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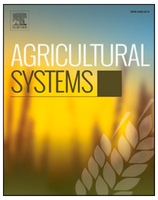

# Relationships between weather and yield anomalies vary with crop type and latitude in Sweden

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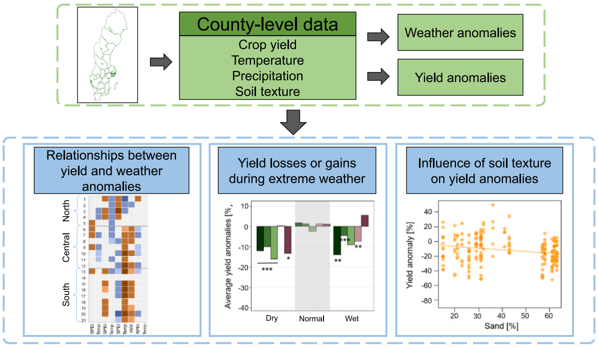
## HIGHLIGHTS

- The impacts of seasonal weather anomalies and soil texture on crop yields were assessed in this study.
- Years with extreme weather during summer resulted in the largest average yield losses.
- Spring-sown crops were more negatively affected by extreme weather than autumn-sown crops.
- Strategies for adapting crop production to future climate must consider differences between crop species and locations.

## GRAPHICAL ABSTRACT



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## ABSTRACT

*CONTEXT:* Information on how crop yields are affected by weather variations and extreme weather is needed to develop climate adaptation measures for arable cropping systems. Here, we analysed the effects of weather anomalies and soil texture on crop yield anomalies across Sweden from 1965 to 2020.

*OBJECTIVE:* The aims of this study were to (i) assess the effects of temperature and precipitation anomalies and extreme weather on crop yield anomalies for major field crops across Sweden, (ii) quantify how crop responses to weather anomalies vary along the north-south climate gradient across Sweden, and (iii) elucidate the impacts of soil texture on yield responses to weather anomalies.

*METHODS:* We used daily mean air temperature, daily total precipitation, soil texture and crop yield data from public databases covering all 21 counties in Sweden. Yield data was detrended to account for the effects of agricultural intensification on crop productivity. To assess seasonal weather influences on crop yields, temporal trends of daily average temperature and daily total precipitation were detrended for each season containing a three-month period. We also used a water balance index and a heat wave index to evaluate the impact of extreme weather.

*RESULTS AND CONCLUSIONS:* Our analyses showed that years with extreme weather during summer (i.e. heat waves, drought or water excess) resulted in the largest negative yield anomalies. Spring-sown crops were more negatively affected by extreme weather compared to autumn-sown crops, which we associate with differences in

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the lengths of the growth period for autumn- and spring-sown crops. Effects of soil texture on yield anomalies were found for spring-sown cereals, where negative effects of drought were exacerbated with increasing sand content. Moreover, we showed that the effects of weather conditions on crop yield anomalies differed between different regions within the country. In northern Sweden, crop yields were more sensitive to excess water, while drought effects were more pronounced in southern Sweden. Similarly, increased summer temperatures favoured crop yields in northern Sweden but had a negative impact on crop yields in the southern part of the country.

*SIGNIFICANCE:* Our study demonstrates that weather impacts on yields vary between crops and locations, and that adaptation to future climate will require crop- and site-specific strategies.

## 1. Introduction

Crop production is highly sensitive to weather variations, and the increased frequency and severity of extreme weather events associated with climate change have a significant impact on global crop productivity (Powell and Reinhard, 2016; Lesk et al., 2022; Monteleone et al., 2022). This poses a major challenge to food production, as one-third of crop yield variability is suggested to be explained by weather variability (Ray et al., 2015). Moreover, changes in average temperature and precipitation, and the increase in the frequency and severity of extreme weather events such as heavy rain, drought periods and heat waves are expected to increase with climate change (IPCC, 2022).

The impact of specific weather conditions on crop growth and development depends on the severity of a given weather event, the crop species, and the phenological stage of the crop (Hatfield and Prueger, 2015). In cold climates, increased temperatures reduce the risk of frost or cold damage and foster crop establishment and root growth, and improve crop development during winter (Uleberg et al., 2014). However, in areas with winter temperatures around 0 °C, a slight increase in temperature might increase the risk of crop damage when snow cover becomes rare and soil and plants are exposed to low temperatures and frequent freeze–thaw cycles (Uleberg et al., 2014; Vico et al., 2014). High annual mean temperature can also accelerate plant development, which leads to earlier maturity and reduced crop yields (Shah and Paulsen, 2003; Gourdji et al., 2013; Jannat et al., 2022). Extremely high temperatures are particularly damaging to crops during the reproductive period due to pollen abortion and reduced grain number and grain weight (Pradhan et al., 2012; Barlow et al., 2015). However, depending on the location, increased temperatures can also increase crop yields due to improved photosynthesis and crop growth (Tian et al., 2014; Lopes, 2022). These beneficial effects of increasing temperature are particularly pronounced in regions where water is not limiting and average temperatures are relatively low (Lobell et al., 2011; Zhao et al., 2016).

It is important to note that the effects of weather events on crop yields can also greatly depend on site-specific soil properties such as texture (Huang et al., 2021; Gupta et al., 2022). Soil texture controls numerous crop-water related properties and functions, including water holding capacity and water transport, which contribute to crop productivity (Juma, 1993; Wang et al., 2022). Precipitation levels, soil water holding capacity, infiltration capacity of the soil, and water loss through evapotranspiration determine the severity of the effects of drought and heavy rainfall on crop yields (Fahad et al., 2017). Huang et al. (2021) found that crops were more sensitive to precipitation and temperature variability in coarse-textured soils compared to medium- and fine- textured soils. Similarly, wheat yields in Sweden and Canada have been shown to be lower during dry years on sandy soils compared to clayey soils (Delin and Berglund, 2005; He et al., 2014). On the other hand, waterlogging after heavy rainfall occurs more often on clayey soils and can lead to oxygen deficiency (Najeeb et al., 2015), resulting in crop damage yield losses (Hakala et al., 2012; Li et al., 2019).

At high northern latitudes, low temperatures and short growing periods are the main limitations for crop growth and productivity (Olesen et al., 2011). However, by the end of the 21st century, it is predicted that many areas in high northern latitudes will not only have increased annual precipitation but will have some of the highest projected increases in average temperature across the globe (IPCC, 2022). Yet the magnitude of the changes in temperature and precipitation might differ between seasons and between local cropping regions. The impact of climate change on crop production will therefore likely differ between crops and among and within countries. Previous research investigating relationships between agricultural production and weather variability at high latitudes based on historical data records has focused on crop yield data and average temperature and precipitation in a few key areas (Almaraz et al., 2008; Eckersten et al., 2010; Peltonen-Sainio et al., 2010; Klink et al., 2014). Some studies have modelled the impact of climate change on future yields for a few selected crops (Rötter et al., 2011; Eckersten et al., 2012; Rötter et al., 2013; Smith et al., 2013; Belyaeva and Bokusheva, 2018; Morel et al., 2021). As a consequence, there is still limited understanding of how yields of main arable crops are impacted by weather variability for many regions at high latitudes. Particularly, there is limited understanding of how the yield of different field crops is impacted by weather anomalies and extreme weather events during different growing seasons. Gaining a better understanding of crop yield responses to weather anomalies and weather extremes can help farmers, advisors, researchers and policymakers to design more resilient cropping systems by identifying crops and regions that are most vulnerable to weather anomalies.

To improve our understanding of the impacts of weather variability and weather extremes on crop production at high latitude agricultural regions, the present study aimed to (i) assess the effects of temperature and precipitation anomalies and extreme weather on crop yield anomalies for spring-sown cereals, oil crops, and root and tuber crops, and for autumn-sown cereals and oil crops across Sweden, (ii) quantify how crop responses to weather anomalies vary along the north-south climate gradient across Sweden, and (iii) elucidate the impacts of soil texture on yield responses to weather anomalies. To do so, we used daily mean air temperature, daily total precipitation, soil texture and crop yield data from public databases covering all 21 counties in Sweden.

## 2. Materials and methods

### 2.1. Study area

Sweden is located in northern Europe, divided into 21 counties, and encompasses a relatively large latitudinal climate gradient between 55° and 69° N (Fig. 1a). This climate gradient results in a large within-country variation in mean annual temperature (Fig. 1b, Supplementary Table S1), with the north belonging to the subarctic climate, while the south is considered a hemiboreal climate (Peel et al., 2007). Since 1965, the mean annual temperatures have increased in southern, central and northern Sweden (Fig. 1b), while there is no clear temporal trend in annual total precipitation (Supplementary Fig. S1). The annual total precipitation is less variable along the south-north direction, but is higher on the west coast than on the east coast (Supplementary Table S1).

We calculated the average length of the growing season for the south, central and northern part of Sweden for the period 1965 to 2020. To do so, we used data of the start and end of the vegetation period in every year provided by the Swedish Meteorological and Hydrological Institute (SMHI, 2022). The average length of the growing season is more than two months longer in the south of Sweden compared to the northern part (219 days in the south compared to 148 days in the north; Fig. 1a). This pronounced difference in the growing season caused by climatic differences within the country is a major driver of the variation in the number and types of crops cultivated across Sweden (Sjulgård et al., 2022). In the northern part, autumn-sown crops are less common compared to southern regions due to the long winters. Since the 1960s, the total area with spring-sown crops has decreased in the whole country, while the area of autumn-sown crops has increased in central and southern Sweden (Supplementary Fig. S2).

### 2.2. Climate, crop yield, and soil texture data

Crop yields and harvested areas for the main arable crops grown in Sweden were obtained for each of the 21 counties from Statistics of Sweden (SCB, 2023). The arable crops included in our study were oat (*Avena sativa L.*), spring barley (*Hordeum vulgare L.*), rye (*Secale cereale L.*), spring and winter wheat (*Triticum aestivum L.),* sugar beet (*Beta vulgaris L.*), potato (*Solanum tuberosum L.),* winter and spring rapeseed (*Brassica napus L.*) and winter and spring turnip rape (*Brassica rapa* spp. *oleifera*). These eleven crops covered around 95% of the total area of all field crops in Sweden in 2019 (Sjulgård et al., 2022). Winter wheat, spring barley and oat are the dominant arable crops, with a total production of about $3 \times 10^6$ tons, $1.4 \times 10^6$ tons and $8.1 \times 10^5$ tons, respectively, in 2020 (SCB 2020). The database included 56 years of data (from 1965 to 2020), and we included each crop-county combination that consisted of at least ten years of crop yield data in our study. For all analyses, the eleven crop species were grouped into five categories based on sowing period and crop type: autumn-sown cereals including winter wheat and rye, spring-sown cereals including spring wheat, spring barley and oats, autumn-sown oil crops including winter rapeseed winter turnip rape, spring-sown oil crops including spring rapeseed, spring turnip rape and tuber/root crops including potatoes and sugar beets. Pearson's correlations between the different crop species within these five categories were assessed. In most counties, moderate to strong correlations ($r > 0.5$) between the yield anomalies of the different crop species within one category occurred (Supplementary Table S2).

Soil texture for each county was obtained from "Miljödata MVM" (Miljödata-MVM, 2020), which is a national database including analyses of soil data of arable fields across Sweden. In this study, we used the average topsoil (0–20 cm depth) sand content (particle size: 0.06–2 mm), silt content (0.002–0.06 mm) and clay content (< 0.002 mm) of each county, and grouped the counties into soil textural classes (Avery, 2006). Soil texture classes at the county level included clay (three counties, $n = 3$), clay loam ($n = 8$), sandy silty loam ($n = 3$) and sandy loam ($n = 7$) (Supplementary Table S1).

Data on total daily precipitation and daily mean air temperature was obtained from the Swedish Meteorological and Hydrological Institute (SMHI; SMHI, 2020). For the analyses included here, we used data from an average of four weather stations per county that were all located in the cropping areas of the different counties (Sjulgård et al., 2022). To assess seasonal weather influences on crop yields, the daily precipitation and temperature data were divided into four, three-month periods: winter (December–February), spring (March–May), summer (June–August) and autumn (September–November).

### 2.3. Determination of yield anomalies and weather

Data analysis and visualisation were carried out in R version 4.2.1 (R Core Team, 2023). To separate yield variations resulting from weather anomalies from general yield increases due to agricultural progress and intensification (e.g. fertilisation, crop breeding, pest and disease management), crop yields were detrended. The detrended time series were obtained through either linear regression or linear plateau models for each crop-county combination (Supplementary Fig. S3). For each combination, the model with the lowest Akaike Information Criterion (Akaike, 1974) was selected as the best representation of the yield trend. If the slope of the linear trend was not significant ($p > 0.05$) for a certain combination, the overall mean of all years was used as the reference.

Yield anomalies were then calculated as the relative yield residuals (θ) from the detrended time series, i.e. the difference between actual and detrended yield, to be able to compare yield anomalies among species and counties:

$$\theta_{i,j,k} = \frac{Y_{i,j,k} - D_{i,j,k}}{D_{i,j,k}} \times 100\% \tag{1}$$

where Y is the observed crop yield and D is the expected yield obtained from the long-term trend, *i* indicates the year, *j* the crop species and *k* the county. Temporal trends of daily average temperature and daily total precipitation were also detrended due to temporal increases over time in some counties (Fig. 1b), and this was done for each season containing a

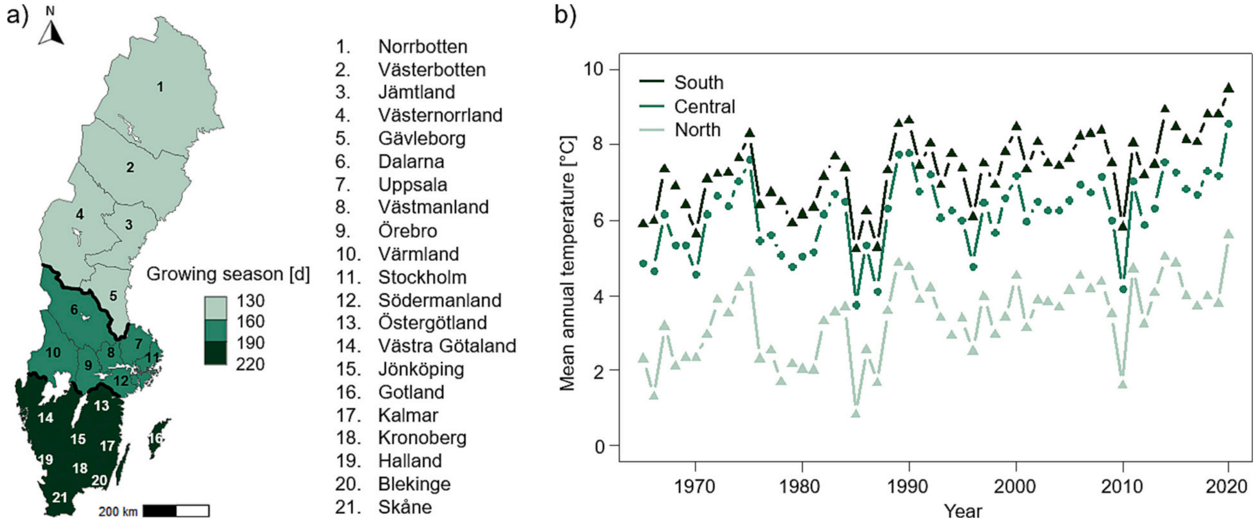

**Fig. 1.** a) Map of Sweden showing the 21 counties and indicating the length of the average growing season in days (green shadings) for each county. The counties were categorized into three regions, namely "north" (light green, 130–160 days growing season), "central" (green, 160–190 days growing season), and "south" (dark green, 190–220 days growing season). (b) Temporal development of mean annual temperature in southern, central and northern Sweden from 1965 to 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

three-month period using linear regression models, yielding seasonal temperature and precipitation anomalies.

### 2.4. Water balance and heat wave index calculation

To assess the impact of extreme weather, we calculated a water balance index and a heat wave index. For this, we used the Standardized Precipitation Evaporation Index (SPEI; Vicente Serrano et al., 2010), and the heat wave index (HWI) defined by Russo et al. (2015). Both indices have the advantage that they allow for comparisons between different regions and between years. The SPEI was used to assess the impacts of the magnitude of droughts and excess water, which has been shown as one of the most suitable indices for capturing the impacts of agricultural drought (Vicente-Serrano et al., 2012; Wang et al., 2016). We used the 3-month SPEI, which includes moisture conditions from the current month and the two preceding months. The water surplus or deficit ($D$) was aggregated at a 3-month time scale and standardized to obtain the SPEI for each season. The value of $D$ was calculated as the difference between precipitation ($P$) and the reference evapotranspiration ($ET_0$) for the month ($i$) as:

$$D_i = P_i - ET_{0i} \tag{2}$$

The monthly reference evapotranspiration was calculated using a modified form of the Hargreaves method (Droogers and Allen, 2002):

$$ET_{0i} = 0.0013 \times 0.408RA \times \left(T_{avg} + 17\right)\left(\left(T_{max} - T_{\min}\right) - 0.0123P\right)^{0.76} \tag{3}$$

where $RA$ is the mean external radiation estimated from the latitude in the centre of a county and the month of the year, $T_{avg}$ is the average daily temperature, $T_{max}$ is the daily maximum temperature, and $T_{min}$ is the daily minimum temperature. The package SPEI (Beguería and Vicente-Serrano, 2017) was used for the calculations of SPEI.

The heat wave index (HWI) was calculated to quantify the occurrence and intensity of heat waves. Because heat waves in Sweden occur almost exclusively during the summer months June–August, we only calculated HWI for the summer period. The HWI takes into account both the amplitude and duration of the heat wave. A heat wave has a duration of at least three consecutive days with a maximum temperature above a daily temperature threshold based on the reference period 1981–2010. The threshold for each county was defined as the 90th percentile of the daily maximum temperature ($T_{max}$) for a 31-day running window during the reference period 1981–2010. HWI was then calculated as the sum of all heat wave magnitudes during the summer months in a particular year. The daily magnitude $M_d(T_d)$ was calculated as:

$$M_d(T_d) = \begin{cases} \dfrac{T_d - T_{30y25p}}{T_{30y75p} - T_{30y25p}} \; if \; T_d > T_{30y25p} \\ 0 \; if \; T_d \leq T_{30y25p} \end{cases} \tag{4}$$

where $T_d$ is the maximum daily temperature on day d during the heatwave. $T_{30y25p}$ are the 25th and $T_{30y75p}$ the 75th percentile values of $T_{max}$ from the 30 year reference period (Russo et al., 2015). The HWMId function in the package extRemes (Gilleland, 2022) was used to obtain the HWI.

To classify periods of the year as extremely dry or wet, values of SPEI were categorized based on commonly used classifications (Ming et al., 2014; Labudová et al., 2017; Zhao et al., 2018). Values equal to or $>1.5$ were considered severely or extremely wet and referred to as “extremely wet” in the remainder of this study, values between 1.5 and $-1.5$ were considered moderate or normal and referred to as “normal” years, and values equal to or smaller than $-1.5$ were considered severely or extremely dry and hereafter referred to as “extremely dry” conditions (Vicente Serrano et al., 2010). For the HWI, values equal to or larger than 3 were considered as severe or extreme heat waves and referred to as “extreme heat waves”, while values smaller than 3 were considered as moderate or normal heat and hereafter referred to as summers with “normal” heat conditions. A HWI of 3 means that the temperature anomaly is three times the difference between the 25th and 75th percentile of the maximum temperature (Chakraborty et al., 2019). SPEI and HWI were not detrended. There was no significant change in the frequency or magnitude of extreme weather events over time (Supplementary Table S4) for almost all season-county combinations.

### 2.5. Statistical evaluation of effects of weather conditions and soil texture on yield anomalies

Linear regressions and Pearson’s correlation coefficients were used to assess the strength of the relationships between crop yield anomalies of each crop type and weather anomalies (precipitation and temperature anomalies), SPEI and HWI. All correlations were conducted at the significance level of $p < 0.05$. To account for the non-normal distribution of crop yield anomalies in years with only extreme weather, the non-parametric Mann-Whitney $U$ test was used to test for significant differences in yield anomalies between years with extreme weather and years with normal conditions. Mann-Whitney $U$ tests were also used to assess differences in yield anomalies between the most sandy (sandy loam, (sand 50–70%, clay 15–18%)) and the most clayey soils (clay, sand 0–45%, clay 55–100%)), for extremely dry (SPEI $\leq -1.5$) and extremely wet (SPEI $\geq 1.5$) years. Spearman’s rank coefficients were used to assess the relationships between sand content and crop yield anomalies under extremely dry and extremely wet conditions.

## 3. Results

### 3.1. Relationships between extreme temperatures and crop yield anomalies

Pearson’s correlation coefficients illustrate the differences in the influence of temperature anomalies and HWI on yield anomalies between crop types and along the north-south gradient in Sweden. Combining the average yield anomalies during years with extreme heat waves (HWI $\geq 3$) shows the magnitude and resulting yield losses or gains (Fig. 2 and Fig. 3). In the southern and central part of Sweden, there was a negative relationship between HWI and temperature on crop yields. Spring-sown cereals and root/tuber crops were particularly impacted by changes in temperature, while the autumn-sown crops were less affected by heat waves during summer (Fig. 2). The average yield anomalies during years with extreme heat waves showed that heat stress was related to average yield declines for the spring-sown crops between 12% and 17% in the central and between 13% and 19% in the southern part (Fig. 3). There was less impact on the autumn-sown crops, with no significant difference in average yield anomalies during extremely hot years compared to normal years (Fig. 3). In contrast, crop yields of spring-sown cereals and root/tuber crops in the northern part showed a positive relationship between temperature anomalies and HWI to yield anomalies (Fig. 2). This indicated a tendency of yield gains during years with extreme heat waves compared to normal years in northern Sweden, although these differences were not significant (Fig. 3).

During spring and winter, there were positive correlations in almost all counties in the central and southern parts between temperature and yield anomalies of autumn-sown cereals. For spring-sown cereals, the relationships between spring and winter temperature anomalies were only positively related to yield anomalies in central and northern Sweden. Similar yet less pronounced results were found for oil crops. In certain counties in central and southern Sweden, there was a positive relationship between spring temperatures and yield anomalies of both autumn- and spring-sown oil crops, while winter temperatures had a comparatively weak impact on yield anomalies of oil crops (Fig. 2, Supplementary Fig. S4).

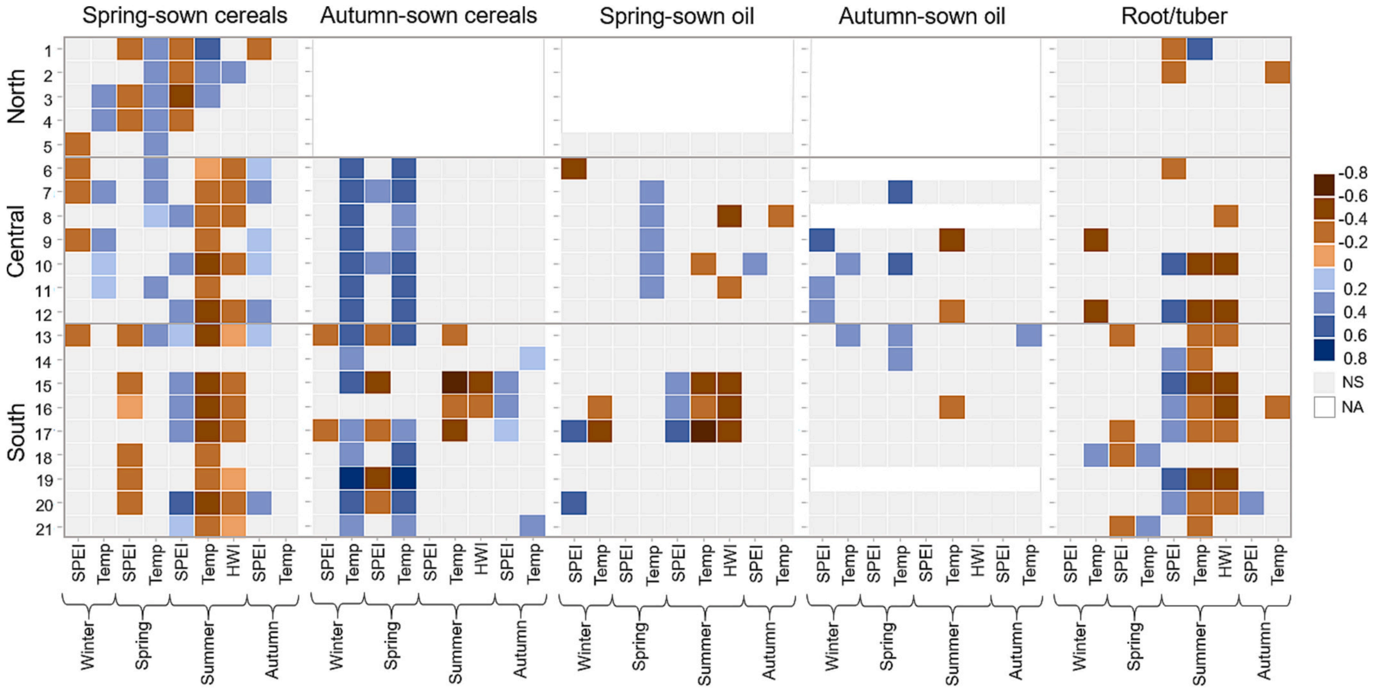

**Fig. 2.** Pearson's correlation coefficients between yield anomalies of each crop group and Standardized Precipitation Evaporation Index (SPEI), heat wave index (HWI) and temperature anomalies (Temp) for each county based on crop yield and climate data from 1965 to 2020. The counties are sorted by decreasing latitude with the corresponding number from Fig. 1 and grouped into the northern, central or southern regions of Sweden. The brown colour shows a negative relationship to crop yield anomaly while blue colour represents a positive relationship. Non-significant (NS; $p > 0.05$) correlations are denoted by grey colour. White areas indicate counties with little or no cropping area of a certain crop group (NA). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

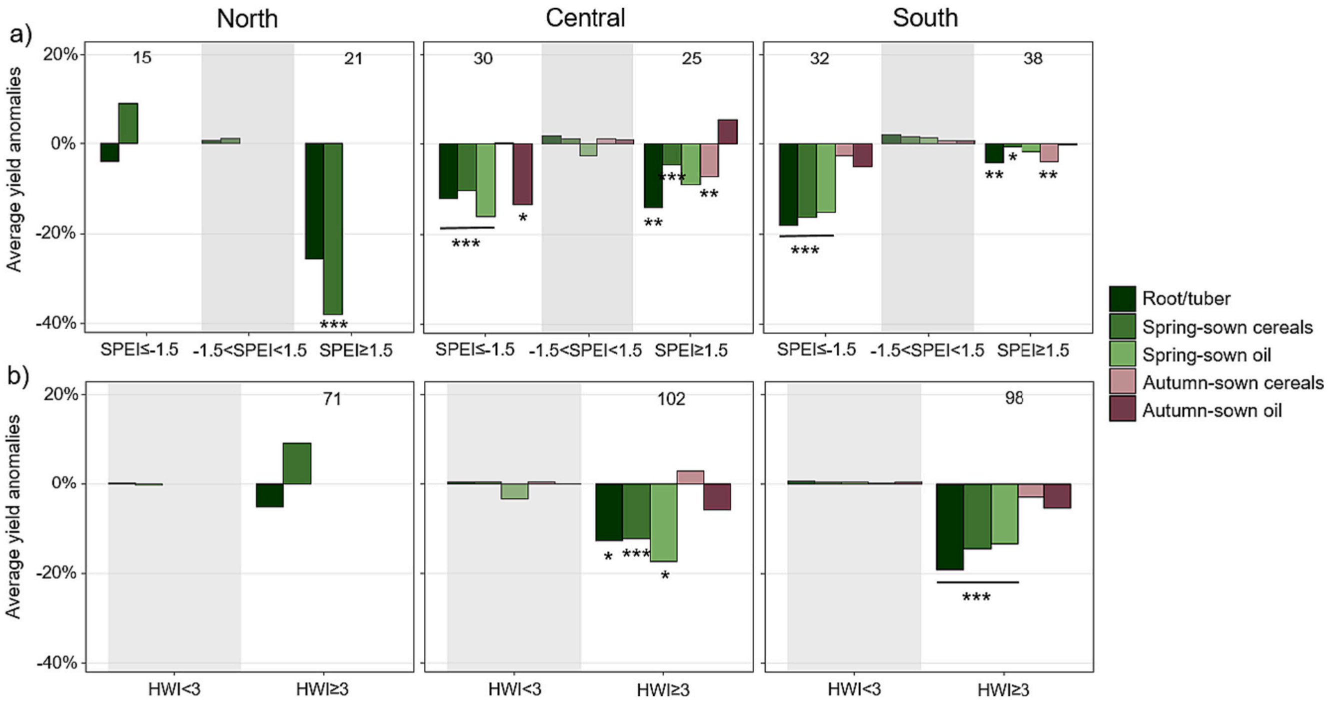

**Fig. 3.** Average yield anomalies in northern, central and southern Sweden during years with a) extremely dry (SPEI $\leq -1.5$) and wet (SPEI $\geq$1.5) summers, and b) extreme heatwaves (HWI $\geq$3) during summer. Significance levels are shown for comparison to years with normal weather conditions ($-1.5 <$ SPEI $<$1.5 and HWI $<$ 3, respectively) as shown with a grey background. The significance levels are * $p < 0.05$, ** $p < 0.01$, ***$p < 0.001$ using the Mann-Whitney $U$ test. Green colour represents spring-sown crops and pink colour autumn-sown crops. The numbers displayed on top of the graphs indicates the number of county and year combinations with the extreme weather. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 3.2. *Relationships between SPEI and crop yield anomalies*

The correlations between SPEI and precipitation anomalies were strong (Supplementary Fig. S5) and as SPEI better describes wet and dry conditions, only SPEI is presented in the results. Summer droughts were shown to have negative effects on yield anomalies for all spring-sown crops. This effect was most pronounced in southern Sweden, as indicated by the yield losses during years with extremely dry summers compare to normal years and the positive correlations between SPEI and yield anomalies in the majority of counties in the south (Fig. 2 and Fig. 3). Yield losses during years with extremely dry summers were 16% for spring-sown cereals, 18% for root/tuber, and 15% for spring-sown oil crops. In the central part, there were also negative effects of drought during summer on spring-sown crops, but with less impact than in the southern part, with associated yield losses between 10% and 16% (Fig. 3). The autumn-sown crops were less affected by drought during summer than the spring-sown crops. Only autumn-sown oil crops in central Sweden experienced yield losses during years with extremely dry summers (Fig. 3).

The spring-sown cereals and root/tuber crops were not only found to be sensitive to extremely dry but also to extremely wet conditions during summer, and this was the case in all parts of Sweden (Fig. 3). However, the yield losses were lower during years with extremely wet summers compared to years with extremely dry summers in the southern part. In the northern part in contrast, we found negative correlations between SPEI and yield anomalies (Fig. 2), with the highest yield losses of 38% for spring-sown cereals and 26% for root/tuber crops in years with extremely wet summers (Fig. 3). In the central and southern parts, autumn-sown cereals also experienced yield losses during years with extremely wet summers (Fig. 3), but with lower yield losses compared to years with extreme drought.

A negative relationship between yield anomalies and SPEI during spring was found for spring- and autumn-sown cereals and root/tuber crops in several of the southern counties (Fig. 2). Yield losses were 9% for spring-sown cereals and 8% for autumn-sown cereals during years with an extremely wet spring in the south. Root/tuber crops were instead favoured by extremely dry spring conditions compare to normal years with yield gains of 5% (Supplementary Fig. S4). In the north, a positive effect of dry conditions in spring on spring-sown cereal yield anomalies were found as indicated by the negative correlation of yield anomalies and SPEI in several counties (Fig. 3). The average yield gain during years with an extremely dry spring was 12% in northern Sweden (Supplementary Fig. S4). During winter, autumn-sown oil crops showed a positive relationship between yield anomalies and SPEI in the central part, with an average yield gain of 19% during years with an extremely wet winter.

### 3.3. *Influence of soil texture on yield anomalies*

In years with normal summer conditions ($1.5 > \text{SPEI} > -1.5$) i.e. when water was presumably not limiting and there was no excess of water, we found no relationships between average sand content in the counties to crop yield anomalies for any crop type (Supplementary Table S5). However, in years with an extremely dry ($\text{SPEI} \leq -1.5$) or wet ($\text{SPEI} \geq 1.5$) summer, our results indicate an influence of soil texture on yield responses, but the impact was different for different crops. For years with an extremely dry summer, we found that yield anomalies of spring-sown cereals were lower in the counties with sandy loam soils compared to clay soils (Fig. 4). Thus, greater sand content exacerbated drought effects on yield losses of spring-sown cereals. However, during years with extremely wet summers, no relationships were found between sand content and yield anomalies of spring-sown cereals (Fig. 4). There were also no differences between clay and sandy loam soils in crop yield anomalies for autumn-sown cereals, oil crops or root/tuber crops during years with either an extremely dry or extremely wet summer (Supplementary Fig. S6 and S7).

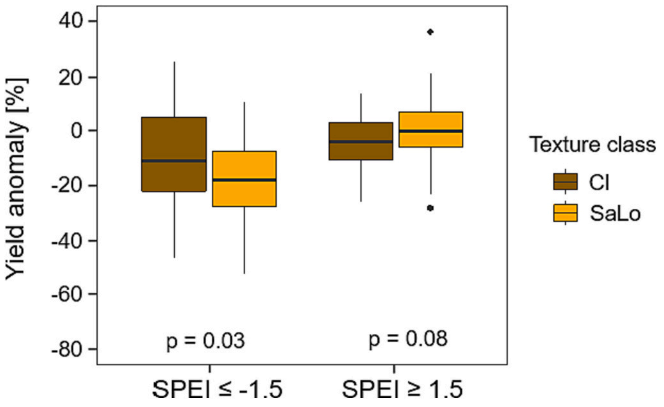

**Fig. 4.** Boxplots of yield anomalies for spring-sown cereals between counties with average soil texture of clay (Cl) and sandy loam (SaLo) for spring-sown cereals and sand content of cropped lands during extremely dry ($\text{SPEI} \leq -1.5$), normal ($-1.5 < \text{SPEI} < 1.5$) and extremely wet conditions ($\text{SPEI} \geq 1.5$), based on crop yield data from 1965 to 2020. $p$ values in are obtained from Mann-Whitney $U$ test for comparison of yield anomalies between the soil texture classes.

## 4. Discussion

### 4.1. *Influence of temperature anomalies on yield anomalies varies by crop and location*

Our results demonstrate that relationships between temperature anomalies and HWI, respectively, and crop yield anomalies are strongly dependent on latitude and crop type (Figs. 2 and 3). Higher average summer temperatures and a higher HWI were related to yield losses, i.e. higher negative yield anomalies, in most counties in central and southern Sweden for spring-sown cereals and root/tuber crops. The same relationship occurred in a few counties for oil crops and autumn-sown cereals (Fig. 2). This is consistent with previous studies showing that warming during summer reduces crop yield (Gammans et al., 2017; Ceglar et al., 2020; Eck et al., 2020) by accelerating crop development and reducing the duration to maturity (Gourdji et al., 2013; Jannat et al., 2022). Heat waves have been shown to be particularly damaging to crops during the reproductive period during summer (Pradhan et al., 2012; Barlow et al., 2015; Koscielny et al., 2018; Magno Massuia et al., 2021).

In years with extreme heatwaves, our results showed that there were substantial yield losses for all spring-sown crops in southern and central Sweden, while autumn-sown crops were less affected by such heat waves (Fig. 3). Similarly, Giannakaki and Calanca (2019) found a stronger negative association between heat stress and yield for spring wheat than winter wheat in Russia. We attribute this to the fact that the flowering of spring-sown crops occurs later in summer when temperatures are generally higher than for autumn-sown crops (Koppensteiner et al., 2021). To adapt to a warmer climate in the future, an adaptation could also be shifting from spring-sown to autumn-sown varieties (Trnka et al., 2011) in southern and central Sweden. Our data already shows that the cultivated areas of spring-sown crops have decreased since 1965, and autumn-sown crops have increased in southern and central Sweden (Supplementary Fig. S2). In the north, higher summer temperatures resulted in increased crop yields for spring-sown cereals and root/tuber crops (Fig. 2), and extreme heatwaves did not result in yield losses in northern Sweden (Fig. 3). Low temperatures and a short growing season in northern Sweden are currently limiting crop growth (Olesen et al., 2011), and crop production might therefore benefit from increased temperatures. Therefore, in the north, crop yields can be expected to increase in the future.

Above average temperatures during spring showed a positive association with increased crop yields for all crop groups (Fig. 2). This is likely due to the positive effect of higher spring temperatures on the growth of autumn-sown crops, and the possibility for earlier sowing of spring-sown crops (Olesen et al., 2011; Rötter et al., 2013). Thereby, plants are more vigorous and further advanced in their development before the potential occurrence of high temperatures and droughts in mid to late summer. In the future, warmer spring temperatures will prolong the growing season, which can promote autumn-sown crops to expand northwards as well as enable earlier sowing of spring-sown crops. However, the also projected increase in precipitation in northern latitudes (Eklund et al., 2015) could complicate sowing and therefore also limit the opportunities for earlier sowing.

Temperature anomalies during winter also showed a positive relationship to the yield anomalies of autumn-sown cereals in both south and central Sweden. Warmer winter temperatures might favour crop establishment and root growth, and a decreased risk of frost or cold damage is probably of higher importance in the central part compare to the south due to lower average winter temperatures. Average temperature in Sweden are projected to increase during all seasons, and the highest increase in temperature is forecasted for the winters in the northern counties, with increases between 3 and 5 °C until the end of the century compared to 1961–1990 (Eklund et al., 2015). Due to the projected increased winter temperatures, overwintering problems could increase in central and northern Sweden. This may limit the expansion of autumn-sown crops to the north more than the potential increase in area due to the projected warmer springs and summers (Uleberg et al., 2014).

### 4.2. *Influence of drought and water excess on yield varies by crop and location*

Similar to temperature anomalies and HWI, our results showed that the relationships between SPEI and crop yield anomalies are heavily dependent on latitude and crop type (Figs. 2 and 3). In southern and central Sweden, yield losses due to drier conditions during summer, indicated by larger negative yield anomalies, were much more pronounced in spring- than in autumn-sown crops (Figs. 2 and 3). Yield losses of spring-sown cereals during years with extremely dry summers were further exacerbated with higher sand content (Fig. 4 and Supplementary Fig. S6), showing that the severity of yield losses due to extreme weather events may vary with soil texture. Similarly, He et al. (2014) found that spring wheat yields were lower during dry years on sandy soils compared to clayey soils. For the other categories of crops included here, we did not observe such relationships between drought effects and soil texture (Supplementary Fig. S7 and S7). We attribute the differences between the sensitivity to drought between spring- and autumn-sown crops to the fact that autumn-sown crops are further in their development and thus have larger and deeper root systems in spring and early summer compared to spring-sown crops. Therefore, autumn-sown crops are less sensitive to drought due to their ability to better access water pools in deeper soil layers.

The analyses provided here also revealed yield reductions during years with an extremely wet summer for spring- and autumn-sown cereals and root/tuber crops (Fig. 3). The average yield loss during years with extremely wet summers was highest for the spring-sown cereals in northern Sweden. Due to low temperatures and less evapotranspiration in colder northern climates, there is a higher risk of waterlogging during periods of excess water in northern latitudes, which can lead to oxygen deficit in the soil, resulting in crop damage and yield losses (Hakala et al., 2012; Li et al., 2019). During wetter than average spring conditions, autumn- and spring-sown cereals and root/tuber crops showed lower yields in southern Sweden, and also for spring-sown cereals in the north. The amount of precipitation in spring has been shown to explain delays in the sowing of spring-sown cereals (Peltonen-Sainio and Jauhiainen, 2014) and potatoes (Jiang et al., 2021), resulting in reduced yield due to the shortening of the growing period. The autumn-sown cereals also experienced yield losses in years with an extremely wet spring in the south (Fig. 3), supporting previous studies showing that autumn-sown cereals can be sensitive to waterlogging early in the season (Peltonen-Sainio et al., 2010; de San Celedonio et al., 2014; Ploschuk et al., 2018). Oil crops were barely affected by variations in spring precipitation patterns according to our results (Fig. 2), which contradicts results from earlier studies in Argentina where oil crops were shown to be more sensitive to waterlogging than cereals (Ploschuk et al., 2018; Ploschuk et al., 2020). However, almost half of the Swedish rapeseed production is in Skåne (SCB, 2020b), the southernmost Swedish county (cf. Fig. 1a). Skåne has relatively sandy soils (Supplementary Table S1) and these soils are less prone to waterlogging than soils with higher clay content, which may explain our findings.

Our results show that both dry and wet conditions are influencing crop yield. In the future, the sensitivity of crop yields to excess water especially in the north of Sweden may be a major challenge due to the largest predicted increase in precipitation in the northern part (Eklund et al., 2015). However, due to the negative impact of drought on crop yields in central and southern Sweden, the future projected increase in precipitation could potentially be beneficial for crop yields. Nevertheless, the increased precipitation might be too small to compensate for the increased evapotranspiration and higher crop biomass as a result of the increased temperature and longer growing season in the future (Ylhäisi et al., 2010).

### 4.3. *Implications*

Understanding the influence of weather variations and extreme weather on crop yields is crucial for farmers and advisors to develop soil and crop management strategies and for policymakers to design future agricultural development programs and climate change adaptation measures. Our results highlight the differences in sensitivity to weather variations and extreme weather between crop types and geographical locations. These findings provide stakeholders with information regarding weather-vulnerable counties and crops in Sweden, which allows policymakers to prioritize support for climate change adaptation measures. Moreover, farmers and advisors need such information to develop management strategies that are adapted to their location. Adaptation measures could include crop breeding programs, technological developments and farm management practices such as crop choice, diversification, irrigation and adjusted sowing dates (Smit and Skinner, 2002; Howden et al., 2007; Raza et al., 2019).

## 5. Conclusions

In this study, we assessed relationships between weather variations and crop yield anomalies for the major Swedish arable crop species. Our work highlights the differences in sensitivity to weather variations and extreme weather between crop types and geographical locations. The already on-going climate change poses challenges to crop production and our study suggests that targeted site- and crop adaptations are needed to help mitigate potential yield losses. The results demonstrate the need for site-specific adaptation strategies in the future, due to differences in the influence and magnitude of weather anomalies along the north-south gradient and due to the influence of soil texture on crop yields in years with extremely dry summers. Crop-specific adaptation strategies are also of high importance, as demonstrated by the differences in sensibility to weather anomalies and extreme weather between crops, especially between autumn- and spring-sown crops. The results can be used by agricultural policymakers to identify weather-vulnerable counties and crops in Sweden and use them as a basis for the development of regional suitable agricultural programs and support for adaptation strategies.

## Declaration of Competing Interest

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

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103757.

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