Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2024:84
Faculty of Natural Resources and Agricultural Sciences

The potential of agricultural management to alleviate extreme weather impacts on Swedish crop production

Hanna Sjulgård

The potential of agricultural management to alleviate extreme weather impacts on Swedish crop production

Hanna Sjulgård
Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment
Uppsala

SLU
SWEDISH UNIVERSITY
OF AGRICULTURAL
SCIENCES

DOCTORAL THESIS
Uppsala 2024

Acta Universitatis Agriculturae Sueciae
2024:84

Cover: Winter wheat in the field before harvest (photo Hanna Sjulgård)

ISSN 1652-6880
ISBN (print version) [978-91-8046-375-1]
ISBN (electronic version) [978-91-8046-411-6]
https://doi.org/10.54612/a.107ri2j3pt

Swedish University of Agricultural Sciences, Department of Soil and Environment, Uppsala, Sweden

Print: SLU Grafisk service, Uppsala 2024

Errata for
The potential of agricultural management to alleviate extreme weather impacts on Swedish crop production

by Hanna Sjulgård

ISBN (print version) [978-91-8046-375-1]
ISBN (electronic version) [978-91-8046-411-6]
Acta Universitatis Agriculturae Sueciae 2024:84
Uppsala, 2024

Page 24	Is now: Figure 4 Should be: Figure 3
Page 26	Is now: Figure 3 Should be: Figure 4
Page 29-42	For all the figures after that, figure numbers should be +1, i.e. Figure 4 on page 29 should be Figure 5; Figure 5 on page 32 should be Figure 6, and so on
Paper I Supplements	Is now: Figure S5 Should be: Figure S4
Paper I Supplements	Figure S4, S6, S7 and S8 should have been removed

The potential of agricultural management to alleviate extreme weather impacts on Swedish crop production

Abstract

Climate change, stagnating crop yields and the increased demand for food pose challenges to future agriculture. Therefore, it is of great importance to assess the potential of agricultural management practices to mitigate the effects of climate change, and especially extreme weather events, on crop productivity. In this thesis, I assessed (1) the spatiotemporal patterns of crop species diversity and crop yields, (2) the vulnerability of crops to extreme weather and the importance of soil properties in mitigating such impacts, and (3) the influence of agricultural management on soil health indicators in Sweden. The analysis of historical crop data revealed an increase in crop diversity from the north to the south of Sweden, in line with increasing temperatures, implying that climatic conditions limit the diversity of crops that can be grown. A continued increase in cereal yields in southern Sweden since the 1960s, and an increase over time in crop diversity in several counties, indicate a potential also for future improvements. Crop yields were shown to be sensitive to excess water and favoured by increased temperatures in northern Sweden, while in southern Sweden, drought effects were more pronounced and increased temperatures had a negative impact on crop yields. Estimates based on satellite images showed a lower winter wheat growth rate and lower peak green leaf area index during drought compared to normal weather conditions. A high importance of plant available water during drought was shown by faster growth of winter wheat on fields with higher plant available water capacity, and by greater spring-sown cereal yield losses on lighter soils at the county level. On-farm analyses showed that higher crop rotational diversity, lower tillage intensity, higher use of organic fertilizers and less fungicide use were associated with improved soil health, and crop yields were influenced by organic matter content, wet aggregate stability and bulk density. Overall, this thesis suggests that targeted site- and crop adaptations are needed to mitigate the effects of extreme weather events on crop productivity.

Keywords: crop yield, extreme weather, crop diversity, crop development, soil properties, soil health, agricultural management

Brukningsmetoders potential för att mildra effekter av extremväder på svenska grödor

Sammanfattning

Klimatförändringarna, minskade skördar och den ökade efterfrågan på livsmedel utgör utmaningar för framtidens jordbruk. Det är därför av största vikt att undersöka potentialen för brukningsmetoder att motverka påverkan från extremväder på svensk grödproduktion. I denna avhandling undersökte jag (1) de rumsliga och tidsmässiga mönstren för mångfald av grödor och skördar, (2) skördarnas och grödutvecklingens sårbarhet för extrema väderförhållanden och markegenskapernas betydelse för att mildra sådana effekter och (3) brukningsmetoders inverkan på jordhälsa i Sverige. Analyser av historiska data visade att mångfalden av grödor har ökat från norr till söder i och med att klimatet blir varmare. En potential för ökande skördar i framtiden visar sig genom att spannmålsskördarna fortsatt att öka i södra Sverige sedan 1960-talet, och genom låga skördar i norr. De sistnämnda visar sig vara känsliga för vattenöverskott och har gynnats av ett varmare klimat. I söder, däremot, är effekten av torka mera uttalad, vilket medför att ett varmare klimat fått en negativ inverkan på skördarna. Jag konstaterade också att vårsådda grödor var mer känsliga för torka än höstsådda grödor. Uppskattningar med hjälp av satellitbilder visade på lägre tillväxthastighet för höstvete och ett lägre index för den maximala gröna bladytan under torka. Höstvetet hade snabbare tillväxt med högre växttillgängligt vatten under torka och det var större skördeförluster i län som överlag hade högre sandhalt i jorden, detta visar på betydelsen av markens förmåga att hålla vatten i ett allt torrare klimat. Analyser på gårdsnivå visade på förbättrad jordhälsa på gårdar med en större mångfald av grödor i växtföljden, mindre intensiv jordbearbetning, oftare användning av organiska gödselmedel och mindre användning av fungicider, och skördarna påverkades av organiskt material, aggregatstabilitet och bulkdensitet.

Denna avhandling tyder på att anpassningar efter olika platser och grödor behövs för att mildra effekterna av extremt väder på grödors produktivitet i framtiden.

Nyckelord: skördar, extremväder, grödodiversitet, grödans utveckling, markegenskaper, jordhälsa, brukningsmetoder

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Sjulgård H, Colombi T, Keller T. 2022. Spatiotemporal patterns of crop diversity reveal potential for diversification in Swedish agriculture. Agriculture, Ecosystems & Environment. 336:108046. https://doi.org/10.1016/j.agee.2022.108046

II. Sjulgård H, Keller T, Garland G, Colombi T. 2023. Relationships between weather and yield anomalies vary with crop type and latitude in Sweden. Agricultural Systems. 211:103757. https://doi.org/10.1016/j.agsy.2023.103757

III. Sjulgård H, Graf L.V, Colombi T, Hirte J, Keller T, Aasen H. Earth observation reveals reduced winter wheat growth and the importance of soil water storing capacity during drought. Submitted.

IV. Sjulgård H, Colombi T, Garland G, Coucheney C, Keller T. Farm-based analysis of relationship between agricultural management, soil health indicators and crop yields across two regions in southern Sweden. Manuscript.

Papers I and II are reproduced with the permission of the publishers.

The contribution of Hanna Sjulgård to the papers included in this thesis was as follows:

- I. Planning of the study collaboratively with the co-authors. Data collection and analysis. Prepared the manuscript with help from the co-authors.
- II. Planning of the study together with Thomas Keller and Tino Colombi. Data collection and analysis. Prepared the manuscript with help from the co-authors.
- III. Planning of the study together with Thomas Keller and Helge Aasen. Data collection with assistance from Lukas Graf. Data analyses. Prepared the manuscript with help from the co-authors.
- IV. Soil sampling and field measurements. Some of the laboratory analyses. Data analyses. Prepared the manuscript with help from the co-authors.

Abbreviations and central variables

DMI	De Martonne Aridity Index
HWI	Heat Wave Index
SPEI	Standardized Precipitation Evaporation Index
CDI	Crop Species Diversity Index
FDI	Functional Crop Diversity Index
STIR	Soil Tillage Intensity Rating
GLAI	Green Leaf Area Index
Sp-Rich	Crop Species Richness

1. Introduction

1.1 Global crop production

Agricultural land covers 38% of the global surface, with one-third used as cropland and two-thirds used as grazing land for livestock. In 2022, the global production of crops reached 9.7 billion tonnes, half of which was produced in Asia (FAO 2024). Since the 1960s, global crop production has increased by 250%, and an estimated 89% of this increase was the result of agricultural intensification and 11% due to the expansion of cropland area (Blomqvist et al. 2020). Increases in crop yields are associated with the green revolution around 1960s due to new technologies and practices, for example irrigation, enhanced crop varieties and an increase in the use of inputs such as pesticides and fertilizers (Pinstrup-Andersen and Hazell 1985; Pingali 2012).

Despite these positive trends, recent studies indicate that crop yields are no longer increasing at the same pace, have stagnated or even started to decrease in many countries (Peltonen-Sainio et al. 2009; Finger 2010; Brisson et al. 2010; Ray et al. 2012; Gerber et al. 2024). Globally, areas where crop yields have stagnated cover around 37%, 35% and 26% of the total global production of wheat, rice and maize, respectively, according to Ray et al. (2012). This stagnation of crop yields largely started during the 1990s and has been mainly attributed to more environmentally friendly agricultural policies and reduced inputs by farmers, lack of investments and climate change (Peltonen-Sainio et al. 2009; Finger 2010; Brisson et al. 2010; Ray et al. 2012; Gerber et al. 2024).

In the future, the demand for food will increase, driven by both an increase in population and income per capita. The global food demand has been projected to increase up to around 50% between 2010 and 2050 (van Dijk et al. 2021). However, increased crop yields are challenged by environmental regulations, which can reduce fertilizer inputs and by which the use of synthetic pesticides may be reduced or even banned (Brunelle et al. 2024). At the same time, future cropping systems need to become more sustainable and have a lower negative impact on the environment (FAO 2020). The growing demand for food, together with the stagnating or reduced crop yields, presents significant challenges for future food production.

1.2 Climate change and implications for crop production

Climate change, showcasing rising temperatures, changes in rainfall patterns and an increase in the frequency and severity of extreme weather events since pre-industrial times, poses increased challenges for global agricultural production. Projections indicate that the average global temperature will continue to increase in the future (IPCC 2022). The impact of higher temperatures on crop growth and production can vary depending on the local climatic context. Increased average temperatures have been shown to reduce crop yields in temperate and tropical climates (Hatfield et al. 2011; Zhao et al. 2017), as rising temperatures can decrease the length of the grain-filling period and shorten the crop life cycle (Farooq et al. 2011; Hatfield and Prueger 2015). On the contrary, increased temperatures in cold climates can increase the growth of crops and extend the length of the growing season, which may favour crop yields (Olesen et al. 2011). However, in cold climates, overwintering problems of autumn-sown crops could increase in areas with temperatures near 0 °C as a result of higher winter temperatures (Uleberg et al. 2014).

Extreme weather events, such as heavy rainfall and periods of drought and extreme heat, have already shown to have a substantial impact on global crop productivity (Zampieri et al. 2017; Santini et al. 2022; Heino et al. 2023). Crop responses to extreme weather vary between crop species and the phenological stage of the crop. In general, the reproductive periods are more sensitive to extreme heat compared with the vegetative phase (Luo 2011; Hatfield and Prueger 2015). Temperatures outside the optimal range may lead to reduced grain number, weight and pollen abortion, resulting in yield losses (Hatfield et al. 2011; Farooq et al. 2011). During drought, most crop phenological stages are affected by water stress, but drought during flowering is thought to result in the largest yield losses (Dietz et al. 2021). Cereals have been shown to be more drought resistant than legumes and root/tuber crops due to a deeper root system (Daryanto et al. 2017; Cohen et al. 2021). On the other hand, excess water can also have a negative impact on crop yields, as excess water limits oxygen availability and hinders root development (Kaur et al. 2020). Understanding how extreme weather affects crop production is essential for developing strategies to adapt cropping systems to climate change.

1.3 The role of soil properties and agricultural management in mitigating extreme weather effects

Agricultural soil is a vital multifunctional resource providing a number of key ecosystem functions including erosion control, habitat creation and the regulation of climate, pests and diseases (Smith et al. 2021; Adla et al. 2022). The magnitude of the effects of extreme weather events on crop production also depends on soil properties and overall soil health. The health of soil has been broadly defined as the combination of physical, chemical, and biological properties that contribute to its ability to support humans, plants, and animals while maintaining or improving environmental quality (Doran and Parkin 1994). A healthy soil can retain enough water and nutrients to support plant growth (Stockdale et al. 2002), provide good soil structure for water to infiltrate, and for roots to grow to access the water and, thereby, also soil nutrient resources (Bronick and Lal 2005). A healthy soil is therefore thought to have higher resilience to extreme weather events due to the ability to provide water and nutrients during dry conditions and reduce the risk of waterlogging during extreme rainfall (Lipiec et al. 2013; He and Dijkstra 2014; Bodner et al. 2015).

Soil properties largely depend on inherent factors, among which soil texture is strongly linked to many other soil properties including water holding capacity, bulk density, porosity and the ability to retain nutrients (Mobilian and Craft 2022). Soil properties can also be affected by agricultural management. When cultivating crops, several agricultural management practices, including tillage, addition of organic and synthetic fertilizers, application of pesticides, irrigation, crop rotation and the use of cover crops, are typically used in the field (Komatsuzaki and Ohta 2007; Stagnari et al. 2010). For example, studies have shown that increased crop diversity and no-tillage can improve soil health (Balota et al. 2014; Mitchell et al. 2017; Nunes et al. 2018; Wulanningtyas et al. 2021). Other studies have shown that soil health can be improved by including organic fertilizers (Das et al. 2023; Li et al. 2023) and with less pesticide use (Aktar et al. 2009; Baweja et al. 2020).

Due to the importance of soils for crop production, it is crucial to sustain healthy agricultural soils. Nevertheless, intensive crop production has resulted in degraded soils. FAO estimated that 33% of the soils globally have already been moderately to highly degraded, primarily due to agricultural management practices resulting in compaction, erosion, acidification, salinization or chemical pollution (FAO and ITPS 2015). Soil degradation reduces soil health and can decrease crop productivity, with projections indicating a 12% reduction in global food production over the next 25 years from 2015 (ELD 2015). The slow process of soil restoration, which can span several decades (Lal 2015) further worsens this problem, highlighting the need to adapt agricultural management practices to increase soil health.

1.4 Swedish climatic conditions and crop production

Sweden is located in northern Europe, with the arable land located between latitudes of 55°N and 68°N (Fig. 1). The climatic conditions differ within the country, with a colder climate in the north compared to the south, and more precipitation in the west compared to the east (SMHI 2023a). The average temperature between 1991 and 2020 varied from 7 to 9 °C in the south and 0 to -2 °C in the north. In the same time period, the average annual precipitation varied from 400 to 600 mm in the southeastern parts up to 1000 mm in the west (SMHI 2022). Due to the higher temperatures and longer growing season in the south, most of the arable land is located in the south and central regions (Fig. 1). In the north, the cropping area is mostly used for ley, and the arable crops are mainly spring-sown oat, barley and potato (SCB 2024). In Sweden, the area of different crops cultivated have changed over time. In the 1960s, barley was the dominant and oat the second most common field crop. Over time, cultivation of winter wheat has increased and the cultivation of barley and oat decreased (Fig. 1). The increase in winter wheat is mainly due to its high yields. A declining number of cows and pigs in Sweden have resulted in a lower demand for barley as animal feed, and oats have overall resulted in less profit in comparison to other crops (Eklöf 2014).

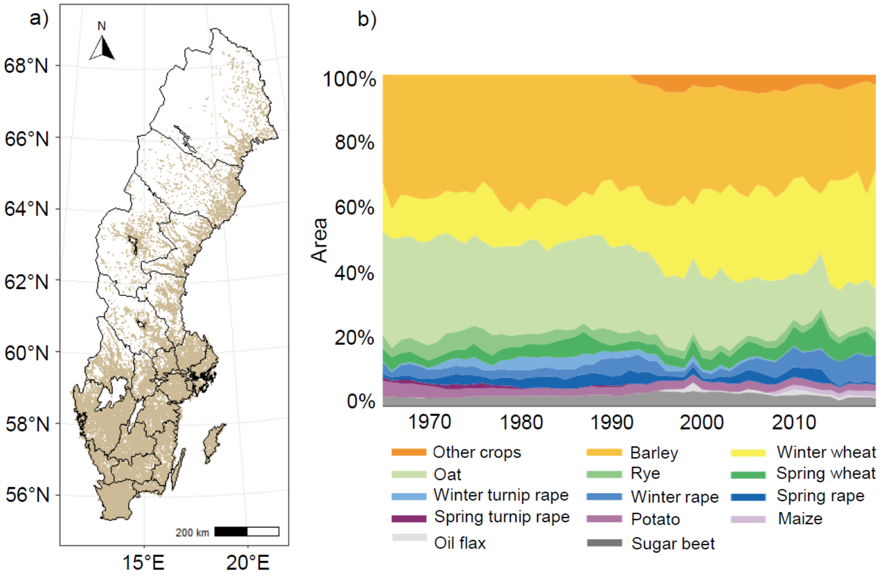


Figure 1. Agriculture in Sweden as shown in terms of (a) spatial distribution with the cropping area shown in brown (black lines delimit administrative counties) and (b) major crops and their percentage of the harvested area each year between 1965 and 2019. Adapted from **Paper I**.

In Sweden, the total cropping area has decreased since the 1960s, from 3.2 million hectares in 1965 to approximately 2.5 million hectares in 2023 (Fig. 2). This decrease is mainly due to conversion of cropping land into forest, as well as for the construction of houses and roads (Jordbruksverket 2021). The productivity of field crops had a rapid increase from the 1960s until the 1980s, but after that, the increase has been slow or even levelled off (Fig. 2).

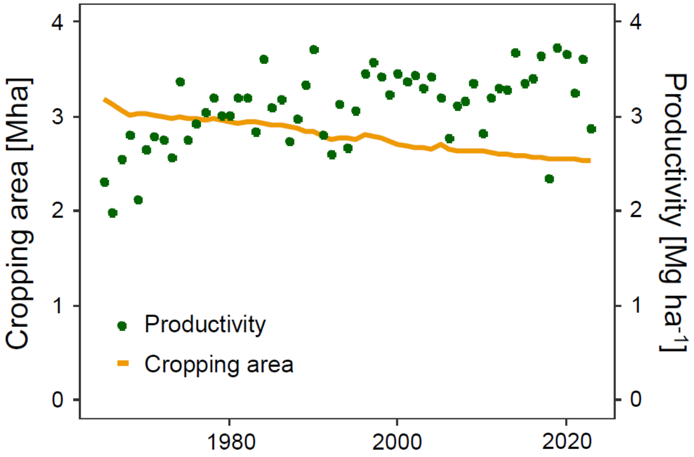


Figure 2. The change in total cropping area (including cropping area from farms with > 2 ha cropped land, and from year 2010 with > 5 ha cropped land) and the total crop productivity in Sweden between 1965 and 2023. Based on data from Statistics Sweden (SCB 2024).

Future climate projections for Sweden show an increase in average temperatures, with the highest increases in the north, based on the moderate climate change scenario RCP 4.5 (SMHI 2024a). The result will be a longer growing season. Due to both higher temperature and a longer growing season, it is expected that new crop species can be introduced, especially in the south (Eckersten and Kornher 2012). It is also expected that crop production will expand towards higher latitudes (Franke et al. 2022). King et al. (2018) estimated that, by 2055 the area within the boreal region in northern Sweden that reaches growing degree days above 1200 will increase from the current 8% to 41%, where 1200 growing degree days refer to the minimal climatic requirement for small cereal crops such as barley and oat.

The average precipitation is also estimated to increase across Sweden in the future, with the largest increase during winter and spring and with higher increase in the north compared to in the south (SMHI 2024a). With an expected wetter and warmer climate in the future, plant diseases and pests are projected to increase, both for the present pests and diseases, and for new types (Wivstad 2010; Roos et al. 2011). Higher temperatures will also lead to increased evapotranspiration, and the risk of drought will increase, especially on the east coast in the southern and central parts of Sweden (SMHI 2019a). As a result, the need for irrigation of cereal crops during the early season has been projected to increase in the south and central parts of Sweden (Grusson et al. 2021).

In the future, the frequency and intensity of extreme weather events are projected to increase, such as short-term heavy rainfalls, extreme heat and drought (SMHI 2019b). These events can have a large impact on Swedish agriculture. For example, the summer drought in 2018 resulted in 44% lower total crop production compared to the previous five-year average (SCB 2018). In addition, an increase in intensive rainfall and waterlogged soils could lead to yield losses due to hypoxic soil conditions (Kaur et al. 2020), delayed sowing, a shorter duration of various growth phases and, in turn, an increased risk of drought and heat stress during summer (Dickin and Wright 2008; Shah et al. 2020). Harvesting could also be delayed due to lodging (when the stems of cereals are bent), thus resulting in yield losses as well (Kristensen et al. 2011).

While climate change can lead to additional challenges for Swedish crop production, the negative impact of weather on crop yields is expected to be more severe in many other regions of the world (Santini et al. 2022; Heino et al. 2023). As a result, the countries responsible for producing a larger proportion of global food will likely shift northward to reduce yield losses resulting from climate change (Franke et al. 2022), ultimately giving Sweden a larger responsibility for global food production in the future.

A global evaluation of temporal yield developments by Gerber et al. (2024) showed that wheat yields in central Sweden have reached stagnation since the 1970s. Eckersten et al. (2012) predicted that the yield of maize will continue to increase in the future but at a lower rate than between 2003 and 2009 for the current cultivars. They also suggested that reduced water availability, resulting from increased temperature in the future, will limit the increase in maize yield (Eckersten et al. 2012). In addition, Morel et al. (2021) estimated that higher temperatures in the future will favour spring-sown cereal yields more in the north than in the south of Sweden.

However, to adapt cropping systems to climate change, agricultural management practices have to be adapted. One strategy currently promoted both in Sweden and globally is the introduction of diverse crop rotations into agricultural systems. A high crop diversity has been suggested not only to alleviate the negative impacts of extreme weather on crop production (Renard et al. 2023), but also to decrease the economic risks (Zabala et al. 2023). In line with agricultural intensification since the 1950s and 1960s

(Pingali 2012; Ickowitz et al. 2019), field sizes have increased and there have been a reduction of agricultural biodiversity (Matson 1997; Frison et al. 2011). Schaak et al. (2023) showed that functional crop diversity (with the crops divided into groups based on functional traits) declined on Swedish farms between 2001 and 2018. However, information about the development of crop diversity over several decades and geographical regions of Sweden is lacking.

Soil health also has an important role in mitigating extreme weather impacts on crop production, and is strongly influenced by agricultural management. However, the exact links between soil management, soil health, and mitigation of the effects of climate change are still unknown. In southern Sweden, Daverkosen et al. (2022) investigated the impact on soil health of management practices related to regenerative agriculture on 17 farm fields. They found that a higher share of perennials in combination with reduced tillage had positive effects on wet aggregate stability, vegetation density, and root abundance and depth. Williams et al. (2020) calculated a soil management index for 20 farm fields in southern Sweden, where a high index resulted from fewer tillage operations, higher crop diversity and higher number of organic amendment applications. They found that a higher index was related to better soil health, with higher levels of active carbon (a measure of easily-oxidisable organic matter), proteins, aggregate stability, respiration and total soil organic matter. These types of on-farm studies are important to evaluate agricultural management practices for improved soil health, but only few have been conducted in a Swedish context and more evaluations are needed to fully understand the relationships. Improved soil health is not only important for mitigating extreme weather impacts on current crop production, but it is also key for contributing to sustainable future cropping systems.

2. Aim and objectives

In this thesis, my overall aim was to assess the potential of agricultural management practises to alleviate extreme weather impacts on Swedish crop production. This involved analyses of different time periods, spanning from years to decades, and on different spatial scales, from single fields to the entire country. The specific objectives of this thesis were to:

1. Assess the potential for diverse crop rotations in Sweden (**Paper I**) and for increased cereal yields at the county level.

2. Identify the vulnerability of different crop types to extreme weather events across geographic regions and soil texture classes in Sweden (**Paper II**).

3. Assess the importance of soil properties for winter wheat development during drought conditions using satellite images at farmers' fields (**Paper III**).

4. Evaluate effects of agricultural management practices on the soil health and crop yield (**Paper IV**).

3. Materials and Methods

3.1 Weather data and climatic indices (Papers I-IV)

The analyses shown in this thesis cover different study areas, from national to county level (Fig. 3a), as well as landscape scale including farm fields in Västra Götaland and Östergötland counties (Fig. 3b). Daily values of cumulative precipitation and average temperature were acquired from the Swedish Meteorological and Hydrological Institute, both from multiple weather stations in each county (**Paper I and II**) (SMHI 2024b) and from gridded interpolated weather data at the location of each farmers' fields (**Paper III and IV**) (SMHI 2023b). In **Paper III**, the air temperature sum was calculated by totalling the daily mean temperatures exceeding the threshold value of 0 °C from the 1st of January through the growing season during the years 2018 and 2021. Based on the daily temperature and precipitation data, I calculated the standardized precipitation evaporation index (SPEI) (Vicente Serrano et al. 2010), heat wave index (HWI) (**Paper II**; Russo et al. 2015) and De Martonne aridity index (DMI) (**Paper III**; De Martonne 1926). The SPEI was used to assess the impacts of droughts and excessive water, the HWI was used to quantify the occurrence and intensity of heat waves, and the DMI was used to assess aridity. A higher DMI suggests more arid conditions, SPEI values > 1.5 are referred to as extremely wet and values < -1.5 as extremely dry conditions, and HWI values > 3 are referred to as extreme heat waves.

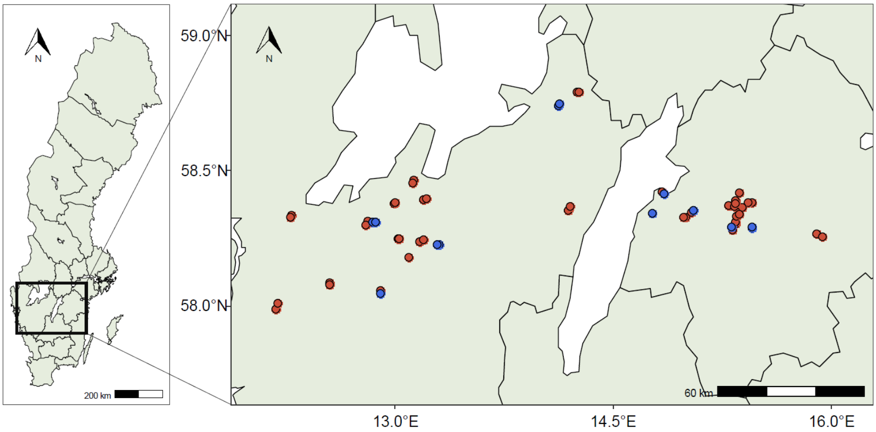


Figure 4. a) Map of Sweden with the borders of the 21 counties. b) Locations of fields included in **Paper IV**. The county to the west is Västra Götaland and to the east Östergötland. The 13 fields also included in **Paper III** are coloured in blue.

3.2 National crop and soil data (Papers I, II and IV)

Yearly data on harvested area (**Paper I**) and average yields (**Paper II**) of different arable crops for each county in Sweden were obtained from Statistics Sweden (SCB 2024). The harvested area of the 13 main crops cultivated in Sweden between 1965 and 2019 was used to assess crop species richness and crop species diversity. These crops consisted of barley (*Hordeum vulgare*), oat (*Avena sativa*), winter and spring wheat (*Triticum aestivum*), rye (*Secale cereale*), sugar beet (*Beta vulgaris*), potato (*Solanum tuberosum*), maize (*Zea mays*), oil flax (*Linum usitatissimum*), winter and spring turnip rape (*Brassica rapa* subsp. *oleifera*) and winter and spring rape (*Brassica napus*). Crop species richness was calculated as the total number of crop species. The crop species diversity index (CDI) was defined as the exponential of the Shannon diversity index (H) as follows:

$$CDI = e^{H} = e^{(-\sum_{i=1}^{n} p_i ln p_i)} \quad \text{Eq. 1}$$

where p is the proportion of crop i of the total crop area.

Of these 13 crops, the eleven crops for which regular yield data existed at the national level were used for further analysis in **Paper II**. These crops were oat, spring barley, rye, spring and winter wheat, sugar beet, potato, winter and spring rapeseed and winter and spring turnip rape. The average crop yields were obtained between 1965 and 2020 for each Swedish county (**Paper II**). Yield anomalies were calculated from detrended time series, which were used to separate variations in yield caused by weather anomalies from increases in yield due to agricultural development and intensification. The detrended time series were obtained through either linear regression or linear plateau models, and the best fit was selected based on the lowest Akaike Information Criterion for each crop-county combination (Fig. 4). A low Akaike Information Criterion implies that the model fits the data better. Where the linear regression had no significant change over time, a horizontal trend based on the mean values was used (**Paper II**). The eleven crops were then divided into different categories consisting of spring- and winter-sown cereals, spring- and winter-sown oil crops and root/tuber crops.

From the Swedish monitoring program of arable soils, I obtained county average soil texture classifications from topsoil samples (0-20 cm depth) (Miljödata-MVM 2020), which were used in **Paper I and II**. The counties with the most clayey and sandy average soil texture were used in **Paper II** to evaluate the impact of soil texture on yield responses to weather anomalies, resulting in three counties included in the texture class clay and seven counties as sandy loam.

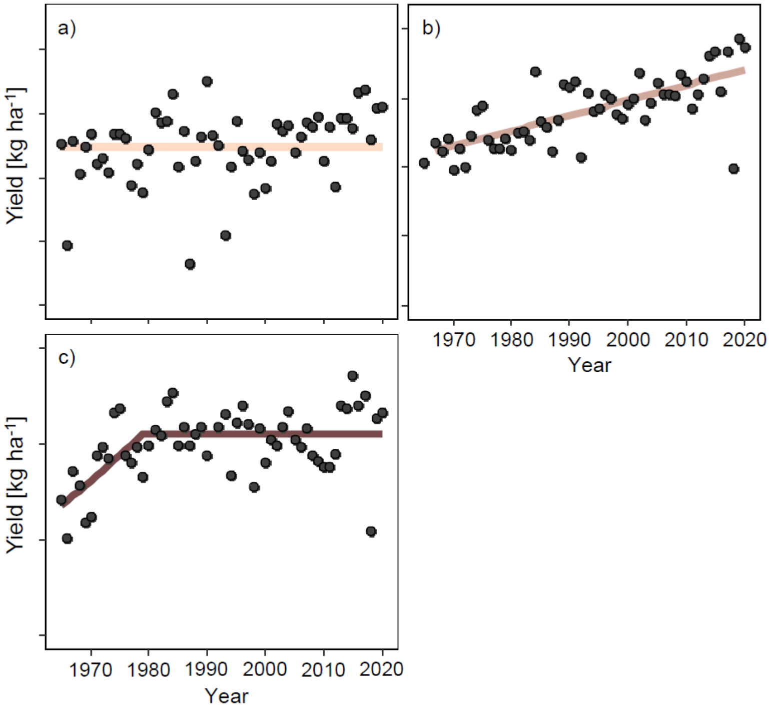


Figure 3. Examples of the different best fitted detrending methods assessing patterns in crop yield over time as (a) no temporal change, (b) linear increase and (c) stagnation.

3.3 Agricultural management data (Papers III and IV)

In **Paper IV**, 32 farmers participated with approximately two fields each, resulting in 67 fields (Fig. 3). The farmers were asked to select a ”good” field with high and/or stable yields and a “poor” field with low and/or unstable yields. The farmers were asked to provide data on crop yield and agricultural management (i.e. crop rotation, cover crops, fertilizers, pesticide use, and tillage methods and depth) for the selected fields for five years, from 2017 to 2021. A relative yield was calculated based on the yield obtained from the farmers together with the average county yield obtained from Statistics of Sweden from the years 2017 to 2021 (SCB 2024). A relative yield (RY) for each field was then calculated as:

$$RY_{i,j} = \sum \frac{Yfarmer_{i,j} - \bar{Y}_{j,k}}{\bar{Y}_{j,k}} \times 100\% \qquad \text{Eq. 4}$$

where Y_{farmer} is the yield obtained from farmers, $\bar{Y}$ is the average county yield, i indicates the year, j is the crop species and k the county. The relative yield was used for fields where the relative yield was based on at least three years of data (29 fields out of 67). A positive relative yield implies that a field performed better than the county average crop yield.

Based on the management information, a functional crop diversity index, soil tillage intensity rating, the frequency of years with organic fertilizer application and the average number of pesticide categories (insecticides, herbicides and fungicides) used per year (2017 to 2021) were calculated for each field. The soil tillage intensity rating (STIR) was developed by the USDA–NRCS (2007) and calculated as:

$$STIR = \sum_{i=1}^{5} (TT_i \times 3.25) \times (Speed_i \times 0.5) \times Depth_i \times AD_i \qquad \text{Eq. 2}$$

where TT is the tillage type factor, AD the share of the area disturbed by tillage, and the depth (inch) and the speed (mph) for each individual field operation in year i. The tillage type factor was 1.0 for ploughing, 0.8 for mixing and some inversion operations, 0.4 for subsoiler and 0.15 for roller. The area disturbed and the speed was based on default values from USDA–NRCS (2007). A functional crop diversity index (FDI) was also calculated from the management information for each field over the five-year crop rotation, as follows:

$$FDI = \left(\sum_{i=1}^{5} FG_i\right) \times \left(\frac{\sum_{i=1}^{5} S_i}{5}\right) \qquad \text{Eq. 3}$$

where FG is the number of unique functional crop groups and S the number of species (including cover crops) in the year i. The functional crop groups were divided into 1) cereals, 2) ley, 3) legumes, 4) potatoes and 5) oilseed crops.

In **Paper III**, the crop rotation was used to select the farmers' fields that had winter wheat grown in both 2018 and 2021 (Fig. 3).

3.4 Soil analyses in farmers' fields (Paper III and IV)

Soil sampling was conducted in 2021 on the 67 farmers' fields. Both loose soil and intact soil cores were collected at five evenly distributed locations per field. The loose soil from the five locations was pooled and homogenized, and a subsample was used for further analyses. The soil was analysed for soil texture and physical properties, including wet aggregate stability, bulk density, penetration resistance, and plant available water capacity. Chemical analyses included pH and cation exchange capacity. Biological analyses included soil organic matter content and basal respiration.

The plant available water content was determined as the difference in soil water content between field capacity and the permanent wilting point, corresponding to -10 and -1500 kPa matric potential, respectively. The soil water content at the permanent wilting point (-1500 kPa) was assessed in loose soil sieved at 2 mm with a pressure plate extractor. Soil water content at field capacity was determined by equilibrating the soil cores to -10 kPa on ceramic plates (ecoTec, Bonn). Bulk density was assessed by drying the soil core samples at 105 °C for 48 h. Wet aggregate stability was measured using a Cornell Sprinkle Infiltrometer (Cornell University, Ithaca, NY) following the Comprehensive Assessment of Soil Health (CASH) protocol (Moebius-Clune et al. 2016). Soil organic matter content was determined as loss on ignition. Soil pH was determined in a 1:5 soil–water suspension, and the exchangeable base cations were analysed using an inductively coupled plasma–optical emission spectrometer (ICP-OES). Titratable acidity to pH 7 was determined, and the cation exchange capacity at pH 7 (CEC_{pH7}) was calculated as the sum of this acidity and the exchangeable base cations. Soil basal respiration was assessed using a Respicond respirometer (Nordgren 1988). Air-dried soil sieved to < 2 mm was rewetted and the CO_2 emitted by soil microorganisms was measured. In addition, soil texture, including the content of clay (< 0.002 mm) and sand (0.06-2 mm), was determined by sedimentation.

In the field, soil penetration resistance was measured using a hand-held penetrologger (Royal Eijkelkamp Company, Netherlands) to a depth of 40 cm. Due to that some fields were tilled after harvest and before measuring penetration resistance, only the subsoil measurements at 20-40 cm depth were used in the analyses.

3.5 Satellite data analysis (Paper III)

Sentinel-2 scenes obtained during the growing season in the years 2018 and 2021 were used to assess the green leaf area index (GLAI) development on the farmers' fields cultivated with winter wheat in both years (**Paper III**). The sentinel-2 scenes were downloaded and processed using the open-source Python Earth Observation Data Analysis Library (EOdal, Graf et al. 2022). Pixels of 10 m x 10 m within the fields containing for example clouds, dark areas, shadows and snow were filtered out before analysis. The green leaf area index (GLAI) was estimated for each pixel using the radiative transfer model PROSAIL (Graf et al. 2023). An average GLAI was calculated from all the pixels within each field for each Sentinel-2 scene. From the development curve of the GLAI, three estimations for crop growth were derived for each field and year: winter wheat growth rate, peak GLAI, and the timing of the latter (Fig. 5).

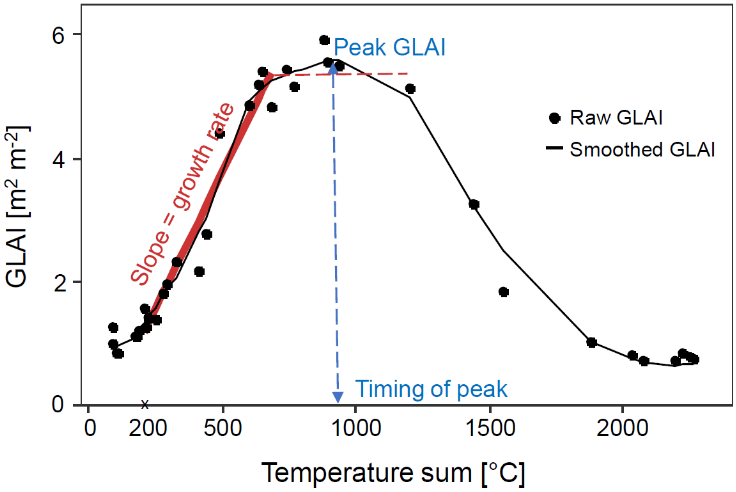


Figure 4. Illustration of the crop growth variables obtained from the green leaf area index (GLAI) temporal development for one field. The growth rate during the vegetative growth phase was obtained from the slope of a linear regression, spanning between a temperature sum of 200 °C until the start of the linear plateau (**Paper III**). The peak GLAI and its timing, in terms of temperature sum, were obtained from the smoothed curve. Reproduced from **Paper III**.

3.6 Statistical analysis (Papers I-IV)

All statistical analyses were conducted using R (R Core Team 2023). Linear regression was used to assess the temporal development of crop species richness (Sp-rich) and crop species diversity (CDI) over years. Linear regression was also used to analyse relationships between clay content, mean annual temperature and precipitation, respectively, and Sp-rich and CDI, respectively, in **Paper I**. In **Paper III**, linear regressions were used to assess the relationships between crop growth variables and soil properties. Multiple linear regression models were used in **Paper IV** to analyse relationships between agricultural management indices, soil health indicators, and relative crop yield, while accounting for differences in climatic conditions and soil texture.

Pearson's correlation coefficients were used to estimate the relationships between crop yield anomalies and temperature and precipitation anomalies, SPEI and HWI in **Paper II**. Spearman's rank correlation coefficients were calculated to investigate the relationships between sand content and crop yield anomalies during extremely dry and wet conditions in **Paper II**, and between the three crop growth variables (Fig. 5) and soil properties in **Paper III**, and between pesticide application and basal respiration on the farm fields in **Paper IV**. Spearman's rank correlation coefficients were used when some of the variables were not normally distributed or when the sample size was small. The non-parametric Mann-Whitney U test was used to assess differences in yield anomalies between years with extreme weather and with normal weather conditions, and, in **Paper II,** to assess differences between sandy loam and clay soils regarding yield anomalies during extremely wet and extremely dry years. The Mann-Whitney U test was also used to assess differences in soil properties between agricultural fields in **Paper IV**. In **Paper III**, a t-test was used to test differences in two of the winter wheat crop growth variables, growth rate and peak GLAI, between the dry year (2018) and the year with normal weather conditions (2021). In **Paper III**, Correlation-Adjusted coRelation (CAR) scores (Zuber and Strimmer 2011) were calculated to estimate the relative importance of soil properties in explaining the variation in the crop growth variables in both the dry and normal weather condition years. Further details of the statistical analyses are available in the respective papers.

4. Results

4.1 Spatial and temporal variation of crop types and crop yields across Sweden

The spatiotemporal patterns of crop species richness (Sp-rich) and crop diversity index (CDI) at the county level were assessed over the period from 1965 to 2019, showing variations in both average number of crops (Sp-rich) and CDI between counties (Fig. 6). In the northern part of Sweden, barley, potato and oat are the dominant field crops, which resulted in a low CDI with an average of 2.1. In the southern part, all major field crops were grown in the southernmost county Skåne, which had an average CDI of 6.3. A higher CDI indicates that more crop species were grown and/or were more evenly distributed across a county. Between 1965 and 2019, CDI increased in thirteen counties, located mainly in the northern and southwestern parts. However, CDI was still lowest in the northern counties.

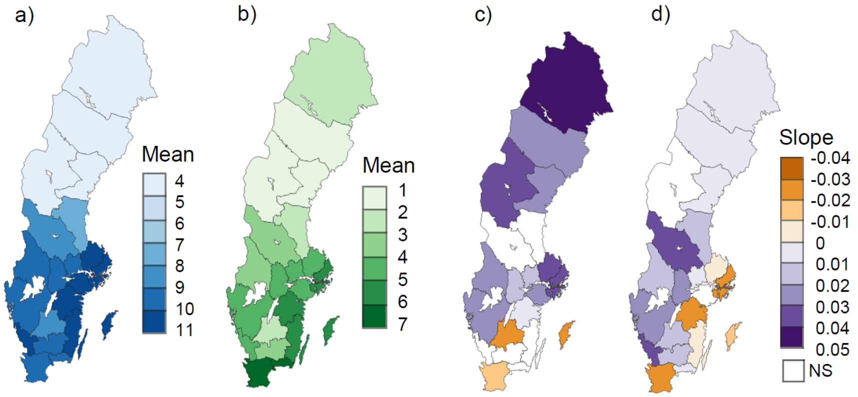


Figure 5. Maps showing the county mean values for the years 1965 to 2019 of (a) crop species richness (Sp-rich) and (b) crop species diversity index (CDI) (see definitions in section 3.3). Maps displaying the change over time as a slope of linear regression between 1965 and 2019 in (c) Sp-rich and (d) CDI. Reproduced from **Paper I**.

The temporal development in crop yields differed between counties and crops. For southern Sweden, the regressions over time indicated that assuming a linear increase in yields was correct for most counties, except for spring wheat, which showed stagnation in yield over time in four counties (Fig. 7). In central Sweden, the number of counties with stagnating cereal yields was larger. Oat and spring barley experienced a stagnation in yield in around half of the counties and spring wheat for all counties with data available, while winter wheat had a linear increase in five and a stagnation in two counties. In most northern counties, no change in spring barley yield over time occurred, showing that yield levels have remained similar from the 1960s through the 2010s (Fig. 7). The crop yields were also generally higher in the southern than in the northern counties. For example, spring barley yields in the northernmost county Norrbotten were on average 2130 kg ha^{-1} between 1965 and 2020, while in the 2010s spring barley yields reached around 5800 kg ha^{-1} in the southernmost county Skåne (SCB 2024).

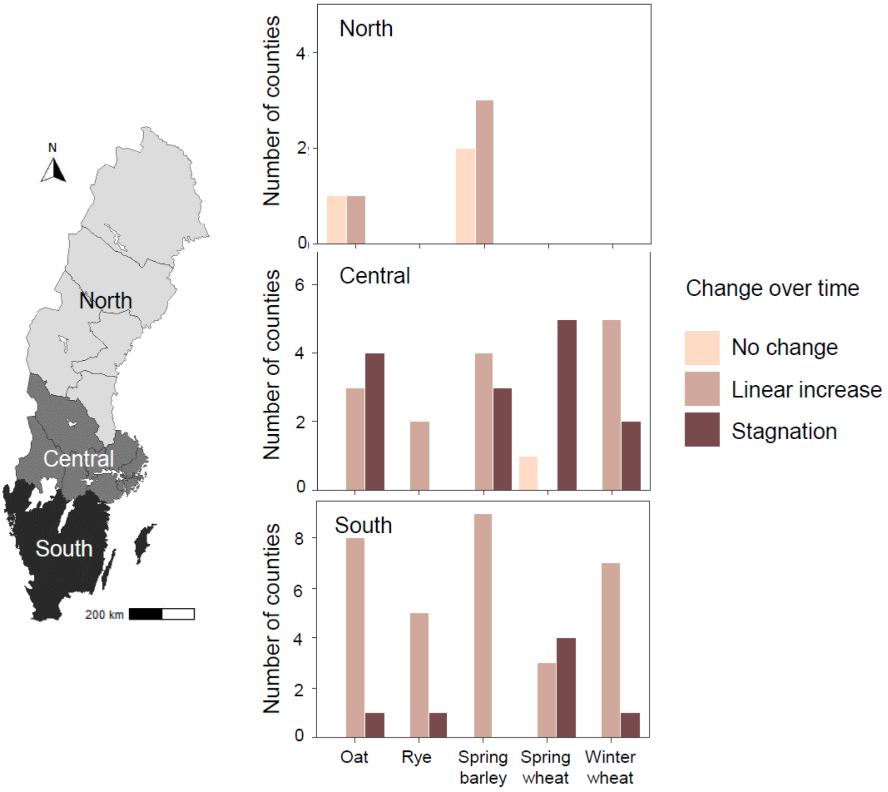


Figure 6. Bar plots show the number of Swedish counties with no change, linear increase or stagnation of crop yields between 1965 and 2020 for oat, rye, spring barley, spring wheat and winter wheat in the northern, central and southern parts of Sweden. The map displays the areas denoted as ‘northern’, ‘central’ and ‘southern’ parts of Sweden. The five counties belonging to the northern part are Norrbotten, Västerbotten, Jämtland, Västernorrland and Gävleborg; the seven counties in the central part are Dalarna, Uppsala, Västmanland, Örebro, Värmland, Stockholm and Södermanland; the nine counties belonging to the southern part are Östergötland, Västra Götaland, Jönköping, Gotland, Kalmar, Kronoberg, Halland, Blekinge and Skåne.

4.2 Relationships between extreme weather and crop yields across Sweden

Detrending of the crop yield time series were conducted and yield anomalies were obtained. The county level analysis of yield anomalies revealed that the yield of spring-sown crops, including spring cereals, oil crops, and root/tuber crops, are particularly vulnerable to extremely dry summer conditions (Fig. 8). In southern Sweden, these crops experienced the largest yield losses during dry summers, with average reductions of 16% for cereals, 18% for root/tuber crops and 15% for oilseed crops. In the central counties, the yield losses were slightly lower than in the southern counties. The autumn-sown cereals and oilseed crops were less sensitive to extremely dry conditions during summer, with significant yield losses only for autumn-sown oil crops in the central counties. In addition, the spring-sown cereals and root/tuber crops were found sensitive to extremely wet summer conditions in all parts of Sweden, with the most pronounced yield losses occurring in the northern counties and decreasing towards the south (Fig. 8).

Extremely hot summers negatively impacted the yield of spring-sown crops (Fig. 8). The latter experienced yield losses on average between 13% and 19% in both the southern and central counties. However, in the north, extreme heatwaves did not result in yield losses for the spring-sown crops. The autumn-sown crops were less affected by heat stress than were the spring-sown crops, showing no significant difference in yield between the years with extreme heat and years with normal weather conditions in the central and southern counties (Fig. 8).

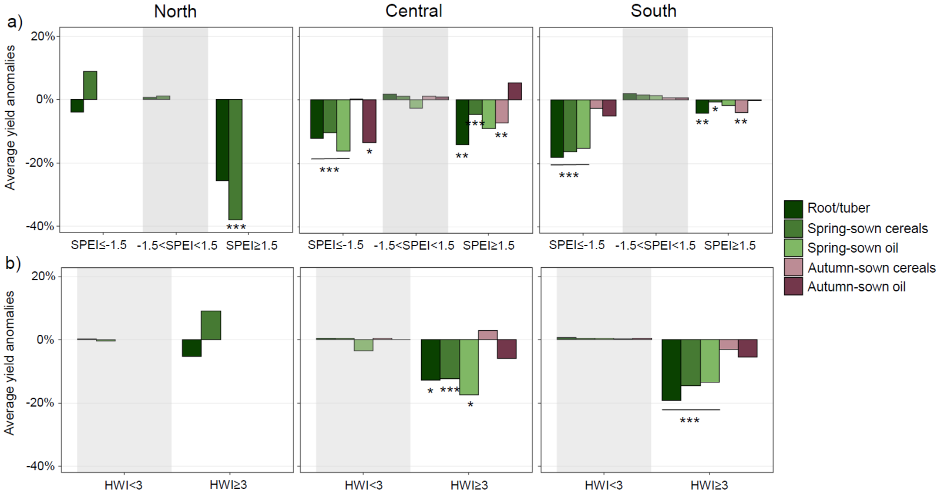


Figure 7. Average yield anomalies of root/tuber crops, spring- and winter-sown cereals and oil crops in northern, central and southern Sweden. (a) Years with extremely dry (SPEI ≤ -1.5), normal (-1.5 < SPEI < 1.5) and wet (SPEI ≥ 1.5) summers, and (b) summers with extreme heat (HWI ≥ 3) and normal summers (HWI < 3). Comparisons to years with normal weather conditions during summer (-1.5 < SPEI < 1.5, and HWI < 3) were conducted with the Mann-Whitney U test. The significance levels are * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Reproduced from **Paper II**.

The relationship between soil texture and yield anomalies during extremely dry and wet summers from 1965 to 2020 was analysed across counties. During years with extremely dry summer conditions, there were higher yield losses for spring-sown cereals in counties with sandy loam soil than in those with clay soils. However, for autumn-sown cereals, no relationship was found between yield anomalies and soil texture (Fig. 9). In years with extremely wet summers, no difference was found in yield anomalies between counties with sandy loam soil compared to clay soils.

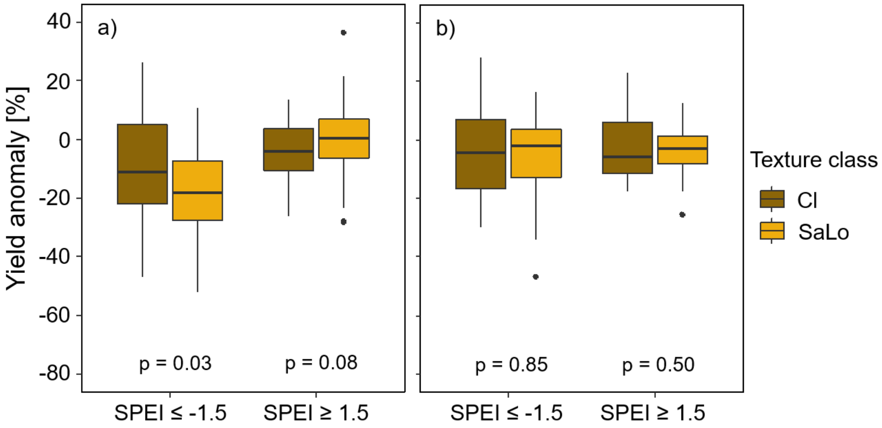


Figure 9. County level yield anomalies for (a) spring-sown cereals and (b) autumn-sown cereals in fields with average topsoil texture of clay (Cl) and sandy loam (SaLo) during extremely dry (SPEI ≤ -1.5) and extremely wet conditions (SPEI ≥ 1.5) between 1965 and 2020. Mann-Whitney U test was used for the comparison of yield anomalies between the soil texture classes, with a significance level of $p < 0.05$. Reproduced from **Paper II.**

4.3 Impact of drought on winter wheat development on farm fields

Satellite images were used to estimate growth variables for winter wheat on farmers' fields. Winter wheat growth rate was lower during the dry year (2018) compared with a year with closer to normal weather conditions (2021) ($p = 0.038$; Fig. 9), indicating a negative impact of drought on plant growth. In addition, the peak GLAI was also lower in this dry year compared to the normal year ($p < 0.001$; Fig. 9).

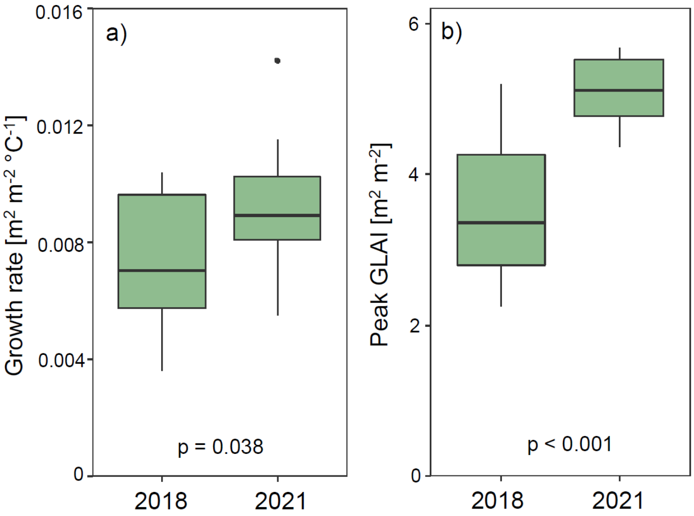


Figure 8. Winter wheat growth rate (a) and peak green leaf area index (GLAI, b) in the dry (2018) and normal weather condition year (2021). p values are obtained from t-test with n = 13. Reproduced from **Paper III**.

The impact of soil properties on winter wheat growth rate and peak GLAI was also assessed. In the dry year (2018), there was a positive relationship between growth rate and plant available water capacity (Tab. 1). However, no relationship was found between plant available water capacity and peak GLAI. In the year with normal weather conditions (2021), neither growth rate nor peak GLAI was correlated with plant available water capacity.

Table 1. Coefficients and p values from linear regression analyses examining the relationships between plant available water capacity on farmers' fields and winter wheat growth rate and the peak green leaf area index (GLAI) during one extremely dry year (2018) and a year with normal weather conditions (2021). Bold style indicates statistically significant results, $p < 0.05$. Based on **Paper III**.

	Relationship with plant available water capacity [%]			
	2018		**2021**	
	Coefficient	**p value**	**Coefficient**	**p value**
Growth rate [m^2 m^{-2} $^\circ C^{-1}$]	0.001	**0.049**	-5.03×10^{-5}	0.870
Peak GLAI [m^2 m^{-2}]	0.183	0.143	-0.032	0.594

Following the same approach as in **Paper III**, I estimated the peak GLAI from satellite images for all the farmers' fields in **Paper IV** with winter wheat grown in 2021. The peak GLAI was then compared with available yield data from 29 fields. The results show that the peak GLAI was well related to the yield obtained from the farmers, with higher yields associated with increased peak GLAI (Fig. 10). The relationship had a coefficient of determination (R^2) of 0.78, indicating that a large proportion of the yield variability could be explained by the peak GLAI.

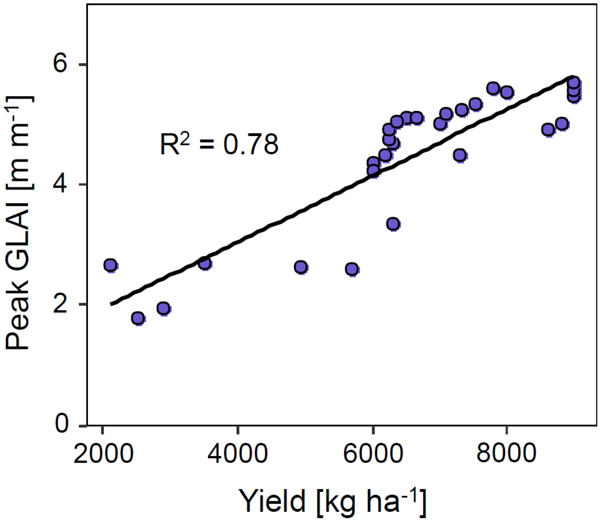


Figure 9. Peak green leaf area index (GLAI) plotted against crop yield obtained from the farmers for fields grown with winter wheat in 2021 ($n = 29$).

4.4 Relationships between agricultural management, soil properties and crop yield

The impact of agricultural management practices on soil properties was evaluated across farmers' fields. For example, I examined whether and how more diverse crop rotations influence soil health indicators. The multiple linear regression models showed a positive relationship between functional crop diversity index (FDI) and basal respiration, which is an indicator of microbial activity (Tab. 2). Fields with higher FDI typically included several years with ley in the crop rotation. As shown in Fig. 11, fields with ley in the crop rotation between 2017 and 2021 had a higher average basal respiration of 0.0117 mg CO_2-C (g soil)$^{-1}$ day^{-1}, compared to 0.0095 mg CO_2-C (g soil)$^{-1}$ day^{-1} for fields without ley.

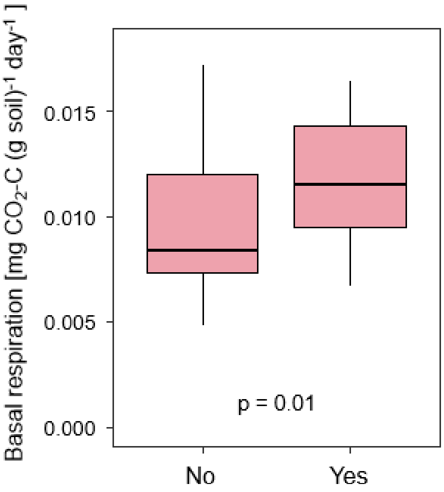


Figure 10. Boxplots of basal respiration in fields with ley (n = 18) and without ley (n = 49) in the crop rotation from 2017 to 2021. The p value is obtained from the Mann-Whitney U test.

In addition, the results revealed that a higher frequency of years with pesticide use was negatively correlated with basal respiration. Further analysis revealed that among different pesticide groups, fungicides had the largest impact on basal respiration, with basal respiration decreasing as the frequency of years with fungicide use increased (Fig. 12). The number of fields with insecticide use was too small to evaluate statistically. For herbicides, there was no relationship between the number of years with application and basal respiration.

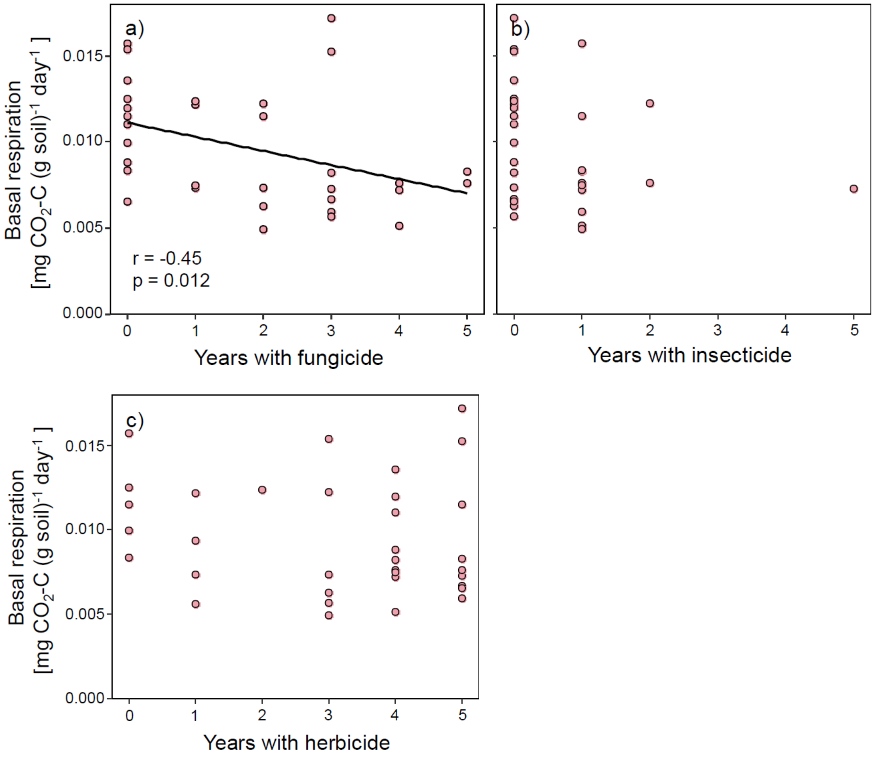


Figure 11. Relationship between basal respiration and the number of years with applications of (a) fungicides, (b) insecticides and (c) herbicides from 2017 to 2021. Regression line and Spearman correlation coefficient (r) are included where the correlation is significant at the $p < 0.05$ level.

Multiple linear regression models were used to investigate relationships between agricultural management practices and soil properties across fields. The results from the multiple linear regression showed that a higher soil tillage intensity rating, indicating a higher soil disturbance, was related to lower soil organic matter content, lower basal respiration and lower wet aggregate stability (Tab. 2). On the other hand, a higher frequency of years with use of organic fertilizers was related with higher basal respiration.

Table 2. Coefficients and p values from multiple linear regression models assessing relationships between agricultural management practices and soil properties. Relationships were assessed between on the one hand soil tillage intensity rating (STIR), frequency of years with organic fertilizer use (Org-fert) and crop diversity index (CDI), and on the other hand soil properties such as soil organic matter content (SOM), basal respiration, subsoil penetration resistance (PR), bulk density, pH, wet aggregate stability (WAS), cation exchange capacity (CEC) and plant available water capacity (PAWC).

	STIR	**Org-fert**	**CDI**	**Pest**
SOM [%]	**-0.59****	0.10	0.14	-0.04
Basal respiration [mg CO_2-C (g soil)$^{-1}$ day^{-1}]	**-0.55***	**0.31****	**0.47*****	**-0.30 ***
Subsoil PR [MPa]	0.08	0.16	-0.04	0.01
Bulk density [g cm^{-3}]	0.05	-0.03	0.05	-0.07
pH	-0.17	0.19	0.05	-0.06
WAS [%]	**-0.64 *****	0.11	0.03	-0.08
CEC [cmol kg^{-1}]	-0.27	0.05	0.03	0.01
PAWC [%]	0.08	-0.09	0.08	-0.08

The fields sampled belonged to farmers that were asked to select a ”good” field with high and/or stable yields and a “poor” field with low and/or unstable yields. Due to the overall lower relative yield in the “poor” fields (**Paper IV**), relationships between relative yield and the soil health indicators were assessed separately for the “good” and “poor” fields. In the “good” fields, the multiple linear regressions showed that a higher soil organic matter content, a higher wet aggregate stability, and a lower bulk density were related to higher relative yield (Tab. 3). In the “poor” fields, none of the soil health indictors were related to the relative yield.

Table 3. Multiple linear regression coefficients from assessing relationships between relative yield for the “good” (n=16) and “poor” (n=13) fields separately to the soil health indicators (soil organic matter content (SOM), basal respiration, subsoil penetration resistance (PR), bulk density, pH, wet aggregate stability (WAS), cation exchange capacity (CEC) and plant available water capacity (PAWC)). Variables of significance: * $p \leq 0.05$, ** $p \leq 0.01$ and *** $p \leq 0.001$. **Based on Paper IV**.

	“Good” fields	**“Poor” fields**
SOM [%]	**0.57***	0.40
Basal respiration [mg CO_2-C (g soil)$^{-1}$ day^{-1}]	0.11	-0.11
Subsoil PR [MPa]	-0.45	-0.50
Bulk density [g cm^{-3}]	**-0.51***	-0.01
pH	-0.34	0.17
WAS [%]	**0.58***	0.35
CEC [cmol kg^{-1}]	0.19	0.36
PAWC [%]	-0.03	0.27

5. Discussion

5.1 There is potential to increase Swedish crop diversity and yields across Sweden

My results demonstrate that climate (temperature, length of growing season) limits crop production in the north of Sweden, as shown by a gradient of increasing crop species richness and CDI from north to south (Fig. 6). In some counties, an increase in CDI occurred between 1965 and 2019, while other counties experienced a decrease. The temporal increase in CDI in several counties shows that it should be possible to further increase crop diversity at the county level in Sweden. Higher crop diversity has been shown beneficial for adapting cropping systems to climate change by improving soil health (Volsi et al. 2022) and by reducing the farmer's economic risks by spreading the risk over several crops (Zabala et al. 2023). For some counties, the increase in CDI was favoured by a change in climatic conditions. Higher average temperatures can enable northward expansion of winter-sown crops as a result of shorter winters, and a longer growing season can favour the introduction of new species in the south (Eckersten and Kornher 2012; Wiréhn 2018). For example, an increased cultivation of winter wheat was found in Dalarna County (central Sweden), and maize has been introduced in the south of Sweden since the 1960s. In addition to increased temperatures, breeding has helped adapt crops to lower temperatures and thereby favoured the northward expansion (Leipner and Stamp 2009).

While the increase in crop yields since the 1960s has been shown to level off or even decrease in many countries (Peltonen-Sainio et al. 2009; Finger 2010; Brisson et al. 2010; Ray et al. 2012), my findings indicate that yields for most cereals are still increasing in southern Sweden (Fig. 7). The continuous linear increase in yield since the 1960s suggests a potential for further increases in crop production. However, the yield of spring-sown cereals has stagnated in many counties in the central part of Sweden. In the northern counties, spring barley yields have remained unchanged since the 1960s, with an average of 2130 kg ha^{-1} in the northernmost county Norrbotten. The southernmost county Skåne surpassed this levels with yields around 2200 kg ha^{-1} as early as in the 1920s, and reached around 5800 kg ha^{-1} in the 2010s (SCB 2024). The higher crop yields in warmer regions illustrate the potential for higher future yields in the north of Sweden, with the projected climate change.

However, not all patterns and changes in crop diversity and crop yields can be explained by climatic conditions. The differences in changes of crop diversity over time between neighbouring counties suggest that also socioeconomic factors play an important role. These factors could include profit, market access and cultural traditions (Le et al. 2024). For example, sugar beet cultivation is located in specific areas in the south of Sweden due to the favorable growing environment and the existing infrastructure for processing of sugar beet (Ness and Brogaard 2008). The overall higher yields and profit in comparison to other cereals have resulted in winter wheat being the major field crop in Sweden. To include a higher variety of crops in the crop rotation is an investment for farmers in both time and money (Knutson et al. 2011), even though cultivating many different crops can buffer the farm business risk (Zabala et al. 2023).

The stagnation of spring-sown cereal yields in central Sweden and spring wheat in some counties in southern Sweden, despite the linear increase of the other cereals in the south, likely also reflects the influence of socioeconomic factors. Stagnated yields in many countries of the world have been attributed to more environmentally friendly agricultural policies resulting in less external inputs by farmers, lack of investments and climate change (Peltonen-Sainio et al. 2009; Finger 2010; Brisson et al. 2010; Ray et al. 2012). However, due to the similarities in agricultural policies and climatic changes between the south and central part of Sweden, probably other drivers, especially socioeconomic factors, are more important in influencing yield trends. For example, an annual report based on interviews with 1,000 Swedish farmers indicated that the perceived profitability is highest in the southern part of the country (Swedbank et al. 2023). A lower profit may limit a farmers' ability to invest in crop production, which can result in lower yield improvements over time. To fully understand the influencing factors, further assessment of farmers' motivations is necessary to determine the underlying causes.

5.2 Changes in climate have positive and negative impacts on crop production in Sweden

Changes in climatic conditions and extreme weather events influence crop production (Hatfield et al. 2011; Santini et al. 2022; Heino et al. 2023). At the county level, my findings indicate that extremely dry and hot summer conditions have led to substantial yield losses for spring-sown cereals, oil and root/tuber crops in the southern and central counties of Sweden between 1965 and 2020 (**Paper II**; Fig. 8). In contrast, the yield of autumn-sown crops was less affected by extreme drought and heat, probably due to the more advanced developmental stage of the crop during the extreme weather occurrence, such as a deeper root system (Thorup-Kristensen et al. 2009) that reaches plant-available water in deeper soil layers.

However, winter wheat development was affected by extreme drought during summer, as observed on farmers' fields (Fig. 9). In the extremely dry year (2018), winter wheat had a lower growth rate and lower peak GLAI compared to a year with normal weather conditions (2021). A higher growth rate was related to a higher peak GLAI in the dry year (**Paper III**), suggesting that faster growth can support a higher biomass during drought stress. The peak GLAI has been related to crop yield in earlier studies (Lambert et al. 2018; He et al. 2020; Yamamoto et al. 2023), with Lambert et al. (2018) reporting R^2 values of 0.62 for maize and 0.80 for millet. In this thesis, I combined the peak GLAI assessed from satellite images with the winter wheat yields obtained from the farmers. The analyses revealed that there was a strong positive relationship between peak GLAI and crop yield (Fig. 10), with an R^2 of 0.78. This suggests that the peak GLAI can be used as an indicator of crop yield under normal weather conditions. However, the prediction accuracy of crop yield may decrease when crops are exposed to extreme weather events later in the growing season. For example, extremely high temperatures have been shown particularly harmful to wheat during the reproductive period (Pradhan et al. 2012; Barlow et al. 2015), which can result in lower yield.

In northern Sweden, extreme heatwaves or drought did not result in significant yield losses for any crop group in the county level analyses that considered the years 1965 to 2020 (Fig. 8). Instead, there was a positive effect of increased average temperatures on spring-sown cereal yields (**Paper II**), indicating that crop production in the north might benefit from the projected increased temperature in the future. Higher average temperatures could allow for earlier sowing of spring-sown crops, resulting in an extended growing season and potentially increased crop yield. For example, a change in sowing date has already been observed in Finland, with an overall earlier sowing of spring cereals in the 1990s and 2000s than in the 1970s and 1980s (Peltonen-Sainio and Jauhiainen 2014).

Nevertheless, the projected increase in precipitation in the future (SMHI 2024a) might challenge an earlier sowing strategy (Kaur et al. 2020). For example, my results showed that extremely wet conditions during spring were related to yield losses in southern Sweden. In addition, negative impacts of extremely wet summer conditions on the yield of spring-sown cereals and root/tuber crops were shown across Sweden, with the largest yield losses in the north (Fig. 8). Improvements in drainage systems may therefore be important to cope with increased precipitation and heavy rainfall in the future. In Sweden, one fourth of the arable land is estimated to need new tile drainage or renovation of the existing tile drainage system (Jordbruksverket 2016). However, this requires large investments for farmers, which together with policies hinders the improvements (Wiréhn 2018). An alternative or complementary strategy for water management is enhancing soil structure to improve water infiltration and soil water retention. Agricultural management strategies that improve soil structure will therefore play an important role in mitigating the impacts of extreme weather on crop production.

Even though there will be an increase in precipitation, the increase in temperatures will also result in higher evapotranspiration, and the risk of a shortage of soil moisture will increase in the future, especially on the east coast of the southern and central parts of Sweden (SMHI 2019a). Grusson et al. (2021) projected an increased need for irrigation in the future, especially during dry years. Iizumi et al. (2024) suggested that the irrigation of winter wheat in southern Sweden has not increased at the pace that is needed to counteract the negative consequences of climate change. The positive effects of irrigation on crop productivity during drought are well known, but there are also constraints on the use of irrigation due to water saving restrictions, and high costs make the willingness to invest low (Grusson et al. 2021).

5.3 Soil properties regulate drought impacts

At the county level, the results showed higher spring cereal yield losses in counties with an average soil texture of sandy loam compared to clay soil during extremely dry summers (**Paper II**, Tab. 1). This suggests that a higher sand content exacerbates drought effects on spring-sown cereal yield losses, due to the smaller water holding capacity of sandy soils compared to clay soils (He et al. 2014; Yu et al. 2023). The amount of plant available water also depends on the depth of the root system. Deeper root systems of barley and oat have been found on clay compared to sandy soils (Wiklert 1961), which reduces the risk of drought stress. On the farmers' fields analysed in **Paper III**, the fields with higher plant available water capacity were shown to support a higher winter wheat growth rate during the dry year 2018 (Tab. 2). This suggests that soils with higher available water capacity can sustain a faster crop growth under drought stress, aligning with previous research which has shown the importance of soil water holding capacity in mitigating drought effects on crops (Wang et al. 2009; Huang et al. 2020).

5.4 Agricultural management practices can improve soil health

Agricultural management practices can influence soil health, which in turn affects crop productivity and cropping system sustainability. However, none of the management practices assessed at the farmers' fields was directly shown to influence the plant available water capacity which was shown to be important in mitigating drought impacts. This shows the difficulties in stating that certain management practices will increase plant available water capacity, however, enhanced water retention and water movement in the soil could also be affected indirectly by for instance an improved soil structure. According to my results, there was a positive effect of lower soil disturbance on increased wet aggregate stability and increased soil organic matter content. A high wet aggregate stability implies better soil structural stability, enhanced water and nutrient movements (Mikha et al. 2021), and increased soil organic matter content has been shown to favour soil health by preserving soil moisture, increasing soil structure stability, favouring biological activity and nutrient storage and turnover (Carter 2002; Fageria 2012). In addition, the results showed that a higher relative yield was related to a higher wet aggregate stability, higher soil organic matter content and lower bulk density in the "good" fields. This is probably also due to some indirect effects such as enhanced root growth as a result of improved soil structure, water retention, aeration and nutrient availability.

Overall for all fields, my results showed that increased crop diversity and the inclusion of ley in the crop rotations were associated with higher basal respiration in the soil (Tab. 2 and Fig. 11). Leys include higher species diversity and richness, and often result in higher soil carbon and nitrogen availability for microorganisms (Cong et al. 2014). Soil microorganisms have been shown to play a crucial role in many processes and functions in the soil, such as assisting plants in pathogen resistance (Wei et al. 2024), nutrient cycling and breaking down organic matter (Wang et al. 2024; Alori et al. 2024). The use of organic fertilizers also contributes to the addition of carbon to the soil, providing additional resources that can be used by microorganisms (Lazcano et al. 2021). This probably influenced the positive relationship I found between the number of years with organic fertilizer use and basal respiration (Tab. 2). Perennial crops, such as leys, also decrease soil disturbance, supporting soil organic matter accumulation and microorganisms in the soil (Means et al. 2022). This likely explains parts of the findings of higher basal respiration and greater soil organic matter content in fields with lower soil disturbance.

Basal respiration was also negatively influenced by fungicides (Fig. 12). This corresponds to earlier studies which found a negative impact of fungicides on microbial activity (Chen et al. 2001; Baćmaga et al. 2016; Karpun et al. 2021), as fungicides can have toxic effects on non-targeted organisms. With increased temperatures and precipitation in the future, pests and diseases are projected to increase. Today, Sweden uses relatively low levels of pesticides compared to the global level, mainly due to its cold winters (Roos et al. 2011; FAO 2022), but the negative impact of fungicides on microorganisms shows that the expected increase in pesticide use to manage these new challenges could result in a negative impact on soil health.

Overall my findings show that agricultural management practices can improve certain soil health indicators. I found that lower tillage intensity was related to a higher wet aggregate stability and higher soil organic matter content, and that basal respiration was related to all management practices assessed. The relationships between a higher relative yield to higher wet aggregate stability, higher soil organic matter content and lower bulk density also show the importance of soil health for crop productivity.

Increased intensification of agriculture has in many countries led to soil degradation (FAO and ITPS 2015; Kopittke et al. 2019). In Sweden, there is a relatively small proportion of land affected by soil degradation (Prăvălie et al. 2024), with a higher amount of degraded soils in the southern part (Gianoli et al. 2023) likely due to the more intensive crop production compared to the north. As climate change will potentially lead to more intensive crop production moving northwards, it will be crucial to use agricultural practices that do not degrade Swedish soils, but instead aim to maintain or enhance soil health.

5.5 Strengths and limitations of national and large datasets versus landscape studies and smaller datasets

In this thesis, various types of data were used, covering both small and large datasets, and different spatiotemporal scales. Crop yields, harvested areas, and weather data were obtained at the county level from public databases for the whole of Sweden spanning over six decades. At a smaller spatial scale, I collected soil samples, agricultural management information and obtained satellite images on 67 fields belonging to commercial farmers. Conducting analyses using large or small datasets and at larger or smaller spatial scales has different advantages and disadvantages (Flather et al. 1997; Wilbanks and Kates 1999; Levin et al. 2016). Large datasets are important for identifying long term trends and spatial patterns. Information about long term trends is important for anticipating future directions and providing support for decisions and policy making (Wilbanks and Kates 1999). A large amount of data also enhances the statistical power, enabling more robust analyses in comparison to small datasets (Kaplan et al. 2014; Columb and Atkinson 2016).

In on-farm studies, it is common to collect the data oneself through soil and crop samples and interviews, which often results in limited and smaller amounts of data. However, collecting the data oneself can result in a deeper understanding of the context and the underlying factors influencing the results. For example, in my thesis, two of the fields cultivated with winter wheat in 2021 had a high peak GLAI but very low yield compared to the other winter wheat fields. Because I visited the fields during the soil sampling in 2021, I was aware that those two fields had a significant amount of weeds, which affected the GLAI estimations. This background knowledge enabled me to understand the outlier result and I could therefore exclude those fields from the analysis presented in Fig. 10.

However, when collecting the data oneself, the data are often more geographically limited and it is more difficult to capture long-term trends. Data gathered by someone else, for example public sector records or published sources, are therefore useful for covering larger areas and timespans, even though the data may contain fewer details (Taherdoost 2021). However, large scale data often cannot capture the local variations. For example, data at the national level will miss the regional differences within a country (Vermeulen et al. 2012) as illustrated in my **Paper I**. In this paper, I found no significant change in CDI over time at the national level in Sweden, but I identified different temporal patterns between counties. County level analyses can help develop more tailored policies and climate change adaptation strategies for specific counties.

Using data covering different scales to assess similar questions could give different insights and increase the overall robustness of the findings. In my thesis, similar findings were found at different scales. For example, the importance of soil moisture availability for mitigating yield losses during summer droughts was indicated by the higher spring-sown cereal yield losses in counties with sandy loam soils compared to clay soils (Fig. 9), and this was also confirmed by the positive impact of plant available water capacity on winter wheat growth assessed on farmers' fields (Tab. 1). In addition, the negative impact of drought on crops was shown by yield losses for winter-sown crops during summer drought in southern Sweden (Fig. 8), and at a more detailed level, by the lower winter wheat growth rate and peak GLAI during a dry summer (Fig. 9).

6. Conclusions and future perspective

The overall aim of this thesis was to evaluate the potential of agricultural management practices to alleviate extreme weather impacts on Swedish crop production. This was done through the analysis of historical data to assess the future potential of crop productivity and crop diversity across Sweden in the context of climate change. It was also done from analyses of the impact of agricultural management practices for improved soil health and in turn crop yield, and the importance of soil properties in mitigating drought impacts on crop development.

Despite trends of stagnated or declining crop yields in many countries, the results revealed that cereal yields in southern Sweden have been continuously increasing since the 1960s, indicating a potential for increased crop productivity in the future. In the north, the results revealed that the cold climatic conditions currently limit crop production, but there is potential to increase crop diversity and yields with the projected warmer temperatures and longer growing periods in the future. The differences in crop diversity trends between counties, and the different temporal development of cereal yields in different parts of Sweden, highlight the influence of not only climatic but also socioeconomic factors. Socioeconomic factors are therefore crucial to take into consideration and adapt as needed to achieve the full potential of diversified cropping systems and increased crop productivity in the future. Future research should further investigate which socioeconomic factors are limiting increases in crop yields, and which factors need to change to enable a sustainable crop production in the future.

In this thesis, I demonstrated that climate change presents both opportunities and challenges for Swedish crop production. While northern regions may benefit from warmer temperatures, they will continue to face challenges related to excess water on crop productivity. The southern regions were shown more vulnerable to drought, and higher temperatures will pose increased challenges. The findings also revealed differences in the sensibility to extreme weather events between crop types, where spring-sown crops were more negatively affected by extreme weather compared to autumn-sown crops. The different impacts between regions and crops suggest that targeted site and crop adaptation strategies to climate change will be needed in the future. However, this study did not explore differences between crop varieties. Therefore, future research could identify waterlogging-resistant varieties, especially for the north, and drought-resistant varieties, especially for southern Sweden, to alleviate extreme weather impacts.

A healthy soil is important for mitigating the negative effects of extreme weather. The results showed the importance of higher plant available water capacity in mitigating drought impacts, both because winter wheat grew better in fields with higher plant available water capacity during drought, and because yield losses in dry summers for spring–sown cereals were higher in counties with more sandy soils compared to clay soils. However, none of the agricultural management practices were shown to directly impact the plant available water capacity, and here further assessments have to be conducted to understand the agricultural management practices most important to reduce yield losses during drought. Nevertheless, lower tillage intensity was related to a higher wet aggregate stability and higher soil organic matter content which indirect can favour water retention in the soil. Basal respiration was also shown related to all management practices, but further research is needed to fully understand the implication of the changes in basal respiration.

In the farmer identified "good" field, a higher relative yield was related to a higher soil organic matter content, a higher wet aggregate stability, and a lower bulk density. These relationships are probably also due to the indirect effects by enhanced root growth, water retention, aeration and nutrient availability from higher wet aggregate stability, higher soil organic matter content and lower bulk density. This shows the importance of soil health for improved crop yield.

In conclusion, this thesis highlights the importance of certain soil properties in enhancing drought resilience and increasing crop yields. The findings emphasize the necessity of adapted agricultural management practices, which may need to be adjusted based on crop type and site conditions, to better mitigate the effects of extreme weather on future crop production in Sweden.

References

Adla K, Dejan K, Neira D, Dragana Š. 2022. Chapter 9 - Degradation of ecosystems and loss of ecosystem services. In: Prata JC, Ribeiro AI, Rocha-Santos T, editors. One Health, Academic Press; p. 281–327. https://doi.org/10.1016/B978-0-12-822794-7.00008-3

Aktar MdW, Sengupta D, Chowdhury A. 2009. Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip Toxicol. 2(1):1–12. https://doi.org/10.2478/v10102-009-0001-7

Alori ET, Osemwegie OO, Ibaba AL, Daramola FY, Olaniyan FT, Lewu FB, Babalola OO. 2024. The Importance of Soil Microorganisms in Regulating Soil Health. Communications in Soil Science and Plant Analysis. 55(17):2636–2650. https://doi.org/10.1080/00103624.2024.2367246

Baćmaga M, Wyszkowska J, Kucharski J. 2016. The effect of the Falcon 460 EC fungicide on soil microbial communities, enzyme activities and plant growth. Ecotoxicology. 25(8):1575–1587. https://doi.org/10.1007/s10646-016-1713-z

Balota EL, Calegari A, Nakatani AS, Coyne MS. 2014. Benefits of winter cover crops and no-tillage for microbial parameters in a Brazilian Oxisol: A long-term study. Agriculture, Ecosystems & Environment. 197:31–40. https://doi.org/10.1016/j.agee.2014.07.010

Barlow KM, Christy BP, O'Leary GJ, Riffkin PA, Nuttall JG. 2015. Simulating the impact of extreme heat and frost events on wheat crop production: A review. Field Crops Research. 171:109–119. https://doi.org/10.1016/j.fcr.2014.11.010

Baweja P, Kumar S, Kumar G. 2020. Fertilizers and Pesticides: Their Impact on Soil Health and Environment. In: Giri B, Varma A, editors. Soil Health [Internet]. Cham: Springer International Publishing; [accessed 2024 Aug 1]; p. 265–285. https://doi.org/10.1007/978-3-030-44364-1_15

Blomqvist L, Yates L, Brook BW. 2020. Drivers of increasing global crop production: A decomposition analysis. Environ Res Lett. 15(9):0940b6. https://doi.org/10.1088/1748-9326/ab9e9c

Bodner G, Nakhforoosh A, Kaul H-P. 2015. Management of crop water under drought: a review. Agron Sustain Dev. 35(2):401–442. https://doi.org/10.1007/s13593-015-0283-4

Brisson N, Gate P, Gouache D, Charmet G, Oury F-X, Huard F. 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Research. 119(1):201–212. https://doi.org/10.1016/j.fcr.2010.07.012

Bronick CJ, Lal R. 2005. Soil structure and management: a review. Geoderma. 124(1):3–22. https://doi.org/10.1016/j.geoderma.2004.03.005

Brunelle T, Chakir R, Carpentier A, Dorin B, Goll D, Guilpart N, Maggi F, Makowski D, Nesme T, Roosen J, Tang FHM. 2024. Reducing chemical inputs in agriculture requires a system change. Commun Earth Environ. 5(1):1–9. https://doi.org/10.1038/s43247-024-01533-1

Carter MR. 2002. Soil Quality for Sustainable Land Management. Agronomy Journal. 94(1):38–47. https://doi.org/10.2134/agronj2002.3800

Chen S-K, Edwards CA, Subler S. 2001. Effects of the fungicides benomyl, captan and chlorothalonil on soil microbial activity and nitrogen dynamics in laboratory incubations. Soil Biology and Biochemistry. 33(14):1971–1980. https://doi.org/10.1016/S0038-0717(01)00131-6

Cohen I, Zandalinas SI, Huck C, Fritschi FB, Mittler R. 2021. Meta-analysis of drought and heat stress combination impact on crop yield and yield components. Physiologia Plantarum. 171(1):66–76. https://doi.org/10.1111/ppl.13203

Columb M, Atkinson M. 2016. Statistical analysis: sample size and power estimations. BJA Education. 16(5):159–161. https://doi.org/10.1093/bjaed/mkv034

Cong W-F, van Ruijven J, Mommer L, De Deyn GB, Berendse F, Hoffland E. 2014. Plant species richness promotes soil carbon and nitrogen stocks in grasslands without legumes. Journal of Ecology. 102(5):1163–1170. https://doi.org/10.1111/1365-2745.12280

Daryanto S, Wang L, Jacinthe P-A. 2017. Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. Agricultural Water Management. 179:18–33. https://doi.org/10.1016/j.agwat.2016.04.022

Das S, Liptzin D, Maharjan B. 2023. Long-term manure application improves soil health and stabilizes carbon in continuous maize production system. Geoderma. 430:116338. https://doi.org/10.1016/j.geoderma.2023.116338

Daverkosen L, Holzknecht A, Friedel JK, Keller T, Strobel BW, Wendeberg A, Jordan S. 2022. The potential of regenerative agriculture to improve soil health on Gotland, Sweden. Journal of Plant Nutrition and Soil Science. 185(6):901–914. https://doi.org/10.1002/jpln.202200200

De Martonne E. 1926. L'indice d'aridité. Bulletin de l'Association de Géographes Français. 3(9):3–5. https://doi.org/10.3406/bagf.1926.6321

Dickin E, Wright D. 2008. The effects of winter waterlogging and summer drought on the growth and yield of winter wheat (*Triticum aestivum* L.). European Journal of Agronomy. 28(3):234–244. https://doi.org/10.1016/j.eja.2007.07.010

Dietz K-J, Zörb C, Geilfus C-M. 2021. Drought and crop yield. Plant Biology. 23(6):881–893. https://doi.org/10.1111/plb.13304

van Dijk M, Morley T, Rau ML, Saghai Y. 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010-2050. Nat Food. 2(7):494–501. https://doi.org/10.1038/s43016-021-00322-9

Doran JW, Parkin TB. 1994. Defining and Assessing Soil Quality. In: Defining Soil Quality for a Sustainable Environment: John Wiley & Sons, Ltd; p. 1–21. https://doi.org/10.2136/sssaspecpub35.c1

Eckersten H, Herrmann A, Kornher A, Halling M, Sindhøj E, Lewan E. 2012. Predicting silage maize yield and quality in Sweden as influenced by climate change and variability. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science. 62(2):151–165. https://doi.org/10.1080/09064710.2011.585176

Eckersten H, Kornher A. 2012. Klimatförändringars effekter på jordbrukets växtproduktion i Sverige – scenarier och beräkningssystem [Internet]. Swedish University of Agricultural Sciences (SLU) Uppsala: Department of Crop Production Ecology. ISBN 978-91-576-9067-8

Eklöf P. 2014. Marknadsöversikt - Spannmål [Internet]. [place unknown]: Jordbruksverket. ISSN 1102-3007. ISSN 1102-3007

Fageria NK. 2012. Role of Soil Organic Matter in Maintaining Sustainability of Cropping Systems. Communications in Soil Science and Plant Analysis. 43(16):2063–2113. https://doi.org/10.1080/00103624.2012.697234

FAO. 2020. Agricultural value chains and social and environmental impacts: Trends, challenges, and policy options: FAO. https://doi.org/10.4060/cb0715en

FAO. 2022. Pesticides use, pesticides trade and pesticides indicators. Rome, Italy.

FAO. 2024. Crops and livestock products [Internet]. [accessed 2024 Jul 11]. https://www.fao.org/faostat/en/#data/QCL

FAO and ITPS. 2015. Status of the World's Soil Resources: Main Report [Internet]. Rome, Italy; [accessed 2024 Jul 17]. https://openknowledge.fao.org/items/f16010ce-1874-4108-bd03-a6a592e2e53a

Farooq M, Bramley H, Palta JA, Siddique KHM. 2011. Heat Stress in Wheat during Reproductive and Grain-Filling Phases. Critical Reviews in Plant Sciences. 30(6):491–507. https://doi.org/10.1080/07352689.2011.615687

Finger R. 2010. Evidence of slowing yield growth – The example of Swiss cereal yields. Food Policy. 35(2):175–182. https://doi.org/10.1016/j.foodpol.2009.11.004

Flather MD, Farkouh ME, Pogue JM, Yusuf S. 1997. Strengths and limitations of meta-analysis: Larger studies may be more reliable. Controlled Clinical Trials. 18(6):568–579. https://doi.org/10.1016/S0197-2456(97)00024-X

Franke JA, Müller C, Minoli S, Elliott J, Folberth C, Gardner C, Hank T, Izaurralde RC, Jägermeyr J, Jones CD, et al. 2022. Agricultural breadbaskets shift poleward given adaptive farmer behavior under climate change. Global Change Biology. 28(1):167–181. https://doi.org/10.1111/gcb.15868

Frison EA, Cherfas J, Hodgkin T. 2011. Agricultural Biodiversity Is Essential for a Sustainable Improvement in Food and Nutrition Security. Sustainability. 3(1):238–253. https://doi.org/10.3390/su3010238

Gerber JS, Ray DK, Makowski D, Butler EE, Mueller ND, West PC, Johnson JA, Polasky S, Samberg LH, Siebert S, Sloat L. 2024. Global spatially explicit yield gap time trends reveal regions at risk of future crop yield stagnation. Nat Food. 5(2):125–135. https://doi.org/10.1038/s43016-023-00913-8

Gianoli F, Weynants M, Cherlet M. 2023. Land degradation in the European Union—Where does the evidence converge? Land Degradation & Development. 34(8):2256–2275. https://doi.org/10.1002/ldr.4606

Graf LV, Merz QN, Walter A, Aasen H. 2023. Insights from field phenotyping improve satellite remote sensing based in-season estimation of winter wheat growth and phenology. Remote Sensing of Environment. 299:113860. https://doi.org/10.1016/j.rse.2023.113860

Graf LV, Perich G, Aasen H. 2022. EOA-team/eodal_notebooks: EOdal Notebooks (Graf et al., 2022) [Internet]. [accessed 2023 Jul 20]. https://doi.org/10.5281/ZENODO.7278252

Grusson Y. Wesström I. Joel A. 2021. Impact of climate change on Swedish agriculture: Growing season rain deficit and irrigation need. Agricultural Water Management. 251:106858. https://doi.org/10.1016/j.agwat.2021.106858

Hatfield JL, Boote KJ, Kimball BA, Ziska LH, Izaurralde RC, Ort D, Thomson AM, Wolfe D. 2011. Climate Impacts on Agriculture: Implications for Crop Production. Agronomy Journal. 103(2):351–370. https://doi.org/10.2134/agronj2010.0303

Hatfield JL, Prueger JH. 2015. Temperature extremes: Effect on plant growth and development. Weather and Climate Extremes. 10:4–10. https://doi.org/10.1016/j.wace.2015.08.001

He J, Shi Y, Zhao J, Yu Z, He J, Shi Y, Zhao J, Yu Z. 2020. Strip rotary tillage with subsoiling increases winter wheat yield by alleviating leaf senescence and increasing grain filling. Crop Journal. 8(2):327–340.

He M, Dijkstra FA. 2014. Drought effect on plant nitrogen and phosphorus: a meta-analysis. New Phytologist. 204(4):924–931. https://doi.org/10.1111/nph.12952

He Y, Hou L, Wang H, Hu K, McConkey B. 2014. A modelling approach to evaluate the long-term effect of soil texture on spring wheat productivity under a rain-fed condition. Sci Rep. 4(1):5736. https://doi.org/10.1038/srep05736

Heino M, Kinnunen P, Anderson W, Ray DK, Puma MJ, Varis O, Siebert S, Kummu M. 2023. Increased probability of hot and dry weather extremes during the growing season threatens global crop yields. Sci Rep. 13(1):3583. https://doi.org/10.1038/s41598-023-29378-2

Huang Z, Liu Y, Tian F-P, Wu G-L. 2020. Soil water availability threshold indicator was determined by using plant physiological responses under drought conditions. Ecological Indicators. 118:106740. https://doi.org/10.1016/j.ecolind.2020.106740

Ickowitz A, Powell B, Rowland D, Jones A, Sunderland T. 2019. Agricultural intensification, dietary diversity, and markets in the global food security narrative. Global Food Security. 20:9–16. https://doi.org/10.1016/j.gfs.2018.11.002

Iizumi T, Sakai T, Masaki Y, Oyoshi K, Takimoto T, Shiogama H, Imada Y, Makowski D. 2024. Management and climate effects to global changes in crop yield stability. https://doi.org/10.21203/rs.3.rs-3895355/v1

IPCC. 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009325844

Jordbruksverket. 2021. Exploatering av jordbruksmark 2016–2020.

Kaplan RM, Chambers DA, Glasgow RE. 2014. Big Data and Large Sample Size: A Cautionary Note on the Potential for Bias. Clin Transl Sci. 7(4):342–346. https://doi.org/10.1111/cts.12178

Karpun NN, Yanushevskaya EB, Mikhailova YV, Díaz-Torrijo J, Krutyakov YA, Gusev AA, Neaman A. 2021. Side effects of traditional pesticides on soil microbial respiration in orchards on the Russian Black Sea coast. Chemosphere. 275:130040. https://doi.org/10.1016/j.chemosphere.2021.130040

Kaur G, Singh G, Motavalli PP, Nelson KA, Orlowski JM, Golden BR. 2020. Impacts and management strategies for crop production in waterlogged or flooded soils: A review. Agronomy Journal. 112(3):1475–1501. https://doi.org/10.1002/agj2.20093

King M, Altdorff D, Li P, Galagedara L, Holden J, Unc A. 2018. Northward shift of the agricultural climate zone under 21st-century global climate change. Sci Rep. 8(1):7904. https://doi.org/10.1038/s41598-018-26321-8

Knutson CL, Haigh T, Hayes MJ, Widhalm M, Nothwehr J, Kleinschmidt M, Graf L. 2011. Farmer perceptions of sustainable agriculture practices and drought risk reduction in Nebraska, USA. Renew Agric Food Syst. 26(3):255–266. https://doi.org/10.1017/S174217051100010X

Komatsuzaki M, Ohta H. 2007. Soil management practices for sustainable agro-ecosystems. Sustain Sci. 2(1):103–120. https://doi.org/10.1007/s11625-006-0014-5

Kopittke PM, Menzies NW, Wang P, McKenna BA, Lombi E. 2019. Soil and the intensification of agriculture for global food security. Environment International. 132:105078. https://doi.org/10.1016/j.envint.2019.105078

Kristensen K, Schelde K, Olesen JE. 2011. Winter wheat yield response to climate variability in Denmark. J Agric Sci. 149(1):33–47. https://doi.org/10.1017/S0021859610000675

Lambert M-J, Traoré PCS, Blaes X, Baret P, Defourny P. 2018. Estimating smallholder crops production at village level from Sentinel-2 time series in Mali's cotton belt. Remote Sensing of Environment. 216:647–657. https://doi.org/10.1016/j.rse.2018.06.036

Lazcano C, Zhu-Barker X, Decock C. 2021. Effects of Organic Fertilizers on the Soil Microorganisms Responsible for N2O Emissions: A Review. Microorganisms. 9(5):983. https://doi.org/10.3390/microorganisms9050983

Le THL, Kristiansen P, Vo B, Moss J, Welch M. 2024. Understanding factors influencing farmers' crop choice and agricultural transformation in the Upper Vietnamese Mekong Delta. Agricultural Systems. 216:103899. https://doi.org/10.1016/j.agsy.2024.103899

Leipner J, Stamp P. 2009. Chilling Stress in Maize Seedlings. In: Bennetzen JL, Hake SC, editors. Handbook of Maize: Its Biology. New York, NY: Springer; p. 291–310. https://doi.org/10.1007/978-0-387-79418-1_15

Levin N, Crandall D, Kark S. 2016. Scale matters: differences between local, regional, and global analyses. Ecological Applications. 26(7):2359–2362. https://doi.org/10.1002/eap.1397

Li X, Qiao L, Huang Y, Li D, Xu M, Ge T, Meersmans J, Zhang W. 2023. Manuring improves soil health by sustaining multifunction at relatively high levels in subtropical area. Agriculture, Ecosystems & Environment. 353:108539. https://doi.org/10.1016/j.agee.2023.108539

Lipiec J, Doussan C, Nosalewicz A, Kondracka K. 2013. Effect of drought and heat stresses on plant growth and yield: a review. International Agrophysics. 27:463–477. https://doi.org/10.2478/intag-2013-0017

Luo Q. 2011. Temperature thresholds and crop production: a review. Climatic Change. 109(3):583–598. https://doi.org/10.1007/s10584-011-0028-6

Matson PA. 1997. Agricultural Intensification and Ecosystem Properties. Science. 277(5325):504–509. https://doi.org/10.1126/science.277.5325.504

Means M, Crews T, Souza L. 2022. Annual and perennial crop composition impacts on soil carbon and nitrogen dynamics at two different depths. Renewable Agriculture and Food Systems. 37(5):437–444. https://doi.org/10.1017/S1742170522000084

Mikha MM, Jin VL, Johnson JMF, Lehman RM, Karlen DL, Jabro JD. 2021. Land management effects on wet aggregate stability and carbon content. Soil Science Society of America Journal. 85(6):2149–2168. https://doi.org/10.1002/saj2.20333

Miljödata-MVM. 2020. Swedish University of Agricultural Sciences (SLU). National data host lakes and watercourses, and national data host agricultural land [Internet]. [accessed 2020 Nov 13]. https://miljodata.slu.se/mvm/

Mitchell JP, Shrestha A, Mathesius K, Scow KM, Southard RJ, Haney RL, Schmidt R, Munk DS, Horwath WR. 2017. Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA. Soil and Tillage Research. 165:325–335. https://doi.org/10.1016/j.still.2016.09.001

Mobilian C, Craft CB. 2022. Wetland Soils: Physical and Chemical Properties and Biogeochemical Processes. In: Mehner T, Tockner K, editors. Encyclopedia of Inland Waters (Second Edition). Oxford: Elsevier; p. 157–168. https://doi.org/10.1016/B978-0-12-819166-8.00049-9

Moebius-Clune BN, Moebius-Clune DJ, Gugino BK, Idowu OJ, Schindelbeck RR, Ristow AJ, Es HM van, Thies JE, Shayler HA, McBride, MB, et al. 2016. Comprehensive Assessment of Soil Health. 3rd ed. New York: Cornell University.

Morel J, Kumar U, Ahmed M, Bergkvist G, Lana M, Halling M, Parsons D. 2021. Quantification of the Impact of Temperature, CO2, and Rainfall Changes on Swedish Annual Crops Production Using the APSIM Model. Frontiers in Sustainable Food Systems. https://www.frontiersin.org/articles/10.3389/fsufs.2021.665025

Ness B, Brogaard S. 2008. GIS proximity analysis and environmental assessment of sugar beet transport in Scania, Sweden. Area. 40(4):459–471. https://doi.org/10.1111/j.1475-4762.2008.00838.x

Nordgren A. 1988. Apparatus for the continuous, long-term monitoring of soil respiration rate in large numbers of samples. Soil Biology and Biochemistry. 20(6):955–957. https://doi.org/10.1016/0038-0717(88)90110-1

Nunes MR, van Es HM, Schindelbeck R, Ristow AJ, Ryan M. 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma. 328:30–43. https://doi.org/10.1016/j.geoderma.2018.04.031

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F. 2011. Impacts and adaptation of European crop production systems to climate change. European Journal of Agronomy. 34(2):96–112. https://doi.org/10.1016/j.eja.2010.11.003

Peltonen-Sainio P, Jauhiainen L. 2014. Lessons from the past in weather variability: sowing to ripening dynamics and yield penalties for northern agriculture from 1970 to 2012. Reg Environ Change. 14(4):1505–1516. https://doi.org/10.1007/s10113-014-0594-z

Peltonen-Sainio P, Jauhiainen L, Laurila IP. 2009. Cereal yield trends in northern European conditions: Changes in yield potential and its realisation. Field Crops Research. 110(1):85–90. https://doi.org/10.1016/j.fcr.2008.07.007

Pingali PL. 2012. Green Revolution: Impacts, limits, and the path ahead. Proc Natl Acad Sci USA. 109(31):12302–12308. https://doi.org/10.1073/pnas.0912953109

Pinstrup-Andersen P, Hazell PBR. 1985. The impact of the green revolution and prospects for the future. Food Reviews International. 1(1):1–25. https://doi.org/10.1080/87559128509540765

Pradhan GP, Prasad PVV, Fritz AK, Kirkham MB, Gill BS. 2012. Effects of drought and high temperature stress on synthetic hexaploid wheat. Functional Plant Biol. 39(3):190–198. https://doi.org/10.1071/FP11245

Prăvălie R, Borrelli P, Panagos P, Ballabio C, Lugato E, Chappell A, Miguez-Macho G, Maggi F, Peng J, Niculiță M, et al. 2024. A unifying modelling of multiple land degradation pathways in Europe. Nat Commun. 15(1):3862. https://doi.org/10.1038/s41467-024-48252-x

R Core Team. 2023. R: The R Project for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. [Internet]. [accessed 2023 Apr 6]. https://www.r-project.org/

Ray DK, Ramankutty N, Mueller ND, West PC, Foley JA. 2012. Recent patterns of crop yield growth and stagnation. Nat Commun. 3(1):1293. https://doi.org/10.1038/ncomms2296

Renard D, Mahaut L, Noack F. 2023. Crop diversity buffers the impact of droughts and high temperatures on food production. Environ Res Lett. 18(4):045002. https://doi.org/10.1088/1748-9326/acc2d6

Roos J, Hopkins R, Kvarnheden A, Dixelius C. 2011. The impact of global warming on plant diseases and insect vectors in Sweden. Eur J Plant Pathol. 129(1):9–19. https://doi.org/10.1007/s10658-010-9692-z

Russo S, Sillmann J, Fischer EM. 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ Res Lett. 10(12):124003. https://doi.org/10.1088/1748-9326/10/12/124003

Santini M, Noce S, Antonelli M, Caporaso L. 2022. Complex drought patterns robustly explain global yield loss for major crops. Sci Rep. 12:5792. https://doi.org/10.1038/s41598-022-09611-0

SCB. 2018. Production of cereal crops, dried pulses and oilseed crops in 2018. Statistiska meddelanden. JO 19 SM 1801.

SCB. 2024. Statistikdatabasen [Internet]. [accessed 2024 Jun 11]. https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/

Schaak H, Bommarco R, Hansson H, Kuns B, Nilsson P. 2023. Long-term trends in functional crop diversity across Swedish farms. Agriculture, Ecosystems & Environment. 343:108269. https://doi.org/10.1016/j.agee.2022.108269

Shah F, Coulter JA, Ye C, Wu W. 2020. Yield penalty due to delayed sowing of winter wheat and the mitigatory role of increased seeding rate. European Journal of Agronomy. 119:126120. https://doi.org/10.1016/j.eja.2020.126120

SMHI. 2019a. Sveriges vattentillgång utifrån perspektivet vattenbrist och torka – Delrapport 1 i regeringsuppdrag om åtgärder för att motverka vattenbrist i ytvattentäkter. Hydrologi, No. 120, ISSN: 0283-7722.

SMHI. 2019b. Climate extremes for Sweden [Internet]. [accessed 2024 Jul 9]. https://doi.org/10.17200/Climate_Extremes_Sweden

SMHI. 2022. Normalperioden 1991-2020 [Internet]. [accessed 2024 Aug 8]. https://www.smhi.se/kunskapsbanken/klimat/normaler/normalperioden-1991-2020-1.166930

SMHI. 2023a. Sveriges klimat [Internet]. [accessed 2024 Jul 18]. https://www.smhi.se/kunskapsbanken/klimat/sveriges-klimat

SMHI. 2023b. Nedladdning av griddad nederbörd- och temperaturdata (PTHBV) [Internet]. [accessed 2023 Mar 8]. https://www.smhi.se/data/ladda-ner-data/griddade-nederbord-och-temperaturdata-pthbv

SMHI. 2024a. Fördjupad klimatscenariotjänst [Internet]. [accessed 2024 Aug 30]. https://www.smhi.se/klimat/framtidens-klimat/fordjupade-klimatscenarier/met/sverige/medeltemperatur/rcp45/2041-2070/year/anom

SMHI. 2024b. Ladda ner meteorologiska observationer [Internet]. [accessed 2024 Jun 11]. https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=core

Smith P, Keesstra SD, Silver WL, Adhya TK. 2021. The role of soils in delivering Nature's Contributions to People. Philosophical Transactions of the Royal Society B: Biological Sciences. 376(1834):20200169. https://doi.org/10.1098/rstb.2020.0169

Stagnari F, Ramazzotti S, Pisante M. 2010. Conservation Agriculture: A Different Approach for Crop Production Through Sustainable Soil and Water Management: A Review. In: Lichtfouse E, editor. Organic Farming, Pest Control and Remediation of Soil Pollutants: Organic farming, pest control and remediation of soil pollutants

[Internet]. Dordrecht: Springer Netherlands; [accessed 2024 Jul 11]; p. 55–83. https://doi.org/10.1007/978-1-4020-9654-9_5

Stockdale E a., Shepherd M a., Fortune S, Cuttle S p. 2002. Soil fertility in organic farming systems – fundamentally different? Soil Use and Management. 18(s1):301–308. https://doi.org/10.1111/j.1475-2743.2002.tb00272.x

Swedbank, Ludvig & Co, Sparbankerna. 2023. Lantbruksbarometern 2023 [Internet]. https://ludvig.se/rapport-kategorier/lantbruk/

Taherdoost H. 2021. Data Collection Methods and Tools for Research; A Step-by-Step Guide to Choose Data Collection Technique for Academic and Business Research Projects.

Thorup-Kristensen K, Salmerón Cortasa M, Loges R. 2009. Winter wheat roots grow twice as deep as spring wheat roots, is this important for N uptake and N leaching losses? Plant Soil. 322(1):101–114. https://doi.org/10.1007/s11104-009-9898-z

Uleberg E, Hanssen-Bauer I, van Oort B, Dalmannsdottir S. 2014. Impact of climate change on agriculture in Northern Norway and potential strategies for adaptation. Climatic Change. 122(1):27–39. https://doi.org/10.1007/s10584-013-0983-1

USDA–NRCS. 2007. The Soil Tillage Intensity Rating (STIR). Idaho.

Vermeulen SJ, Aggarwal PK, Ainslie A, Angelone C, Campbell BM, Challinor AJ, Hansen J, Ingram JSI, Jarvis A, Kristjanson PM, et al. 2012. Options for support to agriculture and food security under climate change.

Vicente Serrano SM, Beguería S, López-Moreno JI. 2010. A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index – SPEI [Internet]. https://doi.org/10.1175/2009JCLI2909.1

Volsi B, Higashi GE, Bordin I, Telles TS. 2022. The diversification of species in crop rotation increases the profitability of grain production systems. Sci Rep. 12(1):19849. https://doi.org/10.1038/s41598-022-23718-4

Wang E, Cresswell H, Xu J, Jiang Q. 2009. Capacity of soils to buffer impact of climate variability and value of seasonal forecasts. Agricultural and Forest Meteorology. 149(1):38–50. https://doi.org/10.1016/j.agrformet.2008.07.001

Wang X, Chi Y, Song S. 2024. Important soil microbiota's effects on plants and soils: a comprehensive 30-year systematic literature review. Front Microbiol. 15:1347745. https://doi.org/10.3389/fmicb.2024.1347745

Wei X, Xie B, Wan C, Song R, Zhong W, Xin S, Song K. 2024. Enhancing Soil Health and Plant Growth through Microbial Fertilizers: Mechanisms, Benefits, and Sustainable Agricultural Practices. Agronomy. 14(3):609. https://doi.org/10.3390/agronomy14030609

Wiklert P. 1961. Om sambandet mellan markstruktur, rotutveckling och upptorkningsförlopp. Grundförbättring. 14(4):221–239.

Wilbanks TJ, Kates RW. 1999. Global Change in Local Places: How Scale Matters. Climatic Change. 43(3):601–628. https://doi.org/10.1023/A:1005418924748

Williams H, Colombi T, Keller T. 2020. The influence of soil management on soil health: An on-farm study in southern Sweden. Geoderma. 360:114010. https://doi.org/10.1016/j.geoderma.2019.114010

Wiréhn L. 2018. Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production. Land Use Policy. 77:63–74. https://doi.org/10.1016/j.landusepol.2018.04.059

Wivstad M. 2010. Klimatförändringarna : – en utmaning för jordbruket och Giftfri miljö [Internet]. Sundbyberg; [accessed 2023 Feb 21]. http://urn.kb.se/resolve?urn=urn:nbn:se:naturvardsverket:diva-1566

Wulanningtyas HS, Gong Y, Li P, Sakagami N, Nishiwaki J, Komatsuzaki M. 2021. A cover crop and no-tillage system for enhancing soil health by increasing soil organic matter in soybean cultivation. Soil and Tillage Research. 205:104749. https://doi.org/10.1016/j.still.2020.104749

Yamamoto S, Hashimoto N, Homma K. 2023. Evaluation of LAI Dynamics by Using Plant Canopy Analyzer and Its Relationship to Yield Variation of Soybean in Farmer Field. Agriculture. 13(3):609. https://doi.org/10.3390/agriculture13030609

Yu M, Zhang J, Wei L, Wang G, Dong W, Liu X. 2023. Impact of soil textures on agricultural drought evolution and field capacity estimation in humid regions. Journal of Hydrology. 626:130257. https://doi.org/10.1016/j.jhydrol.2023.130257

Zabala JA, Martínez-García V, Martínez-Paz JM, López-Becerra EI, Nasso M, Díaz-Pereira E, Sánchez-Navarro V, Álvaro-Fuentes J, González-Rosado M, Farina R, et al. 2023. Crop diversification practices in Europe: an economic cross-case study comparison. Sustainability Science. 18(6):2691–2706. https://doi.org/10.1007/S11625-023-01413-1

Zampieri M, Ceglar A, Dentener F, Toreti A. 2017. Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. Environ Res Lett. 12(6):064008. https://doi.org/10.1088/1748-9326/aa723b

Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P, et al. 2017. Temperature increase reduces global yields of major crops in four independent estimates. Proceedings of the National Academy of Sciences. 114(35):9326–9331. https://doi.org/10.1073/pnas.1701762114

Zuber V, Strimmer K. 2011. High-Dimensional Regression and Variable Selection Using CAR Scores. Statistical Applications in Genetics and Molecular Biology. 10(1). https://doi.org/10.2202/1544-6115.1730

Popular science summary

As the global population continues to grow and income levels rise, the demand for food is projected to increase in the coming decades. Meeting this demand presents challenges to agriculture, particularly when considering additional challenges due to climate change, which has already been shown to affect crop productivity worldwide. Since the green revolution in the 1950 and 1960s, more intensive agriculture and advancements in technologies and practices have led to increases in crop yields. However, in recent years, this increasing trend has slowed down, levelled off, or even turned into a decline in harvest in some countries, raising concerns about the ability to meet future food demand.

Climate change plays a key role in challenging future food production. With climate change, extreme weather events such as droughts, heat and heavy rainfall are projected to increase in frequency and severity in the future, and have already led to substantial yield losses globally. However, soils can help mitigate extreme weather impacts on crop productivity. Healthy soils are capable of supporting plant growth and mitigating negative impacts on crop yields from extreme weather due to their ability to retain plant available water, provide nutrients, and maintain a structure that allows for root development, infiltration of water and soil aeration. Soil degradation is an increasing problem globally, with severe negative consequences for crop productivity. Agricultural management practices must be adapted to prevent further degradation of agricultural soils while maintaining or increasing crop productivity.

The overall aim of this thesis was to evaluate the potential of agricultural management to alleviate extreme weather impacts on Swedish crop production. This was accomplished using historical data across Sweden to estimate potential future impact of climate change on crop yields and to assess the potential of increased crop diversity. In addition, I also assessed the importance of soil texture to help mitigate negative effects of extreme weather impacts, as well as relationship between management practices and soil health on farmers' fields. The results showed that climatic conditions limit what can be grown in different regions of Sweden, particularly in the north with its colder climate and shorter growing seasons. With climate change there is a possibility of northward expansion of certain crops due to increased temperatures and longer growing seasons, as well as a potential for new crops to be introduced in the south. An examination of crop production over time since the 1960s showed that cereal yields were overall still increasing in the south of Sweden in most counties, indicating a potential for increased crop production in the future. In contrast, stagnating cereal yields were dominant in the central regions, while in the north, cereal yields have been at the same level since the 1960s. Low yield levels in the north suggest that there is potential to increase the production under more favourable growing conditions in the future.

My results showed that different counties and crop categories varied in their vulnerability to extreme weather events. The crops grown in the south were more negatively affected by drought and warmer temperatures, while in the north, the crops were more sensitive to water excess while higher temperatures were beneficial. Spring-sown crops were more sensitive to extreme weather in comparison to autumn-sown crops. This may be attributed to the more advanced developmental stage of the autumn-sown crop when extreme weather occurs, which is mainly in summer. These results highlight the need for tailored adaptation strategies for different regions and crops in the future.

The importance of higher supply of plant available water in the soil for improved crop productivity during drought was shown by a faster winter wheat growth in farmers' fields with higher plant available water capacity during a dry year, and also by larger spring-sown cereal yield losses in counties with higher sand content. The results also indicate that soil health can be enhanced through management practices such as higher diversity of crop rotations (with inclusion of leys), lower tillage intensity, higher use of organic fertilizers and less fungicide use. These practices can therefore help to sustain and enhance soil health, which is of utmost importance for future crop production.

In conclusion, this thesis underscores the need for adapted agricultural management practices, which could vary between crops and sites, to mitigate extreme weather impacts on Swedish crop production in the future.

Populärvetenskaplig sammanfattning

I takt med att världens befolkning fortsätter växa och inkomstnivåerna stiger förväntas efterfrågan på livsmedel öka under de kommande decennierna. Att tillgodose denna efterfrågan innebär utmaningar för jordbruket, särskilt med tanke på klimatförändringarna, som redan har visat sig påverka grödors produktivitet över hela världen. Sedan starten på den gröna revolutionen på 1950-60 talet har ett mer intensivt jordbruk och framsteg inom teknik och brukningsmetoder lett till ökade skördar. På senare år har dock dessa skördeökningar saktat in, stagnerat eller till och med övergått till skördeminskning i vissa länder. Detta väcker farhågor om möjligheterna att tillgodose en framtida ökad efterfrågan på livsmedel.

I och med klimatförändringarna förväntas extremväder såsom torka, hetta och kraftiga regn bli allt värre och vanligare. Ett sätt att sprida riskerna är att odla fler olika sorters grödor och ha en ökad grödodiversitet. Åkermarkens egenskaper kan också hjälpa till att mildra de negativa effekterna av extremväder på grödornas produktivitet. En god jordhälsa innebär att marken till exempel kan hålla ett större förråd av vatten och bidra med näringsämnen till grödorna. En god jordhälsa innebär också god markstruktur som gynnar rotutveckling och infiltration av vatten. Jordhälsan är dock hotad på grund av intensiva brukningsmetoder som har lett till en försämring av jordbruksmarken överlag. Brukningsmetoderna måste därför anpassas för att förhindra ytterligare försämring av jordbruksmarken i framtiden.

Det övergripande syftet med denna avhandling var att utvärdera jordbrukets potential att mildra effekterna av extrema väderförhållanden på svensk växtproduktion. Jag använde historiska data över hela Sverige för att uppskatta potentiell framtida påverkan av klimatförändringar på skörd, och potentialen att öka mångfalden av grödor. Dessutom bedömde jag betydelsen av markens textur för att mildra effekterna av extremt väder på grödor, liksom förhållandet mellan brukningsmetoder och jordhälsa på lantbrukares fält. Resultaten visar att klimatförhållandena begränsar vad som kan odlas i olika delar av Sverige, med kallare klimat och kortare växtperiod i norr. Men med ökande temperatur och längre växtperiod kan det ske en utbredning norrut av värmekrävande grödor, och nya grödor kan introduceras i söder. Spannmålsskördarna har överlag ökat sedan 60-talet i de flesta län i södra Sverige, vilket visar en potential för ökad växtproduktion i framtiden. I mellersta Sverige dominerar istället stagnerade spannmålsskördar, det vill säga skördeökningen har avstannat. I norr har spannmålsskördarna legat på samma nivå sedan 1960-talet. Den låga avkastningsnivån i norr tyder dock på att det finns potential att även där öka skördarna under mer gynnsamma odlingsförhållanden i framtiden.

Resultaten för olika län visar att grödor i Sverige skiljer sig i sårbarhet för extremväder. Grödorna som odlas i söder påverkas negativt av torka och varmare temperaturer. Grödorna i norr, däremot, är mer känsliga för vattenöverskott och en högre temperatur visar sig istället vara gynnsam. Vårsådda grödor är mera känsliga för extremväder än höstsådda grödor, vilket kan bero på att den höstsådda grödan har kommit längre i sin utveckling när det extrema vädret inträffar på sommaren. Dessa resultat understryker behovet av skräddarsydda anpassningsstrategier mellan grödor och regioner i framtiden.

Tillväxthastigheten och den maximala biomassan i höstvete var lägre under det extremt torra året 2018 än under det normala väderåret 2021. Betydelsen av mer växttillgängligt vatten i marken för förbättrad grödproduktivitet under torka visades genom snabbare tillväxthastighet av höstvete under det torra året 2018 på fält med mer växttillgängligt vatten. Men även genom större skördeförluster för vårsådd spannmål i län med överlag högre sandhalt jämfört med län med högre lerhalt under torra somrar. Resultaten visar även att jordhälsan kan förbättras genom brukningsmetoder som till exempel en mer varierad växtföljd (och med vall inkluderat), mindre intensiv jordbearbetning, oftare användning av organiska gödselmedel och mindre användning av fungicider (bekämpningsmedel mot svampsjukdomar). Dessa strategier kan därför bidra till att upprätthålla och förbättra jordhälsan, vilket är av största vikt för den framtida matproduktionen.

Sammanfattningsvis understryker denna avhandling behovet av anpassade brukningsmetoder, som kan skilja sig mellan grödor och platser, för att mildra påverkan av extremt väder på svensk växtproduktion i framtiden.

Acknowledgements

I want to express my deepest gratitude to my supervisors Thomas Keller and Tino Colombi. Tino, who made me interested in research during the master thesis and encouraged me that I would be able to succeed as a doctoral student. Without you I would not have chosen this path. Thomas for giving me the possibility to start to work in your research group, to become a licentiate and eventually a PhD student, and for creating many opportunities for me to develop. I am grateful to both of you for always encouraging me and also for making me challenge myself. As well for your exceptional academic expertise, I have learned a lot from you on this journey.

I also thank my supervisors Gina and Elsa C, who were involved in the supervision during a later stage of the PhD, for encouragement and for giving me good comments and feedback. And thank you Gina for language checking the thesis. Also, thank you Magnus and Mats for reviewing the thesis, for your good comments about the smaller details.

I want to thank Helge, who also became like a supervisor. I am grateful that I was able to spend time at Agroscope in Switzerland and learn from you, Lukas and the other members of your group, and for all the nice people I met there. I gratefully acknowledge the travel grant from the Lennart Hjelm's foundation, which allowed me to do the exchange to Zürich, Switzerland. I also greatly acknowledge the funding for this PhD from FORMAS (The Swedish Research Council for Sustainable Development), SLF (Swedish Farmers' Foundation for Agricultural Research) and KSLA (Royal Swedish Academy of Agriculture and Forestry).

During the intensive soil sampling of fields in Östergötland and Västra Götaland, thank you for your great help Laura, Leah and Loraine. During the second round of sampling at the same fields, thank you Getachew, Fredrik and Elsa AV for all the help. We had a great time. I also wish to thank all the

farmers for allowing me to take samples from their fields and giving me their historical data.

Thank you Anna, Alena, Ana, Ann-Christine and Jan for conducting laboratory measurements on my soil samples. And I want to thank Ararso for giving me good advice about sampling methods and equipment. I also want to thank everyone in my research group, Soil Mechanics and Soil Management: Thomas, Ararso, Mitsuaki, Elsa AV, Rebecca, Lorena, Mats, Daniel, Maria and Pascal, and all previous members, who have been there and wanted to help and answer my questions, for your support, and for all our fun group activities.

Thank you Miyanda for being my officemate, for our nice chats, sharing the PhD department representative position with me, and for the nice travel companionship together with Haichao to Vienna. Thank you Tamlyn for also sharing the PhD position in the docent board. I also thank Getachew and Rebecca for our traditional lunches at Logen, and Chris who helped us start it a long time ago. To my colleagues at the Department of Soil and Environment, thank you for the lunch and fika breaks with fun and interesting chats and other great activities.

Last but not least, I want to thank Björn, my parents, Pontus and all my friends for their support. I am grateful for the encouragement, and that some of you even dared to read what I had written. Especially Björn, who read this thesis. Lastly, thanks to Pontus, whose insistence on renovating our house from scratch made this PhD journey seem much more manageable in comparison.

With gratitude,
Hanna Sjulgård

Agriculture, Ecosystems and Environment 336 (2022) 108046

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Spatiotemporal patterns of crop diversity reveal potential for diversification in Swedish agriculture

Hanna Sjulgård [a,*], Tino Colombi [a], Thomas Keller [a,b]

[a] Department of Soil and Environment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden
[b] Department of Agroecology and Environment, Agroscope, Zürich, Switzerland

ARTICLE INFO

Keywords:
Crop diversification
Agrobiodiversity
Crop production
Agriculture
Crop rotation

ABSTRACT

Increasing crop species diversity within a region could improve agricultural sustainability, but knowledge of the spatiotemporal variation of crop species diversity and how this is related to pedo-climatic conditions is limited. In the current study, we used historical crop data records to quantify how crop species diversity is related to pedo-climatic conditions, and how crop diversity developed over time at the national and regional scale in Sweden between 1965 and 2019. Crop diversity was quantified using the exponent of the Shannon index. We found spatial differences across the country, with a significant increase in crop diversity from the north to the south, showing that there is a strong natural control of latitude and associated mean annual temperature on crop diversity in Sweden. Mean annual precipitation and soil texture had no significant relationship with crop diversity across Sweden. At the national level, crop diversity had no significant change over time. At the county level, our analyses revealed different temporal trends between counties. Crop diversity increased over time in certain counties, while in others no change or a decrease occurred. The temporal changes could not be explained by climate trends, and were likely influenced by socioeconomic factors. However, more than half of the counties showed an increase in crop diversity, suggesting that it is possible to increase crop diversity in Sweden. Our study shows that both natural and socioeconomic factors need to be considered to achieve an increase in crop diversity in the future.

1. Introduction

Agricultural intensification and expansion of agricultural land during the last century have led to a simplification of landscapes (Landis, 2017; Matson, 1997). Larger field sizes, removal of non-crop habitats, increased input of pesticides and fertilizers, and monoculture optimized and simplified crop production. However, these developments resulted in a loss in biodiversity (Frison et al., 2011; Matson, 1997). Biodiversity in agriculture includes species and varieties of crops and livestock, their wild relatives, as well as weeds, soil fauna, pollinators, pests and predators (Altieri, 1999; Zimmerer, 2010). Crop species diversity is crucial for the biodiversity of arable cropping systems as it strongly influences the diversity of non-crop species. High crop diversity in the landscape may increase resource continuity and provides nesting sites for insects, which has been associated with a greater diversity of pollinators (Aguilera et al., 2020) and natural antagonists of pests (Palmu et al., 2014). Moreover, higher crop diversity may also increase the diversity of soil microbial communities (D'Acunto et al., 2018; González-Chávez et al., 2010; Lupwayi et al., 1998; Venter et al., 2016), due to diversity in root exudates (Steinauer et al., 2016) and plant litter (D'Acunto et al., 2018). In summary, crop species diversity affects entire agro-ecosystems and thus multiple ecosystem services essential to crop production, such as pest and disease regulation, and nutrient and water cycling (Altieri, 1999).

It has been suggested that crop species diversity will be key to adapt arable systems to climate change (Lin, 2011) by improving crop productivity (Burchfield et al., 2019; Smith et al., 2008) as well as yield stability (Gaudin et al., 2015; Marini et al., 2020; Renard and Tilman, 2019). The frequency and magnitude of extreme weather events such as droughts and heatwaves are projected to increase in the future (IPCC, 2013). Higher crop diversity may alleviate the effects of heat stress (Degani et al., 2019; Marini et al., 2020) and drought (Bowles et al., 2020; Marini et al., 2020) on crop yields. Moreover, diseases and pests are both predicted to increase due to climate change in the future (Lin, 2011). A diverse cropping system can reduce disease pressure (Krupinsky et al., 2002) and promote populations of natural antagonists

---

* Corresponding author.
E-mail address: hanna.sjulgard@slu.se (H. Sjulgård).

https://doi.org/10.1016/j.agee.2022.108046
Received 2 December 2021; Received in revised form 20 May 2022; Accepted 26 May 2022

(Redlich et al., 2018). Therefore, crop diversity will play a crucial role in the functioning of agro-ecosystems under climate change.

The relationships between increased crop diversity, productivity and ecosystem services are complex, and depend on the type of diversification strategy used (Beillouin et al., 2020) and on agricultural inputs such as fertilizers and pesticides (Swift et al., 2004), making the effect of crop diversity context dependent. Strategies to increase crop species diversification may be achieved by including a higher number of crop species into crop rotations, intercropping of several crop species in the field, or by including cover crops (Altieri, 1999; Hufnagel et al., 2020). To a certain degree, crop diversity in a region is determined by natural factors such as soil type, precipitation, temperature and the length of the vegetation period. In addition, socioeconomic factors (Cutforth et al., 2001) and national or regional policies, such as frameworks for subsidies, may affect which crops that are grown and therefore also crop species diversity (Song et al., 2021).

Historical data records on crop diversity can be used to quantify spatial and temporal patterns of crop species diversity at the regional, national or global scale (Aguilar et al., 2015; Aizen et al., 2019; Hijmans et al., 2016; Smith et al., 2019; Vannoppen et al., 2021). However, there is still limited information on spatiotemporal development of crop species diversity and how these trends are related to differences in climate or soil type. Such studies are essential to evaluate the potential to increase crop species diversity in order to adapt cropping systems to climate change. The aims of this study were (i) to quantify spatiotemporal patterns of crop species diversity at the regional and national scale in Sweden, and (ii) to examine relationships between crop diversity and climatic factors and soil texture.

2. Materials and methods

2.1. Study area

Sweden is located in northern Europe between 55° N and 69° N. Due to the large differences in latitude between north and south, the climate in Sweden varies strongly across the country. Southern Sweden belongs to the hemiboreal climate, while central and northern Sweden belong to the subarctic climate (Peel et al., 2007). Sweden is divided into 21 counties (administrative units), and the counties were used as regional entities in our analyses (Fig. 1). To identify the cropping areas of each county, we used a map layer including all arable fields in Sweden obtained from the Swedish Board of Agriculture (Jordbruksverket, 2020). Arable crops are grown in all counties of Sweden, but less agricultural fields are located in the mountain range in north-western Sweden (Fig. 1). For each county, the central coordinates of the cropping areas were determined using the field map layer.

2.2. Data sources and data assembling

Precipitation and temperature are measured by the Swedish Meteorological and Hydrological Institute at meteorological stations across Sweden (SMHI, 2020). Daily values of precipitation and temperature from two to eleven (average four) weather stations per county, located within the cropping areas, were included in the analyses (Fig. 1). Mean annual temperature (MAT) and mean annual precipitation (MAP) were then calculated for each county for each year from 1965 to 2019. Mean values of soil texture for each county were obtained from the national database “Miljödata MVM” (Miljödata-MVM, 2020) that includes data of topsoils (0–20 cm depth) of arable fields.

Yearly data from 1965 to 2019 of the harvested area of different arable crops at the county and national level were acquired from Statistics Sweden (SCB, 2020). The data acquisition method changed during the time period considered in the present study. Until 1999, the data were collected through paper surveys, while from 2000 onwards, the acres were mainly based on information from administrative registers. In our study, we included data for thirteen field crops in Sweden. The crops included were: winter and spring wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), rye (*Secale cereale*), oat (*Avena sativa*), potato (*Solanum tuberosum*), sugar beet (*Beta vulgaris*), maize (*Zea mays*), oil flax (Linum usitatissimum), winter and spring rape (*Brassica napus*) and winter and spring turnip rape (*Brassica rapa*). Barley and rye were separated into spring and winter varieties in some years, while in other years, spring and winter varieties were summarized. To obtain a consistent data set, we merged spring and winter barley, and spring and winter rye, for all years. Apart from these thirteen crops, another three crop species were reported in the statistics by SCB (2020): triticale (× Triticosecale Wittmack), green peas (Pisum sativum) and brown beans (Phaseolus vulgaris). Those crops were included in groups of “mixed grain” or “legumes” for all years until the 1990 s. Hence, due to many years of missing data, these three crops were excluded from the analyses. The thirteen crops included in the study accounted for 94–100% of the total harvested area of all crops (Fig. 1). The total area of all field crops in Sweden was 1.5 million ha in 1965; the area decreased with time, to 1.2 million ha in 2019 (Fig. S1).

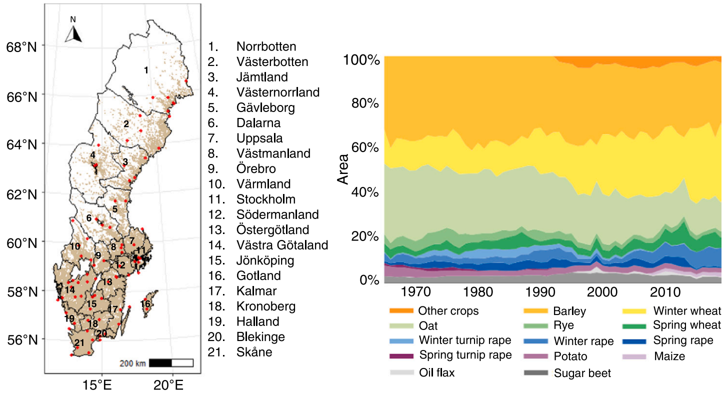


Fig. 1. (Left) Map of Sweden divided into the 21 administrative counties, with cropping areas indicated in brown and the location of representative weather stations indicated by red dots. The figure to the right displays the distribution of different arable crops in Sweden as a percentage of the total harvested area between 1965 and 2019.

2.3. *Quantification of crop species richness and crop diversity*

Crop species richness and crop diversity were determined at the county and national level for every year from 1965 to 2019. We excluded crop species with a harvested area smaller than 0.1% of the total area from any further analyses. Crop species richness was defined as the total number of crop species. Crop species diversity (D) was calculated as the exponential of Shannon diversity index (H) as follows:

$$D = e^{H} = e^{\left(-\sum_{i=1}^{n} p_i \ln p_i\right)} \tag{1}$$

where p_i is the proportion of crop i of the total crop area. The value of D is equivalent to D species at equal areas (Jost, 2006).

2.4. *Data analysis and statistics*

To evaluate the temporal changes in mean annual temperature, mean annual precipitation, crop species richness, and crop diversity, a five-year moving average was used. The moving average included the four preceding years and the year of interest, and was calculated as:

$$Y_{av} = \frac{1}{5}\sum_{n-4}^{n} Y_n \tag{2}$$

where Y_n denotes the value in the year of interest and Y_{av} denotes the five-year moving average of the year of interest.

A principal component analysis (PCA) was performed to identify general patterns between crop species richness, crop diversity, mean annual temperature, mean annual precipitation, longitude, latitude, and clay and sand content. The variables were scaled to obtain the same standard deviation and due to the differences in units of the variables. Linear correlations were applied to relate crop species richness and crop diversity to mean annual temperature, mean annual precipitation and soil texture. Linear regression analysis was used to evaluate temporal trends of crop species richness, crop diversity, mean annual temperature and mean annual precipitation. All statistical analyses were conducted with R version 3.6.3 (R Core Team, 2020) using the packages dplyr and sf to process spatial data, and ggplot2, tmap, plotly and factoextra for visualization of data in plots and maps (Kassambara and Mundt, 2020; Pebesma et al., 2021; Sievert et al., 2021; Tennekes et al., 2021; Wickham et al., 2021, 2020).

3. Results

3.1. *Spatial variation of crop diversity and pedo-climatic conditions*

Soil texture varies across Sweden, and soils in the central-eastern parts are generally rich in clay, while soils in the south are lighter (Fig. 2; Fig. S3). The climate pattern differs across the country, with mean annual temperature increasing from north to south, from about 1–8 °C (Fig. 2). Mean annual precipitation decreases from the west coast with about 800 mm per year to 500 mm per year at the east coast (Fig. 2). Since 1965, the mean annual temperature has increased in Sweden. Across counties, the increase in average annual temperature varied between 0.02 and 0.05 °C/year ($p < 0.05$). In the same period, the average annual precipitation increased in most counties with yearly increases between 0.87 and 4.54 mm/year ($p < 0.05$) (Fig. S2).

We found a strong effect of latitude on crop species richness and crop diversity. In the north of Sweden, only a few crops are grown, and these are barley, potato and oat. In the southernmost counties, nine to eleven crops were grown on average during the years 1965–2019. Similarly, the crop diversity increased from north ($D = 2.1$) to south ($D = 6.3$). Some neighbouring counties had similar average crop diversity, for instance Jämtland and Västerbotten county in the north of Sweden ($D = 1.7$; Fig. 2; Table 1).

The principal component analysis revealed that crop diversity was positively related to mean annual temperature and negatively associated

Table 1
Total crop area, average crop diversity (D), species richness (n) and the slopes of the linear regression of crop diversity and species richness as a function of time for all Swedish counties, sorted by latitude. Also, crop diversity and slope of linear regression for the entire Sweden. NS indicates non-significant correlation ($p > 0.05$).

County	Latitude	Area [$\times 10^3$ ha]	D	D slope	n	n slope
Norrbotten	66.4	7.0	2.1	0.010	4.7	0.042
Västerbotten	64.5	19.2	1.7	0.003	4.6	0.029
Jämtland	63.1	5.7	1.7	NS	4.6	0.034
Västernorrland	63.0	11.6	1.9	0.006	4.9	0.028
Gävleborg	61.4	27.0	2.6	0.013	7.6	NS
Dalarna	60.8	26.8	3.1	0.038	8.3	NS
Uppsala	60.1	98.1	4.6	-0.007	10.2	0.036
Värmland	59.8	44.2	3.7	0.014	9.1	0.029
Västmanland	59.8	81.7	4.4	0.007	9.4	0.020
Stockholm	59.5	49.0	5.1	-0.021	10.3	0.032
Örebro	59.4	66.8	4.7	0.021	9.7	0.018
Södermanland	59.1	78.6	5.0	NS	10.3	0.028
Östergötland	58.4	124.3	5.6	-0.022	10.2	0.008
Västra Götaland	58.2	259.2	4.4	0.023	9.6	0.029
Jönköping	57.5	26.2	3.0	0.011	8.8	-0.029
Gotland	57.5	41.8	5.6	-0.016	10.7	-0.028
Kalmar	57.2	52.4	5.4	-0.008	10.5	NS
Halland	56.9	63.0	4.6	0.032	10.1	NS
Kronoberg	56.7	15.6	3.1	0.014	9.1	NS
Blekinge	56.2	17.4	6.2	0.005	9.4	NS
Skåne	55.9	325.9	6.3	-0.025	10.0	-0.018
Sweden			5.8	NS		

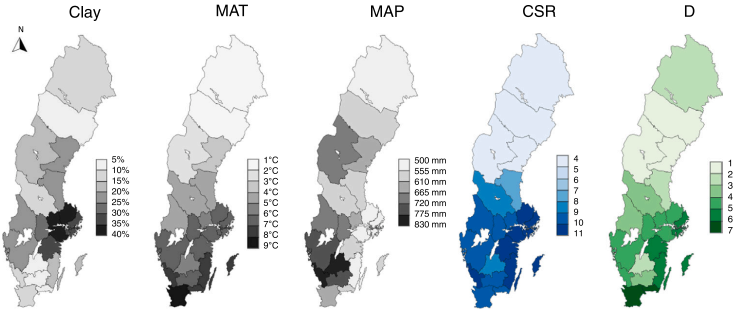


Fig. 2. County mean values (average for the years 1965–2019) of clay content, mean annual temperature (MAT), mean annual precipitation (MAP), crop species richness (CSR) and crop diversity (D).

with latitude (Fig. S4), which was also obtained from correlation analyses. Crop species richness and mean annual temperature were strongly correlated ($r = 0.93$, $p < 0.001$). Similarly, the average (1965–2019) crop diversity was positively correlated to mean annual temperature ($r = 0.88$, $p < 0.001$; Fig. 3). The principal component analysis and the correlation analyses also indicated that crop species richness and the crop diversity were not related to soil texture or mean annual precipitation (Fig. 3; Fig. S3 and S4). However, latitude and mean annual temperature could not explain all differences in crop species richness and crop diversity among counties. We found pronounced differences in average crop diversity between certain neighbouring counties located at similar latitudes, for instance Jönköping ($D = 3.0$) and Kalmar ($D = 5.4$) county located in the south of Sweden (Fig. 2; Table 1).

3.2. *Temporal patterns of crop species richness and crop diversity*

Dominant arable crops in Sweden are winter wheat, barley and oat (37 %, 27 % and 13 %, respectively, of the total area in 2019). Since 1965, the acreage of winter wheat has more than doubled, while the area of oat and barley decreased considerably over the same time. More recently, the area of spring rape, winter turnip rape and spring turnip rape have decreased and cover now less than 1 % of the total area (Fig. 1). The crop diversity at the national level experienced fluctuations over time and was in 2019 at a similar level as at the end of the 1960s. Thus, crop species diversity had no significant change over time for the entire country ($p > 0.05$) (Fig. 4; Fig. 5).

The temporal change in crop species richness and crop diversity differed among counties (Fig. 5). Between 1965 and 2019, crop species richness increased in twelve counties mainly located in the north and central parts of Sweden, with average yearly increases between 0.008 and 0.042 ($p < 0.05$). In three other counties, located in the south of Sweden, crop species richness decreased, with linear regression slopes between -0.029 and -0.018 ($p < 0.05$). Between 1965 and 2019, Norrbotten county in the north of Sweden (cf. Fig. 1) showed the largest increase in crop species richness, while Jönköping county, located in the south (cf. Fig. 1), showed the largest decrease (Fig. 4).

Crop diversity increased in several counties from 1965 to 2019. In 2019, the crop diversity was highest in the southern and central parts of the country, but still at a low level in the north. Between 1965 and 2019, the crop diversity increased in thirteen counties located in the northern and southwestern parts of Sweden, with average yearly increases between 0.003 and 0.038, ($p < 0.05$). In six other counties, located in the southern and eastern parts of Sweden, the crop diversity decreased, with linear regression slopes between -0.025 and -0.01 ($p < 0.05$). Between 1965 and 2019, Dalarna in the central part of Sweden (cf. Fig. 1) showed the largest increase in crop diversity, and Skåne in the central part (cf. Fig. 1) showed the highest decrease (Fig. 4; Fig. 5; Table 1).

4. Discussion

In the current study, we used historical crop data records, which allowed us to analyse spatiotemporal patterns of crop diversity in Sweden. The crop species richness increased from north to south and increased with increasing mean annual temperatures, which implies that there is a strong natural control of geographic location (i.e. latitude) on crop species richness. Latitude controls both the mean annual temperature and the length of the growing season. Therefore, crop diversity also increased from north to south within Sweden. Despite differences in mean annual precipitation and soil texture among counties, precipitation and soil texture were not significantly related to crop diversity at the national scale (Fig. 2; Fig. 3).

At the national level, the crop diversity experienced fluctuations over time with values between five and seven (Fig. 5; Fig. 4). Earlier research suggests that a high crop diversity in agricultural systems is beneficial (Aguilera et al., 2020; D'Acunto et al., 2018; Lin, 2011; Palmu et al., 2014). However, it is difficult to define a critical threshold for crop diversity, above which a system significantly improves important ecosystem services. Crop diversity was lower in Sweden ($D = 6.4$) than the average global level ($D = 8.8$) in 2016 according to data from Aizen et al. (2019). However, cropping systems vary greatly between countries. In comparison to countries with similar climatic conditions, Sweden had a higher crop diversity than the neighbouring counties Norway and Finland ($D = 4.6$ and 5.0, respectively) (Aizen et al., 2019). Crop production in Finland is more concentrated at higher latitudes than in Sweden (Mela, 1996), and the mountainous terrain in Norway affects Norwegian agriculture (Fjellstad and Dramstad, 1999). Hence, differences in crop diversity between countries might be explained by natural factors such as climate, soil properties, or topography that set

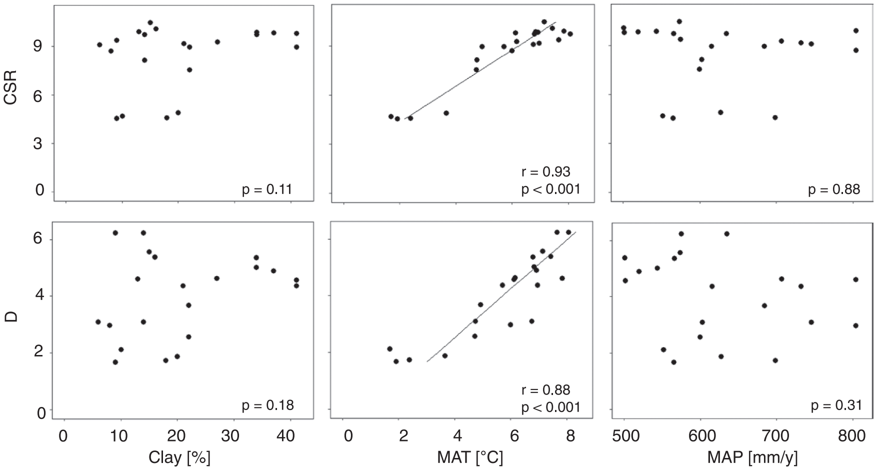


Fig. 3. Scatterplots between county mean values (for years 1965–2019) of crop species richness (CSR; top panels) and crop diversity (D; bottom panels), and clay content, mean annual temperature (MAT) and mean annual precipitation (MAP). Pearson correlation coefficients (r) and regression lines are included for significant correlations at $p < 0.05$.

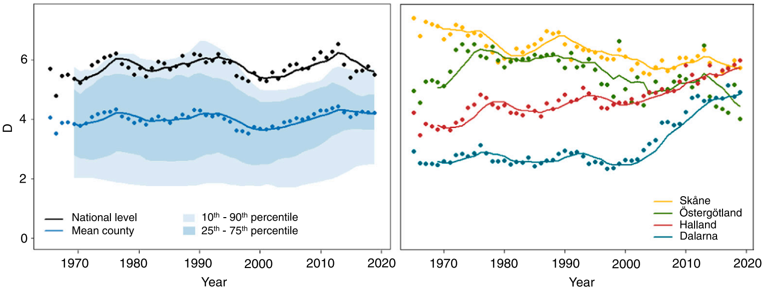


Fig. 4. (Left) Crop diversity (D) at the national and mean county level between 1965 and 2019. The lightest blue show the 10th and 90th percentile range and the darker shade the 25th and 75th percentile range of average crop diversity at county level. (Right) Temporal development of crop diversity in the four counties Östergötland, Stockholm, Halland and Dalarna. Displayed lines and the percentiles are based on five-year moving average values (Eq. 2).

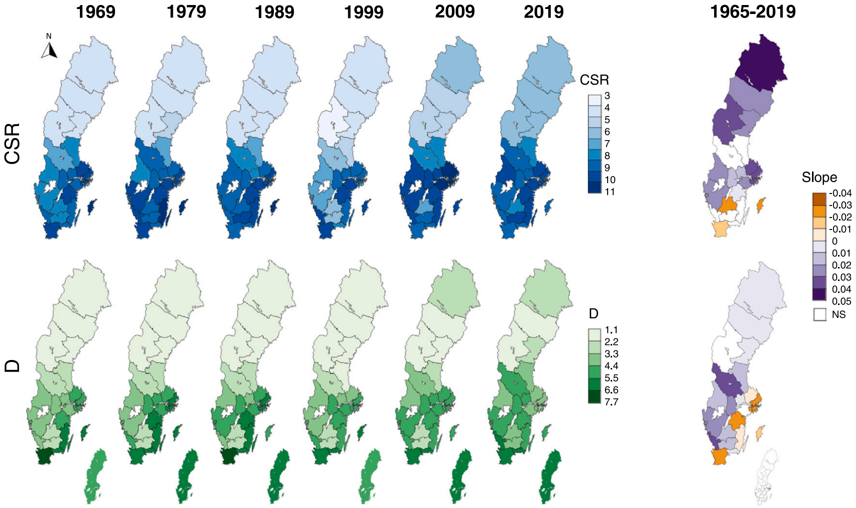


Fig. 5. Maps depicting temporal changes in (top) crop species richness (CSR) and (bottom) crop diversity (D, i.e. the exponent of the Shannon diversity, Eq. 1) at the county level (large maps) and at the national level (small maps). Temporal development is presented to the right using slopes of the linear regression of crop species richness and crop diversity as a function of time. NS indicates no significant temporal change ($p > 0.05$). Displayed data and analyses are based on five-year moving average values (Eq. 2).

constraints to which crops that can be grown. Furthermore, socioeconomic factors such as country-specific policies might also influence differences in crop diversity between countries. For instance in Switzerland, which is not part of the European Union, crop diversity was higher than in the bordering countries Germany and France, which was ascribed to differences in agricultural policies (Garland et al., 2021).

Crop diversity did not change significantly over time in Sweden and was at a similar level in 2019 as at the end of the 1960s (Fig. 5; Fig. 4). At the county level, the temporal trend differed between counties, for both crop species richness and crop diversity. Crop species richness and crop diversity increased in several counties, while it did not significantly change or decreased over time in other counties. Similarly, results from previous studies conducted in other countries revealed differences in temporal trends of crop diversity between national and regional scales (Aguilar et al., 2015; Hijmans et al., 2016; Smith et al., 2019). Here we show that analysing crop diversity at the national scale does not reveal enough information to identify temporal trends and to identify factors controlling diversity. Among counties, the variation in average crop diversity declined over time, which implies that crop diversity become more even across counties (Fig. 4). Mainly the counties with the lowest average crop diversity experienced a temporal increase while mainly the counties with the highest crop diversity decreased over time (Fig. 5; Table 1).

Between 1965 and 2019, crop species richness increased in the north and central parts of Sweden, while the counties with a decrease were located in the south (Fig. 5; Table 1). Oilseed crops are mainly cultivated in the southern counties, and the cultivation of spring-sown oilseed crops, especially spring turnip rape, declined in many counties mainly in response to the ban of certain neonicotinoids in 2013 (Johnsson, 2015). The cultivation of winter turnip rape has decreased over time and even disappeared now in most of the counties. Warmer climate, more winter hardy varieties and higher yields for winter rape in comparison to winter turnip rape all contributed to this decline (Jordbruksverket, 2011). In central Sweden, the increase in species richness over time was mainly because of oil flax. Due to small production, oil flax was only reported in the statistics in 1969 and from 1996 and onwards which resulted in a temporal increase in species richness in several counties. In the most northern part of Sweden, the increased cultivation of spring oilseed crops and spring wheat resulted in increased crop species richness.

Six counties showed a temporal decrease and thirteen counties an increase in crop diversity. The six counties with a decrease in crop diversity were located in the south and eastern parts of Sweden, and half of those counties experienced a temporal decrease in crop species richness as well. Skåne county, in the southern part of Sweden, had the largest temporal decrease in crop diversity due to both a decline in species richness and more unevenly distributed areas between the crops (Fig. 4; Fig. 5; Table 1). Over time, the cultivated area of several crops decreased while the cultivation of winter wheat increased. In 2018, there were two dominant crops in the county, barley and winter wheat, which together accounted for around 60 % of the total area. The cultivated area of winter wheat has increased in several counties in Sweden over time, especially in the southern part, and is in general the cereal with the highest yield in Sweden. In most counties, the cultivated area of barley and oat decreased over time. The cultivated area of barley has decreased in Sweden mainly due to less demand for feed grain because of the decline in the number of pigs and cows, and oat has decreased mainly due to profitability problems in comparison to other crops (Eklöf, 2014).

The thirteen counties with an increase in crop diversity were located mainly in the north and southwestern parts of Sweden. Some counties showed an increase in crop diversity in combination with no temporal change in species richness, which indicates that the cultivated area became more evenly distributed between different crops. For instance, Dalarna county had the highest increase in crop diversity, resulting from more evenly distributed areas between different crops (Fig. 4; Fig. 5). The crops became more evenly distributed with time partly because of increased area of winter wheat and winter rapeseed as a result of increased temperatures (Melin et al., 2010), and also due to a decrease in the dominant crop barley. Increased temperatures extend the length of the growing season, and due to climate change, the length of the growing season is projected to continue to increase in the future in Sweden (Fogelfors et al., 2009). Higher temperatures and longer growing seasons increase the possibilities to grow winter-sown crops in northern Sweden due to shorter winters, and to introduce new crop species especially in the south of Sweden in the future (Eckersten and Kornher, 2012). For instance, the cultivation of maize has increased during the 21st century, mainly in the south of Sweden, and was included in the statistics from 2007. With increasing temperatures, maize is projected to be cultivated at a larger extent and “migrate” north in the future (Eckersten et al., 2008; Melin et al., 2010). However, in the most northern counties, it remains challenging to increase crop diversity due to the short crop growing season and the long winter (Melin et al., 2010).

Diverse cropping systems will become more important in the future, since crop diversity may alleviate effects of heat stress and drought on crop yields (Marini et al., 2020), which are projected to become more frequent and severe due to climate change (IPCC, 2013). Mean annual temperature and precipitation have already increased in Sweden during the time period analysed in this study (Fig. S2), and the temporal increase in crop diversity in thirteen counties shows that it is possible to increase crop diversity under a changing climate in Sweden. According to our results, crop diversity can differ considerably between neighbouring counties at similar latitude (Fig. 2; Table 1). Moreover, some neighbouring counties even had opposite temporal trends of crop diversity, for example, Uppland and Västmanland county in the central parts of Sweden (Fig. 5; Table 1). Due to similar climatic conditions in neighbouring counties, these opposite trends imply that the farmers’ choice of crops was likely influenced by socioeconomic factors. The ecosystem benefits of more diverse cropping systems are well known (Altieri, 1999; Lin, 2011). However, a cropping system must also benefit the farmers both economically and socially, and to increase crop diversity might require financial investments for a farmer (Knutson et al., 2011), which can hinder diversification. Therefore, to promote diversification of agricultural crops, socioeconomic factors need to be taken into account, and suitable policies may need to be developed to ensure food security.

5. Conclusion

Within a country, natural factors limit the number of crop species that can be grown. The increase in crop species diversity from north to the south observed here demonstrates how mean annual temperature and length of the growing season control the spatial pattern of crop diversity. At the national scale, crop diversity did not change significantly over time. While at the county level, there was an increase in crop diversity in certain counties over the last 55 years, and no change or a temporal decrease in other counties. This highlights the importance of looking beyond national scales when evaluating historical developments of cropping systems. Although crop diversity was at a similar level in 2019 as at the end of the 1960 s the temporal increase in crop diversity observed in several counties demonstrates that it is possible to increase crop diversity in Sweden. The variation in the spatiotemporal patterns between counties suggests that crop diversity is affected by an interplay between natural and socioeconomic factors. Climatic conditions constrain crop species richness and diversity, but in order to exploit the full potential of crop diversity, socioeconomic factors may need to change to promote diversified cropping systems.

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.

Acknowledgements

This study was funded by the Swedish Farmers’ Foundation for Agricultural Research (Stiftelsen Lantbruksforskning, SLF, grant number: O-19-23-309), which is greatly acknowledged.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108046.

References

Aguilar, J., Gramig, G.G., Hendrickson, J.R., Archer, D.W., Forcella, F., Liebig, M.A., 2015. Crop species diversity changes in the United States: 1978–2012. PLoS ONE 10, e0136580. https://doi.org/10.1371/journal.pone.0136580.

Aguilera, G., Roslin, T., Miller, K., Tamburini, G., Birkhofer, K., Caballero-Lopez, B., Lindström, S.A.-M., Öckinger, E., Rundlöf, M., Rusch, A., Smith, H.G., Bommarco, R., 2020. Crop diversity benefits carabid and pollinator communities in landscapes with semi-natural habitats. J. Appl. Ecol. 57, 2170–2179. https://doi.org/10.1111/1365-2664.13712.

Aizen, M.A., Aguiar, S., Biesmeijer, J.C., Garibaldi, L.A., Inouye, D.W., Jung, C., Martins, D.J., Medel, R., Morales, C.L., Ngo, H., Pauw, A., Paxton, R.J., Sáez, A., Seymour, C.L., 2019. Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. Glob. Change Biol. 25, 3516–3527. https://doi.org/10.1111/gcb.14736.

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agric., Ecosyst. Environ. 74, 19–31. https://doi.org/10.1016/S0167-8809(99)00028-6.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., Makowski, D., 2020. Positive but variable effects of crop diversification on biodiversity and ecosystem services (preprint). Ecology. https://doi.org/10.1101/2020.09.30.320309.

Bowles, T.M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M.A., Culman, S.W., Deen, W., Drury, C.F., Garcia y Garcia, A., Gaudin, A.C.M., Harkcom, W.S., Lehman, R.M., Osborne, S.L., Robertson, G.P., Salerno, J., Schmer, M.R., Strock, J., Grandy, A.S., 2020. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth 2, 284–293. https://doi.org/10.1016/j.oneear.2020.02.007.

Burchfield, E.K., Nelson, K.S., Spangler, K., 2019. The impact of agricultural landscape diversification on U.S. crop production. Agric., Ecosyst. Environ. 285, 106615 https://doi.org/10.1016/j.agee.2019.106615.

Cutforth, L.B., Francis, C.A., Lynne, G.D., Mortensen, D.A., Eskridge, K.M., 2001. Factors affecting farmers' crop diversity decisions: an integrated approach. Am. J. Altern. Agric. 16, 168–176. https://doi.org/10.1017/S0889189300009164.

D'Acunto, L., Andrade, J.F., Poggio, S.L., Semmartin, M., 2018. Diversifying crop rotation increased metabolic soil diversity and activity of the microbial community. Agric. Ecosyst. Environ. 257, 159–164. https://doi.org/10.1016/j.agee.2018.02.011.

Degani, E., Leigh, S.G., Barber, H.M., Jones, H.E., Lukac, M., Sutton, P., Potts, S.G., 2019. Crop rotations in a climate change scenario: short-term effects of crop diversity on resilience and ecosystem service provision under drought. Agric., Ecosyst. Environ. 285, 106625 https://doi.org/10.1016/j.agee.2019.106625.

Eckersten, H., Andersson, L., Holstein, F., Mannerstedt Fogelfors, B., Lewan, E., Sigvald, R., Torssell, B., Karlsson, S., 2008. Bedömningar av klimatförändringars effekter på växtproduktion inom jordbruket i Sverige (No. 6). Department of Crop Production Ecology. Swedish University of Agricultural Sciences (SLU),, Uppsala.

Eckersten, H., Kornher, A., 2012. Klimatförändringars effekter på jordbrukets växtproduktion i Sverige – scenarier och beräkningssystem (No. 14). Department of Crop Production Ecology. Swedish University of Agricultural Sciences (SLU),, Uppsala.

Eklöf, P., 2014. Marknadsöversikt - Spannmål (No. 2014:08). Jordbruksverket. ISSN 1102–3007.

Fjellstad, W.J., Dramstad, W.E., 1999. Patterns of change in two contrasting Norwegian agricultural landscapes. Landsc. Urban Plan. 45, 177–191. https://doi.org/10.1016/S0169-2046(99)00055-9.

Fogelfors, H., Wivstad, M., Eckersten, H., Holstein, F., Johansson, S., Verwijst, T., 2009. Strategic analysis of swedish agriculture production systems and agricultural landscapes in a time of change. department of crop production. Ecol. (VPE) 10.

Frison, E.A., Cherfas, J., Hodgkin, T., 2011. Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. Sustainability 3, 238–253. https://doi.org/10.3390/su3010238.

Garland, G., Edlinger, A., Banerjee, S., Degrune, F., García-Palacios, P., Pescador, D.S., Herzog, C., Romdhane, S., Saghai, A., Spor, A., Wagg, C., Hallin, S., Maestre, F.T., Philippot, L., Rillig, M.C., van der Heijden, M.G.A., 2021. Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. Nat. Food 2, 28–37. https://doi.org/10.1038/s43016-020-00210-8.

Gaudin, A.C.M., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C., Deen, W., 2015. Increasing crop diversity mitigates weather variations and improves yield stability. PLoS ONE 10, e0113261. https://doi.org/10.1371/journal.pone.0113261.

González-Chávez, Ma. del C.A., Aitkenhead-Peterson, J.A., Gentry, T.J., Zuberer, D., Hons, F., Loeppert, R., 2010. Soil microbial community, C, N, and P responses to long-term tillage and crop rotation. Soil Tillage Res. 106, 285–293. https://doi.org/10.1016/j.still.2009.11.008.

Hijmans, R.J., Choe, H., Perlman, J., 2016. Spatiotemporal patterns of field crop diversity in the United States, 1870–2012. Agric. Environ. Lett. 1, 160022 https://doi.org/10.2134/ael2016.05.0022.

Hufnagel, J., Reckling, M., Ewert, F., 2020. Diverse approaches to crop diversification in agricultural research. A review. Agron. Sustain. Dev. 40, 14. https://doi.org/10.1007/s13593-020-00617-4.

IPCC (Ed.), 2013. Climate change 2013: the physical science basis; summary for policymakers, a report of Working Group I of the IPCC, technical summary, a report in press by Working Group I of the IPCC but not approved in detail and frequently asked questions; part of the Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, New York.

Johnsson, B., 2015. Värdet av våroljeväxter– ekonomiska konsekvenser av ett förbud mot växtskyddsmedel. Jordbruksverket.

Jordbruksverket, 2020. Kartor och Geografiska informationssystem [WWW Document]. URL https://jordbruksverket.se/e-tjanster-databaser-och-appar/e-tjanster-och-databaser-stod/kartor-och-gis (accessed 2.1.21).

Jordbruksverket, 2011. Jordbruket i siffror: åren 1866–2007, ISBN 91–88264-36-X.

Jost, L., 2006. Entropy and diversity. Oikos 113, 363–375. https://doi.org/10.1111/j.2006.0030-1299.14714.x.

Kassambara, A., Mundt, F., 2020. factoextra: Extract and Visualize the Results of Multivariate Data Analyses. Comprehensive R Archive Network (CRAN).

Knutson, C.L., Haigh, T., Hayes, M.J., Widhalm, M., Nothwehr, J., Kleinschmidt, M., Graf, L., 2011. Farmer perceptions of sustainable agriculture practices and drought risk reduction in Nebraska, USA. Renew. Agric. Food Syst. 26, 255–266. https://doi.org/10.1017/S174217051100010X.

Krupinsky, J.M., Bailey, K.L., McMullen, M.P., Gossen, B.D., Turkington, T.K., 2002. Managing plant disease risk in diversified cropping systems. Agron. J. 94, 198–209. https://doi.org/10.2134/agronj2002.1980.

Landis, D.A., 2017. Designing agricultural landscapes for biodiversity-based ecosystem services. Basic Appl. Ecol. 18, 1–12. https://doi.org/10.1016/j.baae.2016.07.005.

Lin, B.B., 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. BioScience 61, 183–193. https://doi.org/10.1525/bio.2011.61.3.4.

Lupwayi, N.Z., Rice, W.A., Clayton, G.W., 1998. Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. Soil Biol. Biochem. 30, 1733–1741. https://doi.org/10.1016/S0038-0717(98)00025-X.

Marini, L., St-Martin, A., Vico, G., Baldoni, G., Berti, A., Blecharczyk, A., Malecka-Jankowiak, I., Morari, F., Sawinska, Z., Bommarco, R., 2020. Crop rotations sustain cereal yields under a changing climate. Environ. Res. Lett. 15, 124011 https://doi.org/10.1088/1748-9326/abc651.

Matson, P.A., 1997. Agricultural intensification and ecosystem properties. Science 277, 504–509. https://doi.org/10.1126/science.277.5325.504.

Mela, T.J.N., 1996. Northern agriculture: constraints and responses to global climate change. AFSci 5, 229–234. https://doi.org/10.23986/afsci.72739.

Melin, M., Sigfridsson, K., Strand, L., 2010. Växtodling i Sverige 2040.

Miljödata-MVM, 2020. Swedish University of Agricultural Sciences (SLU) [WWW Document]. National data host lakes and watercourses, and national data host agricultural land. URL https://miljodata.slu.se/mvm/ (accessed 11.13.20).

Palmu, E., Ekroos, J., Hanson, H.I., Smith, H.G., Hedlund, K., 2014. Landscape-scale crop diversity interacts with local management to determine ground beetle diversity. Basic Appl. Ecol. 15, 241–249. https://doi.org/10.1016/j.baae.2014.03.001.

Pebesma, E., Bivand, R., Racine, E., Sumner, M., Cook, I., Keitt, T., Lovelace, R., Wickham, H., Ooms, J., Müller, K., Pedersen, T.L., Baston, D., 2021. sf: Simple Features for R.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644. https://doi.org/10.5194/hess-11-1633-2007.

R Core Team, 2020. R: The R Project for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. [WWW Document]. URL https://www.r-project.org/ (accessed 1.18.21).

Redlich, S., Martin, E.A., Steffan-Dewenter, I., 2018. Landscape-level crop diversity benefits biological pest control. J. Appl. Ecol. 55, 2419–2428. https://doi.org/10.1111/1365-2664.13126.

Renard, D., Tilman, D., 2019. National food production stabilized by crop diversity. Nature 571, 257–260. https://doi.org/10.1038/s41586-019-1316-y.

SCB, 2020. Statistikdatabasen [WWW Document]. URL http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START_JO/ (accessed 11.13.20).

Sievert, C., Parmer, C., Hocking, T., Chamberlain, S., Ram, K., Corvellec, M., Despouy, P., Brüggemann, S., Inc, P.T., 2021. plotly: Create Interactive Web Graphics via "plotly.js."

SMHI, 2020. Ladda ner meteorologiska observationer [WWW Document]. URL https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=precipitation24HourSum,stations=all (accessed 12.22.20).

Smith, J.C., Ghosh, A., Hijmans, R.J., 2019. Agricultural intensification was associated with crop diversification in India (1947-2014). PLoS ONE 14, e0225555. https://doi.org/10.1371/journal.pone.0225555.

Smith, R.G., Gross, K.L., Robertson, G.P., 2008. Effects of crop diversity on agroecosystem function: crop yield response. Ecosystems 11, 355–366. https://doi.org/10.1007/s10021-008-9124-5.

Song, X., Wang, X., Li, X., Zhang, W., Scheffran, J., 2021. Policy-oriented versus market-induced: factors influencing crop diversity across China. Ecol. Econ. 190, 107184 https://doi.org/10.1016/j.ecolecon.2021.107184.

Steinauer, K., Chatzinotas, A., Eisenhauer, N., 2016. Root exudate cocktails: the link between plant diversity and soil microorganisms? Ecol. Evol. 6, 7387–7396. https://doi.org/10.1002/ece3.2454.

Swift, M.J., Izac, A.-M.N., van Noordwijk, M., 2004. Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agric. Ecosyst. Environ., Environ. Serv. Land Use Chang.: Bridg. Gap Policy Res. Southeast Asia 104, 113–134. https://doi.org/10.1016/j.agee.2004.01.013.

Tennekes, M., Nowosad, J., Gombin, J., Jeworutzki, S., Russell, K., Clouse, J., Zijdeman, R., Clouse, J., Lovelace, R., Muenchow, J., 2021. tmap: Thematic Maps. Comprehensive R Archive Network (CRAN).

Vannoppen, A., Degerickx, J., Gobin, A., 2021. Evaluating landscape attractiveness with geospatial data, a case study in flanders, Belgium. Land 10, 703. https://doi.org/10.3390/land10070703.

Venter, Z.S., Jacobs, K., Hawkins, H.-J., 2016. The impact of crop rotation on soil microbial diversity: a meta-analysis. Pedobiologia 59, 215–223. https://doi.org/10.1016/j.pedobi.2016.04.001.

Wickham, H., Chang, W., Henry, L., 2020. ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics. Comprehensive R Archive Network (CRAN).

Wickham, H., François, R., Henry, L., Müller, K., 2021. dplyr: A Grammar of Data Manipulation. Comprehensive R Archive Network (CRAN).

Zimmerer, K.S., 2010. Biological diversity in agriculture and global change. Annu. Rev. Environ. Resour. 35, 137–166. https://doi.org/10.1146/annurev-environ-040309-113840.

Supplementary information

Supplementary information to "Spatiotemporal patterns of crop diversity reveal potential for diversification in Swedish agriculture" by Sjulgård et al.

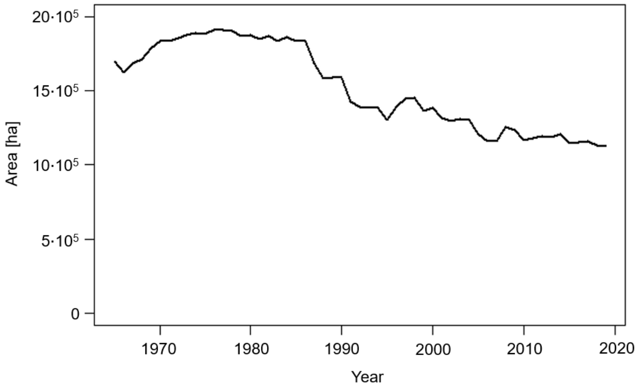


Figure S1. Total harvested area of arable field crops in Sweden between 1965 and 2019. In addition to the ten crops included in this study, also triticale, mixed grain, winter turnip rape, oil flax, green peas and black beans are included here (which accounted for 2-10% of the total area).

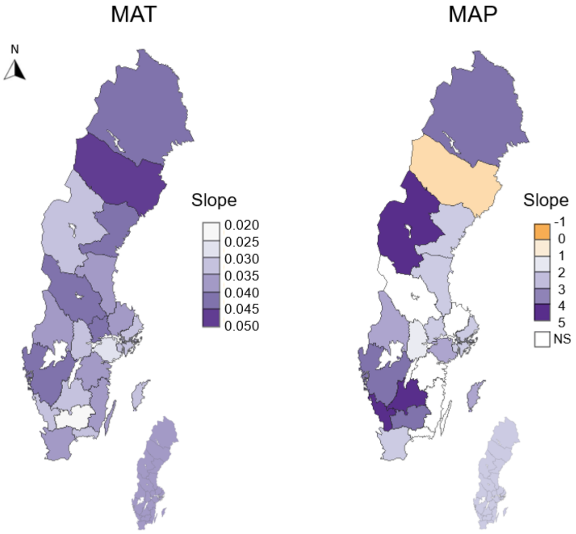


Figure S2. Change in mean annual temperature (MAT) and mean annual precipitation (MAP) between 1965 and 2019 at regional level (large maps), presented by the slope of linear regression. NS indicates non-significant correlation (p > 0.05). The small maps correspond to the national level.

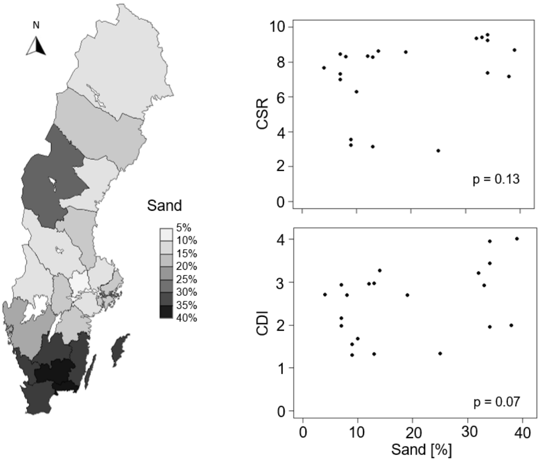


Figure S3. The map displays average sand content in all counties in Sweden. Scatterplots show the relation between average values for each county of crop species richness (CSR) or crop diversity index (CDI) and sand content. P-values higher than 0.05 indicates non-significant correlation coefficient.

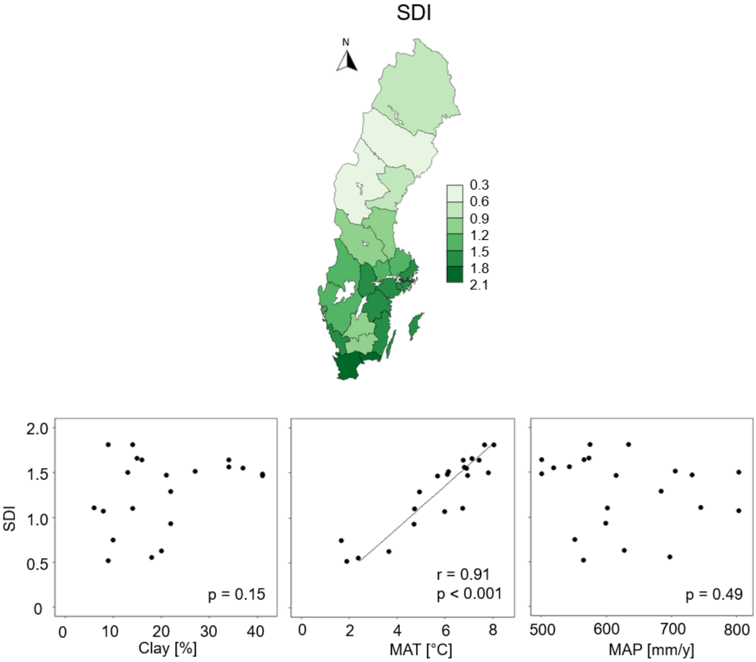


Figure S4. The map presents mean values for each county of Shannon diversity index (SDI) between 1965 and 2019. The scatterplots display the relation between average values of Shannon diversity index and clay content, annual temperature (MAT) and annual precipitation (MAP) in all counties. Pearson correlation coefficients (r) and regression lines are included for significant correlations at $p<0.05$.

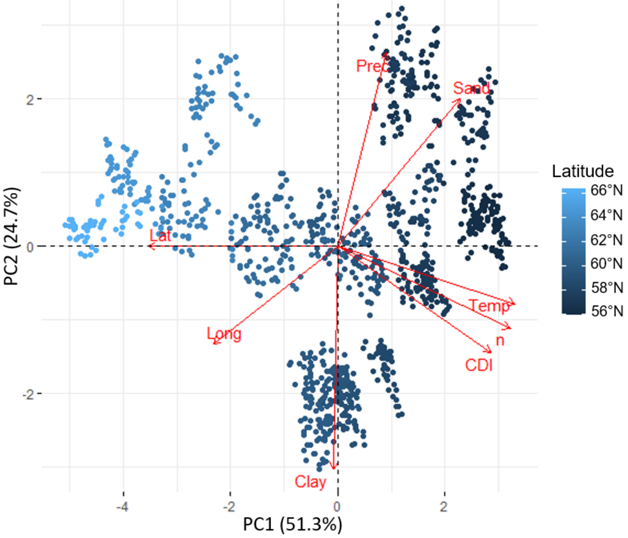


Figure S5. Biplot obtained from principal component analysis illustrating the relationship between PC1 and PC2 for the variables temperature (Temp), precipitation (Prec), crop species richness (n), crop diversity index (CDI), longitude (Long), latitude (Lat), and sand and clay content in the Swedish counties between 1965 and 2019 (n=1155). The dots represent the counties in each year. Colour scale denotes latitude. Presented data are based on five-year moving average values (Eq. 3)

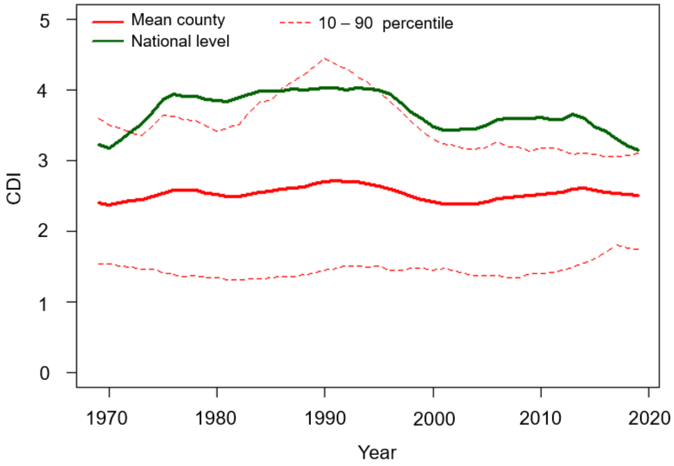


Figure S6. Crop diversity index (CDI) at the national level, and mean, 10th and 90th percentile values of crop diversity index (CDI) at county level from 1965 to 2019. Displayed data are based on five-year moving average values (Eq. 3).

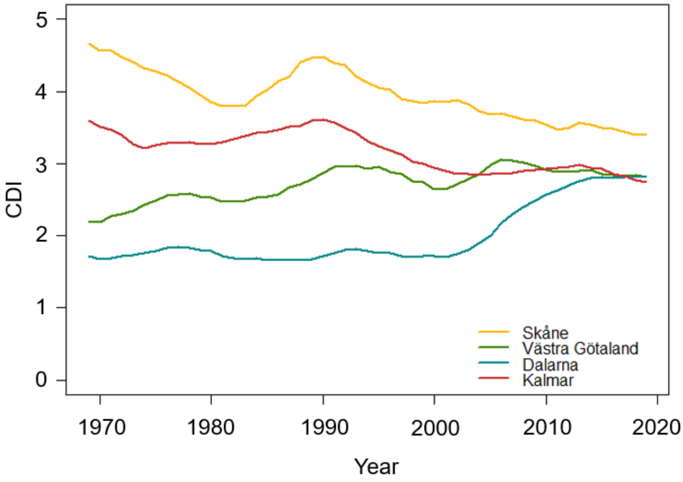


Figure S7. Temporal development of crop diversity index (CDI) in the four counties Skåne, Västra Götaland, Dalarna and Kalmar. Displayed data are based on five-year moving average values (Eq. 3).

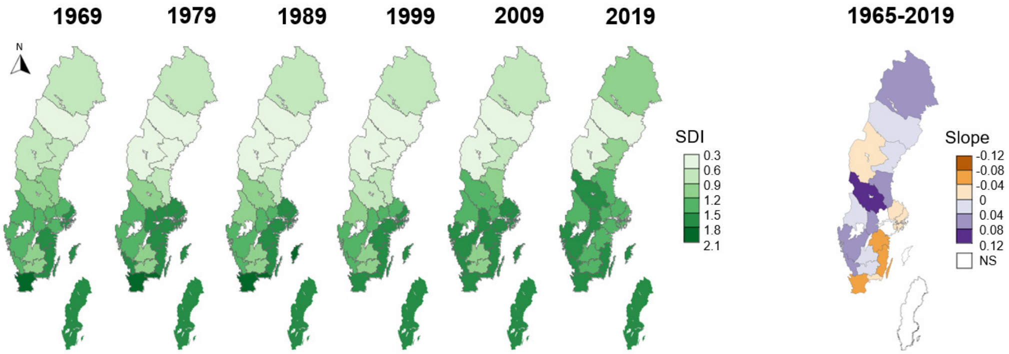


Figure S8. The large time-series maps present Shannon diversity index (SDI) in the different counties for the years 1969, 1979, 1989, 2009 and 2019. The small maps correspond to the national scale. Temporal development is presented to the right, using slopes of the linear regression of Shannon diversity index as a function of time from 1965 to 2019. NS indicates no significant temporal change ($p > 0.05$). Displayed data and analyses are based on five-year moving average values (Eq. 3).

Agricultural Systems 211 (2023) 103757

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

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

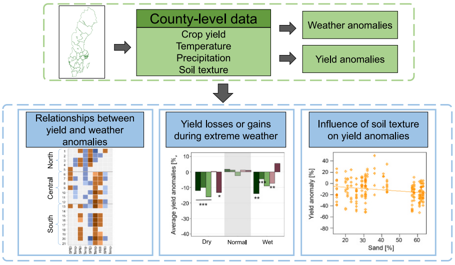
Hanna Sjulgård [a,*], Thomas Keller [a,b], Gina Garland [a,c], Tino Colombi [a]

[a] *Department of Soil and Environment, SLU, Sweden*
[b] *Department of Agroecology and Environment, Agroscope, Zürich, Switzerland*
[c] *Department of Environmental System Sciences, ETH Zurich, Switzerland*

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



ARTICLE INFO

Editor: Kairsty Topp

Keywords:
Weather anomalies
Weather extremes
Crop productivity
Growing season
Field crops

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

---

* Corresponding author.
E-mail address: Hanna.sjulgard@slu.se (H. Sjulgård).

https://doi.org/10.1016/j.agsy.2023.103757
Received 30 April 2023; Received in revised form 28 August 2023; Accepted 29 August 2023

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 3×10^6 tons, 1.4×10^6 tons and 8.1×10^5 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

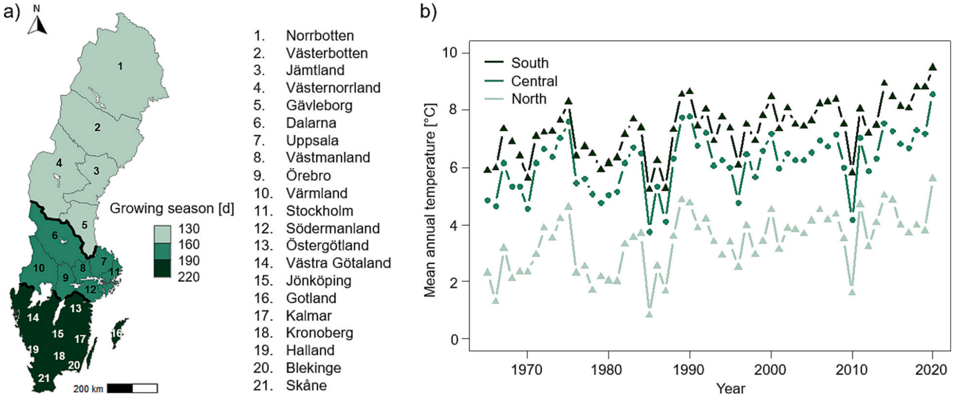


Fig. 1. a) Map of Sweden showing the 21 counties and indicating the length of the average growing season in days (green shadings) for each county. The counties were categorized into three regions, namely "north" (light green, 130–160 days growing season), "central" (green, 160–190 days growing season), 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):

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

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:

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

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 ≤ -1.5) and extremely wet (SPEI $\ge$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 $\ge$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).

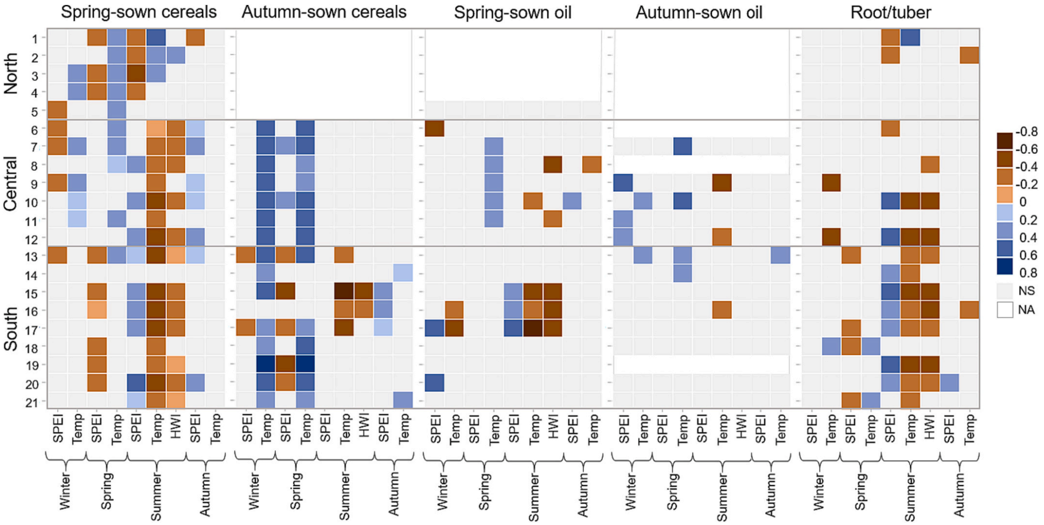


Fig. 2. Pearson's correlation coefficients between yield anomalies of each crop group and Standardized Precipitation Evaporation Index (SPEI), heat wave index (HWI) and temperature anomalies (Temp) for each county based on crop yield and climate data from 1965 to 2020. The counties are sorted by decreasing 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.)

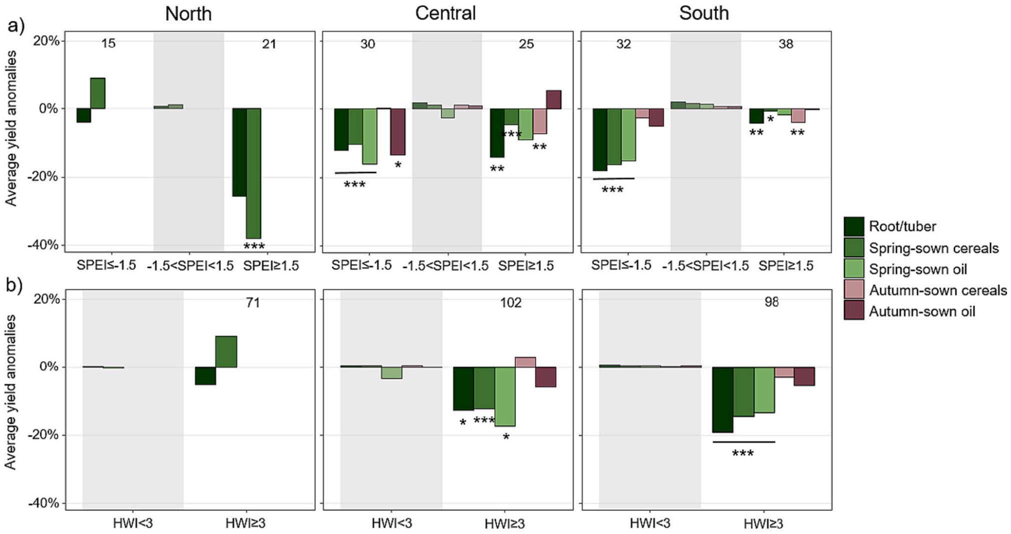


Fig. 3. Average yield anomalies in northern, central and southern Sweden during years with a) extremely dry (SPEI ≤ -1.5) and wet (SPEI ≥ 1.5) summers, and b) extreme heatwaves (HWI ≥ 3) during summer. Significance levels are shown for comparison to years with normal weather conditions ($-1.5 <$ SPEI < 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).

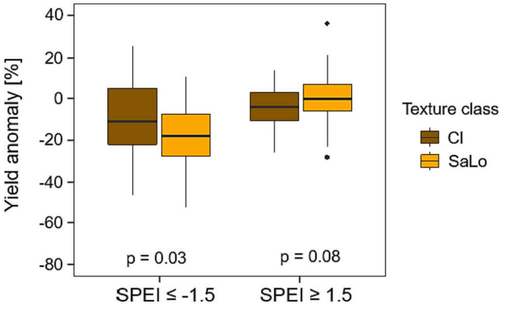


Fig. 4. Boxplots of yield anomalies for spring-sown cereals between counties with average soil texture of clay (Cl) and sandy loam (SaLo) for spring-sown cereals and sand content of cropped lands during extremely dry ($\text{SPEI} \leq -1.5$), normal ($-1.5 < \text{SPEI} < 1.5$) and extremely wet conditions ($\text{SPEI} \geq 1.5$), 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.

Acknowledgements

We would like to thank Dr. Elsa Coucheney (Department of Soil and Environment, SLU, Sweden) for constructive feedback and valuable comments on this manuscript. Funding from the Royal Swedish Academy of Agriculture and Forestry (Kungliga Skogs- och Lantbruksakademien, KSLA; grant number: GFS2020-0061) and the Swedish Farmers' Foundation for Agricultural Research (Stiftelsen Lantbruksforskning, SLF, grant number: O-19-23-309) is greatly acknowledged.

Appendix A. Supplementary data

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

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control 19 (6), 716–723. https://doi.org/10.1109/TAC.1974.1100705.

Almaraz, J.J., Mabood, F., Zhou, X., Gregorich, E.G., Smith, D.L., 2008. Climate change, weather variability and corn yield at a higher latitude locale: southwestern Quebec. Clim. Chang. 88 (2), 187–197. https://doi.org/10.1007/s10584-008-9408-y.

Avery, B., 2006. Soil classification in the soil survey of England and Wales. J. Soil Sci. 24, 324–338. https://doi.org/10.1111/j.1365-2389.1973.tb00769.x.

Barlow, K.M., Christy, B.P., O'Leary, G.J., Riffkin, P.A., Nuttall, J.G., 2015. Simulating the impact of extreme heat and frost events on wheat crop production: a review. Field Crop Res. 171, 109–119. https://doi.org/10.1016/j.fcr.2014.11.010.

Beguería, S., Vicente-Serrano, S.M., 2017. SPEI: Calculation of the Standardised Precipitation-Evapotranspiration Index [Internet] [accessed 2022 Nov 18]. https://CRAN.R-project.org/package=SPEI.

Belyaeva, M., Bokusheva, R., 2018. Will climate change benefit or hurt Russian grain production? A statistical evidence from a panel approach. Clim. Chang. 149 (2), 205–217. https://doi.org/10.1007/s10584-018-2221-3.

Ceglar, A., Zampieri, M., Gonzalez-Reviriego, N., Ciais, P., Schauberger, B., der Velde, M. V., 2020. Time-varying impact of climate on maize and wheat yields in France since 1900. Environ. Res. Lett. 15 (9), 094039 https://doi.org/10.1088/1748-9326/aba1be.

Chakraborty, D., Sehgal, V.K., Dhakar, R., Ray, M., Das, D.K., 2019. Spatio-temporal trend in heat waves over India and its impact assessment on wheat crop. Theor. Appl. Climatol. 138 (3), 1925–1937. https://doi.org/10.1007/s00704-019-02939-0.

de San Celedonio, R.P., Abeledo, L.G., Miralles, D.J., 2014. Identifying the critical period for waterlogging on yield and its components in wheat and barley. Plant Soil 378 (1), 265–277. https://doi.org/10.1007/s11104-014-2028-6.

Delin, S., Berglund, K., 2005. Management zones classified with respect to drought and waterlogging. Precis. Agric. 6 (4), 321–340. https://doi.org/10.1007/s11119-005-2325-4.

Droogers, P., Allen, R.G., 2002. Estimating reference evapotranspiration under inaccurate data conditions. Irrig. Drain. Syst. 16 (1), 33–45. https://doi.org/10.1023/A:1015508322413.

Eck, M.A., Murray, A.R., Ward, A.R., Konrad, C.E., 2020. Influence of growing season temperature and precipitation anomalies on crop yield in the southeastern United States. Agric. For. Meteorol. 291, 108053 https://doi.org/10.1016/j.agrformet.2020.108053.

Eckersten, H., Kornher, A., Bergkvist, G., Forkman, J., Sindhøj, E., Torssell, B., Nyman, P., 2010. Crop yield trends in relation to temperature indices and a growth model. Clim. Res. 42 (2), 119–131.

Eckersten, H., Herrmann, A., Kornher, A., Halling, M., Sindhøj, E., Lewan, E., 2012. Predicting silage maize yield and quality in Sweden as influenced by climate change and variability. Acta Agricult. Scand. Sect. B Soil Plant Sci. 62 (2), 151–165. https://doi.org/10.1080/09064710.2011.585176.

Eklund, A., Mårtensson, J.A., Bergström, S., Björck, E., Dahné, J., Nordborg, D., Olsson, J., 2015. Sveriges framtida klimat. Klimatologi. 14, 94.

Fahad, S., Bajwa, A.A., Nazir, U., Anjum, S.A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Adkins, S., Saud, S., et al., 2017. Crop production under drought and heat stress: plant responses and management options. Front. Plant Sci. https://doi.org/10.3389/fpls.2017.01147 [Internet]. [accessed 2022 Dec 13] 8.

Gammans, M., Mérel, P., Ortiz-Bobea, A., 2017. Negative impacts of climate change on cereal yields: statistical evidence from France. Environ. Res. Lett. 12 (5), 054007 https://doi.org/10.1088/1748-9326/aa6b0c.

Giannakaki, P., Calanca, P., 2019. Russian winter and spring wheat productivity, heat stress and drought conditions at flowering, and the role of atmospheric blocking. Clim. Res. 78 (2), 135–147.

Gilleland, E., 2022. extRemes: Extreme Value Analysis [Internet] [accessed 2022 Nov 18]. https://CRAN.R-project.org/package=extRemes.

Gourdji, S.M., Sibley, A.M., Lobell, D.B., 2013. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. Environ. Res. Lett. 8 (2), 024041 https://doi.org/10.1088/1748-9326/8/2/024041.

Gupta, S., Bonetti, S., Lehmann, P., Or, D., 2022. Limited role of soil texture in mediating natural vegetation response to rainfall anomalies. Environ. Res. Lett. 17 (3), 034012 https://doi.org/10.1088/1748-9326/ac5206.

Hakala, K., Jauhiainen, L., Himanen, S.J., Rötter, R., Salo, T., Kahiluoto, H., 2012. Sensitivity of barley varieties to weather in Finland. J. Agric. Sci. 150 (2), 145–160. https://doi.org/10.1017/S0021859611000694.

Hatfield, J.L., Prueger, J.H., 2015. Temperature extremes: effect on plant growth and development. Weather Clim. Extrem. 10, 4–10. https://doi.org/10.1016/j.wace.2015.08.001.

He, Y., Hou, L., Wang, H., Hu, K., McConkey, B., 2014. A modelling approach to evaluate the long-term effect of soil texture on spring wheat productivity under a rain-fed condition. Sci. Rep. 4 (1), 5736. https://doi.org/10.1038/srep05736.

Howden, S.M., Soussana, J.-F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104 (50), 19691–19696. https://doi.org/10.1073/pnas.0701890104.

Huang, J., Hartemink, A.E., Kucharik, C.J., 2021. Soil-dependent responses of US crop yields to climate variability and depth to groundwater. Agric. Syst. 190, 103085 https://doi.org/10.1016/j.agsy.2021.103085.

IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [place unknown]. https://doi.org/10.1017/9781009325844.

Jannat, A., Ishikawa-Ishiwata, Y., Furuya, J., 2022. Does climate change affect rapeseed production in exporting and importing countries? Evidence from market dynamics syntheses. Sustainability. 14 (10), 6051. https://doi.org/10.3390/su14106051.

Jiang, Y., Ramsay, M., Meng, F., Stetson, T., 2021. Characterizing potato yield responses to water supply in Atlantic Canada's humid climate using historical yield and weather data: implications for supplemental irrigation. Agric. Water Manag. 255, 107047 https://doi.org/10.1016/j.agwat.2021.107047.

Juma, N.G., 1993. Interrelationships between soil structure/texture, soil biota/soil organic matter and crop production. In: Brussaard, L., Kooistra, M.J. (Eds.), Soil Structure/Soil Biota Interrelationships [Internet]. Elsevier, Amsterdam, pp. 3–30. https://doi.org/10.1016/B978-0-444-81490-6.50054-6 [accessed 2023 Jul 3].

Klink, K., Wiersma, J.J., Crawford, C.J., Stuthman, D.D., 2014. Impacts of temperature and precipitation variability in the Northern Plains of the United States and Canada on the productivity of spring barley and oat. Int. J. Climatol. 34 (8), 2805–2818. https://doi.org/10.1002/joc.3877.

Koppensteiner, L.J., Obermayer-Böhm, K., Hall, R.M., Kaul, H.-P., Wagentristl, H., Neugschwandtner, R.W., 2021. Autumn sowing of facultative triticale results in higher biomass production and nitrogen uptake compared to spring sowing. Acta Agricult. Scand. Sect. B Soil Plant Sci. 71 (9), 806–814. https://doi.org/10.1080/09064710.2021.1950205.

Koscielny, C.B., Hazebroek, J., Duncan, R.W., Koscielny, C.B., Hazebroek, J., Duncan, R. W., 2018. Phenotypic and metabolic variation among spring *Brassica napus* genotypes during heat stress. Crop. Pasture Sci. 69 (3), 284–295. https://doi.org/10.1071/CP17259.

Labudová, L., Labuda, M., Takáč, J., 2017. Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the Danubian lowland and the east Slovakian lowland. Theor. Appl. Climatol. 128 (1), 491–506. https://doi.org/10.1007/s00704-016-1870-2.

Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., Davis, K.F., Konar, M., 2022. Compound heat and moisture extreme impacts on global crop yields under climate change. Nat Rev Earth Environ. 3 (12), 872–889. https://doi.org/10.1038/s43017-022-00368-8.

Li, Y., Guan, K., Schnitkey, G.D., DeLucia, E., Peng, B., 2019. Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. Glob. Chang. Biol. 25 (7), 2325–2337. https://doi.org/10.1111/gcb.14628.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science. 333 (6042), 616–620. https://doi.org/10.1126/science.1204531.

Lopes, M.S., 2022. Will temperature and rainfall changes prevent yield progress in Europe? Food Energy Security. 11 (2), e372 https://doi.org/10.1002/fes3.372.

Massuia, Magno, de Almeida, L., Avice, J.-C., Morvan-Bertrand, A., Wagner, M.-H., González-Centeno, M.R., Teissedre, P.-L., Bessoule, J.-J., Le Guédard, M., Kim, T.H., Mollier, A., Brunel-Muguet, S., 2021. High temperature patterns at the onset of seed maturation determine seed yield and quality in oilseed rape (*Brassica napus* L.) in relation to Sulphur nutrition. Environ. Exp. Bot. 185, 104400 https://doi.org/10.1016/j.envexpbot.2021.104400.

Ming, B., Yin-qiao, G., Tao, H., Guang-zhou, L., Shao-kun, L., Pu, W., 2014. SPEIPM-based research on drought impact on maize yield in North China plain. J. Integr. Agric. 14, 660–669. https://doi.org/10.1016/S2095-3119(14)60778-4.

Monteleone, B., Borzí, I., Bonaccorso, B., Martina, M., 2022. Quantifying crop vulnerability to weather-related extreme events and climate change through vulnerability curves. Nat Hazards [Internet]. https://doi.org/10.1007/s11069-022-05791-0 [accessed 2023 Mar 14].

Morel, J., Kumar, U., Ahmed, M., Bergkvist, G., Lana, M., Halling, M., Parsons, D., 2021. Quantification of the Impact of temperature, CO2, and rainfall changes on swedish annual crops production using the APSIM model. Front. Sustain. Food Syst. [Internet]. https://doi.org/10.3389/fsufs.2021.665025 [accessed 2022 Nov 29] 5.

MVM, Miljödata, 2020. Swedish University of Agricultural Sciences (SLU). National data host lakes and watercourses, and national data host agricultural land [Internet] [accessed 2020 Nov 13]. https://miljodata.slu.se/mvm/.

Najeeb, U., Bange, M.P., Tan, D.K.Y., Atwell, B.J., 2015. Consequences of waterlogging in cotton and opportunities for mitigation of yield losses. AoB PLANTS. 7, plv080. https://doi.org/10.1093/aobpla/plv080.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34 (2), 96–112. https://doi.org/10.1016/j.eja.2010.11.003.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11 (5), 1633–1644. https://doi.org/10.5194/hess-11-1633-2007.

Peltonen-Sainio, P., Jauhiainen, L., 2014. Lessons from the past in weather variability: sowing to ripening dynamics and yield penalties for northern agriculture from 1970 to 2012. Reg. Environ. Chang. 14 (4), 1505–1516. https://doi.org/10.1007/s10113-014-0594-z.

Peltonen-Sainio, P., Jauhiainen, L., Trnka, M., Olesen, J.E., Calanca, P., Eckersten, H., Eitzinger, J., Gobin, A., Kersebaum, K.C., Kozyra, J., et al., 2010. Coincidence of variation in yield and climate in Europe. Agric. Ecosyst. Environ. 139 (4), 483–489. https://doi.org/10.1016/j.agee.2010.09.006.

Ploschuk, R.A., Miralles, D.J., Colmer, T.D., Ploschuk, E.L., Striker, G.G., 2018. Waterlogging of winter crops at early and late stages: impacts on leaf physiology, growth and yield. Front. Plant Sci. [Internet]. https://doi.org/10.3389/fpls.2018.01863 [accessed 2023 Apr 3] 9.

Ploschuk, R.A., Miralles, D.J., Colmer, T.D., Striker, G.G., 2020. Waterlogging differentially affects yield and its components in wheat, barley, rapeseed and field pea depending on the timing of occurrence. J. Agron. Crop Sci. 206 (3), 363–375. https://doi.org/10.1111/jac.12396.

Powell, J.P., Reinhard, S., 2016. Measuring the effects of extreme weather events on yields. Weather Clim. Extrem. 12, 69–79. https://doi.org/10.1016/j.wace.2016.02.003.

Pradhan, G.P., Prasad, P.V.V., Fritz, A.K., Kirkham, M.B., Gill, B.S., 2012. Effects of drought and high temperature stress on synthetic hexaploid wheat. Funct. Plant Biol. 39 (3), 190–198. https://doi.org/10.1071/FP11245.

R Core Team, 2023. R: The R Project for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria [Internet]. [accessed 2023 Apr 6]. https://www.r-project.org/.

Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6 (1), 5989. https://doi.org/10.1038/ncomms6989.

Raza, A., Razzaq, A., Mehmood, S., Zou, X., Zhang, X., Lv, Y., Xu, J., 2019. Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. Plants. 8 (2), 34. https://doi.org/10.3390/plants8020034.

Rötter, R.P., Palosuo, T., Pirttioja, N.K., Dubrovsky, M., Salo, T., Fronzek, S., Aikasalo, R., Trnka, M., Ristolainen, A., Carter, T.R., 2011. What would happen to barley production in Finland if global warming exceeded 4°C? A model-based assessment. Eur. J. Agron. 35 (4), 205–214. https://doi.org/10.1016/j.eja.2011.06.003.

Rötter, R.P., Höhn, J., Trnka, M., Fronzek, S., Carter, T.R., Kahiluoto, H., 2013. Modelling shifts in agroclimate and crop cultivar response under climate change. Ecol. Evol. 3 (12), 4197–4214. https://doi.org/10.1002/ece3.782.

Russo, S., Sillmann, J., Fischer, E.M., 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ. Res. Lett. 10 (12), 124003 https://doi.org/10.1088/1748-9326/10/12/124003.

SCB, 2020a. Statistikdatabasen [Internet]. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START_JO/. (Accessed 13 November 2020).

SCB, 2020b. Production of cereal crops, dried pulses and oilseed crops in 2020. Statistiska meddelanden. JO 19 SM 2001.

SCB, 2023. Skördar efter län/riket och gröda. År 1965–2021. Statistikdatabasen [Internet] [accessed 2023 Jan 9]. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START_JO_JO0601/SkordarL2/.

Shah, N.H., Paulsen, G.M., 2003. Interaction of drought and high temperature on photosynthesis and grain-filling of wheat. Plant Soil 257 (1), 219–226. https://doi.org/10.1023/A:1026237816578.

Sjulgård, H., Colombi, T., Keller, T., 2022. Spatiotemporal patterns of crop diversity reveal potential for diversification in Swedish agriculture. Agric. Ecosyst. Environ. 336, 108046 https://doi.org/10.1016/j.agee.2022.108046.

SMHI. 2020. Ladda ner meteorologiska observationer [Internet]. [accessed 2020 Dec 22]. https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=precipitation24HourSum,stations=all.

SMHI, 2022. Klimatindikator - vegetationsperiodens längd [Internet] [accessed 2023 Feb 14]. https://www.smhi.se/klimat/klimatet-da-och-nu/klimatindikatorer/klimatindikator-vegetationsperiodens-langd-1.7887.

Smit, B., Skinner, M.W., 2002. Adaptation options in agriculture to climate change: a typology. Mitig. Adapt. Strateg. Glob. Chang. 7 (1), 85–114. https://doi.org/10.1023/A:1015862228270.

Smith, W.N., Grant, B.B., Desjardins, R.L., Kroebel, R., Li, C., Qian, B., Worth, D.E., McConkey, B.G., Drury, C.F., 2013. Assessing the effects of climate change on crop production and GHG emissions in Canada. Agric. Ecosyst. Environ. 179, 139–150. https://doi.org/10.1016/j.agee.2013.08.015.

Tian, Y., Zheng, C., Chen, J., Chen, C., Deng, A., Song, Z., Zhang, B., Zhang, W., 2014. Climatic warming increases winter wheat yield but reduces grain nitrogen concentration in East China. PLoS One 9 (4), e95108. https://doi.org/10.1371/journal.pone.0095108.

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., et al., 2011. Agroclimatic conditions in Europe under climate change. Glob. Chang. Biol. 17 (7), 2298–2318. https://doi.org/10.1111/j.1365-2486.2011.02396.x.

Uleberg, E., Hanssen-Bauer, I., van Oort, B., Dalmannsdottir, S., 2014. Impact of climate change on agriculture in northern Norway and potential strategies for adaptation. Clim. Chang. 122 (1), 27–39. https://doi.org/10.1007/s10584-013-0983-1.

Vicente Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A Multi-Scalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index – SPEI [Internet] [accessed 2022 Nov 28]. https://doi.org/10.1175/2009JCLI2909.1.

Vicente-Serrano, S.M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J.J., López-Moreno, J.I., Azorin-Molina, C., Revuelto, J., Morán-Tejeda, E., Sanchez-Lorenzo, A., 2012. Performance of drought indices for ecological, agricultural, and hydrological applications. Earth Interact. 16 (10), 1–27. https://doi.org/10.1175/2012EI000434.1.

Vico, G., Hurry, V., Weih, M., 2014. Snowed in for survival: quantifying the risk of winter damage to overwintering field crops in northern temperate latitudes. Agric. For. Meteorol. 197, 65–75. https://doi.org/10.1016/j.agrformet.2014.06.003.

Wang, H., Vicente-serrano, S.M., Tao, F., Zhang, X., Wang, P., Zhang, C., Chen, Y., Zhu, D., Kenawy, A.E., 2016. Monitoring winter wheat drought threat in northern China using multiple climate-based drought indices and soil moisture during 2000–2013. Agric. For. Meteorol. 228–229, 1–12. https://doi.org/10.1016/j.agrformet.2016.06.004.

Wang, L., He, Z., Zhao, W., Wang, C., Ma, D., 2022. Fine soil texture is conducive to crop productivity and nitrogen retention in irrigated cropland in a desert-oasis ecotone, Northwest China. Agronomy. 12 (7), 1509. https://doi.org/10.3390/agronomy12071509.

Ylhäisi, J.S., Tietäväinen, Peltonen-Sainio P., Venäläinen, A., Eklund, J., Räisänen, J., Jylhä, K., 2010. Growing season precipitation in Finland under recent and projected climate. Nat. Hazards Earth Syst. Sci. 10 (7), 1563–1574. https://doi.org/10.5194/nhess-10-1563-2010.

Zhao, C., Piao, S., Huang, Y., Wang, X., Ciais, P., Huang, M., Zeng, Z., Peng, S., 2016. Field warming experiments shed light on the wheat yield response to temperature in China. Nat. Commun. 7 (1), 13530. https://doi.org/10.1038/ncomms13530.

Zhao, Z., Zhang, Y., Liu, L., Hu, Z., 2018. The impact of drought on vegetation conditions within the Damqu River Basin, Yangtze River source region, China. PLoS One 13 (8), e0202966. https://doi.org/10.1371/journal.pone.0202966.

Supplementary Information

Supplementary Information to “Relationships between weather and yield anomalies vary with crop type and latitude in Sweden” by Sjulgård et al.

Supplementary Table S1. Total annual precipitation and mean annual temperature between 1965-2020, and the soil texture class for each county consisting of clay (Cl), clay loam (ClLo), sandy silty loam (SaSiLo) and sandy loam (SaLo). The counties are listed by decreasing latitude.

County	**Total annual precipitation (mm)**	**Mean annual temperature (°C)**	**Soil texture class**
Norrbottens	559	2.2	SaSiLo
Västerbottens	562	2.5	SaSiLo
Jämtlands	663	2.9	ClLo
Västernorrlands	664	3.8	ClLo
Gävleborgs	607	5.5	ClLo
Dalarnas	602	4.9	SaSiLo
Uppsala	590	6.2	Cl
Värmlands	694	5.7	ClLo
Västmanlands	599	6.3	Cl
Stockholms	572	6.6	ClLo
Örebro	680	6.5	ClLo
Södermanlands	536	7.0	Cl
Östergötlands	546	6.8	ClLo
Västra Götalands	743	7.2	ClLo
Jönköpings	673	6.2	SaLo
Gotlands	572	7.4	SaLo
Kalmar	500	7.5	SaLo
Hallands	810	8.2	SaLo
Kronobergs	726	6.8	SaLo
Blekinge	577	7.6	SaLo
Skåne	672	8.2	SaLo

Supplementary Table S2. Pearson's correlation coefficients between crop yields of different crop species in the different crop categories. NA indicates counties with little or no area of at least one of the crops within a crop category. The counties are listed by decreasing latitude.

	Root/tuber	**Autumn-sown cereals**	**Spring-sown cereals**	**Spring-sown cereals**	**Spring-sown cereals**	**Spring-sown oil**	**Autumn-sown oil**
	Sugar beets - potatoes	**Rye – winter wheat**	**Spring barley - oats**	**Spring barley - spring wheat**	**Spring wheat - oats**	**Spring rapeseed –turnip rape**	**Winter rapeseed –turnip rape**
Norrbottens	NA	NA	0.92	NA	NA	NA	NA
Västerbottens	NA	NA	0.74	NA	NA	NA	NA
Jämtlands	NA	NA	0.80	NA	NA	NA	NA
Västernorrlands	NA	NA	0.84	NA	NA	NA	NA
Gävleborgs	NA	NA	0.81	0.72	0.69	NA	NA
Dalarnas	NA	NA	0.66	0.83	0.77	NA	NA
Uppsala	NA	0.85	0.83	0.84	0.76	0.68	0.30
Värmlands	NA	0.29	0.87	0.81	0.86	0.73	NA
Västmanlands	NA	0.68	0.76	0.80	0.65	0.70	0.63
Stockholms	NA	0.79	0.77	0.69	0.63	0.43	0.29
Örebro	NA	0.76	0.87	0.78	0.74	0.67	0.82
Södermanlands	NA	0.73	NA	NA	0.58	0.32	0.47
Östergötlands	NA	0.78	0.86	0.77	0.71	0.40	0.65
Västra Götalands	NA	0.17	0.81	0.16	0.16	NA	0.19
Jönköpings	NA	NA	0.84	0.75	0.83	0.82	NA
Gotlands	0.31	0.66	0.78	0.75	0.74	0.42	0.70
Kalmar	0.31	0.75	0.86	0.64	0.59	0.39	0.63
Hallands	0.37	0.55	0.89	0.61	0.64	0.76	NA
Kronobergs	NA	NA	0.73	0.33	0.58	0.55	NA
Blekinge	0.21	0.65	0.82	0.81	0.81	NA	NA
Skåne	-0.13	0.65	0.82	0.75	0.74	0.49	-0.10

Supplementary Table S3. For each season, the number of years with extreme weather (extremely dry (SPEI ≤ -1.5) and wet conditions (SPEI ≥ 1.5) and extreme heat waves (HWI≥3)) were summarized for every decade (1970s, 1980s, 1990s, 2000s and 2010s). The temporal development were assessed with Pearson's correlation coefficients and displayed in the table. Significant correlations are denoted as bold and with an asterisk. The counties are listed by decreasing latitude. NA indicates counties where the extreme weather did not occur during any year in at least three of the decades.

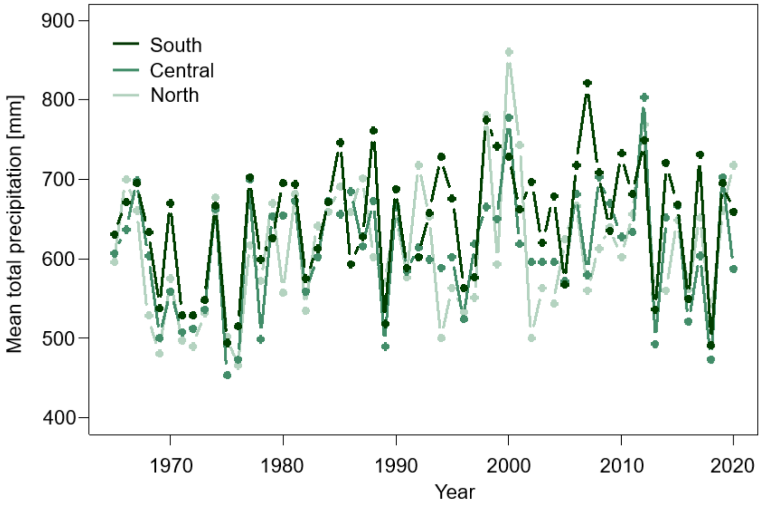
County	**Winter SPEI≥1.5**	**Winter SPEI≤ -1.5**	**Spring SPEI≥1.5**	**Spring SPEI≤ -1.5**	**Summer SPEI≥1.5**	**Summer SPEI≤ -1.5**	**Autumn SPEI≥1.5**	**Autumn SPEI≤ -1.5**	**Summer HWI≥3**
Norrbottens	NA	NA	0.79	**-0.94 ***	NA	-0.87	NA	NA	-0.51
Västerbottens	-0.73	NA	0.85	-0.29	0.87	NA	-0.87	NA	-0.24
Jämtlands	-0.37	NA	0.84	-0.71	NA	NA	NA	NA	-0.62
Västernorrlands	-0.69	0.94	0.00	**-0.94 ***	NA	NA	0.26	NA	-0.52
Gävleborgs	NA	NA	0.85	-0.58	0.77	NA	NA	NA	-0.47
Dalarnas	NA	NA	-0.29	-0.71	NA	NA	-0.97	0.94	-0.74
Uppsala	NA	NA	-0.35	0.00	-0.28	NA	-0.95	NA	0.42
Värmlands	NA	NA	0.83	0.74	NA	-0.85	-0.68	-0.69	-0.69
Västmanlands	NA	NA	0.71	**0.90 ***	-0.50	NA	NA	NA	-0.76
Stockholms	NA	NA	0.85	-0.35	NA	-0.76	-0.87	NA	-0.52
Örebro	NA	NA	**0.91 ***	-0.58	0.00	NA	0.17	NA	-0.42
Södermanlands	NA	NA	0.29	0.88	NA	NA	-0.77	NA	0.42
Östergötlands	NA	0.19	0.80	0.57	NA	NA	NA	NA	0.10
Västra Götalands	NA	NA	0.86	0.87	0.77	NA	NA	NA	0.38
Jönköpings	NA	-0.94	0.80	0.38	0.94	NA	-0.98	NA	-0.57
Gotlands	-0.87	NA	0.85	0.84	NA	-0.76	-0.73	NA	-0.42
Kalmar	NA	NA	0.88	0.71	NA	-0.24	NA	NA	-0.62
Hallands	0.00	NA	0.87	-0.71	-0.87	NA	0.10	NA	-0.22
Kronobergs	NA	-0.94	0.82	-0.58	0.00	-0.69	NA	NA	-0.35
Blekinge	0.76	NA	0.87	0.30	NA	-0.69	-0.88	NA	-0.73
Skåne	0.87	-0.94	0.84	0.00	NA	-0.76	-0.69	NA	-0.65

Supplementary Table S4. The change in the magnitude of the value of SPEI or HWI during years with extreme weather (extremely dry (SPEI ≤ -1.5) and wet conditions (SPEI ≥ 1.5) and extreme heat waves (HWI≥3)) were assessed temporally between 1965 and 2020. The temporal development were assessed with Pearson’s correlation coefficients and displayed in the table. Significant correlations are denoted as bold and with an asterisk. The counties are listed by decreasing latitude. NA indicates counties with less than four years with the extreme weather condition.

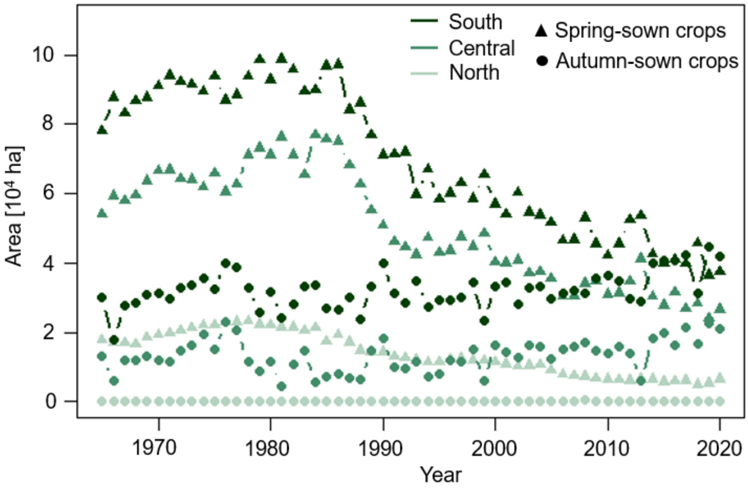
County	**Winter SPEI≥1.5**	**Winter SPEI≤ -1.5**	**Spring SPEI≥1.5**	**Spring SPEI≤ -1.5**	**Summer SPEI≥1.5**	**Summer SPEI≤ -1.5**	**Autumn SPEI≥1.5**	**Autumn SPEI≤ -1.5**	**Summer HWI≥3**
Norrbottens	NA	NA	-0.92	0.73	**0.99 ***	0.57	NA	0.39	0.15
Västerbottens	NA	-0.79	NA	0.88	-0.01	-0.54	0.98	-0.05	0.48
Jämtlands	-0.15	-0.48	0.85	0.34	0.50	-0.03	0.92	-0.71	0.13
Västernorrlands	-0.72	-0.48	0.76	0.94	0.99	-0.85	0.62	0.15	0.02
Gävleborgs	-0.87	-0.37	-0.08	0.90	NA	0.10	**1.00 ***	NA	-0.03
Dalarnas	NA	-0.55	-0.31	NA	-0.71	0.54	0.53	-0.51	0.00
Uppsala	0.82	-0.48	-0.58	0.13	-0.66	**1.00 ***	-0.87	-0.53	0.10
Värmlands	0.02	NA	0.65	-0.67	-0.01	0.14	-0.76	-0.11	0.12
Västmanlands	NA	NA	-0.59	0.21	0.52	0.46	-0.97	0.49	0.08
Stockholms	-0.14	NA	NA	0.32	-0.28	NA	-0.36	-0.43	-0.13
Örebro	-0.39	NA	NA	0.45	-0.17	0.58	NA	**-0.94 ***	-0.03
Södermanlands	NA	-0.48	NA	NA	-0.31	-0.97	0.66	-0.68	0.45
Östergötlands	-0.94	NA	0.98	0.93	-0.74	-1.00	**-1.00 ***	NA	-0.11
Västra Götalands	0.58	0.10	-0.05	0.90	-0.94	0.62	0.67	0.32	-0.67
Jönköpings	-0.78	**-0.99 ***	-0.28	0.87	-0.72	-0.93	0.55	0.64	0.18
Gotlands	0.97	**1.00 ***	-0.89	0.59	-0.76	**-1.00 ***	NA	0.68	0.21
Kalmar	**-0.96 ***	-0.95	0.36	0.52	-0.76	NA	NA	-0.92	0.29
Hallands	NA	0.37	0.56	-0.32	-0.20	0.29	-0.54	0.69	-0.34
Kronobergs	0.22	0.99	-0.63	0.45	-0.90	**0.98 ***	0.34	0.74	0.20
Blekinge	0.91	-0.57	NA	-0.38	0.46	0.29	-0.32	-0.27	0.27
Skåne	0.82	0.05	-0.22	-0.05	0.21	-0.23	-0.71	**1.00 ***	-0.15

Supplementary Table S5. Spearman correlation coefficients (r) and p-values between average topsoil sand content of cropped lands and crop yield anomalies for each crop group during normal moisture conditions (1.5 > SPEI > -1.5).

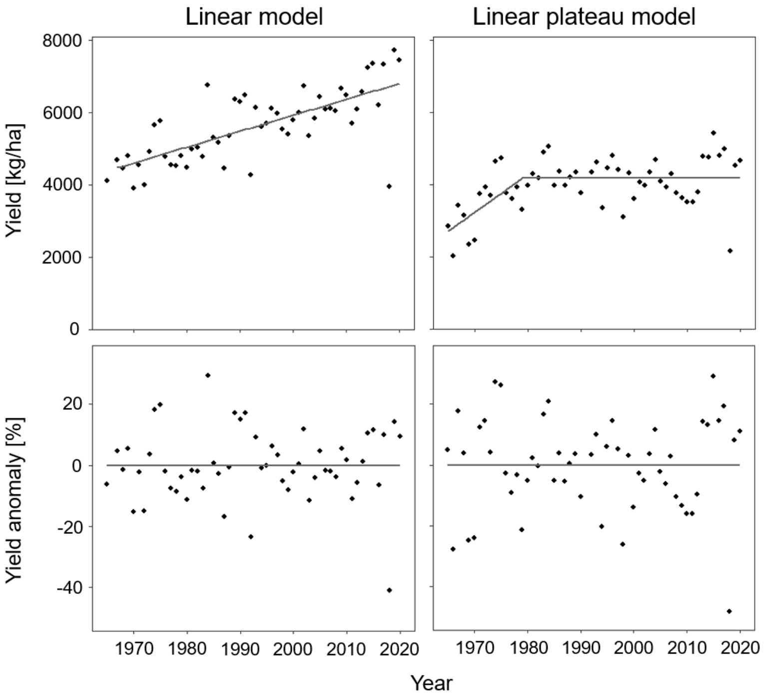
	1.5 > SPEI > -1.5	
Crop group	**r**	**p-value**
Root/tuber	0.01	0.68
Autumn-sown cereals	-0.01	0.67
Spring-sown cereals	0.02	0.30
Autumn-sown oil	-0.04	0.34
Spring-sown oil	0.07	0.06



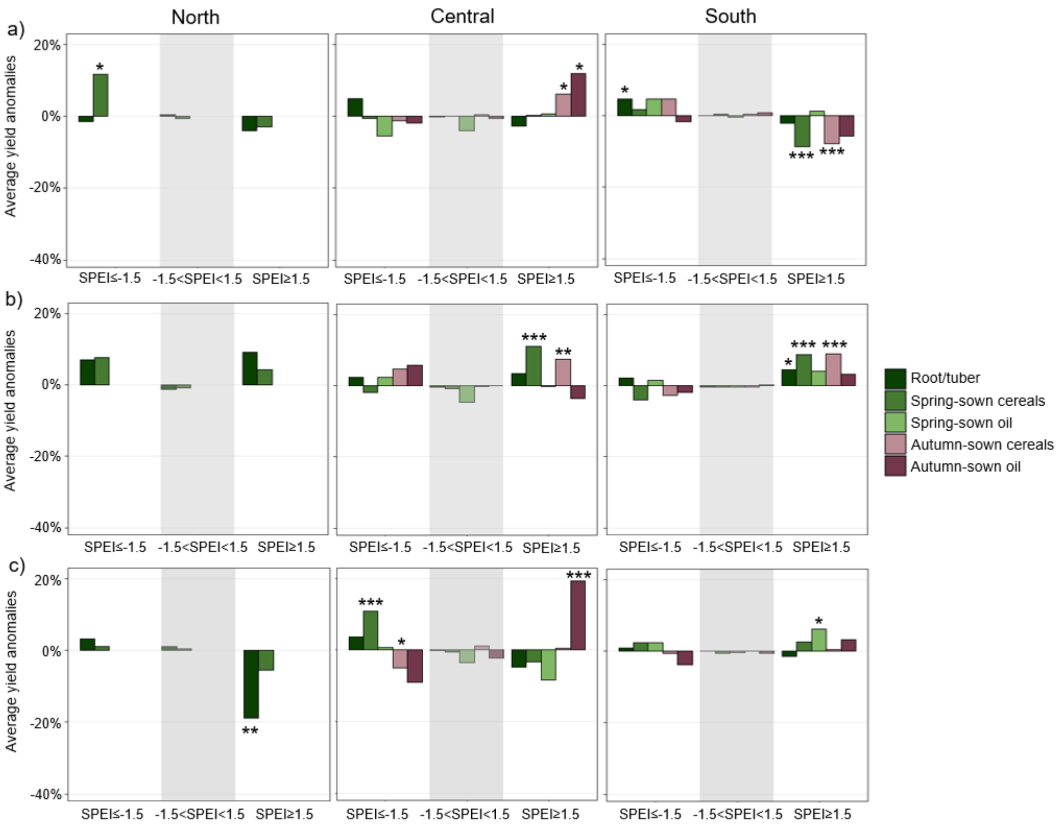
Supplementary Figure S1. Temporal development of mean total precipitation in southern, central and northern Sweden (cf. Fig. 1) from 1965 to 2020.



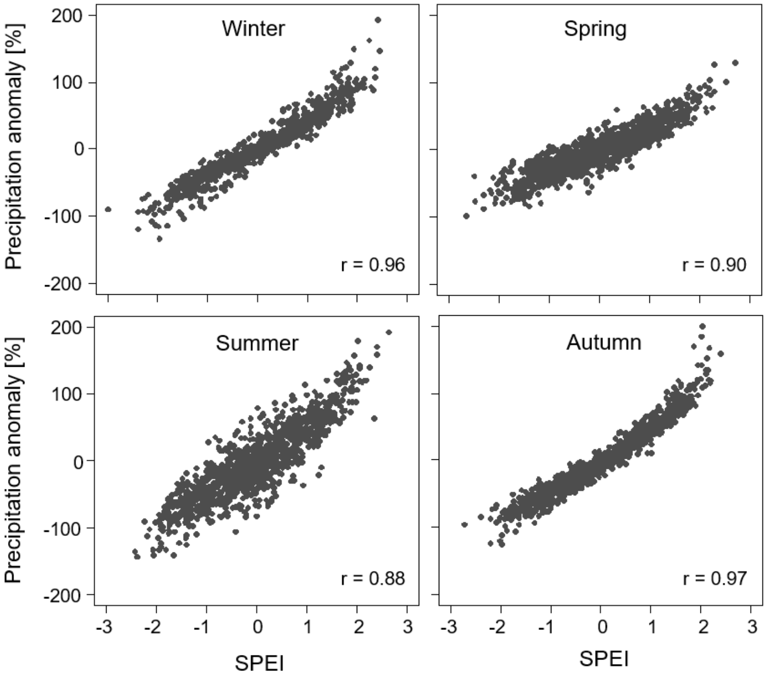
Supplementary Figure S2. Temporal development of the arable cropping area used for spring-sown crops (spring wheat, spring barley, oats, spring rapeseed, spring turnip rape, potatoes and sugar beets) and autumn-sown crops (winter wheat, rye, winter rapeseed, winter turnip rape) in southern, central and northern Sweden from 1965 to 2020.



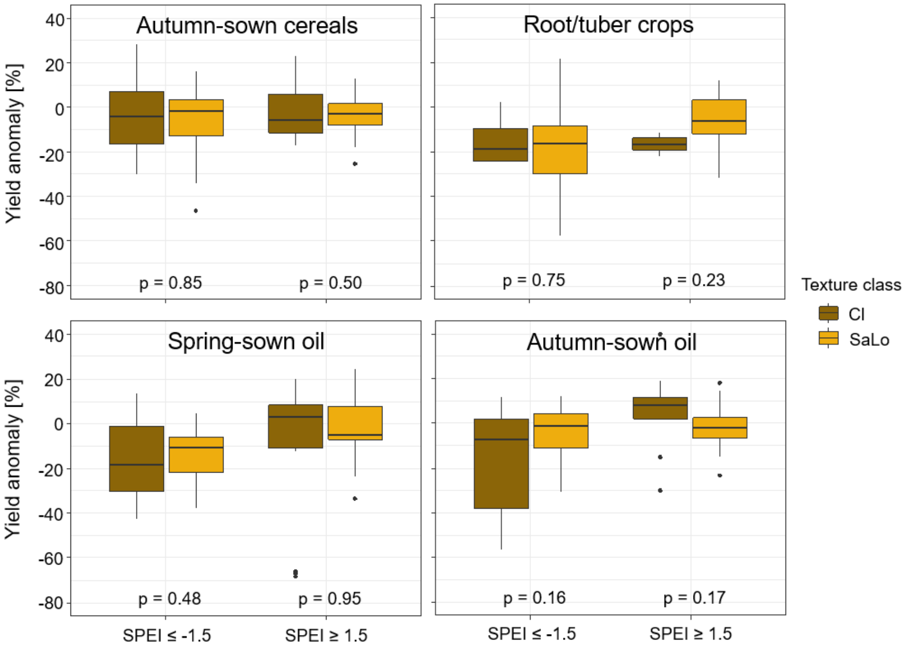
Supplementary Figure S3. Examples of detrending of crop yield, using either linear or linear plateau model. Yield anomalies were then obtained as the relative difference (in %) between actual and detrended yield for each year.



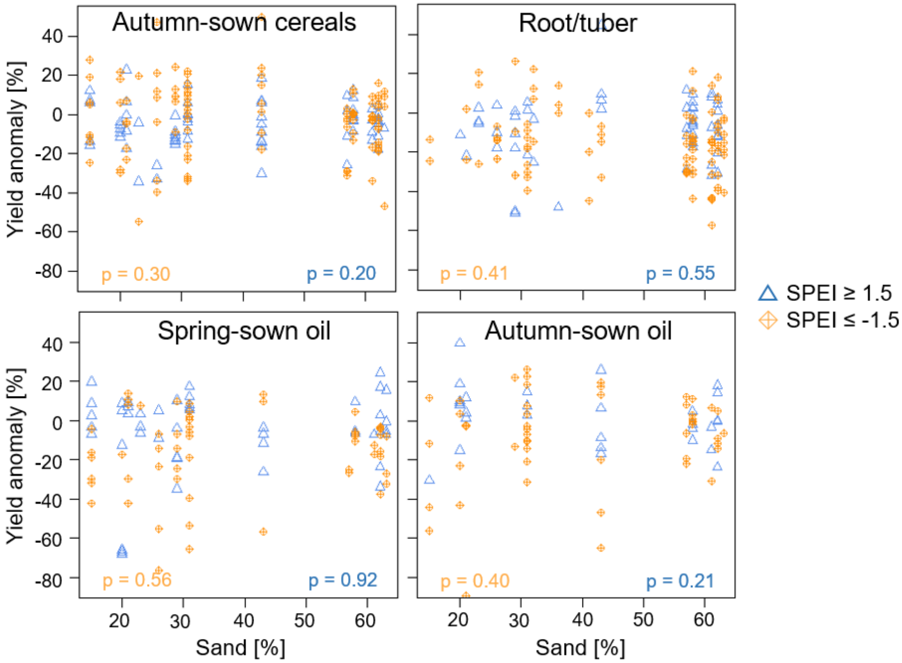
Supplementary Figure S4. Average yield anomalies in northern, central and southern Sweden during years with extremely dry (SPEI ≤-1.5) and wet (SPEI ≥1.5) conditions during a) spring, b) autumn, and c) winter. Significance levels are shown for comparison to years with normal weather conditions (-1.5< SPEI <1.5) as shown with a grey background. The significance levels are * $p<0.05$, ** $p<0.01$, ***$p<0.001$ calculated from the Wilcoxon-Mann-Whitney test. Green colour represents spring-sown crops and pink colour autumn-sown crops.



Supplementary Figure S5. Relationship between precipitation anomalies and SPEI for the four seasons of a year with Pearson's correlation coefficients (r). Data from all 21 counties and 56 years are included.



Supplementary Figure S6. Boxplots of yield anomalies for the different crop groups harvested in counties with the average soil texture of clay (Cl) or sandy loam (SaLo) during extremely dry (SPEI ≤ -1.5) and extremely wet conditions (SPEI ≥ 1.5), based on crop yield data from 1965 to 2020. p values are obtained from Mann-Whitney U test for comparison of yield anomalies between the soil texture classes.



Supplementary Figure S7. Scatterplots between yield anomalies during extremely dry (SPEI ≤ -1.5) and extremely wet conditions (SPEI ≥ 1.5) for the different crop groups and average topsoil sand content of cropped lands, based on crop yield data for 1965 to 2020. Spearman correlation coefficient (r) and regression line are included for significant correlation at p < 0.05.

ACTA UNIVERSITATIS AGRICULTURAE SUECIAE

DOCTORAL THESIS NO. 2024:84

The potential of agricultural management practices to alleviate extreme weather impacts on Swedish crop production was evaluated in this thesis. This was done through the analysis of historical data to assess the future potential of crop productivity and crop diversity across Sweden in the context of climate change. Also, from analyses of the impact of agricultural management practices for improved soil health and in turn crop yield, and the importance of soil properties in mitigating drought impacts on crop development.

Hanna Sjulgård received her graduate education at the Department of Soil and Environment at the Swedish University of Agricultural Sciences, Uppsala. She holds a degree in agronomy and a Master of Science in soil science from the same university.

Acta Universitatis Agriculturae Sueciae presents doctoral theses from the Swedish University of Agricultural Sciences (SLU).

SLU generates knowledge for the sustainable use of biological natural resources. Research, education, extension, as well as environmental monitoring and assessment are used to achieve this goal.

ISSN 1652-6880
ISBN (print version) 978-91-8046-375-1
ISBN (electronic version) 978-91-8046-411-6