huge increase from the calculated IWD of 573 million m³ during an average year in the historical reference period.
- There is a large variability in irrigation demand between crops and years in the region. Per unit area, vegetables, potatoes, sugar beets, and fruit and berries require the most irrigation. However, in terms of total volumes, the largest demand comes from widely cultivated crops such as grains, ley. Hence, climate adaptation could also imply changed crop rotation and cultivation of less water demanding crops in a future climate. However, since the driest years were not found significantly drier but rather more frequent, this may attract investments in irrigation equipment. Our results show that at worst, an average year might become as dry as the driest year in 1981–2010.
- The region has great opportunities to increase crop production by irrigation already in the current climate. We found a considerable discrepancy between the volumes that are actually irrigated today and those required to optimize water access for crops. Currently, only about 3% of Sweden's freshwater use is for irrigation. However, achieving full crop optimization would require water use equivalent to 28% of Sweden's current freshwater consumption. If irrigation equipment is installed at large scale in the region, it must thus be preceded by local water accounting to ensure water availability for other users and ecology. More efforts must be put into assessing water availability and variability in the region, to search for opportunities to store water from high flow seasons in reservoirs. This will be even more critical with global warming and longer dry spells.

CRedit authorship contribution statement

Berit Arheimer: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Hugo Rudebeck:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Magnus Persson:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Maria Elenius:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Berit Arheimer reports financial support was provided by Swedish Research Council Formas. If there are other authors, they 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.1 HYPE model description

This Appendix gives a complementary overview of the HYPE model and more details for specific parts important to modeling soil water in order to estimate irrigation water demand. Complete and continuously updated documentation of the HYPE model is also found at the host maintaining the open-source code (e.g. Swedish Meteorological and Hydrological Institute, n.d.).

A.1.1 Stores and fluxes within and between sub-catchments

Spatial variability in water balance and fluxes across a landscape is simulated through meteorological forcing, topography,

hydrological response units (HRU; i.e. soil and vegetation types), human alteration and features of waterbodies along the river network (Fig. A.1). When setting up the HYPE model, a river-basin or catchment is divided into parts, not overlapping, called sub-basins, which are defined by topography. At each timestep, with driving through precipitation and temperature initiate alterations of the air-land-vegetation-soil-groundwater processes, which together with human withdrawals, discharges and dam regulations, cause a response in water storages in various compartments along the river network and eventually discharge at the sub-basin outlet. Normally the model runs with a daily or hourly time-step.

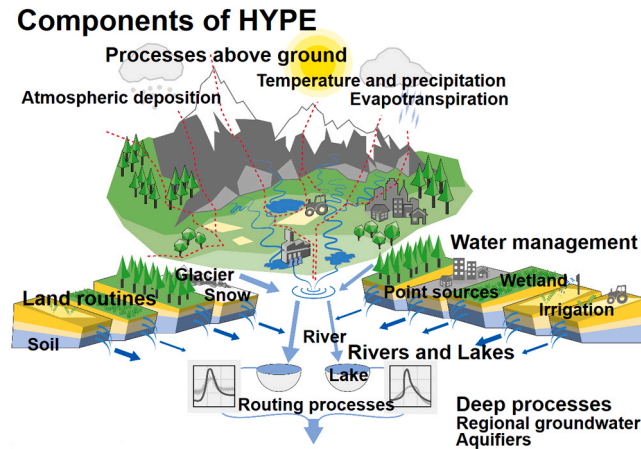


Figure A.1. The major components of the HYPE model that can be calculated within each sub catchment in the model domain

Upstream sub-basins contribute to a downstream sub-basin with an inflow to the sub-basin's main river. The sub-basin river network can be composed of the main river, a lake at the outlet of the sub-basin, and one conceptual local stream and lake that receive (part of) the runoff from the sub-basin's land. The land area of a sub-basin is divided into HRUs composed of combinations of land use, soil type and soil depth. The HRUs are normally not influencing each other; each responds to the forcing data (precipitation and air temperature) depending on the characteristics and parameters of the HRU. The surface waters (e.g. lakes, rivers and constructed ponds) depend on inflow from surrounding or upstream areas. They are calculated in series for the river network located within the sub-basin (Elenius et al., 2024; Lindström et al., 2010).

A.1.2 Driving variables

The driving variables in HYPE are temperature and precipitation. Both temperature and precipitation are adjusted for height within each sub-basin for the different HRUs. Interception losses are simulated as a reduction of the precipitation before it reaches the soil surface of an HRU. The HYPE parameter in question, p_{cluse} , depends on the land use and is defined as the removal fraction of precipitation, i.e. precipitation is multiplied by the factor $(1 - p_{cluse})$.

A.1.3 Processes affecting irrigation water demand

A.1.3.1 Evapotranspiration. Potential evapotranspiration is calculated for each HRU based on land use and atmospheric variables. The actual evapotranspiration is calculated as a fraction of a modeled potential evapotranspiration (ET_{POT}). The model in this paper uses HYPE's default model algorithm for ET_{POT} together with regional calibration. The algorithm is temperature and land use dependent, and has a sinusoidal seasonal adjustment (c_{season}). The regional correction factor $cevp_{corr}$, adjusts the rate in larger regions. HYPE does not simulate evaporation separate from transpiration, except within the irrigation routine which focuses on estimating the potential transpiration for irrigated crops (Table A.1) in agricultural HRUs. ET_{POT} is calculated for the top two soil layers, assuming an exponential decrease with depth, if the air temperature (t_{AIR}) is above a threshold (parameter $ttmp$). The potential evapotranspiration also depends on a rate parameter ($cevp$) which is landuse dependent (Eq. A.1). In addition to ET_{POT} , actual evapotranspiration of the land HRUs depends on the current soil moisture relative to field capacity, and is linearly reduced to be zero at the wilting point:

$$ET_{pot} = (cevp \times c_{season}) \times (t_{AIR} - ttmp) \quad (A.1)$$

The procedures in the irrigation routine estimating the potential transpiration and the threshold for water stress in agricultural HRUs are explained in the main text, section 2.2.2.

A.1.3.2 Soil water. In HYPE the soil routine can use up to three soil layers, and for the current study all agricultural HRUs were assigned three soil layers. The depth of each layer is 0.25 m for the first layer, 1 m for the second layer, and 2 m for the third layer for

agricultural HRUs (Strömqvist et al., 2012). The soil types associated with agricultural land use in our model setup are; sandy soils, loam, silt, silty clay loam and heavy clay, each with different water holding capacities. The soil physical properties in S-HYPE are based on the soil properties used in the Pollution Load Compilation for the Baltic Marine Environment Protection Commission (Johnsson et al., 2023) and then further refined in the model calibration process. The soil water routine in HYPE includes several different processes including runoff, infiltration, drainage, percolation, upwelling, saturated surface runoff and macropore flow.

A.1.3.3 Subsurface Runoff. Runoff depends on the water table in relation to the drainage level. Runoff occurs when soil water reaches above field capacity in the soil layers. Runoff depends on soil water in the effective porosity (also used to calculate the groundwater table) and a recession coefficient (rc). If the soil is not saturated, runoff from the soil layer depends only on the water of that soil layer ($soil(k)$ is the water content in soil layer k , $k=1-3$). Runoff occurs from all three soil layers ($runoff(k)$) down to the drainage level, which is the depth of the stream ($streamdepth$) (Eq. A.2).

$$runoff(k) = \{rc(k) \times (soil(k) - wp(k) - fc(k)) \quad wp(k) + fc(k) < soil(k) < wp(k) + fc(k) + ep(k) \quad 0 \quad soil(k) < wp(k) + fc(k) \quad (A.2)$$

where $wp(k)$ is the wilting point, $fc(k)$ the field capacity, and $ep(k)$ the effective porosity in soil layer k . For the soil layer at drainage level, e.g. in the third soil layer, and if the soil layer is not saturated, the runoff depends on the water level above the stream depth and (Eq. A.3) replaces (Eq. A.2).

$$runoff(k) = \{rc(k) \times \frac{deltah \times ep(k)}{soillayerthick(k)} \quad deltah > 0 \quad deltah < 0 \quad (A.3)$$

where

$$deltah = \frac{(soil(k) - wp(k) - fc(k))}{ep(k)} \times soillayerthick(k) - (soillayerdepth(k) - streamdepth) \quad (A.4)$$

where $soillayerthick(k)$ is the thickness and $soillayerdepth(k)$ the depth of the lower border of soil layer k . Soil layers that lie entirely below the stream depth have no groundwater runoff. If a soil layer is saturated the runoff of the soil layer depends also on the water in the soil layer(s) above. For example, if the drainage is in soil layer 3 and both soil layer 2 and 3 are saturated, the groundwater table in soil layer 1 determines the runoff of soil layer 3. The runoff is limited to the water above field capacity in the third layer though:

$$runoff(3) = MIN(soil(3) - wp(3) - fc(3), rc(3) \times \frac{deltah}{soillayerthick(3)} \times ep(e) \quad (A.4)$$

where

$$deltah = \frac{(soil(3) - wp(3) - fc(3)) \times soillayerthick(3)}{ep(3)} - (soildepth(3) - streamdepth) + \frac{(soil(2) - wp(2) - fc(2)) \times soillayerthick(2)}{ep(2)} + \frac{(soil(1) - wp(1) - fc(1)) \times soillayerthick(1)}{ep(1)} \quad (A.5)$$

If the stream depth is below the bottom of the lowest soil layer, the extra depth will act as a level to increase $deltah$ and the runoff from the lowest soil layer.

A.1.3.4 Infiltration. Infiltration is calculated from the sum of rain and snowmelt. Part of the available water for infiltration may not infiltrate into the soil, due to limitations by the soil's infiltration capacity and other properties of the soil. The calculation of actual infiltration will consider effects of surface runoff, macropore flow and frozen soil. If the infiltration rate is greater than a threshold ($mactrinf$, mm/timestep) then macropore flow and surface runoff may occur. In addition, the water in the upper soil layer needs to be larger than another threshold determined by a soil type dependent parameter multiplied by the water not available for runoff. The two flows are calculated as a percentage of the infiltration above the first threshold. If the finally calculated infiltration is greater than zero, it is added to the upper layer soil water. This is done regardless of whether there is space in the soil pores there or not. If the water exceeds the water pore volume it is assumed to lie on the ground, but it still belongs to the upper soil layer.

A.1.3.5 Drainage. Runoff in drainage pipes occurs when the water table (the percentage of filled pores of the effective porosity) rises above the pipe's depth, for agricultural classes a drainage depth of 0.95 m is assumed. Runoff depends on the groundwater surface elevation over the pipe ($deltah$, m), and a recession coefficient ($trrcs$). The recession coefficient depends on soil type, while drainage pipe level depends on the land-use class. The recession parameter is adjusted with the correction parameter ($rrccorr$) for different parameter regions:

$$trrcs = trrcs \times (1 + rrcscorr) \quad (A.6)$$

A.1.3.6 Percolation. The flow of water downwards through the soil layers is only possible for water over field capacity. For a frozen soil, percolation is only acting on the liquid water of the soil. A maximum percolation (mm/d) limits the flow between soil layers, there is one parameter limiting the percolation from the first soil layer ($mperc1$) and another parameter limiting the percolation from the second soil layer ($mperc2$), these parameters are soil type dependent. Flow is also limited by how much water the lower layer can receive.

Drainage from the first to the second soil layer is described by Eq. (A.7).

$$perc1x = MIN((soil(1) - wp(1) - fc(1), mperc1) \quad (A.7)$$

However, if there is not enough capacity in the second soil layer the drainage is according to Eq. (A.8) instead and fills the second soil layer.

$$perc1 = wp(2) + fc(2) + ep(2) - soil(2) + perc2 \quad (A.8)$$

Drainage from the second to the third soil layer can be at most what the third soil layer can receive (Eq. A.9) If the second soil layer does not reach field capacity with $perc1x$ added gives $perc2=0$. But if the second soil layer with $perc1x$ added exceeds field capacity then the percolation from the second soil layer becomes according to Eq. (A.10).

$$perc2x = MIN(soil(2) + perc(1) - wp(2) - fc(2), mperc2) \quad (A.9)$$

$$perc2 = MIN(soil(2) + perc1 - wp(2) - fc(2), perc2x) \quad (A.10)$$

A.1.3.7 Upwelling. Flow may enter the lowest soil layer, i.e. regional groundwater flow. Upwelling to soil layers above may occur if the soil layer is filled.

A.1.3.8 Saturated surface runoff

Surface runoff due to a high ground water table occurs when the water table in the upper soil layer reaches above the surface. It depends on a recession parameter ($srrcs$) which is dependent on land use. The recession parameter is corrected with the correction factor ($rrcscorr$) for different parameter regions. It is defined as an increase:

$$srrcs = srrcs \times (1 + rrcscorr) \quad (A.11)$$

$$surface\ runoff = MAX(srrcs \times (soil(1) - wp(1) - fc(1) - ep(1)), 0) \quad (A.12)$$

A.1.3.9 Macropore flow. Macropore flow occurs when the potential infiltration and water in the upper soil layer is large. It is caused by a limited infiltration capacity of the soil. Macropore flow is added to the layer in which the water table is located. The water is added to this layer only until it is full and the excess is trapped in the layer above.

A.2 Crops

Crop data was provided by the Swedish Board of Agriculture as field block data, containing geospatial information on the crop classes, which are used to monitor agricultural land and to administer agricultural subsidies in Sweden. The crops were categorized in groups with similar irrigation needs (Table A.1). This classification was made in collaboration with experts at the Swedish Board of Agriculture with regional know-how.

Table A.1
The crops categorized into similar crop groups

Crop	Crop group
Winter barley	Winter grain
Winter wheat	Winter grain

(continued on next page)

Table A.1 (continued)

Crop	Crop group
Winter triticale	Winter grain
Rye	Winter grain
Spring barley	Spring grain
Oats	Spring grain
Spring wheat	Spring grain
Spring triticale	Spring grain
Strawberry cultivation / Strawberry farming	Fruit and berries
Other berry cultivation / Other berry farming	Fruit and berries
Fruit cultivation / Fruit farming	Fruit and berries
Nurseries with cultivation of permanent crops	Fruit and berries
Legume or clover mixtures for forage/silage	Fodder crops
Maize	Fodder crops
Field peas	Fodder crops
Garden peas / Green peas	Fodder crops
Faba beans / Field beans	Fodder crops
Sweet lupins	Fodder crops
Protein crop mixtures (legume/cereal)	Fodder crops
Brown beans	Fodder crops
Vetch	Fodder crops
Chickpeas	Fodder crops
Soybeans	Fodder crops
Other beans	Fodder crops
Table potatoes	Potatoes
Starch potatoes	Potatoes
Sugar beets	Sugar beets
Fodder beets	Sugar beets
Cereals for forage/silage	Ley and grassland
Mown and grazed ley on arable land with a forage crop not eligible for agri-environmental support	Ley
Mown and grazed ley on arable land	Ley
1–2 year mown and grazed ley on arable land (for forage cultivation only)	Ley
Mown ley on arable land (under contract with forage drying plant)	Ley
Grass seed ley (annual)	Ley
Grass seed ley (perennial)	Ley
Clover seed ley	Ley
Forage crops	Ley
Oilseed rape	Winter oil plants
Turnip rape	Winter oil plants
Sunflowers	Winter oil plants
Oil crop trials / Experimental oil crops	Winter oil plants
White mustard	Winter oil plants
Oil radish	Winter oil plants
Linseed	Winter oil plants
Fibre flax	Winter oil plants
Vegetable cultivation	Vegetables
Culinary herbs and vegetable seed crops	Vegetables
Horticultural crops (excluding vegetables, fruit, and berries)	Vegetables

A.3 Climate model ensemble

The model ensemble used in the study contained combinations between five global circulation models (GCMs) and nine regional circulation models (RCMs) and two different model initializations for the different GCMs (Table A.2).

Table A.2

Climate model ensemble. The table shows the different model combinations of GCM, RCM and GCM model initialization and for which RCP they were run. Note that CLMcom-CCLM4–8–17 and CLMcom-BTU-CCLM4–8–17-cordex-reklies have the same RCM (CLMcom-CCLM4–8–17) but cordex-reklies is a project specific setup in the ReKliEs-DE project which is used for the RCP 8.5 scenario, the same applies to GERICS-REMO2015 and GERICS-REMO2015-cordex-reklies. This is the setup used in the Climate Change Scenario tool at SMHI (<https://www.smhi.se/en/climate/tools-and-inspiration/climate-change-scenario/about-the-scenario-tool>)

(continued on next page)

Table A.2 (continued)

GCM	ICHEC-EC-EARTH						MPI-M-MPI-ESM-LR						CNRM-CERFACS-CNRM-CM5			MOHC-HadGEM2-ES			NCC-NorESM1-M		
Initializati on	r12i1p1			r12i1p1			r1i1p1			r2i1p1			r1i1p1			r1i1p1			r1i1p1		
RCP	2.	4.	8.	2.	4.	8.	2.	4.	8.	2.	4.	8.	2.	4.	8.	2.	4.	8.	2.	4.	8.
RCM	6	5	5	6	5	5	6	5	5	6	5	5	6	5	5	6	5	5	6	5	5
CLMcom-CCLM4-8-17	x	x	x					x	x												
CLMcom-BTU-CCLM4-8-17-cordex-reklies							x														
CNRM-ALADIN63													x	x	x						
DMI-HIRHAM5	x	x	x													x	x	x			
GERICS-REMO2015	x	x														x	x		x	x	x
GERICS-REMO2015-cordex-reklies			x															x			
KNMI-RACMO22E	x	x	x										x	x	x	x	x	x			
MPI-CSC-REMO2009							x	x	x	x	x	x									
SMHI-RCA4				x	x	x	x	x	x							x	x	x	x	x	x

A.4 Validation data

For validation of the irrigation routine, regionally modeled irrigation volumes from S-HYPE were compared to independent irrigation estimates derived from a national survey conducted by The Swedish Board of Agriculture in 2016 (Table A.3).

Table A.3

Validation data for irrigation estimates derived from a national survey conducted by the Swedish Board of Agriculture in 2016. The survey

provided irrigated areas and estimated irrigation volumes per production region (PO18), without crop-specific information. Survey-based irrigation volumes were compared with modeled irrigation estimates from S-HYPE model using the reported irrigated areas

PO18	Irrigated area (ha)	Irrigation amount - survey (mm)	Irrigation amount - S-HYPE (mm)
1	14 155	96	73
2	23 421	88	84
3	4 883	82	70
4	2 175	71	65
5	2 571	83	79
6	822	93	115
7	2 694	108	68
8	7	152	92
9	287	72	43
10	70	115	83
11	156	35	14
12	147	9	21
13	59	36	2
14	-	-	-
15	-	-	-
16	-	-	-
17	-	-	-
18	-	-	-

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2026.103288](https://doi.org/10.1016/j.ejrh.2026.103288).

Data availability

The data that support the findings of this study are publicly available in Zenodo at [10.5281/zenodo.14778227](https://zenodo.org/record/14778227)

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