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Impacts of climate change on agricultural yield and the economic feasibility of adaptation in Sweden

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Climate change alters precipitation patterns and temperature. The impact thereof on agricultural yields varies across production seasons and crops. The purpose of this study is to examine the nonlinear effect of seasonal precipitation on the yields of winter wheat, spring wheat, oats, and spring barley using Swedish county-level data from 1979 to 2021. To this end, we use Poisson Pseudo-Maximum Likelihood regressions with high-dimensional fixed effects. Results show that increased precipitation during the early growing season enhances crop yields except for spring barley. Increased precipitation in the second, main growing season negatively affects all crops, but the magnitude of the impact is small compared to that in the early growing season. The impacts are generally more beneficial in the southern part of the country. Irrigation of winter wheat in the spring could be profitable for farms that own irrigation equipment, but for spring crops this would only be the case under extremely dry conditions. Results point to the need for well-tailored climate adaptation strategies.

Key words: costs, crop mix, irrigation, precipitation, revenues, season

Introduction

Climate change can negatively affect agricultural production through droughts, flooding, and high temperatures. The impact thereof on yields depends on the vulnerability of different types of crops to weather conditions, location, and the timing of weather events throughout the production season (Schlenker et al. 2007, Peltonen-Sainio et al. 2009, You et al. 2009, Eck et al. 2020, Wenng et al. 2020). The economic consequences for agricultural production depend on the value of different crops and farmers' adaptation possibilities in terms of crop choice, irrigation, and measures taken to improve water storage and drainage.

The Scandinavian countries, with their rainfed agricultural system, experienced substantial summer droughts in 2018 and 2022 alongside both droughts and flooding in 2023 (SMHI 2024). Even though there is a predicted overall increase in annual precipitation in northern Europe, Grusson et al. (2021) argue Swedish agriculture may need more irrigation to counterbalance within-year fluctuations in precipitation and temperatures. Based on simulation with a water-food-energy model, Campana et al. (2022) suggest that improved irrigation practices could increase crop yields in Sweden by 10–60% under conditions similar to those during the 2018 drought. However, the role of nonlinearities in the impact of weather events on yields and the economic implications for farmers' production choices are little studied (Wiréhn 2018).

Economic studies on climate change impacts on agricultural production typically use either modelling approaches or conduct econometric analysis on panel data. Using the former method, Nelson et al. (2014) show that although the mean biophysical yield effect of climate change could be a 17% reduction globally by 2050, adaptation could reduce yield loss to 11%, and increased crop areas could further help to limit consumption losses to 3%. Similar results are found at regional level for irrigated agriculture in California (Medellín-Azuara et al. 2011). Müller and Robertson (2014) predict a global decrease in crop yields for wheat, maize, rice, soybean, and groundnut, with reductions ranging from 10% to 38% by the year 2050 in the absence of adaptation. Using a multi-sectoral computable general equilibrium, Ciscar et al. (2011) show that the effects of climate change differ dramatically across different European regions, with Northern Europe benefitting economically as a result of the favourable effects on agriculture from increased annual precipitation. Harrison et al. (2016) and Schattman et al. (2021) point out that climate impacts on water availability and land use affect multiple sectors, emphasizing the need for knowledge for future water needs.

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Numerous studies use econometric techniques to quantify the impact of climate change on crop productivity. Several studies show the significance of nonlinearities in the impact of weather variables on crop productivity and agricultural profits (Reidsma et al. 2010, Chen et al. 2016, Zhang et al. 2017), while Zhang et al. (2017) illustrate the importance of accounting for an extended set of climatic variables, in particular humidity and wind speed. Based on Ricardian analysis, results in Van Passel et al. (2017) suggest that European farms, in particular those in Southern Europe, are negatively impacted by climate change, while Bareille and Chakir (2023) reach an opposite conclusion, arguing that French agriculture would benefit from warmer summers. Nainggolan et al. (2023) conclude that in the future, climate change is likely to lead to an increase in the area share of cereals at the expense of grasslands in the Scandinavian countries.

Few studies examine the role of the timing of precipitation over the production season on crop yields, given the different stages of the growing season as well as the harvesting season. Instead, most studies consider only the growing season. Exceptions include Wiréhn (2018) that qualitatively analyses the role of precipitation during harvest season and Kath et al. (2021) who find that higher precipitation and temperatures harm coffee bean production in both growing and harvesting season. The role of economic incentives for farm-level climate change adaptation in the boreal context is little studied, despite its importance given increased demand for food security planning following the decline in international security and the increase in the risk of climate change impacts on agricultural trade (Horn et al. 2022).

The objective of this study is to examine how changes in precipitation influence the yield of the four main cereal crops in Sweden: winter wheat, spring wheat, oats, and spring barley, measured in terms of kilograms per hectare (kg ha-1). We acknowledge that the impact of precipitation on crop yield varies across crops and throughout the early and main growing seasons as well as the harvest season. Moreover, we account for the possibility of a nonlinear effect of precipitation on yield because both water shortage and surplus could limit crop growth, and we assess spatial heterogeneity in impacts. Finally, we investigate whether changes in precipitation could serve as an economic motive for changing crop composition or increasing irrigation practices. Our analysis utilizes county-level panel data on agricultural yields per hectare for the period 1979 to 2021. The yield data is integrated with location-matched weather data, including precipitation, temperature, relative humidity, and soil moisture across both the growing and harvest seasons. The identification strategy takes advantage of the county-level plausibly exogenous variation in seasonal precipitation once county fixed effects and time-varying county-level characteristics have been considered. The economic trade-offs are illustrated using the identified nonlinear precipitation impacts in combination with data on crop prices and irrigation costs.

Material and methods

Data on agricultural yield

We extract annual data on agricultural yield, measured in kg ha^{-1}, from the Swedish Board of Agriculture database (Swedish Board of Agriculture 2023a). We choose to begin our analysis from 1979 to ensure consistency with the period covered by the weather data available. Our data therefore spans the period from 1979 to 2021 (43 years in total) and includes county-specific information for all 21 counties in Sweden. Not all crop yields are reported each year in all counties, as the Swedish Board of Agriculture omits yield statistics when there are too few farms cultivating a crop. Such observations are excluded from our analysis. The list of crops and associated number of excluded observations over the study period can be found in Table S1 in the Supplementary Material. We consider four main cereal crops: winter wheat, spring wheat, oats, and spring barley, that together covered 36% of the arable land in 2021. The harvest season for all these crops is similar, typically in August to September. This aligns with Weidow (2023), who notes small grains are usually harvested between August 10 and 25. While no official data on harvesting times exist, this period reflects common practice and may shift with weather, as warm, dry summers bring earlier harvests, and cool, wet ones delay them. In contrast, the timing of the early and main growing seasons varies. The former is essential for crop establishment, while the latter is essential for biomass development. Fogelfors (2001) reports that most agricultural land in Sweden is ready for planting between 20 March and 20 May, with minor exceptions near the mountains. Spring planting varies with weather and can differ even within counties, often starting earlier on the plains than in forested areas. Our proposed planting periods are therefore chosen to accommodate these realities. For winter wheat, the first (early) growing season is assumed to extend from April to May, while the second (main) growing season spans June to July. For spring wheat, spring barley, and oats, the first growing season is assumed to encompass April to June, with the second growing season occurring in July.

Data on weather variables

The weather dataset comprises monthly details on temperature (°C), precipitation (mm), relative humidity (%), and soil moisture (m^3m^{-3}), and spans from 1979 to 2021. To obtain this data, we utilize the GPS coordinates for individual counties in Sweden, employing ArcGIS for extraction. The gridded precipitation and temperature data originate from the Swedish Meteorological and Hydrological Institute (Swedish Meteorological and Hydrological Institute 2023). These weather data are gridded at a resolution of 4 km by 4 km (De Toro et al. 2015). The relative humidity and soil moisture data are obtained from the Copernicus Climate Change Service and are provided at a resolution of 0.25° by 0.25° (Copernicus Climate Data Store 2023). We merge the weather and yield data using the year and county identification number variables, creating an unbalanced panel. The locations of the counties in Sweden are shown in Figure 1.

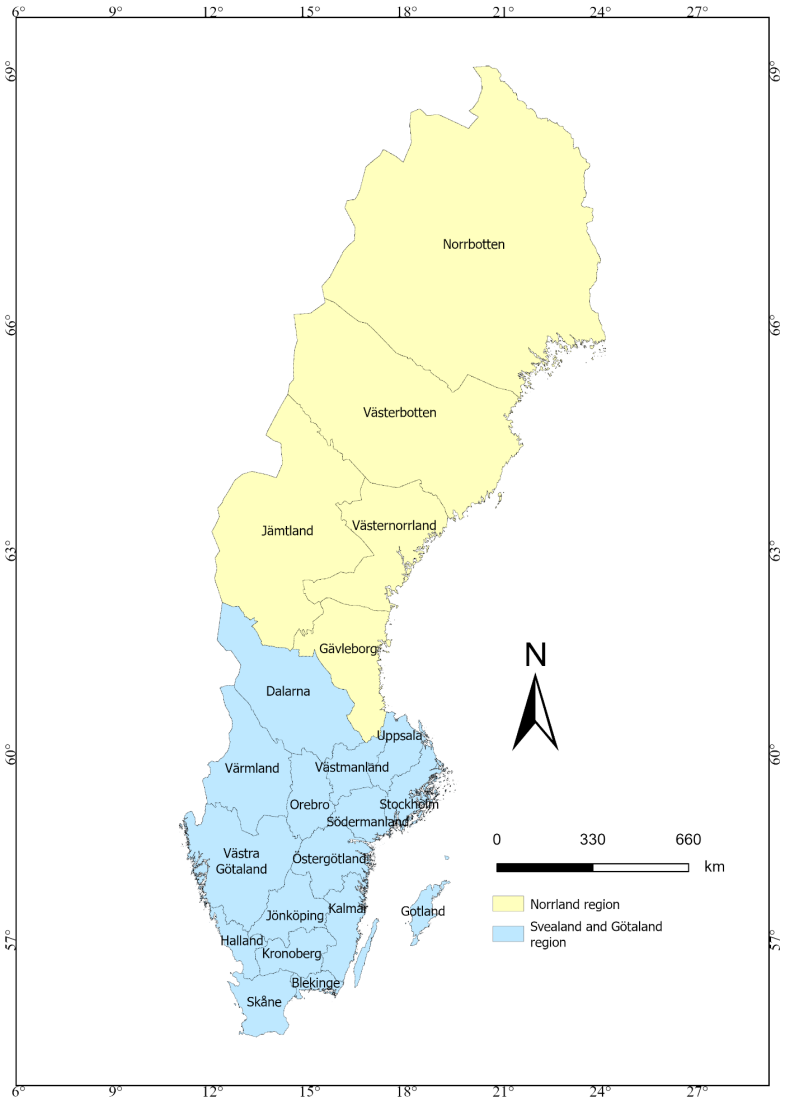

Fig. 1. The Swedish counties and regions

Summary statistics for yield and weather data

Table 1 presents the summary statistics. Panel A of Table 1 contains the county level and national average yields. We show that the yields of winter wheat, spring wheat, oats, and spring barley, averaged across counties and years, are 5 527, 4 322, 3 517, and 3 545 kg ha^{-1}, respectively. Given that larger areas are cultivated in counties with higher productivity, the national averages are higher, equalling 6 029, 4 505, 3 780, and 4 077 kg ha^{-1}, respectively. The national average yield figures are later used to translate estimated average percentage effects of seasonal precipitation into absolute changes in yield. Winter wheat is more common in regions with lower precipitation during the growing seasons, see panel B. All crops receive similar levels of precipitation during the harvest season.

Other weather factors vary across both the growing and harvest seasons and among crops. The summary statistics for the remaining weather variables are not reported here but are available on request.

Table 1. Summary statistics

	Winter wheat	Spring wheat	Oats	Spring barley
	Mean	Mean	Mean	Mean
	(Std.dev)	(Std.dev)	(Std.dev)	(Std.dev)
	(1)	(2)	(3)	(4)
Panel A: Crop yields (kg ha^{-1})				
Average across counties	5526.923	4321.740	3517.357	3544.569
	(1117.193)	(827.865)	(870.453)	(1003.406)
National average	6029.302	4505.349	3780.465	4076.744
	(803.994)	(534.925)	(548.244)	(598.795)
Panel B: Precipitation (mm)				
Growing season-1	45.697	54.647	54.647	54.647
	(16.427)	(14.880)	(14.880)	(14.880)
Growing season-2	77.935	83.322	83.322	83.322
	(27.092)	(39.794)	(39.794)	(39.794)
Harvest season	77.236	77.236	77.236	77.236
	(25.656)	(25.656)	(25.656)	(25.656)

Note: The data is based on observations spanning from 1979 to 2021. Standard errors are reported in parentheses.

Data on crop prices and irrigation costs

Average producer prices for the studied crops during the last 10 years (2015–2024) were obtained from the Swedish Board of Agriculture (2025a) and adjusted to the 2024 price level (Statistics Sweden 2025a, 2025b). The Swedish grain market follows global price trends, leading to price volatility (Engelmann 2014). We therefore use inflation-adjusted average prices in our calculations to reflect long-term economic conditions of Swedish producers. Average prices were calculated as monthly prices weighted with respect to delivered quantity and referring to normal quality at 14% water content and, for winter wheat, 11% protein content. Crops yields were allocated to bread and fodder grain quality based on estimates in Ugander et al. (2012). Based thereon, prices for winter wheat, spring wheat, spring barley, and oats equalled 2.16, 2.39, 2.06, and 1.75 SEK ha^{-1}, respectively.

Irrigation cost estimates were obtained from Gilbertsson (2019) and were deflated to 2024-year value using the agricultural producer price index obtained from the Swedish Board of Agriculture statistical database. The investment costs for irrigation then amount to 1 798 SEK ha^{-1}, while the operational cost of irrigating 30 mm ha^{-1} amounts to 300 SEK ha^{-1}, equivalent to 10 SEK mm^{-1} as reported in Gilbertsson (2019). Gilbertsson´s (2019) calculations build on the assumption that irrigation is carried out twice a year, with machinery having a lifetime of 15 years. The interest rate is set to 6 percent, argued to be relevant for a private agent that considers a partly risky investment. Gilbertsson (2019) notes that the cost per hectare is similar for farms with 100 and 200 hectares to be irrigated, suggesting that the scale of operations does not affect the above estimates in this range.

Model specification

We aim to identify the causal effect of precipitation on agricultural yield during the growing and harvest seasons. A crop inside a county serves as a unit of observation in the analysis. Precipitation has a causal effect under the identifying assumption that there is a random variation (Maccini and Yang 2009, Damania et al. 2020, Branco and Féres 2021, Kotz et al. 2022). Our analysis applies a technique called Poisson Pseudo-Maximum Likelihood regression with a high-dimensional fixed effects (PPML-HDFE) model. Previous studies recommend this model when the dependent variable consists of non-negative data and the model specification includes a battery of fixed effects. The model does not require specifying a distribution for the dependent variable and is not limited to count data (Correia et al. 2020). Additionally, this method has been shown to provide consistent estimator, even in the presence of heteroscedasticity and measurement errors (Silva and Tenreyro 2006). We estimate variations of the

following PPML-HDFE specification in the baseline regression:

$$Yield_{cist} = \beta_1 P_{cist} + \beta_2 {P_{cist}}^2 + \alpha_1 T_{cist} + \alpha_2 H_{cist} + \alpha_3 S_{cist} + \delta_c + \emptyset_{ct} + \varepsilon_{cist}, \quad (1)$$

where $Yield_{cist}$ is agricultural yield in kg ha^{-1} in county *c*, for crop *i*, during agricultural season *s* in year *t*. Three seasons are considered: the first and second growing periods, and the harvest period. We analyse the effects of precipitation across the three seasons to obtain unbiased estimates. Insufficient precipitation during either of the growing seasons can result in decreased yield while excessive rainfall gives rise to challenges, including delayed field operations, fungus attacks, reduced nutrient use efficiency, flooding, and an increased risk of soil compaction. Moreover, high precipitation during harvest may lead to reduced yield by shortening the available harvest days and obstructing harvest operations (De Toro et al. 2015). Hence, too little or too much precipitation could be expected to lead to smaller yields than intermediate levels of precipitation, motivating the use of a quadratic functional form in Eq. (1).

The variable P_{cist} refers to the average precipitation measured in millimetres over the growing and harvest seasons. The expression ${P_{cist}}^2$ denotes the square of precipitation during each season and captures nonlinearities in the impact, shown to be significant by, e.g., Schlenker and Roberts (2006), Chen et al. (2016), and Jessoe et al. (2018). The term T_{cist} stands for average temperature measured in °C, H_{cist} denotes relative humidity (%), and S_{cist} is soil moisture (%). The term δ_c is a time-invariant county-level fixed effect, which is used to account for county-level heterogeneity, such as soil quality, topography, infrastructure (e.g., roads and irrigation systems), quantity and quality of agricultural machinery, and farmers dependence on agricultural activity for their income (Li et al. 2016).

To facilitate the statistical computations related to multiple fixed effects, the 43 years are grouped into 5 decades: [1979,1988], [1989,1998], [1999,2008], [2009,2018], and [2019,2021]. Depending on the specific model specification, $\emptyset_{ct}$ incorporates either county-by-decade fixed effects or county-specific linear time trends into the analysis. We employ county-by-decade fixed effects to control for county-specific unobservables that vary over time, such as soil properties potentially evolving differently across counties due to localized variations in climate change impacts; the development of county-specific production practices; input prices; the quality of seasonal weather forecasts (Jagnani et al. 2021), and pest outbreaks. County-specific linear time trends, on the other hand, capture long-term, linear changes in yield within each county over time, such as a consistent increase in yield in a specific county due to the successive adoption of new farming technology. It can be noted that simple time fixed effects overlook the possibility of county specific developments and, therefore, are not used in our estimations. The term ε_{cist} denotes model error terms. The identifying assumption is that, once we control for county and decade fixed effects, any remaining seasonal variations in weather are considered to be random. This assumption enables a causal interpretation of the coefficients, as they represent the impact of climate change on agricultural yield. Standard errors are clustered at the county level to account for spatial correlation within counties, following the approach recommended by Abadie et al. (2022).

We carry out robustness exercises exploring alternative methods, e.g., a linear regression with a large dummy-variable set. Such a model is well-suited for situations where we need to control for categorical variables with a fixed number of groups (StataCorp 2023), such as the 21 counties in Sweden. Another robustness test utilizes a panel fixed effects model to eliminate time-invariant characteristics that might confound the estimates (Garg 2019). Finally, the standard errors are adjusted to account for spatial clustering across Swedish counties.

Results and discussion

We commence with the baseline findings, which assess the impact of precipitation on crop yields throughout both the growing and harvest seasons. Sensitivity analysis is performed to validate the robustness of the baseline results, followed by an analysis of spatial heterogeneity. Finally, we examine economic trade-offs in crop choice and irrigation.

Baseline results: Crop- and season-specific yield responses to precipitation

We estimate Eq. (1) to obtain the baseline results for the growing and harvest seasons. Two specifications are considered for each crop, differing in variables reflecting time-varying county-level characteristics. The first (odd-numbered) columns for each crop include county-by-decade-fixed effects, while the second (even-numbered) columns use county-specific time trends. Table 2 provides the seasonal effects of climate change on agricultural

yield for all the four crops. Our preferences lie with the first specifications as county-by-decade-fixed effects enable researchers to control arbitrary unobserved county-specific confounding factors (i.e., shocks that may not follow a linear pattern) over time (Jagnani et al. 2021, Liu et al. 2023).

Based on our preferred estimates, the findings suggest that increased precipitation during the initial growing season (referred to as precipitation growing-1) affects crop yields, with both linear and nonlinear terms being significant, see columns 1, 3, 5, and 7. We calculate the marginal effect of precipitation on crop yields including only statistically significant linear and/or quadratic coefficients. Thus,

$$dYield_{cist}/dP_{cist} = 100(\beta_1+2\beta_2 P_{cist}) \; or \; 100(\exp(\beta_1+2\beta_2 P_{cist}) - 1),$$

evaluated at the mean precipitation level for each crop (cf. panel B, Table 1). The estimates imply that a 1 mm rise in precipitation during the first growing season increases the yields of winter wheat, spring wheat, and oats by about 0.47%, 0.01%, and 0.15%, respectively, while decreasing spring barley yield by about 0.01%. Based on average national yields (cf. panel A, Table 1), this translates into an increase of 28.33 kg ha^{-1} for winter wheat, 0.45 kg ha^{-1} for spring wheat, and 5.67 kg ha^{-1} for oats, and a reduction of 0.41 kg ha^{-1} for spring barley.

The negative impact on spring barley is consistent with previous research findings showing that more early-season precipitation can reduce barley yields (Hakala et al. 2012), for example due to its lower waterlogging tolerance compared to wheat (Xu et al. 2022) and its roots becoming more susceptible to fungal pathogens (Sapkota et al. 2023) under wet conditions. Another reason is that delayed sowing of barley, due to wet conditions, shortens its growing period and risks lowering yields (Lu et al. 2017). Moreover, spring wheat grows mostly on specific fertile soils with medium clay and high humus content, making the crop robust to weather variations. Oats grow on more varied soils that are often more drought-sensitive (Fogelfors 2001). These differences likely explain the greater impact of precipitation on oats compared to spring wheat.

For the second growing season (referred to as precipitation growing-2 in Table 2), we find significant positive coefficients for the linear precipitation term and significant negative coefficients for the nonlinear term in the case of winter wheat (column 1). For spring wheat, oats, and spring barley, there is a significant negative linear relationship between second growing season precipitation and yield, while the quadratic term is insignificant, see columns 3, 5, and 7. Evaluated at the mean levels of precipitation, the estimates suggest that a 1 mm increase in precipitation during the second growing season reduces yields by about 0.10% for winter wheat, 0.11% for spring wheat, 0.14% for oats, and 0.10% for spring barley. This corresponds to a decrease by 6.03 kg ha^{-1} for winter wheat, 4.96 kg ha^{-1} for spring wheat, 5.29 kg ha^{-1} for oats, and 4.08 kg ha^{-1} for spring barley. Our results on spring crops can be compared with the results in Sjulgård et al. (2023), where it is concluded that yield losses for spring-sown cereals during years with extremely dry summers are about 16%. Our results suggest that for summers with a precipitation similar to the drought year 2018, a reduction by 44 mm in the second growing season compared to the mean would reduce spring crop harvests by 20–28%. The higher effect in our study is likely attributed to this study's consideration of nonlinearity in the impact.

The results further show that increased precipitation during the harvest period has a weak, linear positive effect on the yield of winter wheat only (column 1). The finding indicates that a 1 mm increase in precipitation during harvest season above the average leads to a winter wheat yield boost of roughly 0.12%, equivalent to an increase of about 7.24 kg ha^{-1} in the national average yield. This contradicts findings of Eckersten et al. (2008). There are no significant effects on the other crops. This unexpected result motivates the heterogeneity analysis conducted in the manuscript. Results further show that higher temperature during the first growing season reduces spring wheat and oats yields, while it negatively affects the yields of all crops during the second growing season. Higher temperature during the harvest season do not affect any of the crop yields.

In the presence of nonlinearity, the impact of a 1 mm change in precipitation on yields will vary with the level of precipitation. We calculate the marginal impact of precipitation on yields as described above for a seasonal precipitation ranging from –30 to +30 mm compared to the mean, see Figure 2. This range on precipitation is chosen because 30 mm is a standard amount of irrigation on a single occasion (Gilbertsson 2019). Result shows that although increased precipitation in the first growing season is beneficial at mean precipitation levels for spring wheat and oats, the marginal effect becomes negative for increases >5 mm. For winter wheat, negative marginal effects are only found for precipitation increases >27 mm. For the second growing season, nonlinearity is only of importance for winter wheat, where the marginal effect is positive when precipitation is reduced by more than 26 mm, while it is otherwise negative. Nonlinearity in precipitation impact is not of empirical importance for any crop during the harvest season.

Table 2. Season-specific effects of climate change on agricultural yield: PPML-HDFE model.

	Winter wheat		Spring wheat		Oats		Spring barley	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Precipitation growing-1	0.01293***	0.01253***	0.01213***	0.01115***	0.01571***	0.01451***	0.01409***	0.01257**
	(0.00208)	(0.00210)	(0.00366)	(0.00364)	(0.00363)	(0.00394)	(0.00506)	(0.00544)
Growing-1 squared	-0.00009***	-0.00009***	-0.00011***	-0.00009***	-0.00013***	-0.00012***	-0.00013***	-0.00012**
	(0.00002)	(0.00002)	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00004)	(0.00005)
Precipitation growing-2	0.00208**	0.00223**	-0.00111**	-0.00093*	-0.00137**	-0.00147***	-0.00095*	-0.00102**
	(0.00085)	(0.00097)	(0.00050)	(0.00052)	(0.00057)	(0.00049)	(0.00052)	(0.00049)
Growing-2 squared	-0.00002***	-0.00002***	-0.00000	0.00000	-0.00000	-0.00000	-0.00000	-0.00000
	(0.00000)	(0.00001)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Precipitation harvest	0.00118*	0.00087	0.00075	0.00110	-0.00061	-0.00070	0.00049	0.00028
	(0.00062)	(0.00078)	(0.00115)	(0.00113)	(0.00118)	(0.00106)	(0.00101)	(0.00103)
Harvest squared	-0.00001	-0.00000	-0.00001	-0.00001	0.00000	0.00000	-0.00000	-0.00000
	(0.00000)	(0.00000)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
Observations	556	559	447	454	731	734	857	858
Other weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-by-decade-fixed effects	Yes	No	Yes	No	Yes	No	Yes	No
County-specific time trends	No	Yes	No	Yes	No	Yes	No	Yes

Note: The dependent variables are agricultural yields in a specific county for the four crops indicated in the column headings. The results in columns 1–8 are derived from a Poisson Pseudo-Maximum Likelihood regression with a high-dimensional fixed effects model. Other weather controls include temperature, relative humidity, and soil moisture throughout both the growing seasons 1 and 2, as well as during the harvest period. Robust standard errors, clustered at the county level, are presented in parentheses. *** $p< 0.01$, ** $p< 0.05$, * $p< 0.10$

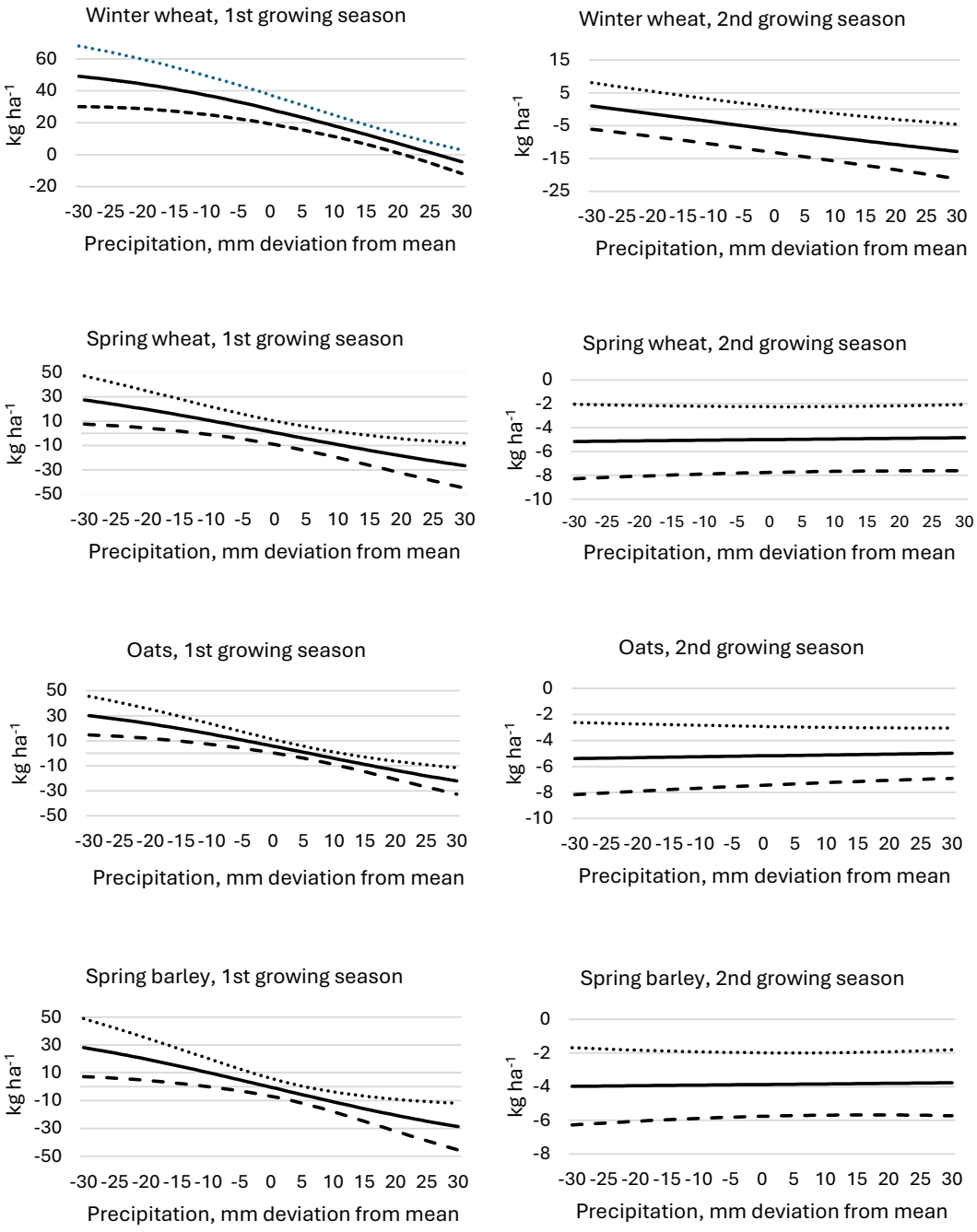

Fig. 2. Marginal impact on crop yield in kg ha^{-1} due to a 1 mm increase and decrease in precipitation in the first and second growing seasons for different deviations in precipitation from the mean. The solid graph indicates the predicted effect, the dotted and dashed graphs indicate, respectively, the upper and lower bounds of the 95% confidence interval related to the impact of precipitation on yields.

Robustness tests

We assess the robustness of the baseline estimates as follows. First, we re-estimate the PPML-HDFE model in Eq. (1) with county-specific linear time trends instead of county-by-decade fixed effects. The results are similar to those above. Second, we estimate a linear regression with a large dummy-variable set, see Table S2 in the Supplementary Material. The baseline results are robust to this exercise, except for precipitation during the harvest season, where no effect is observed. The third robustness check employs a panel fixed effects model, see Table S3. Our main conclusions remain mostly robust, in particular for the first growing season. The fourth robustness check addresses the issue of spatial clustering in standard errors, with results being reported in Table S4 in the Supplementary Material. Spatial correlations in yield could, for example, be caused by crop disease outbreaks.

A failure to consider spatial correlation among the error terms can potentially lead to underestimating the true variance-covariance matrix, resulting in overestimation of t-values (Schlenker et al. 2006). Our robustness test adjusts standard errors to account for spatial dependence, following Conley (1999) and Hsiang (2010). Assuming spatial autocorrelation with a lag of 1 and utilizing, alternatively, a 200 km and 400 km cutoff distance, we find that outcomes align closely with the baseline findings above. Finally, we examine the effects of season-specific interactions between temperature and precipitation on yield, finding that the associated coefficients are not significant. These results are not reported in this paper.

Heterogeneity

The effects of precipitation could vary across space. We therefore explore whether the effects differ between two geographic regions in Sweden: Svealand and Götaland (the southern region) on one hand and Norrland (the northern region) on the other. The former includes the counties of Blekinge, Dalarna, Gotland, Halland, Jönköping, Kalmar, Kronoberg, Skåne, Stockholm, Södermanland, Uppsala, Värmland, Västmanland, Västra Götaland, Örebro, and Östergötland. The latter includes the counties of Gävleborg, Jämtland, Norrbotten, Västerbotten, and Västernorrland, see Figure 1. Since winter wheat cultivation is limited in northern Sweden, this region serves as a reference category. This segmentation into two regions is motivated by farmers in the northern part of the country having to choose among a narrower set of crop varieties, because plant breeding activity and the development of new cultivars tends to be strongly related to the size of agricultural area and the economic strength of the sector in a region (cf. e.g., Solberg and Breian 2015). Also, farmers in south Sweden can benefit from the development of new cultivars in other countries in the Baltic Sea region with a large agricultural sector such as Denmark and Germany, whereas these cultivars may not be suitable for the northern part of the country.

Table 3 presents the findings related to the specific coefficient of concern, i.e. the interaction between the Svealand and Götaland region with precipitation in the three different seasons. The Norrland region serves as the baseline category. The results generally show that yields are less sensitive to changes in precipitation in the Svealand and Götaland region compared to Norrland. Exceptions to this are the impacts on spring barley in the first growing season and winter wheat in the second growing season, where effects are amplified. When heterogeneity is considered, there is no significant effect on winter wheat of precipitation in the harvest season.

We check whether these findings are biased by the exclusion of missing observations using the three-step approach proposed by Chamberlin and Ricker-Gilbert (2016). First, we estimate a probit model to assess the effects of weather variables and fixed effects on the likelihood of observing a particular crop yield. Second, we obtain the predicted probabilities (P_i) and compute inverse probability weights (IPW) as ($1/P_i$). Third, we re-estimate the crop yield model in Eq. (1) using the IPW as weights. The results, reported in Table S5, show that the estimated coefficients with IPW are generally similar to those without the weights, indicating that the excluded observations do not bias our estimates. We also examined heterogeneity in the effects across the eight NUTS II (Nomenclature of Territorial Units for Statistics) regions. This analysis confirmed the presence of spatial heterogeneity but results are not presented here. Decreased degrees of freedom and multicollinearity issues lead to the exclusion of certain NUTS II units in each specification.

Table 3. The effects of precipitation on crop yields: Regional differences

	Winter wheat	Spring wheat	Oats	Spring barley
	(1)	(2)	(3)	(4)
Precipitation growing-1	0.01367***	0.01266***	0.01392***	0.00888*
	(0.00189)	(0.00372)	(0.00362)	(0.00457)
Precipitation growing-1 squared	-0.00009***	-0.00011***	-0.00013***	-0.00014***
	(0.00002)	(0.00003)	(0.00003)	(0.00004)
Precipitation growing-2	0.00204**	-0.00209***	-0.00269***	-0.00253***
	(0.00093)	(0.00047)	(0.00051)	(0.00054)
Precipitation growing-2 squared	-0.00002***	-0.00000	-0.00000	-0.00000
	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Precipitation harvest	0.00098	-0.00059	-0.00317**	-0.00151*
	(0.00071)	(0.00105)	(0.00137)	(0.00080)
Harvest squared	-0.00001	-0.00001	0.00000	0.00000
	(0.00000)	(0.00001)	(0.00001)	(0.00000)
Svealand-Götaland * precip growing-1	-0.00076*	-0.00051	0.00213	0.00776***
	(0.00045)	(0.00094)	(0.00132)	(0.00216)
Svealand-Götaland * precip growing-2	0.00004	0.00099***	0.00156***	0.00164***
	(0.00065)	(0.00018)	(0.00031)	(0.00027)
Svealand-Götaland * precip harvest	0.00020	0.00140***	0.00291***	0.00203***
	(0.00030)	(0.00026)	(0.00091)	(0.00047)
Observations	556	447	731	857
Other weather controls	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes
County-by-decade-fixed effects	Yes	Yes	Yes	Yes
County-specific time trends	No	No	No	No

Note: The dependent variables are agricultural yields in a specific county for the four crops indicated in the column headings. The results in columns 1–4 are derived from a Poisson Pseudo-Maximum Likelihood regression with a high-dimensional fixed effects model. Other weather controls include temperature, relative humidity, and soil moisture throughout both the growing seasons 1 and 2, as well as during the harvest period. The regression models also incorporate whether a specific county belongs to the Svealand and Götaland region (coded as 1 if yes). The Norrland region of Sweden is taken as the reference category. Robust standard errors, clustered at the county level, are presented in parentheses. *** $p< 0.01$, ** $p< 0.05$, * $p <0.0$

Economic implications

We first examine how changes in precipitation up or down by 30 mm from the mean in the first growing season affect crop revenues. The focus on this season is motivated by the substantially higher impact of changes in precipitation. To calculate the yield impact, we use the marginal impacts (see Fig. 2), taking the national average yield (see Table 1) as a point of departure. Yields are then multiplied by the respective crop prices. Results show that if precipitation is reduced (increased) in the early growing season, i.e. because of climate change, this would have a larger negative (positive) impact on revenues for winter wheat than for other crops, providing an incentive to alter the crop composition. Second, the findings show that if precipitation is 30 mm below the mean, irrigation by 30 mm has the potential to increase revenues from winter wheat yields by 2 631 SEK ha^{-1}, cf. Figure 2. A corresponding amount of irrigation would in the same situation only increase revenues for spring crops by between 935 and 1 081 SEKha^{-1}. The higher the level of precipitation, the smaller are the economic gains from irrigation, explained by the nonlinear relationship between precipitation and yields.

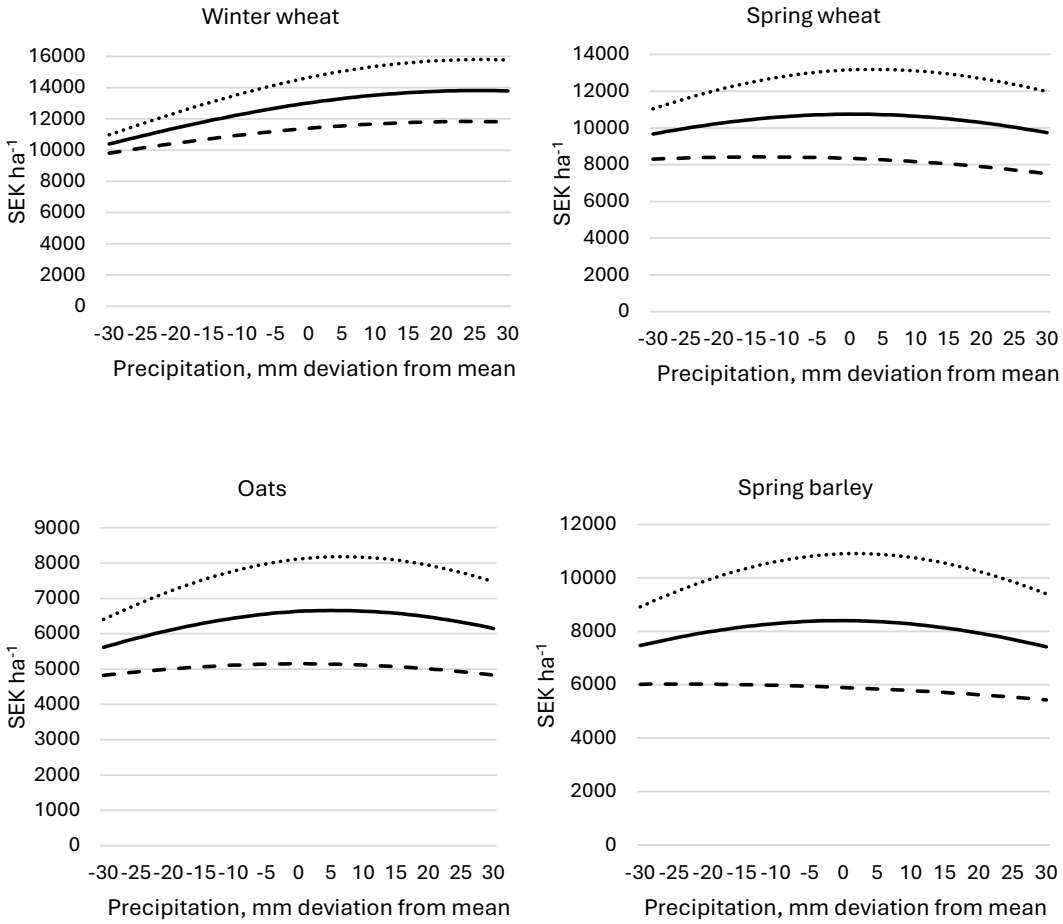

Fig. 3. Impact of increased and decreased precipitation by up to 30 mm in the first growing season, SEKha^{-1}. The solid graph indicates the predicted effect, the dotted and dashed graphs indicate, respectively, the upper and lower bounds of the 95% confidence interval.

However, irrigation also implies a cost, raising the question of the economic viability. We calculate net revenues from irrigation by 30 mm when (i) precipitation in the early growing season is 30 mm below the mean, and (ii) precipitation in the early growing season is equal to the mean. In addition, we consider whether a farmer possesses irrigation equipment, therefore incurring only the variable costs, or if investment in such equipment is necessary, see Table 4. Results show that a farmer who already possesses irrigation equipment would make a profit from irrigation for all crops when precipitation is 30 mm below the mean, with the highest profits being obtained for winter wheat. Irrigating the same amount in a year with a mean level of precipitation, the corresponding net revenues would remain positive for winter wheat but turn negative for spring crops. If a farmer needs to purchase irrigation equipment, irrigation by 30 mm would remain profitable for winter wheat in the extremely dry early growing season. However, it should be noted that for this to hold in practice, the investment costs would need to be distributed across a sufficiently large, irrigated area, and may therefore only be relevant if climate change leads to a high frequency of such dry early seasons. At the mean level of precipitation, the net revenues for winter wheat would be negative if irrigation equipment must be purchased. For spring crops, the economic outcome would be generally negative if investments were needed.

Table 4. Net revenues in SEKha^{-1} of irrigation by 30 mm in the early growing season for farms possessing irrigation equipment, for different levels of precipitation.

		Winter wheat	Spring wheat	Oats	Barley
Farm owns irrigation equipment	Net revenue when precipitation is 30 mm below mean, SEKha^{-1}	2331	782	720	635
	Net revenue when precipitation is at the mean, SEK ha^{-1}	768	-1313	-783	-1283
Farm needs to purchase irrigation equipment	Net revenue when precipitation is 30 mm below mean, SEKha^{-1}	533	-1016	-1078	-1163
	Net revenue when precipitation is at the mean, SEK ha^{-1}	-1330	-3111	-2581	-3081

Consistent with these results, only around 3% of the total acreage of winter crops is currently irrigated, while farms owning irrigation equipment irrigated around 22% of their winter crop acreage in 2023 (Swedish Board of Agriculture 2023b). Somewhat surprising perhaps, these farms also irrigated 20% of their spring crop acreage in the same year, potentially explained by the extreme weather conditions in that year. Also, the effect of precipitation and irrigation on spring crops might vary with local growing and climate conditions that are not fully reflected in our county-level data. In contrast, winter wheat is typically grown on the plains in the southernmost part of the country, i.e., Götaland, with less variable growing conditions.

The farms that are likely to possess irrigation equipment are those for which irrigation is known to be profitable, i.e. farms that cultivate potatoes, sugar beets, and field grown vegetables. These farms are typically located in the southernmost part of the country. For them, irrigation of winter wheat in the spring could be profitable for a wide range of precipitation levels. Although such farms only represented around 2.5% of all farms in 2023 (Swedish Board of Agriculture 2025b), their total acreage of winter wheat in the same year equalled 99 386 ha, corresponding to around 17.3% of the total acreage of winter wheat (Y. Olsson, Swedish Board of Agriculture, 25 February 2025, pers. comm.), supporting our results.

Conclusions

Our findings show that increased precipitation during the early growing season positively impacts the yields of winter wheat, spring wheat, and oats, but negatively affects spring barley, with the largest effect observed for winter wheat. Increases in precipitation during the main growing season adversely influences all crop yields but the magnitude of the impact is small compared to that in the early growing season. The impacts of deviations in precipitation from the mean are generally more beneficial in the southern part of the country.

Examining the economic implications, our results suggest that if climate change leads to reductions in precipitation during the early growing season, this would have a larger negative impact on winter wheat revenues compared to other crops, providing incentives for shifting to other crops. Irrigation of winter wheat by 30 mm in the early growing season could be profitable for farmers possessing irrigation equipment already at the mean level of precipitation in our data, and even more beneficial if precipitation falls below the mean. At present, farmers cultivating specialty crops such as potatoes, sugars beets, and field grown horticultural crops are those that tend to possess such equipment, and statistics available from the Swedish Board of Agriculture (2023b) confirms that such farms irrigate a larger share of their winter grain acreage than other farms. The results suggest that investments in irrigation of winter wheat, and irrigation of spring crops on farms that possess irrigation equipment, would only be economically relevant if precipitation in the early growing season is substantially below mean level. To further explore the economic potential for irrigation of spring crops, data with a higher spatial resolution could be needed. Also, for farms to be resilient to extreme weather, it is necessary to jointly consider precipitation and the options to adapt through irrigation, stress-resistant crops, and adjusted fertilizer and pesticide use (Hakala 2020).

Extreme weather events such as droughts and large amounts of precipitation can often affect neighbouring countries in a similar manner as Sweden, and if sufficiently widespread, such events can affect relative prices of different cereal crops. Such changes in crop prices are not considered in our calculations. European studies taking climate induced price adjustments into account, such as Hristov et al. (2020), have so far not considered differential impacts of precipitation across the agricultural year, or differential impacts on winter and spring wheat, such as those shown in this study. It can therefore be important to analyse the implication of such differential impacts in future analyses of the impact of climate change on European cereal markets. Also, if many Swedish farmers would find irrigation profitable, this could become a challenge for other water-dependant sectors, necessitating further research on efficient water allocation across sectors and policy instruments that can achieve that.

Our study has limitations. For example, due to lack of data, we are not able to fully account for the variation in the timing of crop planting and harvesting across space and time. Although fully separate county-level analyses could provide more localized insights, our current modelling framework does not support such granularity. We acknowledge this as a limitation and suggest that future research could build on our approach through more spatially detailed analyses. The combination of the three seasons with a spatial disaggregation of the country into two large regions has also limitations: the Norrland region has few observations and the difference in the timing of seasons in Götaland and Svealand is not obvious, given that some parts of Götaland are geographically close to Svealand and the highlands of Småland in Götaland experience a later spring than surrounding areas. In addition, the start and end of agricultural seasons may fluctuate yearly. Further, one can note that the data availability

in the Scandinavian countries (see also Mohammadi et al. [2023] and Sjulgård et al. [2023]) differs substantially from that in the United States, where detailed, state- and crop-specific actual planting and harvesting dates are available (U.S. Department of Agriculture 1997). Hence, there is a need for improved official data in the Scandinavian countries to support analysis of climate change adaptation in agriculture. Finally, we do not examine measures to counteract flooding and wet spells. While almost all arable land in Sweden is drained and cover trenching is judged to be profitable (Board of Agriculture 2013), the drainage needs maintenance on about 25% of the land (Board of Agriculture 2016). The yield effect of such maintenance and hence the economic benefits can be expected to depend on soil type as well as precipitation and temperature. Other measures to prevent flooding and wet spells could also be relevant, such as buffer strips, cover crops, and hedges. The yield benefits and economic consequences thereof under different climatic conditions have not been quantified. This suggests that further research on the topic should be undertaken. Finally, our results underscore the importance of encouraging farmers to transition to crops that are more robust to extreme weather conditions and for the government to provide economic incentives for plant breeders to increasingly develop robust cultivars of cereals considering the varying climatic conditions from south to north.

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We utilized ChatGPT-4 to improve spelling and grammar. However, the authors have thoroughly reviewed the content and retain full responsibility for it.

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