Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2023:56
Faculty of Natural Resources and Agricultural Sciences

Climate and Agriculture in the Little Ice Age

The case of Sweden in a wider European perspective

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SWEDISH UNIVERSITY
OF AGRICULTURAL
SCIENCES

DOCTORAL THESIS
Uppsala 2023

Acta Universitatis Agriculturae Sueciae
2023:56

Cover: The Weather Peasants (1542)
(artist: Sebald Beham, *Courtesy National Gallery of Art, Washington*)

ISSN 1652-6880
ISBN (print version) 978-91-8046-164-1
ISBN (electronic version) 978-91-8046-165-8
https://doi.org/10.54612/a.3rnsodears

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Print: SLU Grafisk Service, Uppsala 2023
Kungl. Gustav Adolfs Akademien för svensk folkkultur made a financial contribution to the publishing of this thesis.

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Abstract

Agriculture was and is inherently dependent on weather and climate. This dependency varies over time and space. The climatic regime of the Little Ice Age (ca 1300–1850) with its reduced average temperatures has been proposed to have presented agriculture in Europe with particular challenges. And yet, in the centuries after the Late Medieval Agrarian Crisis of the 14th and 15th centuries, population and agricultural production expanded markedly in many regions of Europe. This thesis employs the large amounts of agricultural and climatic data available from the Early Modern period as well as a comprehensive set of quantitative methods to explore agrometeorological relationships in central and southern Scandinavia, Switzerland, and Spain during the years ca 1500–1900. This thesis also contributes novel long time series of harvest, sowing, and hay-cutting dates, the latter two types of dates being exceptionally rare in European historiography. Results show that farmers faced different types of agrometeorological constraints in the regions studied here. Nonetheless, harvests in central agricultural areas generally tended to be larger during cooler years. Only in marginal agricultural areas did an opposite signal prevail. In other words, by the Early Modern period, if not earlier, agriculture in large parts of Europe appears to have been well adapted to the lower average temperatures of the Little Ice Age.

Keywords: climate and agriculture, historical agrometeorology, Little Ice Age, Scania, Jämtland, Sweden, Europe

Klimat och jordbruk under den lilla istiden. Sverige i ett större Europeiskt perspektiv

Abstrakt

Jordbruket är och var beroende av väder och klimat. Detta beroende har dock varierat över tid och rum. Tidigare forskning har menat att klimatet under den Lilla Istiden (ca 1300–1850) med en långsiktig reduktion i genomsnittliga temperaturer utsatte jordbruket i Europa för särskilda utmaningar. Samtidigt skedde en kraftig expansion i både befolkning och jordbrukets produktion i stora delar av Europa under 1500-talet och framåt efter den senmedeltida agrarkrisen. Den här avhandlingen använder stora mängder av klimat- och jordbruksdata tillsammans med kvantitativa metoder för att undersöka agrometeorologiska förhållanden i centrala och södra Skandinavien, samt Schweiz och Spanien under åren ca 1500–1900. Avhandlingen bidrar också med nya långa tidsserier över skörde-, sånings- och slåtterdatum, varav de senare två typerna av jordbruksdatum är mycket ovanliga i den publicerade historieforskningen. Resultaten visar att jordbrukare i de olika regionerna bemöttes av olika agrometeorologiska utmaningar, dock med vissa generella mönster. Ett viktigt resultat var en tendens till större skördar i centrala jordbruksbygder under kallare somrar (eller vårar i Spaniens fall). Endast i marginalbygder var skördarna systematiskt lägre när temperaturerna föll under den huvudsakliga växtsäsongen. Med andra ord, från 1500-talet och framåt förefaller jordbruket i stora delar av Europa ha varit väl anpassat till de lägre temperaturerna som förhärskade under den Lilla Istiden.

Nyckelord: klimat och jordbruk, historisk agrometeorologi, Lilla Istiden, Skåne, Jämtland, Sverige, Europa

Preface

My interest in agrarian history began during my bachelor studies. Specifically, I became deeply enmeshed in the economic history of sugar beet cultivation and sugar production which was the subject of both my bachelor's as well as my master's thesis. Initially, climate did not seem relevant to this history, and I had not yet begun to seriously consider the role of climate in history. However, the history of sugar does demonstrate the power of technology and market forces to transform agriculture and overcome climatic constraints. Sugar from sugar beet can now be produced in Scania at cost-competitive terms with tropical sugar cane production. With global warming, sugar beet cultivation, just like maize cultivation, might expand northwards. Curiously, I ended up partly working with remnants of the EU sugar subsidy programme in a brief interlude outside academia at the Swedish Board of Agriculture.

For my PhD, I was initially tasked with producing new estimates of agricultural productivity during the agrarian revolution in Sweden. Sugar was not particularly relevant to this process, but my main supervisor Patrick Svensson, who hired me, hinted that I might possibly include something about sugar beet cultivation at the margins of the project. This slight concession somehow turned me on to a path that ultimately led to more than marginal alterations to the thesis project.

Very early on in my doctoral studies, possibly inspired by the very severe agricultural drought of 2018, I decided to investigate, not sugar cultivation, but the historical relationships between climate and agriculture. My supervisors, Patrick Svensson and Marja Erikson, were not only supportive but also enthusiastic about this endeavor, even though they themselves had barely touched the field of climate history. The energy and enthusiasm that Marja and Patrick brought to our supervisory meetings from the start have

been incredibly helpful to me, in addition to their continual critical and constructive scrutiny of my thesis work, including their repeated question (especially Marja's): 'Where are the peasants?!' when presented with correlation coefficients and regression tables. I hope that you, the reader, will try to keep the human actors in the peasant and farming households in mind, despite my best efforts to abstract and aggregate them into numbers.

Working often alone in an interdisciplinary research project, in a field in which neither I nor my current supervisors had much previous experience, presented many challenges. When seeking advice from dendroclimatologists, I was repeatedly referred to Fredrik Charpentier Ljungqvist. After contacting Fredrik, he was more than happy to join the supervisory team, bringing much-needed expertise in the field of the history of climate and society. Fredrik brought sincere dedication to the project and has been indispensable, generously and patiently providing comments on manuscript after manuscript.

I would like to thank all the people at the Division of Agrarian History, not only for their support but also for all the conversations and moments of laughter. In particular, I would like to thank Jakob Starlander, who has shared this journey with me from the start, offering warmth and humor, and leading the way both personally and professionally. I would also like to thank Jesper Larsson, Head of the Division, for his patience and support throughout my doctoral studies.

Special thanks go to Rodney Edvinsson for being the opponent at my end-seminar, as well as Heli Huhtamaa, the opponent at my half-time seminar, for their helpful comments and Heli's invitation to conduct a research visit to Bern University.

I am grateful to the Kungliga Gustav Adolfs Akademien för svensk folkkultur and the Faculty of Natural Resources and Agricultural Sciences at SLU for the financial support that made this thesis possible. I also want to thank The Royal Swedish Academy of Letters, History and Antiquities, Margareta och Robert Berghagens Stiftelse, and Kungliga Gustav Adolfs Akademien för svensk folkkultur for the stipends that enabled me to conduct a research visit to Bern University and present at numerous conferences, as well as travel for archival research.

My family has been patient with me. On too many occasions, I have been physically present but not quite there. Thank you for putting up with me and for all the incredible support. Anna and Karl – I love you.

Dedication

Till Anna och Karl.

Contents

List of publications

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

1. Skoglund, Martin Karl (2022). Climate variability and grain production in Scania, 1702–1911. *Climate of the Past*, 18(3), pp. 405–433.
2. Skoglund, Martin Karl. The impact of drought on northern European pre-industrial agriculture. *The Holocene,* in revision.
3. Skoglund, Martin Karl. Farming at the margin: Climatic impacts on harvest yields and agricultural practices in central Scandinavia, c. 1560–1920. *Agricultural History Review*, accepted, in press.
4. Ljungqvist, F. C., Christiansen, B., Esper, E., Huhtamaa, E., Leijonhufvud, L., Pfister, C., Seim, A., Skoglund, Martin Karl and Thejll, P. Climatic signatures in early modern European grain harvest yields. *Climate of the Past,* in revision.

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The contribution of Martin Karl Skoglund to the papers included in this thesis was as follows:

1. Martin Karl Skoglund is the sole the author of this paper.
2. Martin Karl Skoglund is the sole the author of this paper.
3. Martin Karl Skoglund is the sole the author of this paper.
4. Martin Karl Skoglund drafted the current state of research regarding Swedish climate–harvest relationships, contributed with text about Spanish agriculture, provided literature suggestions, gave input on detrending methods, conducted exploratory data analysis, and edited the text.

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Abbreviations

BiSOS	Bidrag till Sveriges Officiella Statistik [Contributions to Sweden's Official Statistics]. The main publication for official statistics in Sweden during the 19th and early 20th centuries.
DJF	December, January and February.
GDD	Growing Degree Days.
HCS	History of Climate and Society.
HDSA	Historical Database of Scanian Agriculture.
JJA	June, July, August.
LIA	Little Ice Age. A climatic period, partly defined by cooling.
LMAC	Late Medieval Agrarian Crisis. An agrarian crisis during the Late Medieval period characterised by population losses and farm abandonment in parts of western and northern Europe.
MAM	March, April, May.
MWP	Medieval Warm Period.
MXD	Maximum Latewood Density.
NAO	North Atlantic Oscillation.
SEA	Superposed Epoch Analysis.
SON	September, October, November.
SPEI	Standardized Precipitation Evapotranspiration Index.
TRW	Tree-ring Width.

1. Introduction

Farmers have always been aware of their dependence on the fickleness of the weather. Over the long spans of human history, farmers have also had to adapt to long-term weather patterns, or the climate, in their vicinity (Shennan 2018). These dependencies and adaptations can appear simple. For example, in a region with long, dark winters and short growing seasons, like Jämtland in central Scandinavia, fast-ripening varieties of six-row barley appears an obvious adaptive choice, at least for those farmers wishing to cultivate grains (Welinder 2019).[1] Similarly, it seems obvious that an almost complete absence of rainfall on the well-drained soils of Scania (Sw. *Skåne*) in southernmost Sweden will cause massive crop losses, like in the summer of 2018. Both these phenomena, however, interact with a variety of other natural and societal factors, which quickly increases the complexity and the difficulty in studying them, not least in an historical context where the sources available for such studies are limited.

This thesis studies climate-agriculture relationships in different regions of Europe. In particular, it focuses on Scandinavia, where the available source material allows for a thorough study of the relationships of dependence and adaptation between agriculture and climate over a time span of several centuries. Special attention is given to Scania between ca 1700–1910 and to Jämtland between ca 1560–1920. To date, such studies have been lacking. Previous studies have had a larger regional perspective, aggregating southern

[1] In these longer timescales and for many parts of the historical period, it makes more sense to speak of Scandinavia rather than Sweden. For example, before being incorporated into the Kingdom of Sweden in 1645, Jämtland and Härjedalen were part of Norway (and the kingdom of Denmark-Norway). Likewise, Scania was a core province of Denmark until 1658, when it was ceded to Sweden. Thus, in this thesis I employ the geographical term Scandinavia when possible. When deemed appropriate the term Sweden is employed, the use of which implies the geographical boundaries of present-day Sweden. Jämtland and the neighbouring province of Härjedalen have been intricately connected throughout history and together they formed the county of Jämtland since 1811. Throughout this thesis I employ the term Jämtland to refer to both Jämtland and Härjedalen, except when discussing intraregional differences.

or northern Sweden, or Sweden as a whole, thus masking significant parts of local variety and context (Edvinsson et al. 2009, Holopainen et al. 2012). Alternatively, they have considered specific regional or local contexts, in for example Scania, Halland in southwestern Sweden, or Jämtland, but lacked the amount of evidence, the systematic methods, and the focused research questions employed in this thesis (e.g. Mattson 1987; Palm 1997:131–138; Holm 2012:21–26).

The impact of climate on agriculture is a crucial part of, in some instances even fundamental to, broader climate and society studies (White et al. 2018b:331; Degroot et al. 2021; White et al. 2023). In spite of this, our understanding of the historical impacts of climate on agriculture in Europe remains greatly limited for most of the historical period (Ljungqvist et al. 2021). This thesis adds several new contributions to the current state of research regarding the relationships between climate and agriculture in the pre-industrial period, how to study those relationships, as well as new insights into the climate history of Europe.

1.1 Aim, scope and research questions

The aim of this thesis is to investigate how pre-industrial agriculture in Europe was affected by climate variability and change, with a particular focus on two Scandinavian regions, Scania and Jämtland, between ca 1700–1910 and ca 1560–1910, respectively. Other regions studied include Spain, Switzerland, and other parts of the southern Sweden during the period ca 1500–1800. The intent is to cover the most fundamental or common agrometeorological relationships over long periods of time in different regions.

The choice of regions is motivated by the need to study areas that are climatologically distinct, yet also share common characteristics in terms of institutions, farming methods, and type of crops grown. Thus, this thesis incorporates regions where the natural conditions, including climate, were and are highly favorable to intensive agricultural production, like the plains of Scania, the river valleys of Spain, and the *Kornland* plains in central Switzerland. It also includes marginal agricultural areas like Jämtland in central Scandinavia and dry mountainous areas with poor soils in Spain (Pfister 1983; Simpson 1995:34–35; Cong & Brady 2012; Welinder 2019). In the former cases, one may expect that the climate sensitivity of agriculture was lower, or at least of a different character, than in the latter cases. The distinctness of these regions allows for a broader discussion of how the climate-agriculture relationship was shaped by other contextual factors, while the similarities allow for interregional comparison and the ability to contextualize the results within the larger Scandinavian and European research tradition.

The study period begins in a time of consolidation for agriculture during the aftermath and recovery from the so-called the Late Medieval Agrarian Crisis (LMAC) (Antonsson 2004:13; Larsson 2009:17; Lagerås 2007:90).[2] Another notable historical periodization is that of the Little Ice Age (LIA). The concept of the LIA has been broadly defined as a period of long-term reductions in average temperatures, beginning in the mid-13th century, or even as late as mid-16th century, depending on the location and the type of evidence under consideration (Büntgen & Hellman 2014; White 2014a; Wanner et al. 2022). The LIA has been seen as an integral part of the LMAC. However, the LIA continued long after the end of the LMAC: it lasted well into the 19th century in many parts of Europe and even up until the early 20th century in high latitude regions (Linderholm & Gunnarson 2019). Nonetheless, the LIA has in many cases been associated with increased hardships for societies (Parker 2013; Campbell 2016). However, from an agricultural perspective, the post-LMAC period was a time of recovery, stability (possibly stagnation) and even growth (Le Roy Ladurie 1982:93–192; Lagerås 2015:17–19; Campbell 2016:348, 400). How could this have been possible, given the climatic conditions of the LIA? This thesis argues that the answer to this question lies not only in agricultural improvements (although they certainly played a large role), but also in differences between and adaptations within local and regional agricultural systems across Europe, where, for example, temperatures that were cooler on average were not necessarily bad, even in some northern European contexts (Edvinsson et al. 2009:122–126).[3]

The later part of the study period, starting roughly in the 18th century and ending around the turn of the 20th century, was a period of agricultural transformation in many parts of Europe, including Scania and Jämtland, commonly described as "the agrarian revolution" in Swedish historiography

[2] It is also commonly referred to as the Crisis of the Late Middle Ages; more recently, Bruce Campbell (2016) has preferred 'the Great Transition'.

[3] The term 'northern Europe' is used loosely here to include most of western and central Europe north of the Alps. When the term 'northernmost Europe' is employed, it refers to the northernmost settled North Atlantic islands (e.g., Iceland and the Faroe Islands) and the northern parts of Fennoscandia and Scotland.

(Wichman 1962a:100; 1962c:171–176; Chorley 1981; Olsson & Svensson 2010; Gadd 2011; Hallberg et al. 2022a). Switzerland also experienced an agricultural revolution during the 18th and 19th centuries, while Spanish agriculture has been seen as more stagnant during this period (Pfister 1983; Simpson 1995). In the early 20th century, some elements of the older European farming systems still remained. However, with the onset and progression of the 20th century, the transformation of agriculture had become so thorough that to continue the study beyond this point would have been a comprehensive task beyond the scope of this already far-reaching thesis. Thus, the early 20th century constitutes an appropriate ending point.

In order to study climate-agriculture relationships in pre-industrial Europe, the following research questions are posed:

1. How did the climate and the variability thereof affect agricultural production in different parts of Europe, and Scandinavia in particular, during the period ca 1500–1910?
2. What were the main agrometeorological risks in each of the regions studied?
3. What were the history and frequency of these risks during the study period, and to what degree were pre-industrial farming systems resilient to these risks?

1.2 Background

Today, in light of the challenges presented by a rapidly changing climate, the possible role of the climate in history has drawn increasing attention (Pfister et al. 2018b:10; Ljungqvist et al. 2021; Pfister & Wanner 2021:14). That being said, scholars have long debated the extent to which climate change and variability affected human societies. Back in 1955, the economic historian Gustaf Utterström argued that the climate had played an important role in demographic fluctuations during the early modern period. Utterström's (1955) endeavor was, however, limited to stating a hypothesis based on sporadic documentary evidence, due to the paucity of available data. Much has changed since then. There are, for example, long time series of agricultural prices and output for large parts of Europe, especially for western and northern Europe. Knowledge of the climate of the past has also improved dramatically, especially in the last two decades (Büntgen et al. 2011; Ljungqvist et al. 2016; White et al. 2023).

Climate history is an expanding interdisciplinary field of historical research, and the role of climatic impacts on societies has been discussed on several different levels, as for example in so-called impact order models. One fundamental assumption commonly underlying such models of climate-society relationships is the effect climate has on primary production. By directly impacting crops, livestock, vegetation in pastures, microorganisms, water bodies, and marine life (first-order impacts), climate has additional secondary impacts on livelihoods and the economy through prices, the spread of disease, and the availability of transport, and tertiary impacts on mortality, as well as human and animal well-being (Ljungqvist et al. 2021). These impacts are difficult to estimate, given the complexity introduced by interacting or confounding factors, not least human agency (van Bavel et al. 2019; Degroot et al. 2021). However, if we merely content ourselves with generalizing or assuming first-order impacts on agriculture, without actually considering the specifics of the agro-climatic context (e.g., the type of crops grown, soil quality, and management practices in relation to the local climate) or the available evidence, we risk fostering, as the economic historian Jan de Vries (1981:22) put it, the "banalization of agrarian history". The approach taken in this thesis is to study first-order impacts on agriculture, the results of which can be helpful for studies focusing on other aspects of the climate-society relationship.

One of the most-discussed and well-researched periods is the aforementioned LIA. The effects of the LIA on agriculture are generally assumed to have been detrimental, largely based on those episodes of extreme cold when the cold was, arguably, responsible for harvest failures and consequent societal hardships (Parker 2013; Degroot et al. 2021). However, most of the evidence to date is based on idiosyncratic and episodic sources. There are few systematic statistical studies of long-term relationships between agriculture and climate at a regional level in pre-industrial Europe (Ljungqvist et al. 2021). Those that exist give a mixed picture, if anything, regarding the dominant agrometeorological threats. Cold in northernmost Europe and the most marginal mountainous areas (Dybdahl, 2012; Huhtamaa & Helama 2017a; Huhtamaa & Helama 2017b; Martin et al. 2023). But outside these regions, harvest-temperature relationships have frequently been shown to be reversed. For example, harvests in southern Scandinavia and parts of the southern Low Countries appear to have benefitted from cooler and wetter conditions in the summer (Edvinsson et al. 2009:122–126; Soens 2022). Occasionally it has even proved difficult to identify any clear climatic signal in historical harvests at all (Palm 1997:138–139; Bekar 2019). For many regions of pre-industrial Europe, there are very few or no statistical studies of climate-agriculture relationships. The lack of such studies hampers the reliability of assumptions of the extended social impacts of extreme weather events. Relying on qualitative or sporadic reporting is not enough. Studies have shown that there can be discrepancies between what is being reported in regards to a particular weather or climatic event in qualitative sources and what is found in the available quantitative sources (Quieroz et al. 2020).

The concept of risk has been fundamental in debates about agricultural development in pre-industrial Europe. McCloskey (1976) argued that one of the more important motivations for farmers to continue adhering to the open-field system for centuries, despite the purportedly inefficient interspersing of strips, was that it helped to spread risk in an era when there were few safety nets. While the specific nature of such risks has occasionally surfaced in these debates, it remains largely unclear what the risks actually were, even though they are generally taken to be weather- or climate-related (de Vries 1981:21–22; McCloskey 1991; Lilja 2012:86–88; Nyström 2019). Connected to this argument is the notion that farmers in "feudal" systems were risk-averse and subsistence-oriented (Scott 1976; Henningsen 2001). Again, it is often unclear what type of risks farmers were avoiding and, empirically, it seems difficult to make the argument that agriculture before enclosures was not as prone to harvest failures as in enclosed farming systems (Edvinsson 2009; Alfani & Ó Gráda 2017; Nyström 2019). Understanding what specific type of agrometeorological risks farmers faced is crucial to debates on risk-motivated behaviors of pre-industrial farmers, since they determine what type of actions were possible in order to mitigate these risks (van Bath 1977; de Vries 1981; Bekar 2019).

Jämtland and Scania in Scandinavia offer two potentially contrasting examples when it comes to the specific risks farmers faced. The two regions share a somewhat similar trajectory during the study period, such as a large reliance on barley cultivation (although much more so in Jämtland) and a significant phase of agricultural growth in the late 18th and 19th centuries (somewhat later in Jämtland). However, the regions differ starkly in terms of natural conditions, especially in their respective climates. Winters in

Jämtland are long-lasting, usually with frozen ground covered by a persistent snow cover. Springs are generally short: thawing and ice breakup on the large lakes usually occur in May, with summer arriving in early June. Freezing temperatures and frost occur already in late July in the mountainous areas, with the rest of Jämtland following in August or September, clearly limiting the growing season. In contrast, winters in Scania are much shorter and milder. Snow cover and the freezing of large bodies of water, if they occur, are intermittent.[4] Spring begins in March and lasts about two months before passing into summer in May. Summers usually last well into September, and the first autumn frost generally does not come before October.

Differences of similar magnitudes can be identified in the other regions included in this thesis. In Switzerland, the most apparent agro-climatic risks are shaped by variations in elevation and ruggedness. To some extent they are also shaped by whether a given area is located to the north of the Alps, where Atlantic westerlies play an important role in shaping the climate, or the south, where the climate is more influenced by the Mediterranean (Pfister et al. 2018a:266–267). Livestock production had a special importance in the more mountainous parts of Switzerland, similar to Jämtland. Intensive forms of grain production could be found in the more low-lying areas of the central Swiss Plateau (Pfister 1983). Spain has large mountainous areas that are more densely populated than their Swiss counterparts (Schuler et al. 2004). Most of Spain, with the exception of the northern provinces along the Atlantic coastline, is also very arid, especially in the summer. However, it is not uniformly arid. In fact, Spain has one of the most heterogeneous climates in Europe (Beck et al. 2018). Nonetheless, the prevalence of summer droughts has led to a winter-spring season of cereal cultivation in most of Spain, and the generally arid conditions have also led to a clear difference between irrigated, more intensively cultivated lands, the *regadio*, and non-irrigated, more extensively cultivated lands, the *secano* (Simpson 1995:36; Mørch 1999). Irrigated and non-irrigated lands clearly would have suffered different risk patterns. An important difference between Spain and more northerly areas of Europe such as Switzerland or Scandinavia, is the much lower share of livestock production in Spanish farming systems and a greater emphasis on cereals (and of course on perennial crops like olives trees and vines) (Braudel 1981:135; Pfister 1983; Mørch 1999; Dahlström 2006:96–

[4] While the freezing of the sounds between the Danish islands in 1658 that famously allowed King Charles X Gustav to march his troops on the ice between islands of Jutland, Funen, and Zealand was not unique, it was certainly unusual enough to make the march seem a gamble (Speerschneider 1915; Weilbull 1949:28).

97). As a general rule, the share of livestock appears larger in more marginal and hence risky agricultural areas (Pfister 1983; Parry & Carter 1985).

Diversification in pre-industrial agrarian societies has been argued to have made them more resilient (Pretty 1990; Camenisch 2018:71; Lagerås & Magnell 2020). Michaelowa (2001:7–8) argued that English farming systems in the 18th century were more resilient to climatic shocks than their French counterparts due to their greater diversification in terms of grain crops. Similarly, Alfani (2011) found that the more diversified mountainous districts fared better than the less diversified lowland plain districts in the northern Italian famine of the 1590s. At the same time, certain forms of intensification, which can imply trade-offs with diversification, have been proposed to increase resilience in relation to certain agrometeorological risks, like drought (Nyström 2019; Dardonville et al. 2020). Being able to produce a greater surplus in a more intensified system would also mean that the margins left after the fixed seed deductions (for next year's sowing, taxes, and consumption) would be greater than in a more extensive system with smaller surpluses (Pfister & Wanner 2021:257). Discerning how harvests for different crops were affected by weather and climate variation is critical in order to understand how resilience and vulnerability took form over time in the pre-industrial farming systems of Europe. Scania presents an especially interesting case study in this regard, given that it was one of the most intensively cultivated regions in Scandinavia, but also pursued a crop mix that was much more diversified compared to some of the other regions studied in this thesis, notably Jämtland (Bohman 2010:29, 73; Welinder 2019).

1.3 Disposition

In the following section, section 2, I discuss the relevant previous research that has helped inspire and guide this thesis project, with thematic subsections focused on agriculture (section 2.1) and climate (section 2.2), as well as a subsection focused on research that explicitly considers the relationships between agriculture and climate (section 2.3). Then, in section 3, I outline the theoretical framework for this thesis, and in section 4 I discuss the methods I have employed. Section 5 outlines and discusses the data and sources. Section 6 presents and summarizes each of the four papers included in this thesis, which is then followed by section 7, where the overall results of the thesis are discussed and set in a broader research context. Section 7 ends with a conclusion and is then followed by references and appendices.

2. Previous research

2.1 Pre-industrial agriculture in Europe

In medieval and early modern Europe, livestock husbandry and crop cultivation were integrated in a mutually dependent system where energy and nutrients circulated internally, also known as the mixed farming system (Grigg 1974:152–153; Pretty 1990; Clark 1992; Allen 2008). In the earlier parts of the thesis study period, i.e., in the 16th century, variations of the open-field system with a rotating fallow were present over large parts of western and northern Europe, including, notably, Switzerland and Sweden (Frandsen 1999:147; Myrdal 2011b:264–265; Renes 2010). In Spain, a comparable mixed farming system was mainly prevalent in the north (Olarieta et al. 2019). There was a greater separation between the arable and livestock husbandry in much of the rest of Spain, as well as a greater emphasis on sheep (rather than cattle as in western and northern Europe) and a greater reliance on the mule as the preferred draft animal (Simpson 1995:37; Le Roy Ladurie 1982:111; Franklin-Lyons 2022:35–36). Nonetheless, in principle, replenishing and maintaining the nutrient levels of the arable land in Spain would have required similar mechanisms as in the mixed farming systems of northern and western Europe, i.e., using a combination of fallow and crop rotations, as well as manure from humans (night soil) and livestock (van Bath 1963:9).

Farming system defined broadly includes agricultural practices, institutions, and technologies, as well as ecological aspects. The mixed farming system can be seen as an example of human niche construction and was part of the local biosphere, where the culturally defined spaces such as the infields, meadows, and the outlying lands (Sw. *utmark*) were to some extent intertwined with the space occupied by the local flora and fauna (Eriksson et al. 2021). In the typical example of a medieval and early modern mixed farming system, livestock were fed upon pastures in the various outlying lands as well as on the stubble after a harvest in the infields (Jupiter 2020). In Sweden and Switzerland during the winter and spring livestock were fed with hay cut from the meadows, and manure was collected and distributed on the infields as fertilizer (Pfister 1983:293; Gadd 2005; Eriksson et al. 2021). In Spain it was more common to employ pastures throughout the year (Collantes 2009).

Allowing livestock to graze on the stubble after a harvest had the benefit of further fertilizing the arable fields (Pfister 1983; Dahlström 2006:19). Livestock were also directly fed with crops cultivated on the arable land, such as oats or barley (Hallberg et al. 2022a). By transferring and circulating energy and nutrients from not only the infields and meadows, but also the broader outlying lands, a more intensive form of agricultural production was made possible on the infields (Olarieta et al. 2019). Medieval and early modern fixed farming systems undergirded prolonged periods of impressive population growth in many parts of Europe (Pfister & Wanner 2021:277). However, there were limits to this system. It has been proposed, for example, that arable expansion at the expense of meadows and outlying lands could lead to soil exhaustion over time, even though pinpointing such processes can be elusive for historical research (Gadd 2000:235–238; Allen 2009; Bohman 2017b). The rotating fallow also posed limits in terms of intensification (van Bath 1963:19–21).

If one were to draw a border between the natural ecosystems of the local biosphere within which farming systems operated, and the more apparent cultured aspects of the landscape like the infields or meadows, it should not be drawn too sharply. There were certainly interactions, and over time a mutual dependence developed between the two, similar to the dependencies between livestock and crop cultivation within the mixed farming system. Nor should the outward boundaries of these systems be drawn too sharply (Olarieta et al. 2019): mixed farming systems and the local biosphere within which they were embedded were not completely autonomous and isolated systems. Trade in both grains and livestock across large regions hint at broader processes of circulation and, to some extent extraction, of energy (Dalhede 1999: 68; Federico et al. 2021). Furthermore, local biospheres were part of large-scale global systemic interactions between the lithosphere, hydrosphere, and the atmosphere (Pfister & Wanner 2021:23–24).

These were some of the common systematic features of mixed farming systems in Europe. However, there were endless varieties of composition in terms of crops and livestock (and technologies!) in these farming systems over both space and time. In some instances, these differences were clearly dependent on local natural conditions, whereas in others there was a larger dependence on societal drivers like markets (van Bath 1963:195, 212–217; Grantham 1980; 1989; Campbell & Overton 1993, Simpson 1995:33–37; Vestbö-Franzén 2004; Mrgić 2011; Myrdal 2011a:109; Pfister & Kopsidis 2015; Franklin-Lyons 2022:34).[5] Another common reality for farmers across Europe during the medieval and early modern periods was a feudal institutional regime that itself came in varieties and could have very different implications in terms of rights and obligations, stretching from serfhood to politically enfranchised freeholding peasant farmers.[6] One almost ubiquitous factor in this feudal regime was the tithe, originally proposed as a tax of one tenth of production paid to the church but over time increasingly assimilated into the tax apparatus of burgeoning states. Ecclesiastical institutions and offices, as well as the secular nobility, were mostly exempt from the tithe, but almost the whole of the European peasant population was subject to it (Goy 1982:5–7).

The village itself was also an institution, in many instances formally so through village bylaws. Variants of the open-field system, where fields were divided into strips belonging to different owners, necessitated a village organization that would regulate agricultural activities such as sowing, harvesting, livestock grazing, and economies of scale in relation to pasture and the building of fences (Dahlman 1980:124–125; Renes 2010; Jupiter 2020). A long-running debate in agricultural and economic history concerns the motivations or underlying reasons behind open-field farming. These motivations include: long-term consequences of rules for inheritance where land was divided between several of the children (usually male) over successive generations, equitable distribution (e.g., of risks — the assumption being that risks to agricultural production differed significantly across different fields, even in the same village area), and population growth.

[5] The role of natural conditions, particularly climate, in shaping agricultural systems is further developed in section 2.3.

[6] A central debate on the agricultural transformations in the 18th and 19th centuries concerns the respective roles of institutions vs markets (Olsson & Svensson 2010; Pfister & Kopsidis 2015).

While it continues to be debated whether individually consolidated plots were more efficient than open-field plots, it seems clear that villages and open-field systems served many important functions in the management of agricultural activities and facilitated the transfer of knowledge within the village (Nyström 2019; Jupiter 2020; Fischer 2022). This last point is understudied in historical research. The spread of knowledge and literacy amongst the peasant and farming populations was intrinsically linked with the agricultural reform movement across many parts of Europe in the 18th and 19th centuries (Svensson 2006; Jones 2016). Enclosures did not only change the physical and legal structures of the village landscapes and agricultural practices — they were also associated with a transformation in how agricultural knowledge was acquired and applied (Fischer 2022).

The open-field system has been argued to be part of a "feudal" — or a *moral economy* — rationale, where farmers were bound by tradition and the collective and, importantly, were averse to risks (Scott 1976; McCloskey 1991; Henningsen 2001). In contrast, after enclosure reforms and increasing market integration, farmers were able to make individual choices and thus pursue more risky profit-seeking strategies in farming (Svensson 2006). Risk can in this context essentially be divided into two categories: one relating to the market and taking risks in relation to storage and speculating on future prices, the other relating to the vagaries of weather (van Bath 1977; de Vries 1981; McCloskey 1991; Nyström 2019). This thesis will be mainly concerned with investigating the latter type of risk.

There were apparent similarities in agricultural technologies across Europe. Wheat (common and spelt), rye, barley, and oats were the most common cereals and formed the bulk of the foodstuff for the majority of the European population, at least until the introduction of the potato (van Bath 1963:262–266). The cultivation of these cereals required similar methods and tools, including the plough or the ard plough, variants of the harrow, the threshing flail (and, over time, increasingly mechanized threshers), and so on (Myrdal 1999:135–138). This is not to imply that there was a complete stagnation in technology; there was certainly innovation and not least a diffusion of technologies across space and time (Bairoch 1969; Myrdal 1999:132–140). From the 18th century onwards, these changes became more rapid and contributed significantly to the agricultural transformations in, for example, Scandinavia (Gadd 1983:157–161; Morell 2022:30–31). An important difference in terms of agricultural technologies was the use of irrigation systems in parts of Spain and other Mediterranean regions (Grigg 1974:123–124). By contrast, irrigated arable fields were largely absent in northern Europe, where ditching and drainage systems were much more prominent (Kaijser 1999:38–41; Gadd 2011:156; Myrdal 2011a:84–85). Irrigation and ditching have obvious implications for the vulnerability of agriculture to excessively dry or wet conditions. Moreover, implements that are more efficient could potentially reduce vulnerability by reducing the time spent on activities such as ploughing or harvesting per unit area (Gadd 1983:259–263; Dardonville et al. 2020).

2.1.1 Historical grain varieties

A common and sometimes necessary generalization in studies of historical agriculture in Europe is that the cultivated crops, especially the four main grains of wheat, barley, rye, and oats, were uniform and coherent categories with more or less fixed (and similar) characteristics: an oat is an oat, as it were. Given the nature of plant breeding since the late 19th century, especially the increased selection and homogenization of agricultural plants, such a generalization might almost seem feasible when looking at late 20th-and early 21st-century agricultural systems. However, the method of plant breeding and seed distribution was fundamentally different for most of history prior to the late 19th century. The essence of this difference was that instead of selecting for one "optimal" yielding genetic variety and its seeds, there was a continual selection of a diversity of seeds and genetic varieties, allowing for greater overall diversity of crop characteristics (Leino 2017:65). For the four main grains, this meant that there was historically a wide diversity of varieties of grain, mainly locally or regionally based.

Barley

Barley was one of the predominant grains grown in Sweden up until the 18th century, but with a slower rate of growth after the 16th century compared to rye and oats (Leino 2017:40). Figure 1 below shows the composition of crops across Sweden ca 1690. Barley was a versatile crop in the sense that it could be utilized for a variety of purposes like making porridge, baking bread, as fodder, and, importantly, being malted to make beer (Fogelfors 2015). Matti Wiking Leino (2017:185) has argued that, due to the longevity and ubiquity of barley as *the* agricultural crop in historical Sweden, it is the grain most adapted to local environmental conditions.

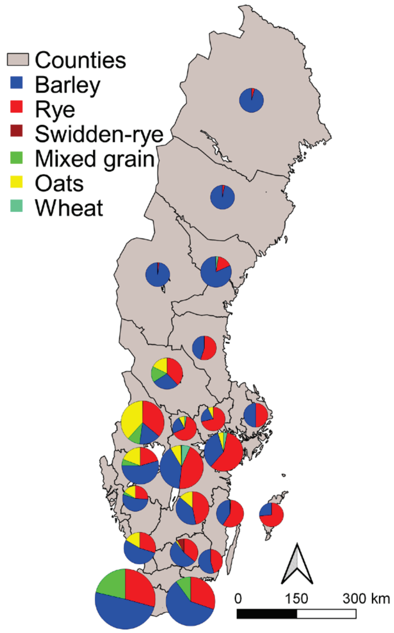

Figure 1. Composition of grain crops across Sweden ca 1690, based on data from Palm (2016b). Circle size is determined by total grain production in each county (using ca 1810 borders to include Jämtland County), relative to the county with the largest production, Malmöhus (the largest circle on the bottom left). Minimum size has been slightly increased for readability.

In Spain, barley has a long history of cultivation and is currently the most cultivated type of grain. Barley varieties were also important in Switzerland, especially in the mountainous regions (Steffenson et al. 2016). In Scandinavia and other parts of northern and central Europe, barley was mainly cultivated as a spring crop, whereas winter barley was more common in southern European countries. Spring barley was known for its ability to grow in the poorest of soils and in extreme agricultural climates like those prevalent in subarctic Lappland, the northernmost province of Sweden (Leino 2017:197–199).

Most local varieties of barley in Sweden were six-row or four-row until the 18th century, after which two-row varieties became increasingly common. The most striking characteristic of barley compared to the other three grains is the potential for extremely short crop periods. Six-row varieties of barley could be sown in the very latest stages of spring, i.e., late May or even early June, and still ripen in time for an autumn harvest in August or early

September. The rapid ripening periods of northern Fennoscandian barley varieties like *Lappkorn* ("Laponian barley"), *Norrlandskorn* ('Norrlandian barley'), and *Bråkorn* (roughly "Bustle-barley") are what made arable agriculture possible in the northernmost parts of Sweden (Leino 2017:193–200).[7] The short crop period presumably also facilitated the planning and execution of the yearly and seasonal timetable for agricultural work. *Sydsvenskt sexradskorn* ("Southern Swedish six-row barley") was one of the main local varieties of barley within the food production system in southern Sweden during the study period. In the woodlands of Scania, it could reportedly be sown as late as June and harvested in mid-August. It has been argued that this type of late sowing can be seen as a risk-mitigating strategy, because the *Sydsvenskt sexradskorn* was sensitive to frost (Leino 2017:192). At the same time, it is known from more northerly parts of Scandinavia that a late sowing dramatically increased the risk for autumn-frosts ruining the crop and that, in general, autumn frosts were a greater threat than spring frosts (Huhtamaa 2015; Ljungqvist & Huhtamaa 2021). In Spain, six-row winter varieties of barley appear to have been dominant. Genetically, the most common barley varieties in Spain appear quite distinct from other parts of Europe, either having more in common with wild barley varieties from Morocco or appearing more or less "indigenous" to the Spanish central plateau (Martínez-Moreno et al. 2017:19). While wheat was the culturally preferred food grain, the importance of winter barley for the Mediterreanean region should not be underestimated (Engelbrecht 1930). In contrast to spring barley in northern Europe (see below), winter barley in the Mediterranean appears to have been more drought tolerant and was grown in more arid areas (Mørch 1999).

In Switzerland, as in other parts of central and western Europe, two-row barley varieties appear to have been the most common type in the pre-industrial period (Jones et al. 2011; Steffenson et al. 2016). In Sweden, it does appear that the actual and gradual spread from the southern provinces seems to have begun in the 18th century at the latest, whereas in Spain two-row varieties became increasingly common in the 20th century (Leino 2017:208–209; Martínez-Moreno et al. 2017:14).[8] Two-row varieties of barley have been noted to be more tolerant to frost. The 16th century Spanish

[7] *Norrlandskorn* could be further distinguished by local varieties like *Dalakorn*, *Hälsingekorn*, *Jämtlandskorn* and *Valbyggekorn* (Leino 2017:193).

[8] Leino argues that the general spread of two-row barley during the Middle Ages and Early Modern period has been underestimated (Leino 2017:203).

agronomist Gabriel Alonso de Herrera noted in *Agricultura General* that two-row barley was the preferred choice in colder areas (Herrera 1818:chap. 8). Beer brewing is also more commonly associated with two-row varieties, whereas four- or six-row varieties seem to have been more commonly employed as fodder, in bread baking, or in making porridge (Jones et al. 2011:7).

Two-row varieties of barley are generally higher yielding and have historically been perceived as a qualitatively finer type of grain compared to six-row varieties. In return for this higher yield and quality, two-row varieties require better soils and more intensive agricultural farming methods overall (e.g., more consistent application of manure and soil preparation much earlier in the spring) (Leino 2017:203–204). An interesting observation here is that more intensive forms of grain production do not necessarily increase risk; rather, adopting frost-tolerant varieties went hand-in-hand with intensification of production. Another type of agrometeorological threat that is commonly associated with barley (and spring crops generally) is drought, at least in northern Europe (Pribyl & Cornes 2020b:196). Moreover, another potential drawback with spring crops is that they do not utilize the growing season as completely as autumn crops, and the yield is frequently more meager compared to overwintering grains as a result.

Rye

Due to its pollination biology, which facilitates rapid adaptation to local environmental circumstances and farming practices, rye can be considered a highly dynamic crop. Accordingly, there have actually been more differences within each local variety of rye than between them (Larsson et al. 2019). Nonetheless, as landraces, including those of rye, are partly shaped by specific farming practices, there are more or less uniformly identifiable traits associated with particular patterns in farming practices (especially sowing times), thus engendering particular local varieties of rye. The dynamic character of rye can be exemplified by documentary evidence from Sweden that suggests the sowing time of rye varieties could vary markedly, all the way from April to the following February, and then harvested from August to September. Some varieties, like *Senråg* (“Late Rye”), could reportedly be sown all through December in Scania, or in extreme cases it could even be sown in the early spring. This type of late sowing allowed for the incorporation of autumn rye into a two- or three-field system, which bypassed the need for a full year of fallow after the preceding harvest (Leino 2017:167–169).

Autumn rye facilitated autumn grazing within the dominant open-field systems. Grazing did most likely damage the plants to some extent, while also reducing the risk for damages associated with overwintering (Leino 2017:160, 178). In terms of frost resistance, autumn rye varieties are generally seen as more hardy compared to spring crops (Hömmö 1994). However, in central Europe spring frosts could cause severe yield reductions to the autumn rye crop. Autumn rye was also susceptible to snow mold during overwintering (for example *Microdochium nivale*, which is found across most of Europe, or *Sclerotinia borealis*, which is present in northernmost Europe: see Jamalainen 1949; Možný et al. 2012).

Rye was also sown as a spring crop, which was planted mainly in areas with poor soils that made the cultivation of autumn rye difficult. Spring rye has a slower rate of ripening and a lower stocking level, which requires more seed per unit of area compared to autumn rye (Leino 2017:182).

Oats

Whilst not a particularly demanding crop in terms of soil and nutrients, oats are generally sensitive to drought and are well-suited to "wet" regions with high amounts of precipitation like Scotland, southwestern Scandinavia, or the mountainous *Hirtenland* of Switzerland (Pfister 1983; Dodgshon 2006). In fact, by the early 17th century oats had become the dominant crop in large parts of western Sweden, and in the subsequent centuries up until the end of the 19th century oat cultivation continued its absolute and relative expansion (Hallberg et al. 2022a). Whereas the establishment of oats as the main crop in the west of Sweden has been seen as an adaptation to the region's wetter climate, the rapid growth of oat cultivation in the 19th century has been explained in terms of market demand and exports to other European countries, primarily England (Myrdal 2011a:112; Hallberg 2013:99–100, 105). Oats have a particular benefit in that they are not susceptible to many of the crop diseases that other cereals are prone to (Andersson et al. 2015). A drawback with oats is that they are sensitive to drought (Pribyl & Cornell 2020b; Raud Westberg 2022). Besides being used for human consumption, the importance of oats as a fodder crop meant that it was a crop highly integrated into the agricultural and economic system as a "fuel" for draft animals and in transport (Hallberg et al. 2022a).

Spelt and common wheat

In Switzerland, spelt wheat (henceforth spelt) was one of the most common cereals during the study period (Pfister 2007:203). There is also a history of spelt cultivation in northern Spain. Spelt is usually considered to be better adapted to colder conditions and long photoperiods compared with common wheat (henceforth wheat), with the latter being the more dominant in Mediterranean regions such as Spain (Campbell 1997; Ratajczak et al. 2020). Another difference between spelt and wheat is that the latter is a generally higher yielding and more demanding crop in terms of soil. Wheat was arguably better suited to the winter-spring cereal crop season practiced in the Mediterranean, and spelt as an autumn crop with the summer as the main growing season. The main limit to growing spelt in the Mediterranean appears to be that it matures relatively late, making it more vulnerable to terminal drought in the regularly occurring drought season (Curzon et al. 2021). By relegating the wheat harvest season to the start of the dry season, Spanish farmers were presumably much less exposed to the type of excessively rainy harvest season that threatened farming in many other parts of Europe.

Spelt and particularly wheat were less important in Scandinavia during the historical period, even though they were important crops during parts of its pre-history (Lagerås & Larsson 2020). Wheat, being more temperature-sensitive than rye or barley, was not favored in the Scandinavian climate, at least not during the medieval and early modern periods. However, the same climatic reason is less apparent for spelt, which is a hardier and more cold-tolerant crop. Spelt may have become less attractive in relation to other crops like (hulled) barley with the introduction of more efficient harvesting techniques (Pedersen & Widgren 2011).

2.2 European climate during the "Little Ice Age"

The European climate of the last twelve centuries has been subject to periodization attempts. Between roughly 800–1250 CE there was, for instance, a rise in average temperatures in Europe and elsewhere, which has spawned the concept of the Medieval Warm Period (MWP).[9] Following the MWP around the start of the 14th century, there was a drop in average temperatures in the boreal parts of the globe, which lasted until the 1850s (or even the early 1900s in northern Sweden, see Figure 2 as well as Figure 9 in Section 5.3.2). This latter period has been referred to as the "Little Ice Age" (Rohr et al. 2018:248; Pfister & Wanner 2021:171). In both these periods there were different changes in inter-annual weather variability, as well as warmer and colder years, or spans of years, respectively. In addition, there are sub-periodizations based on solar or glacial activity, such as the "Spörer Minimum" (c 1460–1550), the "Grindelwald fluctuation" (c 1560–1630), the "Maunder Minimum" (c 1645–1715), and the "Dalton Minimum" (c 1790–1830) (Eddy 1976; Pfister et al. 2018a:269, 279; Wanner et al. 2022).

The LIA was not uniformly cold. Rather, it involved spatially and temporally differentiated climatic variability across Europe, as well as globally. It should be noted that the LIA is very much a living concept, evolving over time with changing periodicities as new research sheds further light on the climate of the past (Büntgen & Hellmann 2014; Collet & Schuh, 2018a; Wanner et al. 2022). Researchers have identified and debated a multitude of causal mechanisms within the climate system that can be associated with the LIA, such as orbital cycles, reductions in solar activity, changes in ocean currents and atmospheric circulation, (increased) volcanic eruptions, and deforestation or reforestation induced by human settlement (Zorita et al. 2018:24–25). Volcanic eruptions in particular have been identified as a form of climate forcing that have led to more extreme or detrimental forms of climatic variability in the relatively short term, e.g., a handful of years (Sigl et al. 2015). The onset of the LIA may have been partly triggered and maintained by clusters of volcanic eruptions working in tandem with other internal forcing mechanisms (see Miller et al. 2012 and Brönniman et al. 2019b).

[9] Another common term here is the Medieval Climate Anomaly, which is arguably a more relevant term when discussing climatic conditions (i.e., temperature and hydrolimate) globally (Bradley 2015:548–550). Since the focus of this discussion is on Europe, and most of the reconstructions describing this period in Europe are temperature-based, the term Medieval Warm Period has ultimately been judged more relevant here.

Returning to the climate and changes thereof, the available climate data is much more detailed than a consideration of only periodizations (e.g., LIA) and sub-periodizations (e.g., Maunder Minimum) would suggest. For example, there is instrumental meteorological data from many cities across Europe, including Scandinavia, beginning at the early 18th century on a monthly, daily, or sometimes even sub-daily basis. These early instrumental measurements frequently contain the type of biases historians are accustomed to be working with, such as who took and documented the measurements, why the measurements were undertaken at a particular time or what understanding of time (e.g., calendar) was being employed (Pfister 2018:37–38; White et al. 2023). They also contain biases better understood by meteorologists, such as the effects of placing an instrument in a sun-exposed location or measurements at a particular time of day (Moberg et al. 2002; 2003; Böhm et al. 2010). With the help of large data sets, computer-assisted algorithmic methods can also aid in correcting for biases and homogenizing climatological time series (Squintu et al. 2020).

Describing the climate over time and space can be quite exhaustive, given that there are continuous oscillations, different types of variability on different time scales (e.g., seasonal vs annual or annual vs decadal), and stochastic local variation. While there was geographical and temporal variety during the LIA in Europe, research on many different locations throughout Europe and Scandinavia has been able to identify some commons trends. In what follows, I will focus on research regarding the climate of Sweden as well as central Europe before moving on to research that focuses on the climate history of the Iberian Peninsula, in both cases during the early modern period. Wanner et al. (2022) argues that the reduced average temperatures associated with the LIA were above all a winter phenomenon, affecting the other seasons to a lesser extent, at least in central Europe. The LIA appears to have been most strongly expressed in central European winters during the years 1500–1800 with average temperatures 1.1 °C below the 1961–1990 reference period (Pfister et al. 2018a:276–277). In Stockholm, winters were also generally cold during the period 1500–1700, slightly warmer during the 18th century, and then somewhat colder again during the 19th century, see Figure 2.

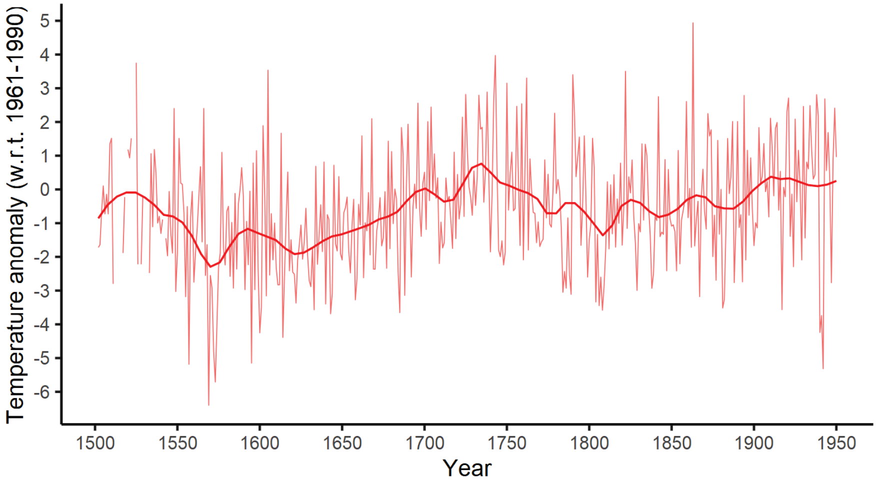

Figure 2. Reconstructed mean winter-spring (JFMA) temperature anomalies (w.r.t. 1961–1990 mean) for Stockholm, 1500–1950. Thick line shows a 31-year Gaussian smoothing and thin line shows annual variation. Data from Leijonhufvud (2010).

However, there were years or decades within the LIA where sharp drops in summer temperatures occurred, such as during the last decades of the 16th century and the early 17th century, the 1640s (although not as marked in Sweden), the last decades of the 17th century, and large parts of the 19th century (see Figure 2). Spring temperatures were especially low in the 1690s, years of particular hardship in large parts of northern Europe, in particular the Baltic Sea region (Leijonhufvud et al. 2010; Dribe et al. 2017b).

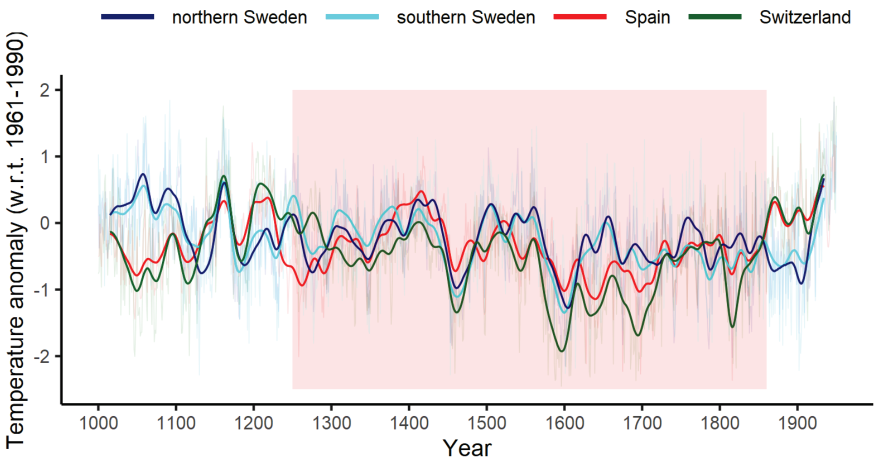

Figure 3. Summer (JJA) temperature anomalies (w.r.t. 1961–1990 mean) in Spain, Sweden and Switzerland 1000–1950, based on reconstruction from Ljungqvist et al. (2019). Thick curves show a 31-year Gaussian smoothing, whereas thin curves show annual values. LIA as defined by Wanner et al. (2022) in the shaded red area (1250–1860).

Except for an interlude of warmer temperatures in its middle, especially in Sweden, most of the 17th century was cold, with more pronounced reductions in average temperatures in the early and late decades of the century (Wanner et al. 2022). After the "long" cold 17th century, which ended in roughly 1710, the 18th century saw a "return" to milder and warmer temperatures, albeit with some notable exceptions with extremely cold temperatures, such as the 1740s and 1770s. However, as can be seen Figure 2, differences between the 17th and 18th centuries were less pronounced in Sweden.

The last prolonged period of greatly reduced average temperatures encompassed the first decades of the 19th century, which includes years like 1816, the "Year Without a Summer". The exceptionally cold temperatures and lack of sunlight, caused by the eruption of Mount Tambora in 1815, resulted in a disastrous year for agriculture in parts of Europe (but not Scandinavia) (Pfister & White 2018:552–553). In fact, many catastrophic climate or weather events that have severely disrupted harvests and caused agricultural crises throughout the last 500 years (and beyond) have been linked to similar eruptions or series of volcanic eruptions (Huhtamaa & Helama 2017b; White et al. 2022). Wet winters and cold, wet springs and summers in the 1590s, 1690s, 1740s, 1770s, and 1810s have been linked to volcanic eruptions (Pfister et al. 2018a:268–269). However, volcanic eruptions do not always have spatially consistent effects across Europe, with large-scale regional differences along northern-southern and western-eastern divides. Besides cooling generally occurring in the year following an eruption, especially in northern and western Europe, there is also a weak tendency for dry conditions during the same year and in the year following a volcanic event in parts of central and eastern Europe, as well as southern Scandinavia (Fischer et al. 2007; Seftigen et al. 2017).

Another influence on temperatures in most of northern and central Europe comes from the North Atlantic Oscillation (NAO). The NAO represents differences in sea-level pressure between Iceland and the Azores, which significantly affects the strength of the westerlies in western and northern parts of Europe. A positive NAO describes cyclonic conditions around Iceland and anticyclone conditions around the Azores. A negative NAO denotes below average sea-level pressure in the Azores region and above average pressure around Iceland. Large negative NAO anomalies have been associated with some of the more exceptionally cold winters in central and northern Europe during the early modern period (Pfister et al. 2018a:274–275).

Whereas the climate in northwestern and central Europe experienced some common climatic trends during the LIA, differences within Europe should not be ignored. Notably, summer temperatures in Sweden during the 1540s, 1630s, and 1640s exhibit opposite trends to Spain/Switzerland, as can be seen in Figure 2 (see also Figure 9 in section 5.3.2 showing central Scandinavian growing season temperatures). A clear break can be seen in the late 19th century when the LIA abates in Spain and Switzerland but intensifies in Sweden until the early 20th century. Furthermore, northern and southern Sweden differ to some extent, where average summer temperature anomalies are slightly higher in southern compared to northern Sweden. However, given that the proxies used to reconstruct the summer temperatures in Figure 2 vary in their spatiotemporal coverage and skill, comparisons, especially those of greater magnitudes, should be made with caution.

Despite the commonalities between Swiss and Spanish summer temperatures, the Alps is commonly noted as an important separator in the European climate, where the areas to the north of the Alps are heavily influenced by Atlantic westerlies, whereas in the Mediterranean region south of the Alps high atmospheric pressures regularly generate warm and dry summers (Pfister et al. 2018a:266–267). This contrast is perhaps weaker in regards to the Iberian Peninsula, which is also heavily influenced by Atlantic weather patterns, than it is for example between Italy and Germany. Within the Mediterranean region, there are further differences. However, given that Spain is one of the regions studied in this thesis, the following discussion will focus on the state of research regarding the climate history of early modern Spanish.

Most of the available evidence regarding year-to-year variations in the Spanish climate during this period comes from either tree-rings or documentary evidence describing rogation ceremonies (Domínguez-Castro et al. 2008; Ruiz-Labourdette et al. 2014). Such ceremonies were regularly conducted in Spain to aid people against weather or climatic stresses in the form of *Pro Pluvia* Rogations (prayers for rain) or *Pro Serentiate* Rogations (prayers for the cessation or reduction of rain). According to a study of rogation ceremonies in Toledo, central Spain, the periods 1600–1675 and 1711–1775 experienced the most drought, whereas the years in between, i.e., 1676–1710 were less drought-prone. Tree-ring proxies indicate that in southern Spain, the 1590s stand out for being exceptionally wet, at least during the winter and spring, with somewhat dry summers. In central Spain, the summers of the 1590s–1610s appear to have been exceptionally dry. Based on rogation ceremonies in the 18th century, the period 1755–1782 seems to have been generally quite dry in large parts of central Spain, followed by frequent extreme rain events in the years 1783–1788. Overall, in Spain the late 18th century is known for the so-called Maldà Anomaly (ca 1760–1800), which was characterized by a destabilization of the normal climatic conditions in the western Mediterranean, with oscillations between extreme rainfall and extreme drought (Barriendos & Llasat 2003; Oliva et al. 2018). The coldest period in the mountains of the Iberian Peninsula, i.e., most of the inland territory, was roughly 1620–1715. Cooling also occurred between 1570–1620 but was not as dramatic as that in northwestern or central Europe (Oliva et al. 2018). The period between 1715 and the Maldà Anomaly experienced milder temperatures.

2.3 Agriculture and climate in Europe during the early modern period

In recent years, a new term has developed to describe studies of the historical relationships between climate and human societies, i.e., Climate and Society Studies, or the History of Climate and Society (HCS) (Degroot et al. 2022). HCS incorporates the recent surge in these types of studies, many of them of an interdisciplinary nature, where researchers and methods from a wide range of disciplines are included. While largely coincidental, one might say that the year 2021 was the unofficial launch of HCS, when a flurry academic publishing explicitly or implicitly adopted the term HCS (although the genre itself is much older). These publications include: a monograph titled *Climate and Society in Europe – The Last Thousand Years*, written by the pioneer in the field of climate history and historical climatology, Christian Pfister, and the paleoclimatologist Heinz Wanner (Pfister & Wanner 2021); a research review titled "Climate and Society in European History" (Ljungqvist et al. 2021); another review concerning the Nordic countries titled "Climate in Nordic historical research" (Ljungqvist & Huhtamaa 2021), and finally what might be called a sort of research manifesto, the *Nature* article "Towards a rigorous understanding of societal responses to climate change" (Degroot et al. 2021). A commonly expressed notion in these publications is that the study of agriculture is a crucial part of HCS.

During the last 150 years, while the relationship between climate and agriculture has periodically drawn the attention of historians, agriculture has interested historians almost by default, given that it is the agrarian societies since the First Agricultural Revolution (or the Neolithic Revolution) that gave rise to written source materials and the discipline of history itself (Scott 2017:13). Of course, historians have also been drawn to agriculture by an interest in agriculture in itself, as evident by my own discipline of *agrarian history* (Myrdal & Morell 2011). In the following, I will start out by outlining, based on previous research, the natural conditions to which agriculture has adapted over the *longue durée*, here including and predominantly focusing on climate. Subsequently, I will turn to a discussion of studies that have attempted to quantitatively study how climate has affected agriculture over time, with a focus on crop and livestock production.

2.3.1 Agriculture and climate in Europe over the *longue durée*

Long-term differences in agriculture across space can be connected to differences in physical geography and climate (Le Roy Ladurie 1971:20, 118–119; Mills 2007). Carl-Johan Gadd (2000) has argued that before the agricultural transformation in the 19th century, agriculture in Sweden was to a large extent shaped by natural conditions. Similar arguments can and have been made for other parts of Europe, including Spain and Switzerland (van Bath 1963:23–25; Pfister 1983; Simpson 1995:36). Intermediating factors in these relationships are changes over time in natural conditions themselves, cultural preferences, technological diffusion, institutional change, and the influence of markets (Vestbö-Franzen 2005; Malinowski 2016; Federico et al. 2021; Franklin-Lyon 2022). Nonetheless, natural conditions to some extent shaped the baseline of what was possible or feasible in terms of agriculture (Braudel 1981:49–50).

In most of the inland of northern Scandinavia, cereal cultivation was very limited and, due to the short and cool growing season, mostly concentrated on the cultivation of a single type of crop – barley (Welinder 2019).[10] In most of Spain and other parts of the Mediterranean region, summers were prohibitively dry, leading farmers to prefer the winter-spring months for cereal cultivation instead of the spring, summer, and early autumn months, which constituted the main cereal growing season in most other parts of Europe. Wheat was much more common in southern Europe, compared to northern Europe due to the accumulated heat requirements (usually conceptualized as Growing Degree Days, GDD) and wheat varieties' sensitivity to frost (van Bath 1963:263; Foss 1925). Other examples of locally adapted crop specialization include that of oat cultivation in western Sweden due to the wetter climate prevalent there, as well as rye in the east (or barley in southern Sweden) due to a dry spring-early summer seasonal pattern. Historical research has shown that mitigation or adaptation in response to the constraints set by natural conditions has been possible (Kjærgaard 1991; Bohman 2017a, 2017b). Improved agricultural techniques, e.g., in fertilization, as well as crop selection and breeding, have allowed wheat to become one of the most important crops in Scandinavia (Almås 2002; Dalgaard & Kyllingsbæk 2003; Morell 2011:184). Another example with long historical roots is the use of irrigation systems in Spain (Butzer et

[10] Note that barley was also the dominant crop in southernmost Sweden (see Fig. 1), such as in Scania, which offers some of the richest soils and most favorable conditions for arable agriculture throughout Scandinavia.

al. 1985). Land reclamation is perhaps the most common way agrarian populations have actively manipulated the constraints of nature, the most striking example being the Low Countries (van Bath 1963:199–203; Kaijser 1999:37–41).

The limits to cereal cultivation in agroclimatically marginal areas like northernmost Europe or the most rugged areas of the Alps or the Carpathian Mountains certainly played a role in keeping population numbers low in those regions (Pfister 1983; Galloway 1986; Welinder 2019). However, low population densities also had the benefit of making large spaces available for extensive forms agricultural production, mainly in the form of livestock husbandry, which predominantly focused on cattle, sheep, goats, or reindeer herding, but also included swidden-agriculture (Dodgshon 2009). In northern Sweden, Norway, and the Swiss Alps, these large spaces were partly used for summer farms. These were a form of satellite farming enterprise where livestock could graze upon large summer pastures accompanied by members of the peasant household - in Scandinavia usually the women and the young — who also worked producing secondary milk and cheese products at these farms (Netting 1972; Cole 1972; Larsson 2009:95–97). In Spain, a type of transhumance was practiced where herds of sheep were taken to pastures in elevated mountainous regions in the summer and towards lower elevations and river valleys in the winter and spring (Ruiz & Ruiz 1986).

These spatial differences only tell part of the story: neither the climate nor the human societies were static and thus any analysis would be incomplete without a temporal element and a considerable allowance for contingency. How exactly climatic change or variability would have affected agriculture or an agrarian society depended largely on how the current farming systems were structured; e.g., the compositional make-up of livestock and crop production, what agricultural methods were employed, and the natural conditions like soils in the area (de Vries 1981:22; Michaelowa 2001:4–5, 7; Mrgić 2011). As already indicated, climate played a role in shaping these factors. There are thus both long-term as well as shorter-term relationships between climate, weather, and agriculture — with a layer of socio-cultural intermediation in between (Degroot et al. 2021).

Taking other factors into account, it can be generally proposed that farming systems were adapted to the long-term climate in their region, and when there were significant shifts in the climate regime, this led to stress on the farming system and society in question, at least in the short to medium-term before adaptations could be made (Burke & Emerick 2016; Leino 2017:13; Shennon 2018). The most notable example here, at least in European historiography, is the cooling of the LIA which was supposedly detrimental to farming systems adapted to the warmer temperatures of the MCA (White et al. 2018:333). Pfister et al. (2018b:269) note that many climatic shocks occurred during periods of high vulnerability for populations in continental Europe, which were marked by population growth and declining incomes (see also Pfister & Brázdil 2006). These societally shaped vulnerabilities interacted with the vulnerability of agriculture to climate and weather in a forceful way. Recent publications by the historians Bruce M. Campbell (2016) and Geoffrey Parker (2013) have been particularly important for popularizing the notion of how periods of simultaneous demographic, economic, environmental, and climatic stress led to much human and animal suffering. Of course, social forces came to play the predominant role in many of these cases. Esper et al. (2017) and Ljungqvist et al. (2018) found for example that effects from climate or even from plague on the economy were largely obfuscated by the devastating impacts of the Thirty Years War (1618–1648).

Caution should be taken, however, before universally assuming that colder temperatures were universally and necessarily bad (Le Roy Ladurie 1971:118–119; Degroot 2018:300–303; Haldon et al. 2018). While late spring frosts frequently caused crop losses, the autumn frost seasons in many parts of continental Europe and southern Scandinavia are well outside historical harvest seasons (Wetter & Pfister 2011; Pribyl et al. 2012; Marchi et al. 2020). Many of the historical spring crop varieties cultivated in northern Europe were in fact primarily sensitive to drought (Pribyl 2020). Excessive rain during the harvest season could certainly be detrimental but wetter conditions were for the most part beneficial during the preceding summer months, although probably less so on marginal or less well-drained lands (Edvinsson et al. 2009:125–126; Brunt 2015). In the southern third of Sweden, drought and not cold has been argued to have been the most severe threat to crops (consider that the vast majority of Scandinavian grain production occurred in this region, especially if Denmark is included! See Fig. 3 below and Edvinsson et al. 2009:126; Wei et al. 2021; Hallberg et al. 2022b).[11] In the Low Countries, there appears to have been division between

[11] The combined share of the northern counties, i.e., Västernorrland, Kopparberg, Gävleborg, Jämtland, Västerbotten and Norrbotten, in total grain production in Sweden was roughly 15% in 1810 (Hallberg et al. 2022b).

localities more sensitive to drought and those more sensitive to cold during the early phases of the LIA (Soens 2022). Perhaps the most telling example of the ambiguity of cold conditions is the fact that the Dutch Golden Age coincided with the some of the colder episodes of the LIA, as analyzed by Degroot (2018).

Pei et al. (2015, 2016) and Waldinger (2022) identified positive relationships between growing season temperatures and large-scale harvest aggregates. However, both studies relied on aggregating the highly unbalanced and heterogeneous yield ratios from Slicher van Bath (1963), effectively assuming large parts of Europe (all of Europe in Pei et al. 2016, eastern or western in Pei et al. 2016, and France, Germany, Sweden and Poland in Waldinger 2022) to be homogenous agricultural entities over the period 1500–1800. Both the underlying data, as well as the implicit assumption inherent in such aggregation have questionable validity.[12]

Nonetheless, there is some evidence implying negative impacts of cold across Europe, for example looking at economic indices like grain prices (e.g., Ljungqvist et al. 2022). Large-scale studies of medieval and early modern grain prices have found that colder periods were associated with higher grain prices, and vice versa (Esper et al. 2017; Ljungqvist et al. 2022). However, there is a lack of reliable studies showing corresponding relationships between crop harvests and temperatures. Holopainen et al. (2012) did find such patterns for wheat yields and prices in 19th century Sweden; however, those results are not easily generalizable to other parts of Europe. Several other climatic (and of course non-climatic!) factors could have affected grain prices. Colder summers were usually also wetter, and this combination may have led to large storage losses through mold and vermin in times when storage facilities were inadequately isolated (Pfister 2005; Claridge & Langdon 2011). Overland transports would similarly have suffered from excessive rain (Batten 1998). Other important considerations include the mutual dependence of crop and livestock production, where

[12] A more careful aggregation and realistic estimation of yield ratios based on data from van Batch (1963) and van Zanden (1998) can be found in de Pleijt & van Zanden (2016). De Pleijt & van Zanden (2016) find that yields increased in eastern Europe until the 18th century and in western and southern Europe until the 17th century, whence yields stagnated in large parts of Europe (but not eastern Europe), followed by a sharp increase in western Europe in the 18th century. For comparison, according to Pei et al. (2015), long-term yields across Europe decreased by more than 50% between the early 16th century and the late 17th century, a period which simultaneously experienced a significant growth in population. Supposedly, yield ratios around 1800 were still below the early 16th century peak! In Pei et al. (2016), yields decreased in eastern Europe by more than 60% between the early 16th and the 17th century, and increased in the 18th century. In other words, completely opposite trends to those estimated by de Pleijt & van Zanden (2016) for eastern Europe.

colder conditions could have negatively affected pastures and livestock and thus indirectly hit crop production through the availability of fertilizer (Utterström 1955; Michaelowa 2001; Costello et al. 2023). Excessive wetness could also lead to nutrient run-off from the top layers of the soil (Pfister 2006:205). Lower temperatures slowed down soil nitrogen mineralization rates, thus potentially contributing to lower yields over the medium-term (Dessureault-Rompré et al. 2010). Finally, given that markets were imperfectly integrated, it is possible that areas or phenomena more sensitive to colder temperatures (like transport and storage) had an outsized effect on grain prices (Pfister 2006:202–206; Collet 2010; Campbell 2018:20; Federico et al. 2021).

While the impact of episodes of extreme cold and wet summers are generally acknowledged, the long-term general impacts of the shift to the LIA are less clear (Pfister & Wanner 2021:282–286). Over time, farming systems as well as the plant material itself would have adapted to the new climatic regime, although this process is exceedingly difficult to study empirically given the lack of available sources and the complexity inherent in such a process of multi-level adaptation (see for example Tello et al. 2017). Nonetheless, one could argue that the gradual recovery in population levels after the LMAC suggests that some degree of adaptation had likely occurred, given that, although the frequency and severity of plague outbreaks decreased, the LIA persisted for several centuries (Lagerås 2015:17–18; Pfister & Wanner 2021:254; Wanner et al. 2022). Overall, it seems quite certain that the main driver of the LMAC was the Black Death and subsequent plague outbreaks, while the LIA reinforced trends of, for example, farm abandonment in parts of western and northern Europe, especially in marginal agricultural areas where growing season temperatures set the actual geographical limit of arable agriculture (Solantie 1992; Antonsson 2004:122; Izdebski et al. 2020)

Instances with extreme cold or drought might exemplify cases where the effects from climate, and the climate-society relationship, are most evident. A fundamental assumption underlying much research in the HCS is the dependence of agriculture, and thus agrarian societies, on climatic conditions and weather outcomes (Degroot et al. 2021). However, even in modern contexts where the available data is much more available and detailed, it has frequently been difficult to identify clear non-ambiguous relationships between meteorological indicators and agricultural yields. This has been explained by the tendency for non-linearity in some of these relationships, as well as the heterogeneity of weather or high-frequency climate (Schlenker & Roberts 2014; de Toro et al. 2015; Beillouin et al. 2020). While the interplay between agrarian structures and natural conditions can appear stable, the boundaries of the possibilities of agriculture in the face of natural constraints have shifted over time and multiple avenues for adaptation have existed in many contexts. In other words, contingency and change have existed in the relationship between agriculture and nature. Nonetheless, the relative stability in these relationships lend themselves, at least to some extent, to systematic study. In the following section, I will describe the research conducted in the last 70 years that fits within a field that I term *historical agrometeorology*, which covers Europe during the pre-industrial period (although not going back further than the Middle Ages), focusing mainly on quantitative studies and on crop and livestock production.

2.3.2 Historical agrometeorology

The modern science of agrometeorology concerns the study of how climate and weather impact agricultural production, with the aim of utilizing the understanding of these relationships to improve agricultural practices. In the historical disciplines, scholars have also tried to estimate climate and weather impacts on agricultural production. However, rather than the improvement of current practices in agriculture, the predominant aim of this research has been to improve our understanding of past societies. As has already been noted, climatic impacts on agriculture are considered among the first and most fundamental impacts of climate on society in most historical models (Krämer 2015; Ljungqvist et al. 2021).

Most of the scholarship regarding the Swedish context has been guided by Utterström (1955), who argued that colder periods were especially detrimental to fodder supplies and the maintenance of livestock. As a reaction, grain production would acquire a more prominent role during such periods. Recently, Costello et al. (2023) has identified such patterns in pastoral regions of north-west Europe. Utterström (1955:107–108) also argued that the relationship between climate and agriculture in Sweden could be divided into two main regions. In northern Sweden, temperature was the constraining factor, while in southern Sweden precipitation that had that role, at least after the 17th century (this hypothesis is developed further in section 3.4.1). In the late 1950s (and much later than that as well), there was still a general lack of agricultural and in particular climatic data to systematically test these hypotheses.

The first quantitative estimation of the weather dependence of Swedish historical agriculture, to this author's knowledge, was Palm (1997), who studied conditions on a one-field (Sw. *ensäde*) farm run by a few generations of local bell-ringers in Halland, southwestern Sweden, during the period 1760–1865. Palm (1997:137–139) found several specific relationships between annual and monthly weather patterns and yields of particular grain varieties, although the relationships were in general quite weak. Furthermore, Palm (1997:112–114) found adjustments in the agricultural work calendar at Djäknebol in relation to temperature and precipitation variability. The local nature of Palm's (1997:143) study did not permit any wider generalizations on Utterström's (1957:107) hypothesis regarding the general agrometeorological dependencies in southern Sweden. Edvinsson et al.'s study (2009) represents one of the first attempts to quantitatively examine and test this hypothesis, using a variety of sources and mainly focusing on the 18th, 19th, and early 20th centuries. The authors found that grain crops in the southern parts of Sweden generally performed better in years of low temperature differences between winter-spring and the summer seasons; i.e., during periods of warm winter-springs and cold summers. The results also largely conformed to the hypothesis proposed by Utterström that agriculture was constrained primarily by summer precipitation in southern Sweden and by temperature in northern Sweden. Edvinsson et al. (2009:125) found wheat to be the most climate-sensitive crop, while autumn crops in general were more sensitive than spring crops, at least in the 18th and early 19th centuries. Holopainen et al. (2012) also found a positive correlation between spring temperatures and wheat yields, as well as a tendency for inverse climate-grain price relationships in comparison with climate-grain yield relationships during the 19th century in Sweden.

There have been few, if any, attempts to quantify historical climate-agriculture relationships in other parts of Scandinavia. Broadening the scope slightly to Fennoscandia by including Finland, we find multiple examples of such studies (Huhtamaa & Ljungqvist 2021). In general, the agrometeo-rological patterns in Finland have followed those described by Utterström (1957:107) for northern Sweden; i.e., growing season temperature was the main constraint. Within Finland, the northern and eastern parts were more temperature-sensitive compared with the main agricultural districts in the south (Solantie 2012; Huhtamaa et al. 2015). Besides general growing season temperatures, winter severity and the onset of the growing season have also been argued to be especially important for cereal harvests in Finnish pre-industrial agriculture. In a quantitative estimation of the relationship between grain yields and temperatures, Huhtamaa et al. (2015) found January and June to be the most important months. Effects from February and in particular March were much weaker and the harshness of the winter temperatures in the northernmost provinces of Finland had no clear effect on grain yields, which indicates a more complex relationship between yields and winter severity. Huhtamaa et al. (2015) proposed that January possibly had a particular role to play in the risk for the development of fungi, which could be heightened if, for example, the ground remained unfrozen after December and was subsequently covered by a thick snow layer in January. Warmer growing season temperatures had a positive impact on grain yields across Finland, where the effect was particularly clear in the northern provinces. Solantie (2008) and Huhtamaa et al. (2015) have argued that the maxima reached in daylight hours in June explains the particular importance of that month.

Looking outside the Nordics, the Low Countries, England, Switzerland, and the Iberian Peninsula are the most studied regions from the perspective of historical agrometeorology. Jan de Vries (1981:29–30) represents one pioneering example: he estimated the role of winter temperatures, and in particular the extent of freezing during March, on various agricultural and economic indicators, finding that dairy production was negatively affected by colder temperatures in that month. Grain yields in a collection of polders in South Holland were negatively correlated with winter (November through March) precipitation (i.e., more rain = lower yields[13]), although correlations varied by locality. Tim Soens (2022) studied grain yields and tithes in the southern Low Countries during the 14th and 15th centuries; he found no consistent relationships valid for the entire region. For example, while there were some harvest failures in the notoriously wet years of 1315 and 1316, many localities brought in excellent harvests when the same meteorological conditions prevailed in the 1398 and 1399. Brussels and Cambrai exhibited

[13] These types of clarifications (e.g., more rain = lower yields) are employed throughout the thesis in parentheses. Only outcomes in one direction are stated, but they should be interpreted as being valid in the other direction as well. Thus, the above example could also be read as less rain = higher yields. They are mainly intended for pedagogical purposes and are not to be taken as declaration of mathematical or causative certainty. They are, however, indicative of statistically significant signs (positive or negative) of correlation.

negative correlations between tithes and summer temperatures (i.e., warmer summers = smaller harvests), whereas Heist showed positive correlations (i.e., warmer summers = larger harvests). Single monthly or seasonal climatic indicators explained about 10 per cent or less of historical harvests (Soens 2022).

Pre-industrial English agriculture was notoriously susceptible to excessive rain during the growing season, particularly during harvest times. Quantitative studies have mostly found effects on harvests from July and August temperature and hydroclimatic conditions, and there seems to be no readily identifiable temperature signal from the summer season as a whole (Titow 1960; Brunt 2004, 2015). Bekar (2019), who studied persistence in harvests shocks in medieval England, partly considered climatic shocks as well. He found a weak negative relationship between a variable based on interacted temperature and hydroclimatic series and grain yields (only statistically significant at the 10 per cent level). Furthermore, both temperature and precipitation appeared to have negative effects on yields in OLS models; in other words, both warmer temperatures and increased precipitation decreased yields, although the effects were modest overall.

Kathleen Pribyl (2012) has shown that April-July temperatures could explain up to 62 per cent of variation in grain harvest dates in the East Midlands of England during the late 18th and early 19th centuries. The warmer the growing season, the earlier the grain could be harvested. Pribyl (2017) has also identified a relationship, albeit weaker, between the length of the harvest in the Middle Ages and oak-based hydroclimate proxies, where wetter conditions in July and August was associated with longer harvest times. A similar association between grain harvest dates and growing season temperatures has been found by Wetter & Pfister (2011) in early modern southern Germany and Switzerland, where, again, warmer temperatures were associated with earlier harvest dates. Harvest outputs in central Europe generally appear to have been badly affected by cold springs and wet summers (Pfister 2005). Wet autumns also appears to have negative effects on the subsequent year's harvest, presumably because of nutrient run-off (Pfister 2006:203).

In Spain, where the main crop season occurs between November and July, spring droughts have presented the most apparent agrometeorological threat. Cold winters and springs also appear to have posed a threat (Barriendos 2005; Llopis Agelán et al. 2020; Moreno et al. 2020). Excessive precipitation has also been identified as a threat to Spanish grain production, given the association between such meteorological events and incidences of the common (wheat) bunt (Moreno et al. 2020). In neighboring Portugal, excessive precipitation between August and October, together with above average precipitation and temperatures between December and April, have been proposed as the main agrometeorological constraints for wheat and rye production, at least in the years around 1800 (Silva 2020).

To summarize, it is mainly in the northernmost regions of Europe that a readily identifiable positive signal between growing season temperatures and grain harvests appears during the pre-industrial era. In areas to the south of these regions, relationships are generally of a smaller magnitude and more heterogeneous. The positive association between growing season temperatures and harvest only occurs in some areas and pertains mainly to temperature-sensitive crops like wheat and some varieties of autumn rye, or some temperature-sensitive phenological phenomena, such as the ripening of the crop. Nonetheless, it has usually been possible to identify at least some primary or baseline agrometeorological relationships in these areas. An important task for future research in this regard is to explain the more readily identifiable (in comparison with climate-harvest relationships) negative relationship between temperatures and grain prices (i.e., warmer temperatures = lower grain prices, see Ljungqvist et al. 2022). Local- or regional-level agrometeorological relationships are further discussed in sections 3.2–3.5.

3. Theoretical framework

This section outlines the theoretical framework of this thesis. Firstly, definitions of weather and climate are given. Secondly, I elaborate on ways in which the impact of climate on pre-industrial agriculture can be modelled. Thirdly, I offer a hypothesis regarding what dominant agrometeorological patterns can be discerned in the study areas, based on previous research.

3.1 Climate vs weather vs …?

In order to study the relationship between climate and historical agricultural production, one needs define what constitutes climate as well as provide some insight into how the concept has developed over time. Earth's climate system is immensely complex and variable, and our understanding of it is as yet far from complete, not least in a pre-industrial context that lacks greenhouse gas emissions as a dominant forcing factor (IPCC 2021). Over the last decades, however, researchers have made several significant strides in understanding the climate of the past in Europe (see Pfister & Wanner 2021 for an accessible and relevant overview of the European climate during the last millennium). Europe (and in particular Scandinavia) is one of the most studied regions (together with North America and East Asia), which has led to a rich record of climate reconstructions based on various proxy records, some of which are of particular interest for this thesis (Gunnarsson et al. 2011; Luterbacher et al. 2016; Seftigen et al. 2017; Fuentes et al. 2018; Ljungqvist et al. 2019).

So, what is climate? The most straightforward definition of climate is the long-term average of weather at a given locality. Weather itself can be defined as the current or short-term atmospheric state of factors like cloudiness, temperature, radiation, precipitation, and moisture in a particular location. The weather changes with the passing of time; thus, one must turn to a description of the average weather. After a given length of time, one can start to describe the average weather as climate. The discursive shift from weather to climate depends on particular social and cultural customs. For example, the German language contains the term *Witterung* (similar to *väderlek* in Swedish), which is a sort of middle term between weather and climate that describes meteorological conditions lasting several days or weeks (Pfister & Wanner 2021:25). A common definition defines climate as averages of meteorological phenomena over 30 years or longer (WMO 2017). These are arbitrary definitions, since neither climatological, biological phenomena, nor climate-society relationships operate at such specific time-scales. In practical research applications, such as paleoclimate reconstructions, different time-scales are used: these range from a few years to fifty, hundreds, or thousands of years (Brönnimann et al. 2018). The primary interest of this thesis is not a fundamental understanding of climate in and of itself; rather, it is in how average weather across different time-scales has related to variations in agriculture. Most historical climate data before the late 19th century, with some exceptions, is on a monthly, seasonal or even longer time-scale. This thesis will refer to short-term variations over less than 30 days in a given year as "weather", while any average that combines monthly or seasonal averages in a time series that stretches over a number years will be referred to as "climate". For example, the shift in summer (JJA) or July temperatures from one year to the next (within the context of a time-series!) will be described as climate variability.

In climatological sciences, it is also common to separate low-frequency and high-frequency climate when analyzing different types of variability (Esper et al. 2002; Christiansen & Ljungqvist 2017). An important distinction is often made in this regard between long-term cycles or secular shifts, which can be described as climate or climatic *changes* that are of low-frequency character, versus short-term or high-frequency variations that can be framed as climate or climatic *variability* (Wanner & Siegenthaler 2000). The varying effects of low frequency and high frequency climate variations are difficult to disentangle analytically, or even to conceptualize, but constitute an important topic for research (Esper et al. 2017; Ljungqvist et al. 2022).[14]

[14] Time-series analysis is largely dependent on making such distinctions; i.e., detrending (Durbin & Watson 1950 1951).

3.2 Modelling the impact of climate on pre-industrial agriculture

Agriculture is inherently dependent on weather. Even if weather at any given moment in time can appear capricious, fickle, or "random", there is an underlying structure (climate) behind weather. Similarly, there is a structure to the dependence of agriculture on weather and climate. Some specific meteorological outcomes will more frequently be associated with beneficial or detrimental outcomes for agricultural output (Trnka et al. 2016; Lecerf et al. 2019; Wallach et al. 2019; Beillouin et al. 2019).

These structures can be described as agrometeorological or agro-climatic relationships, where agrometeorological concerns more short-term, detailed, and specific relationships, and agro-climatological more long-term, broad, and generalized relationships. For example, the near-exclusive reliance on barley cultivation in northernmost Fennoscandia and North Atlantic islands like Iceland and the Faroe Islands, or the dominance of a late-winter/spring season of cereal cultivation in large parts of Spain and Italy (in contrast to a late-spring/summer season in northern Europe) can be classified as agro-climatological relationships. A study of the specific effect of growing season temperatures on barley yields in northern Europe or hydroclimate indices on wheat yields in Spain would belong to the agrometeorological (e.g., Brunt 2015; Huhtamaa et al. 2015; Peña-Gallardo et al. 2019). This thesis is mainly concerned with studying agrometeorological relationships, although the agroclimatic context can to some extent be illuminated through studying agrometeorological relationships over time.

Crops are affected by the independent and interactive effects of a multitude of climatic variables, including temperature, soil moisture, precipitation, daylight, and wind strength. Livestock production is more complicated, given stalling and the use of a combination of live vegetation as well as previously harvested fodder as livestock feed; however, it can also to some extent be modelled partly as a function of climatic variables (Jalvingh 1993; Dahlström et al. 2006; Godde et al. 2021). This thesis is mainly concerned with crop (and fodder) production. Weather and climatic indicators by themselves only explain a part of total harvest variation. Other important variables include soil (e.g., texture, organic matter, water content, nutrients, and pH-values), farm management (e.g., sowing and harvesting dates, irrigation, fertilization, the variety of crop sown, seeding density, and the quality of the seed), and the incidence of pests and weeds. Of these, pests and weeds are some of the most difficult factors to control for (Pasley et al. 2023).

The strength of the influence of climatic indicators is controlled to some extent by these other indicators. High incidence of crop pests can cause crop losses even during weather conditions that otherwise would have been beneficial (although many pests are themselves related to climate variability, see Moreno et al. 2020). Historical actors, farmers who made decisions regarding, for example, when to sow or when to harvest, how much manure to apply to a particular field, or when and how much to plough, could also mitigate the influence of climatic factors (Palm 1997:101, 109–114). A distressing example here is historically frequent phenomenon of seed shortage, which could affect the harvest in the subsequent year even if weather conditions were adequate (see Bekar 2019). While sowing and harvesting dates ultimately depended on decisions and subsequent actions taken by farmers, they were also affected by variations in weather and climate. Sowing could be affected by the timing of thaw, rainfall, or cloud cover (farmers preferred to sow in clear, sunny conditions). Harvesting was, in turn, influenced by overall growing season temperatures, as well as by weather conditions during the harvest season (rain can delay harvesting, for example, while an early frost can force premature harvesting) (Wetter & Pfister 2011).

Further complicating the modelling of climate and weather impacts on crops is the fact that different crops are affected in different ways, and many of these relationships are non-linear (Semenov & Porter 1995; Wallach et al. 2019:3). The influence of temperature, for instance, on the yields of a given crop can only be expected to be strictly linear within a certain threshold range. Extremes in either tail of the outcome distribution can be expected to be detrimental for yields, following an exponential rather than a linear function in many cases (Hatfield & Prueger 2015). Furthermore, crops have different requirements at different stages of development (Lecerf et al. 2019). Indeed, modern crop models often explicitly include various different stages of crop development to estimate the final crop yield (Pasley et al. 2023). The combination of factors affecting crop development, and the non-linearity present in these relationships, mean that there are inherent limitations in terms of the magnitude one can expect from linear estimations (though marginal agricultural areas constitute a possible exception here: see section 3.4.3).

The number of potential meteorological variables relevant for successful crop development (from the point of view of the farmer) is thus very large. They involve worlds in themselves that are the subjects of whole fields of research, such as the rhizosphere, pedosphere, biosphere, and atmosphere (McNear 2013; Fogelfors 2015, Peng et al. 2020). To include all possible (and potentially important) interactions directly is a task that, in terms of conceptual complexity and data requirements, is outside the scope of this thesis, or any single piece of research for that matter (Carter et al. 2018). Indirectly, they are all potentially included. Any given crop model, outside of very controlled experimental settings, will be far from perfect. In any case, overfitting is hardly the goal, since generalizability would be lost. Practical limitations in combination with the increasing availability of computing power has led to crop modelling becoming more common than crop experiments. Crop models commonly assume uniformity in soil conditions, homogenous crops, and idealized management practices (Wallach et al. 2019). Furthermore, most crop models are based on a post-World War II context (mainly from the 1980s onwards) with more detailed cross-sectional data, not least climatic data, where aggregation is presumed to be more valid given greater homogeneity in agricultural practices across space during that period. An important benefit in using historical time-series (here taken to mean series covering not only decades but potentially centuries) is the possibility of studying much longer time horizons using actual empirical data. In the following, the agro-climatic contexts for the regions studied in this thesis are described, including a delineation of the hypothesized agrometeorological relationships.

3.3 The role of temperature and precipitation in crop development

Different stages of crop development have different temperature requirements.[15] What is optimal from the plant's physiological perspective is usually not practicable in a given agricultural context. Sowing is generally undertaken at temperatures far below those at which maximal germination occurs. Across much of Europe, the sowing of cereals is usually done when daily mean temperatures range between 5–15 °C, whereas maximal

[15] By temperature, I am mainly discussing ambient temperature, which can be defined as the temperature in the air surrounding the crop.

germination for many crops occurs in soil temperatures ranging between 20–25 °C (Pfister 1983; SCB 2009; Royo & Briceño-Félix 2011; Bringéus 2013). Sowing at colder temperatures allows for deeper root establishment, making the crop more drought-resistant (Fogelfors 2015:259). In fact, there is an upper (and lower) temperature threshold for all stages of crop development, below (or above) which one can expect crops yields to be higher. Cooler summer temperatures (summer temperatures in Europe as usually well above minimum thresholds required for crop growth) can thus allow maximiziation of each stage of crop development in relation to the full growing season, or, as already mentioned, reduce the risks of drought. By implication, it cannot be assumed that warmer growing season temperatures are necessarily beneficial, even in a northern European context.

In crop models, temperatures are mainly summarized as maxima, minima, means, or combinations thereof using Growing Degee Days (GDD) (Wallach et al. 2019). GDD estimates the number of days when temperatures are above (and, frequently, below) a certain threshold value, calculated as the minimum thermal requirement for crop growth subtracted from the daily mean temperature (see McMaster & Wilhelm 1997). Baseline thermal temperature requirements range between 0–10 °C. For locally adapted crops, the thermal requirements can be negatively correlated with latitude due to differences in daylight. For the historical barley variety *bere*, cultivated in Scotland and possibly in other North Atlantic islands, the baseline thermal temperature requirement has been estimated at slightly above 1 °C (Martin et al. 2023). In continental Europe or in Sweden, the baseline is usually set at around 5 °C (Morel et al. 2021).

As already noted, there is a temperature limit over which plant growth stagnates. Therefore, some estimations of GDD use upper threshold limits, usually set at 30 °C or a little less (Burke & Emerick 2016; McMaster & Smika 1988). The overall relationship between crop growth and temperature in temperate climates generally follows a skewed normal distribution, where crop growth approximates a linear curve until it reaches the maximum temperature threshold, after which growth decreases exponentially, as illustrated in Figure 4 (Criddle et al. 2005).

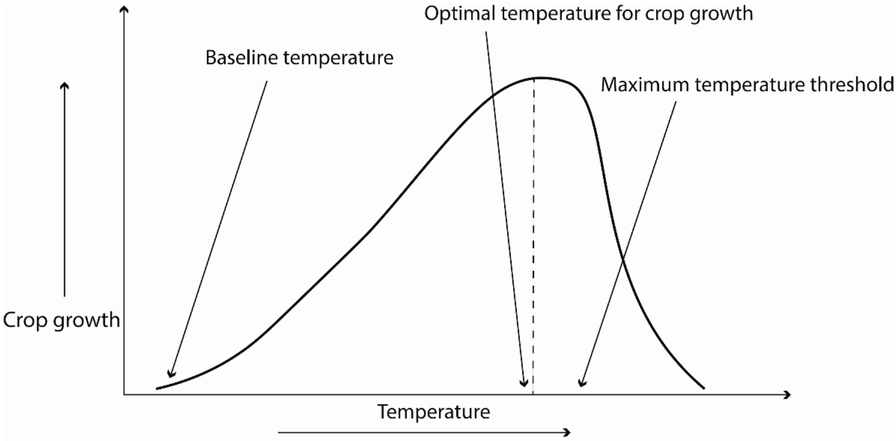

Figure 4. Idealized version of the relationship between crop growth and temperatures in temperate climates. Author's drawing.

Empirical evidence tends to indicate decreased yields across large parts of Europe at thresholds much below 30 °C. For example, Beillouin et al. (2020) studied the impact of various climatic indicators on harvest yields across Europe during the 20th century and found that in "Northern Europe" (Finland, Sweden, Denmark, the United Kingdom and the Netherlands) yields of winter wheat plateaued and started to decrease with mean maximum (the monthly/seasonal mean of daily maxima) spring temperatures at 16 °C or above. Mean maximum spring temperatures above 15 °C were detrimental for cereal cultivation in western, southwestern and northern Europe. Mean maximum summer temperatures above ca 23 °C decreased yields in "Western Europe" (Belgium, France and Germany), whereas in "Northern Europe" the effects were less marked but yields nonetheless stagnated already at mean maximum summer temperatures above ca 18 °C (Beillouin et al. 2020). For reference, Figures 5 and 6 show March-May and June-August mean maximum temperatures during the period 1901–1980.

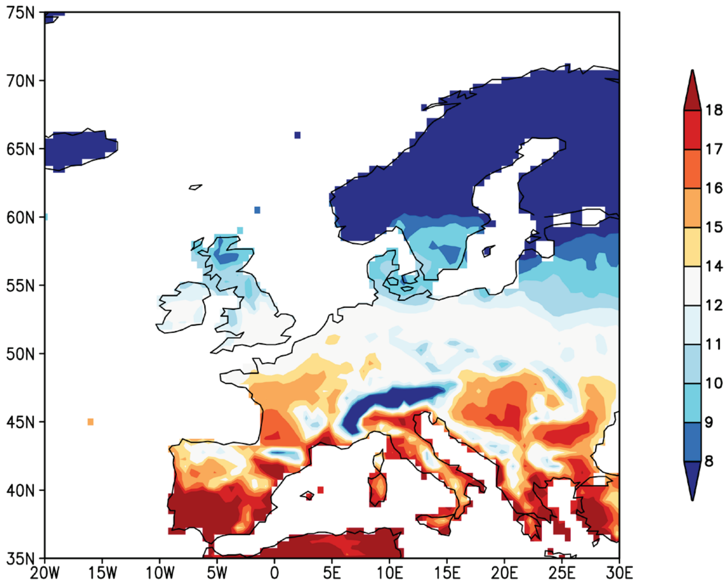

Figure 5. MAM mean maximum temperatures across Europe, 1901–1980. CRU TS 4.06 data (Harris et al, 2020). Map made using https://climexp.knmi.nl.

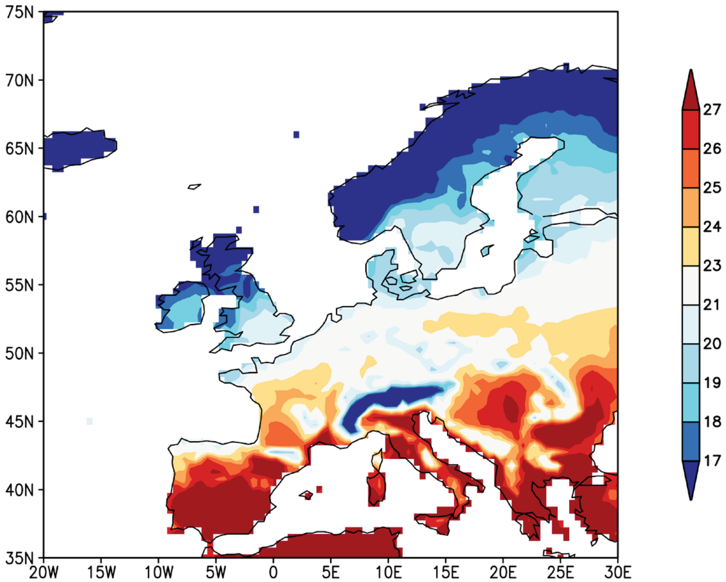

Figure 6. JJA mean maximum temperatures across Europe, 1901–1980. CRU TS 4.06 data (Harris et al, 2020). Map made using https://climexp.knmi.nl.

The curves representing these relationships were much more skewed than the one shown in Figure 4. This supports the assumption that there is a structure in the dependency of crops on temperature (and other meteorological indicators) that can be identified, to some extent, using parametric analysis. If the curve had instead approximated a normal distribution (the classic bell curve) very closely, the linear correlation coefficient of that relationship would be close to 0 with a p-value of 1.

Water is necessary for biochemical processes in the soil and for crop development. The vast majority of the farming systems studied in this thesis were rain-fed. In Sweden and Switzerland more or less all cereal cultivation and fodder production was rain-fed. Only smaller garden plots, which were common and important for dietary reasons, were irrigated (Hallgren 2016:132–133). In Spain, irrigated cereal cultivation did occur, but it was mostly relegated to dry and intensively managed lands located close to rivers (Franklin-Lyons 2022:33, 44–46; Grau-Satorras et al. 2021; Natàlia et al. 2014). During sowing and germination, precipitation requirements are smaller and large amounts of rain during this period of crop development is usually detrimental for the crop development process. Water requirements then increase with each stage of crop development until flowering, at which point the water requirement is temporarily reduced before it increases again for the grain filling stage. In the final stage of ripening just before and during harvest, very little rain is generally preferred in order to allow the grains to dry adequately.

Dates for harvesting vary both within and between countries. In Sweden, barley harvest dates during the study period ranged from early August to late September (SCB 2009; Bringéus 2013:25; Wichman et al. 1968:139). Autumn rye could be harvested from late July to September, depending on the rye variety and the locality (Bringéus 2013:36; Leino 2017:160). By September 29, on Michaelmas, most of the harvesting was usually completed (Pribyl 2017:12). In Switzerland, overwintering grains were usually harvested in the latter half of July and spring grains in August (Pfister 1983; Wetter & Pfister 2011). In Spain, grains were usually harvested between June and July, depending on the locality. In drier regions harvesting tended to be done earlier, while in wetter regions harvesting was undertaken further into the summer season (Simpson 1995:150; Royo & Briceño-Félix 2011). In large parts of Europe, excessive rain was the most common menace during harvest time (Wetter & Pfister 2011; Brunt 2015; Pribyl 2017:143).

Inadequate crop drying reduced quality and could cause rot. However, in Spain where harvesting was done around the start of the dry season, excessive rain at harvest time can be expected to have been an issue mostly in the north (see also section 2.1.1). Too little rain at any stage before the final ripening phase can cause severe harm or even lead to the withering of the crop, while too much rain can cause similarly serious harm and rot. Soil types differ greatly in their water retention capacities (Panagea et al. 2021). In the aforementioned study by Beillouin et al. (2020), increased precipitation during the spring and summer was beneficial but effects stagnated rapidly after ca 1–2 mm $^{d-1}$ in western Europe.[16]

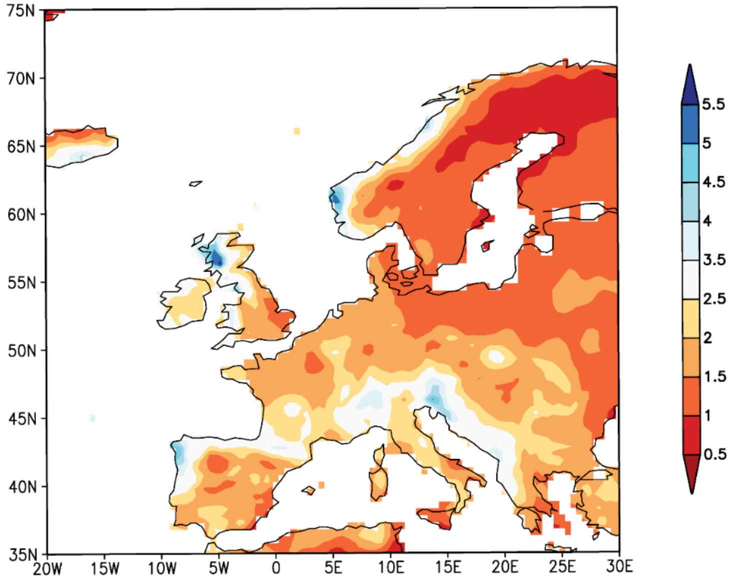

Figure 7. Mean MAM precipitation (sums) across Europe, 1901–1980. CRU TS 4.06 data (Harris et al, 2020). Map made using https://climexp.knmi.nl.

In the western Mediterranean (Italy, Spain and Portugal), increased precipitation during late winter and spring up until ca 1–2.5 mm $^{d-1}$ led to increased yields. In northern Europe, yields increased up to ca 3 mm $^{d-1}$ summer (JJA) precipitation (Beillouin et al. 2020). This can be compared with the long-term mean in the sum of seasonal precipitation across Europe in Figures 7 and 8.

[16] mm $^{d-1}$ stands for millimeters per day.

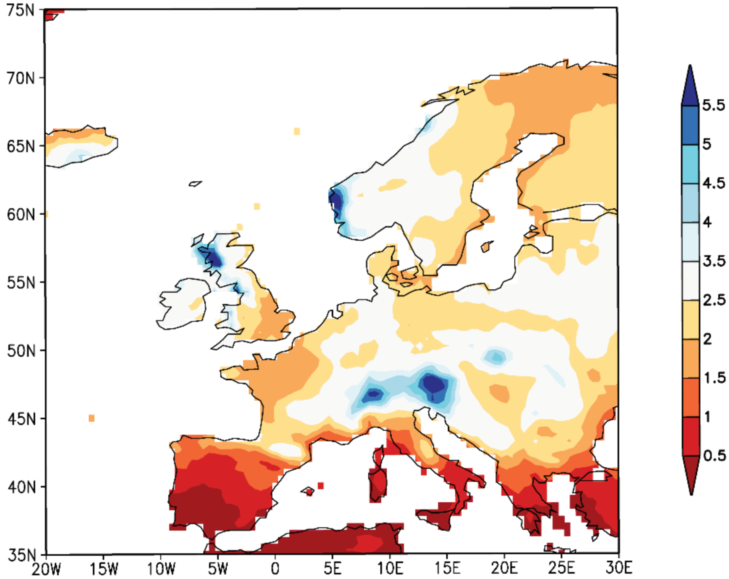

Figure 8. Mean JJA precipitation (sums) across Europe, 1901–1980. CRU TS 4.06 data (Harris et al, 2020). Map made using https://climexp.knmi.nl.

Because of the limited amount of historical research, much of the discussion above has had to rely on studies of agrometeorological relationships in the 20th and 21st centuries. Extrapolating from 20th and 21st century conditions to earlier periods is hazardous, given the large changes in agriculture that have occurred, including mechanization, use of chemical inputs, and, not least, new types of crops that have been optimized for the context of industrial agriculture (Morell 2011:166–168; Hagenblad et al. 2012). For example, Trnka et al. (2015) found that the main adverse "weather event" for cereal cultivation in northwestern Europe between 1980–2010 was "field inaccessibility", presumably caused by the inability to operate heavy machinery like tractors in soils that are too wet. Field inaccessibility caused by heavy rains was certainly an issue in a context of pre-industrial agriculture as well, but the difference between mechanized tractors and horse- or ox-driven ploughs can be assumed to be large, especially when considering soil compaction caused by the weight of mechanized vehicles (Ankli 1980; Trnka et al. 2015).

Together with the issues in extrapolating across time, extrapolation across space can also be problematic. It is commonly emphasized that agriculture was increasingly homogenized with industrialization (Grigg 1982; Finberg & Collins 2000; Morell 2011). Indeed, it has even be argued that agriculture started to become more homogenized through the various (largely pre-industrial) agrarian revolutions that took place across many European countries in the 19th century that brought technological diffusion, and increased market integration and enclosure reforms (Chorley 1981; Gadd 2000). However, it has to be noted that even in today's more homogenous agricultural context there are considerable differences in agrometeorological relationships across Europe (Trnka et al. 2015; Beillouin et al. 2020).

3.4 Hypothesized agrometeorological relationships

3.4.1 Sweden

In a context where agriculture was more locally adapted and heterogeneous across space, spatial aggregation can lead to model misspecification and has to be done with caution. In Sweden, as already noted, harvests in the north and south exhibit opposite signs in correlations with summer temperatures, which makes aggregation problematic. When Holopainen et al. (2012) studied the impact of temperature fluctuations on a general crop index across Sweden, a very weak and inconsistent climatic signature was detected, but a clear positive temperature signature across the spring (i.e., warmer springs = larger harvests) was found when the authors focused only on wheat. During the 19th century wheat was still a relatively marginal crop mostly grown in similar agroclimatic contexts in southern Sweden, which makes aggregation less of an issue (see also section 2.1.1). Wheat requires more GDD compared with traditional varieties of rye, barley, and oats (Foss 1925). Given this context, a positive temperature signal can be expected in wheat harvests. Barley, which was one of the most important crops across Sweden in the 19th century, can only be expected to exhibit a positive association with growing season temperatures (i.e., warmer growing season = larger barley harvests) in the sparsely populated northern two-thirds of Sweden. An opposite association (i.e., warmer summers = lower harvests) is more likely in southern Sweden (roughly the southern third, below the *limes norrlandicus*, see Fries 1949 and Figure 7), where the growing season was less constrained by early autumn frosts and where springs, especially along the Baltic coastline, are relatively dry (Edvinsson et al. 2009:126; Teutschbein et al.

2022). Warmer temperatures during the summer might, in this context, increase the risk of drought. Furthermore, when paired with increased daylight hours, warmer temperatures can stimulate the crop to undergo development stages prematurely in relation to the yield potential when taking advantage of the full growing season (Johansson & Staiger 2014; Aslan et al. 2015; Göransson et al. 2019). To the extent that rye and oats were cultivated in the north, a corresponding pattern of divergent signals between the north and south can be expected. The negative association with summer temperatures and cereal harvests (excluding wheat) in southern Sweden should be regarded alongside a positive relationship with summer precipitation (i.e., wetter summers = larger harvests).

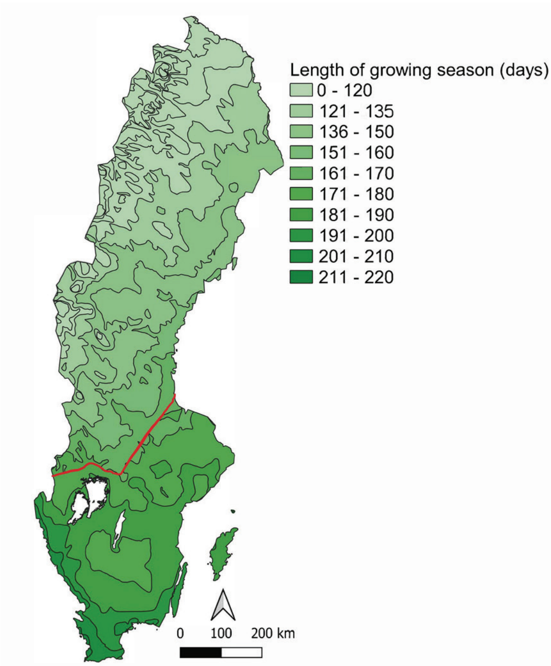

Figure 9. Length of growing season (days above 5°C) across Sweden during the meteorological reference period 1961–1990. Limes norrlandicus marked with a red line. Map projected by author based on data from SMHI (2023).

In northern Sweden, here roughly the areas north of the *limes norrlandicus*, as in other parts of northernmost Europe, pre-harvest autumn frost was a common threat facing farmers. Such events could lead to large-scale harvest failures and force farmers to harvest the crop when it was not yet ripe, so-called “green-years” (Sw. *grönår*) (Holm 2012:23). This would have increased difficulties in drying the crop, given the higher moisture content in its unripe form. Expected linear agrometeorological relationships for Sweden are summarized in Table 1 below.

Table 1. Expected linear agrometeorological relationships for grain production in Sweden, ca 1500–1900.

Sweden	Northern	Southern
Spring temperature	+	(+)
Summer temperature	+	-
Summer precipitation/soil moisture	(-)	+
Winter temperature	(+)	+
Winter precipitation	(-)	(-)

Notes: Positive associations (i.e., higher values of the given climatic indicator = larger harvests) are marked with +, negative associations (i.e., higher values of the given climatic indicator = smaller harvests) are marked with -. Parentheses indicate a weak relationship. Author’s estimation.

3.4.2 Spain and Switzerland

Spain is one of the largest countries in Europe, contains numerous mountainous areas, and is partly surrounded by two different oceans. As a result, Spain possesses the most heterogeneous climate in all of Europe (Beck et al. 2018). Three broad agro-climatic zones can be distinguished. In the northernmost parts of Spain, the climate is more maritime with milder summers and more abundant precipitation that keeps soils wet throughout the year. Soils where cereals are grown in the north are predominantly cambisols with moderate fertility and water retention capabilities. The high-altitude plateau regions of central Spain are drier than the northern areas bordering the Atlantic, and have a more continental climate with warm summers and cold winters. Cambisols are also heavily present there (Gómez-Miguel & Badía-Villas 2016). Most of the central, southern, and eastern regions experience dry and warm summers. Parts of southern Spain, while dry, are also very fertile, especially the clayey vertisols of northern Andalusia (e.g., in Sevilla, Córdoba and Jaén). In almost all of Spain, except in the regions bordering the Atlantic, soils dry up during the summer. In the southeast and parts of the northeast (e.g., some areas in Aragón), soils are dry throughout the year (Gómez-Miguel & Badía-Villas 2016:12). The ubiquity of summer drought has led Spanish farmers to relegate the main cereal-growing season between November and June. In northern Spain, the cereal-growing season can extend even further into the summer. The period September/October until May usually experiences moderate amounts of precipitation and mild/cool temperatures in most parts of Spain, although regional and local variation is, as already noted, significant. In June, the warm dry period begins. Most of the cereal cultivation in Spain appears to have been rain-fed. Local examples of irrigated cereal cultivation can be found, especially in the south and east (Sarrión 1995; Palerm-Viqueira 2010; Catalayud et al. 2022). By relegating the season for cereal cultivation to the winter and spring months, Spanish farmers largely avoided the dry season. These factors combine to make generalizations of hypothetical agrometeorological relationships in Spain difficult. Nonetheless, it can be expected that more rain during the spring was generally beneficial in eastern and southern Spain, whereas in northern Spain, where the soils are more wet and there is more reliable rain throughout the year, one would expect a negative association with rain (i.e., more rain = lower harvests). With regards to temperature, a positive association can be expected in northern Spain and high-altitude areas (i.e., warmer temperatures = larger harvests).

Differences in altitude can be expected to yield widely different agrometeorological relationships (e.g., Pfister 1983; Royo & Briceño-Félix 2011; Peña-Gallardo et al. 2019). High-altitude areas can be expected to have been vulnerable to colder temperatures and frost events. Cereal cultivation in very high altitudes can be expected to show a positive association with temperature (i.e., warmer springs = larger harvests) and a negative association with precipitation (i.e., more rain = lower harvests). A caveat here is that many of the high-altitude areas of Spain can also be very dry, or exhibit radically different microclimates.

Similar to Spain, Switzerland has a very mountainous geography. However, this thesis mainly includes data from the Swiss *Kornland*, which is made up of plains and semi-hilly terrains at lower altitudes mostly located in the central plateau region between the Jura Mountains and the Swiss Alps, where farmers cultivated both spring and autumn crops (Pfister 1983; Sluchter 1989). Previous research has stressed the hazards associated with cold springs, wet summers, and, to some extent, wet late autumns/early winters in the *Kornland*. Grain production in the *Kornland*, despite the cultivation of different crops, was susceptible to years with extreme cold and wet springs and summers (Pfister 1978; Pfister 2006:203; Pfister & Wanner 2021:282). Ticino and parts of Valais, such as the Rhône valley, have areas with warmer temperatures and more sunshine compared to other parts of Switzerland, while at the same time being very mountainous regions. Conditions for cereal cultivation in these areas varied greatly depending on altitude and vicinity to large lakes (Sluchter 1989). Expected linear agrometeorological relationships for Switzerland and Spain are summarized in Tables 2 and 3 below.

Table 2. Expected linear agrometeorological relationships for grain production in Switzerland, ca 1500–1800.

Switzerland	***Kornland*** **(valleys and plains at lower altitudes)**
Autumn and winter precipitation	-
Autumn and winter temperature	+
Spring precipitation	(-)
Spring temperature	+
Summer precipitation	-
Summer temperature	(+)

Notes: See Table 1. No expectations for autumn and winter precipitation and temperature on grain production due to the dominance of spring crops.

Table 3. Expected linear agrometeorological relationships for grain production in Spain, ca 1500–1800.

Spain	Northern	Central plateau, eastern and southern
Late autumn and winter temperatures	+	(+)
Late autumn and winter precipitation	(-)	+
Spring and early summer temperature	+	(-)
Spring and early summer precipitation	(-)	+

Notes: See Table 1.

3.4.3 Marginal vs central agricultural areas

Mean temperature and the sum of precipitation during a whole month or an entire season can capture large amounts of agriculturally-relevant meteorological information. Based on empirical research, a single indicator can be expected to capture up to 10–30 per cent of explained variation in harvest output, where the lower end maxima can be expected in central agricultural areas and the higher end in areas that are more agriculturally marginal (Palm 1997:138–139; Edvinsson et al. 2009:122–126; Brunt 2015;

Huhtamaa & Helama 2017b; Bekar 2019; Soens 2022; Martin et al. 2023). It can be conceptualized as risk dispersal. Putting all one's eggs in one basket, or being heavily dependent upon a single climatic indicator, will dramatically increase risk, given the inherent inter-annual variability in most climatic indicators. In other words, the closer a harvest indicator follows a single climatic indicator, the more marginal that particular agricultural unit can be considered to be, and vice versa. This suggests that only weak associations can generally be expected in linear estimations between harvests and single climatic indicators, even in instances where the data are reliable and valid. As already mentioned, extreme years will have larger and more clearly discernible impacts, even in central agricultural areas (Soens 2022). Note that harvest *dates* are not included among harvest indicators here. Harvest dates appear to have been largely dependent on a single climatic indicator, namely growing season temperatures, even in agricultural areas that can be considered central, as in parts of England and southern Germany (Wetter & Pfister 2011; Pribyl et al. 2012).

Crops are primarily dependent on conditions during actual crop development, a period that can be termed "the growing season". However, for overwintering crops, conditions during winter when the crops are largely dormant can also be important. Excessive precipitation in the autumn or early winter can lead to nutrient run-off or waterlogging. Waterlogging can deprive plants of oxygen and stimulate the development of root diseases. Crop diseases like *Ergot* or *Fusarium head blight* prefer mild and humid conditions and can survive the winter (Parry et al. 1995; Miedaner & Gieger 2015). Development of the fungi *Sclerotinia borealis*, which is prevalent in northernmost Europe, is stimulated by unfrozen soils that are subsequently covered with a thick snow cover (Jamalainen 1949). These pre-growing season effects are more difficult to estimate than current-year effects, given their indirect and complex nature (Vogel et al. 2021). In general, overwintering crops were less prevalent or even non-existent in marginal agricultural areas like northernmost Europe or the Swiss *Hirtenländer* (Pfister 1983; Huhtamaa et al. 2015; Martin et al. 2023).

There are other reasons why lagged effects might be important. In pre-industrial agriculture, seed was obtained from the previous year's harvest. A poor harvest could result in a seed shortage. Bekar (2019) has shown that harvests in medieval England were persistent, where a scarce harvest had a negative impact on the harvest in the subsequent year. Pests or extreme weather events were often the culprits behind scarce harvests (Brunt 2015; Moreno et al. 2020; Hoyle 2020). However, army confiscations in times of war or inadequate transport and storage can be expected to have had similar or even worse effects on seed supply (Parker 2013; Slavin 2019; Franklin-Lyons 2022:199). Increased market integration, improved access to credit, and the establishment of public granaries can, on the other hand, be expected to have reduced persistence in harvests caused by seed shortages (Bekar 2019). Given that increased output leads to fixed deductions taking an increasingly lower share of harvest output, productivity increases should also have lessened the risk of seed shortage (Pfister & Wanner 2021:257). This implies that farms more specialized in intensive grain production and farms in central agricultural areas should have been less exposed to harvest persistence than farms with more extensive grain production or farms in marginal agricultural areas (Edvinsson et al. 2009:132–133).

Thus, even though agriculture is fundamentally dependent on weather and climatic conditions, the exact nature of this relationship is determined by a large set of factors that are changeable across space and time. Nonetheless, this section was able to delineate some hypotheses regarding baseline agrometeorological relationships in the areas studied by this thesis. The next section describes how these implications and hypotheses have been tested.

4. Methods

The methods in this thesis are largely quantitative, employing statistical approaches developed in different fields of the social and natural sciences, such as economic history and paleoclimatology. Each paper employs different, specific methods, but all of them employ some kind of combination of simple statistical techniques, such as calculations of means or standard deviations, and more demanding ones like parametric (in terms of assumptions) and algorithmic (in terms of assumptions and computing power) approaches. Each paper also required extensive data management, in order to prepare and sort data prior to analysis. The most widely used software was *R* and to a lesser extent *QGIS*.

4.1 Combining algorithmic and historical approaches

The first paper used the *ACMANT* software and technique to homogenize the Lund instrumental temperature series, as well as to fill relevant gaps using a network of homogenized temperature series from neighboring regions (Domonkos 2011; 2021). Hierarchical cluster analysis using the *R* package *cluster* was employed to aggregate farms into similar clusters based on their similarities in variability with regard to production over time (Maechler et al. 2019). The second paper used the *R* package *NbClust* to cluster farms based on their climatic sensitivity using K-means clustering (Charrad et al. 2014). The third paper employed the Indicator Saturation technique from the *R* package *gets* to identify structural breaks in the aggregated tithe data (Castle et al. 2015; Castle & Hendry 2020; Sucarrat 2020). These algorithmic methods are useful in that they allow for computing-intensive analysis based on actually observed values in the data. A potential downside, which is discussed in paper one, is that they can be difficult to interpret in a historically relevant way. One commonly employed solution to this issue is to always compare and situate results from algorithmic methods within the historical context, using available literature as well as primary sources, inspired by the type of source criticism generally considered indispensable to historians. This does involve further risks of confirmation bias, a difficult problem to avoid entirely, but which would have been greater had the studies only relied on manual methods. It should be further noted that algorithms are also subject to potential biases when it comes to the choice of parameters and input data (Gibson & Ermus 2019). Manual methods alone would also have placed considerable constraints on what would have been computationally possible. Thus, in most cases a combined approach was considered useful and arguably superior to relying on either algorithmic or manual methods alone.

4.2 Parametric methods

Linear estimations like Pearson's correlation analysis and OLS (Ordinary Least Square) regressions were important parts of the main analysis. The validity of these types of parametric analysis are based on a series of assumptions. In historical time series, issues of stationarity and autocorrelation are important considerations (Jörberg 1972:12–13). In many instances, detrending is required. Since trends were in many cases non-linear and were instead difference stationary, detrending methods allowing for variable trends were employed, mainly using *normalized yield anomalies* based on loess smoothers (Papers I and II) or Butterworth high-Pass filtering (Papers III and IV) (Butterworth 1930; Bauernfeind & Woitek 1996; Beillouin et al. 2020). In OLS modelling, which was used in Paper III, multicollinearity was checked using variance inflation factors and the weak autocorrelative structure that sometimes remained even after detrending was addressed by using Cochrane-Orcutt estimations (Cochrane & Orcutt 1949; Gujarati 2011).

Much of the data was collected from previously published databases. An active effort was made to become acquainted with the context of the sources underlying these databases, in order to understand their limitations and potential, by consulting the relevant literature or the persons involved in their establishment. Preparation of data was, where possible, done in line with previous research; this included, for example, using various threshing or conversion coefficients from Olsson & Svensson (2017) and Hallberg et al.

(2016:46–47). Sorting or aggregation of data was made with a combination of historically-informed and algorithmic approaches. For example, when aggregating farm-level tithes for the first paper using hierarchical cluster analysis, the results were compared to established historical categorizations. Similarly, after aggregating tithes to the county level in Paper III, a so-called indicator saturation technique from the *R* package *gets* was employed to identify structural breaks in the data. These breaks were then compared with changes in the sample and the historical context. A very similar approach was used when homogenizing the Lund instrumental temperature series in Appendix A in Paper I.

4.3 Combining series of agricultural dates

In Paper III, combined series of agricultural dates were constructed using methods similar to those in previous research. Basically, this meant removing differences in means in order to get a unified mean for all series, while keeping common year-to-year variations (Holopainen et al. 2006; Labbé et al. 2019). This approach is based on the assumption that there is a synchronicity in year-to-year variations of temperature-sensitive phenomena within a defined region that also experiences high spatial correlation in temperatures. The latter assumption is easily demonstrated empirically, whereas the former assumption carries more uncertainties. However, to the extent that cross-sectional data was available, there was good correspondence in year-to-year variations, which supported the former assumption as well.

4.4 GIS mapping

Climate is mainly a geographical concept and spatial analysis commonly forms a crucial part of climatological studies. In Jämtland, spatial differences in climate-agriculture relationships have been proposed as particularly relevant. GIS-mapping, specifically choropleth maps using the QGIS software, was therefore employed in the third paper to see if there are discernable differences in terms of the climatic sensitivity of agricultural production across the region. Choropleth maps are colored in a gradient scale according to a specified parameter. While simple to comprehend at first glance, they can mask significant variation within a given spatial unit of analysis. Furthermore, they can give the impression of larger differences between two bordering units of analysis, in this case parishes, than would be the result if smaller units, such as farms, were analyzed. There are also other possible visual biases, such as the perception of darker or larger units as “more”, compared to brighter or smaller units (Schiewe 2019). Nonetheless, in this instance parishes are the smallest unit of analysis for which there is sufficient available source material, which takes the form of tithes. The maps are thus representative for the source material employed and well suited for the overall analysis, which is focused on parish- and county-level results, even though much more differentiation will certainly have existed at the village or farm level. The following section presents and critically discusses the source material employed in this thesis more thoroughly.

5. Sources and data

This thesis employs a wide variety of sources. To estimate harvests over time, tithes, official statistics (BiSOS), and yield ratios reported by county governors were used. For the climate, climate reconstructions and early instrumental measurements were employed. Dates in the agricultural calendar were obtained from agrometeorological and phenological observations, farmers' dairies, and other types of chronologies. These sources are all discussed below.

5.1 Tithes

Tithes, more specifically grain tithes, are employed throughout this thesis as a source for early modern grain harvests. The tithe was a tax that affected an overwhelming majority of Europe during the medieval and early modern period (van Bath 1963:53). The tithe was established throughout Scandinavia by the 13th century at the latest and was not abolished until the very end of the study period in the early 20th century (Granlund & Andersson 1982; Hallberg 2016:1). In continental Europe, the tithe was present much earlier, though surviving records seldom go further back than the 13th or 14th century (Dodds 2002; Soens 2022). Tithe revenues, in kind or cash, flowed from peasant households to parish coffers, tax farmers, the church, and the crown. After the Reformation, tithes went to local parish churches and the crown. In other words, the tithe was not only geographically widespread, it was vertically integrated into many layers of society. It was nominally a tax of one tenth of all production, but in practice the amount varied by category and location (Goy 1982:15). Formal regulations set at the national, provincial, or local level determined the structure of the tithe. Informal negotiations, from outright tax evasion to various forms of tax exemptions, played an important role at the local level in many cases (Goy 1982:33–34, 51; Leijonhufvud 2001:76–81).

Tithes were paid in kind or cash. They could be fixed, meaning that they were based on a stipulated or agreed upon estimate of what constituted the average production in a given tax unit, which in most cases was the household. Fixed tithes can be helpful when trying to estimate how much was usually produced around the date of regulation, although such estimates are in many instances troubled by significant underestimation (Leijonhufvud 2001:75–76). This thesis is mainly interested in the variation in production over time on peasant farms and how that variation was affected by climate. Such a task requires tithes that fluctuated from year to year, depending on harvest outcomes, referred to here as harvest-dependent tithes or just tithes. Given that tithes were nominally related to production, they have played an important role in estimating agricultural productivity or production over time in, for example, Spain, France, Sweden, the Low Countries, and parts of central Europe, particularly during the early modern period (Goy 1982:5–7; Olsson & Svensson 2010; Hallberg et al. 2016).

Notable recent research efforts in collecting and digitizing tithe records have been made in Sweden during the last three decades. Lotta Leijonhufvud (2001) collated tithes at the county level across Sweden, using its present-day boundaries, from the 1540s to the late seventeenth century. Mats Olsson and Patrick Svensson (2010) used more than 80 000 farm-level tithe observations to estimate the impact of enclosure on agricultural growth during the agrarian revolution (ca 1700–1860). These tithe observations were subsequently published in a freely available database in 2017, the *Historical Database of Scanian Agriculture* (henceforth HDSA) (Olsson & Svensson 2017). Erik Hallberg, Lotta Leijonhufvud, Martin Line, and Lennart Andersson Palm (2016) collated parish-level harvest-dependent tithes across Sweden, again using its present-day boundaries, from 1665 until the point at which tithes were fixed (which varied considerably across administrative units). These data have also been made freely available and can be found in the large Swedish data repository, *Svensk Nationell Datatjänst* (Hallberg et al. 2016; 2017). While there are a number of countries in Europe with rich surviving sources for tithes, Sweden probably has the most easily accessible material. This thesis has employed all of these tithe databases to some degree. The HDSA was extensively utilized in Papers I and II. About 7,500 parish-level tithe observations from the database published by

Hallberg et al. (2017) were used in Paper III, together with about 2,500 additional parish-level tithe observations collected by the author. Finally, county-level tithe observations from Leijonhufvud (2001) were employed in Paper IV.

There are long-term tithe series from a number of regions in Spain, including Andalusia, Galicia, Segovia, Mallorca, the Basque region, Toledo, Murcia, Valencia, Segovia, and Leon (Ponsot 1969; Pérez and Galán 1981; Eiras Roel 1982; Ciria 2007; Santiago-Caballero 2014). Switzerland offers a similar array of surviving tithe records. Pfister (1984) assembled tithe series covering 18 different locations in Switzerland from the early 16th century up to the early 19th century. Head-König and Veyrassat-Herren (1972) published a similar series for Geneva. A total of 19 Swiss and 10 Spanish tithe series were employed in Paper IV.

Tithes are not without limitations. In dialogue with other critical scholars, Joseph Goy (1982:33) conceded that tithes by themselves "should be used *as an indicator of the social climate* rather than as an index of agricultural production" (emphasis in original). Goy also stressed that tithes had to be checked for internal and external consistency using other complementary material (Goy 1982:31–33). I will now discuss some of the main source critical issues pertaining to tithes, including actual empirical tests thereof, with a particular focus on Swedish conditions.

One of the most important and straightforward limitations to tithes is that coverage is not consistent over time and space. As previously mentioned, tithes were subject to local level regulations. In Sweden, for example, there are differences from the county all the way down to the farm level with regards to when tithes were fixed, as well as what material has survived or been located in the archives (Lilja 2008:103–104; Hallberg et al. 2016:7, 14). This presents particular issues when trying to establish a representative aggregated time-series or when comparing different units of analysis. As discussed in the method section, this was partly solved by using algorithmic methods to aggregate data or to identify and adjust changes to the mean brought about by changes to the sample composition. For Papers I, II, and III, this thesis followed the approaches suggested by Olsson & Svensson (2017) and Hallberg et al. (2016:46–47) when it comes to adjusting tithe series from different areas or sources in order to obtain representative aggregated series.

Another uncertainty concerns weights and volumes. In Sweden, Spain, and Switzerland (as well as in other countries), tithes were generally estimated after the harvest by counting bundles pre-specified by volume while the harvested grain was still on the field and did not account for weight per se (Goy 1982:16; Hallberg et al. 2016:6). Better harvests were not only more voluminous, but were also heavier, yielding even more output after threshing. This means that there is potential for harvests to have been underestimated in good years and overestimated in bad years (this issue is further explored in section 5.3.1). The final delivery of the tithe was commonly made in threshed grain.[17] The measures used, barrels, bushels, and the like, were not uniform across space and time, which introduces additional uncertainty if local practices deviated from formal regulations (Leijonhufvud 2001:48–52, 267–268). Tithes were often estimated in rounded numbers in the given measure. As a general rule, numbers were rounded down. Lindegren (1980:215), in his study of tithes in Bygdeå between 1620–1640, found that such rounding led to underestimations of tithes ranging between 3–9 per cent. This was counteracted to some degree by standardized additions to the tithe, so-called *övermål* (roughly translated as overshoot) (Helmfrid, 1949:12).

Since tithes were estimated before threshing but usually paid afterwards, this gave peasants an opportunity for tax evasion. Helmfrid (1949:99–101), in his comprehensive study of tithes in Östra Eneby in southeastern Sweden, argued that the degree of underestimation due to the threshing process was generally very limited. Furthermore, Swedish authorities took considerable pains to ensure that tithes were accurately collected by implementing threshing controls. In 1627, a new regulation stipulated that a special building for conducting threshing controls for the crown's share of the tithe should be built in each parish, though actual threshing controls were more likely carried out in the peasants' barns. By the 1680s such controls appear to have been common throughout Sweden (Hallberg et al. 2016:6). Protocols pertaining to the collection of tithes in kind were similar in other parts of Europe; as a general rule, they involved local representatives with a financial interest in the proper collection of the tithe. For example, in Spain, tithes were estimated directly after the harvest while the sheaths were still in the field. The salary of the collector was connected to the amount of tax

[17] In Sweden after the reformation, the part paid directly paid to the parish priests was often paid directly in unthreshed quantities (Olsson & Svensson, 2010, 2017).

collected, which was similar to the system in Sweden where the parish priest obtained part of his income from tithes (Santiago-Caballero 2014). This implies that local tax collectors had a financial incentive to root out or minimize tax avoidance.

Beyond outright tax avoidance, exemptions for paying tithes could be made for numerous reasons. For example, in Sweden, newly established farms were usually exempted from paying taxes for the first few years (Leijonhufvud 2001:73; Berglund 2006:52–53). Exemptions could also be made for households that had sent an adult male to serve in the army during the numerous wars of the 17th century (Palm 1993:235–241). Leijonhufvud (2001) addressed the issue of tithe exemptions and found no apparent trends; thus, she concluded that they were unlikely to cause any serious distortions over time. Olsson & Svensson (2010) tested the co-variation of farm-level tithe observations across Scania and argued that they appeared to follow year-to-year weather and climatic oscillations. Furthermore, they showed that harvest-dependent tithes in Scania showed good correspondence with other harvest measures (Olsson & Svensson 2010). In the studies conducted for this thesis, tithes consistently showed good correspondence with other harvest indicators, such as yield ratios (see section 5.4).

5.2 Phenological and agricultural observations

Phenological observations of discrete natural or agricultural calendar events in a given year are valuable for understanding agrarian and climate history. They can help provide insight into the daily workings of farming operations in a historical context, but also shed light on the climate of the past. In fact, phenological observations have been employed in multiple studies to reconstruct growing season temperatures in several parts of Europe, such as Finland, Estonia, France, England, Switzerland, and southern Germany (Tarand & Nordli 2001; Chuine et al. 2004; Holopainen et al. 2006; Wetter & Pfister 2011; Pribyl et al. 2012). Harvest dates, mainly of autumn grains or grapes, are the most widely employed indicators in this regard; time series of sowing dates are comparatively rare in the historiography (one exception with regard to Sweden is Palm 1997:106–107). Hay-cutting dates, especially longer time series going back beyond the 19th century, are even rarer, if not altogether absent, in published historical works.

In Paper III, long time series of agricultural dates, including harvesting, sowing and hay-cutting, were reconstructed going back to the very last years of the 17th century. Observations of agricultural dates were collected from a variety of sources, including farmers' diaries, meteorological and weather observations, and documentary material left by military officials. All these disparate sources differ in their content, structure, and purpose. However, when it comes to describing discrete agricultural dates there is less scope for ambiguity. A specific activity, such as sowing, is noted in relation to a particular date in observational tables, or described in a sentence in a diary. This is not to say that there is no ambiguity at all. For example, what is being sowed is not always indicated, even though it can generally be deduced from the month the activity is taking place. If the start of sowing is described as occurring in May, then it is obviously sowing of spring crops. In Jämtland, spring sowing was more or less synonymous with sowing barley, the main grain crop, or peas and barley. Sometimes a term directly denoting sowing was not used; rather, the dialect term *våranden* (literally the word for spring used as a verb) was used to describe the start of the spring sowing. The term *våranden* implies a broader set of events in addition to sowing, such as ploughing. Sometimes, the terms *våranden*, sowing, and ploughing are all used interchangeably. For example, in 1831 Anders Kjelsson from Myssjö parish notes in his diary that *våranden* was begun on May 16 and finished on May 21, whereas in 1832 he instead notes that ploughing was begun on May 7 and finished on May 17 (Kjelsson 1832). Similarly, Olof Andersson from Alsen parish notes in his diary that in 1868 he began sowing on May 14 1868 and that on May 22 *våranden* was complete (Andersson 1868). Since these activities are not described separately within a given year and sowing usually took one to two weeks for an average farmstead, it has been concluded that the terms are used interchangeably. The start of hay-cutting was sometimes described as *höanden* (hay used as a verb, "haying"). Most commonly, however, the term *slåtter* was used, which can be translated as "hay-cutting". Hay-cutting was the most intensive and prolonged activity in the agricultural calendar, taking around eight weeks. However, the meadows from which the hay was cut could be spread out over quite large areas, and not all meadows were cut simultaneously. Furthermore, in these sources the term "hay" refers to many different types of fodder plants that grew on the meadows. This is not an issue in and of itself; however, it does mean that the time series for hay-cutting is less specific that those of sowing and harvesting that concerns a specific crop; i.e., barley. The terms used for describing the start of harvest dates are less ambiguous than those of sowing in that, for example, no term analogous to *våranden* is used. In these sources, barley harvest dates are usually indicated by phrases such as harvesting (Sw. *skördanden*), "the grain was cut" (Sw. *skars säden*), or "the barley was cut" (Sw. *skars kornet*). Occasionally, rye harvesting is described separately. However, given the overall dominance of barley, it was assumed that when harvesting was noted without reference to a specific grain, it referred to the main harvest; i.e., the harvest of barley.

Given that the Gregorian calendar was instituted in 1753 in Sweden, a short note of calendar forms is in order. In effect, the shift to the Gregorian calendar led to the previous Julian calendar being forwarded 11 days. Most of the agricultural dates extracted from the sources employed here are from after the 1760s and thus well after this calendar reform. The main reference series for harvest and sowing dates (see section 4.3) begin in 1699 and 1701, respectively, and continue until the 1780s; these present a possible challenge in this regard. However, the primary source material clearly states that all the dates presented are in the "new style" (Sw. *nya stilen*; i.e., the new Gregorian calendar). These main reference series were published in the Swedish Royal Academy of Sciences in 1767 by the county clerk Olof Granbom and the regimental auditor Eric Tryggdahl (Granbom & Tryggdahl 1767). After cross-checking this material with the more extensive primary material, numerous inaccuracies were found in the former and thus the latter was employed. One exception was made for the year 1716, when the date of May 18 seemed more much realistic in comparison with the unprecedentedly early date of April 18 given in the primary material. The gaps and inaccuracies in the published material relating to harvest dates have not been identified in previous research, even though the material has been used, for example, to reconstruct spring-summer temperatures in Trøndelag in the 18th century (Nordli 2004; Dybdahl 2016:89–91).

5.3 Official statistics

5.3.1 BiSOS

Bidrag till Sveriges Officiella Statistik, BiSOS, represents one of the first attempts to collect comprehensive agricultural statistics at a national level. From the year 1865 there are published data on, for example, seed and harvest volumes by crop, acreages, and the number of cattle. This thesis employs data on seed and harvest volumes from BiSOS in order to estimate time series of yield ratios. Since the collection of the BiSOS statistics was one of the first attempts of its kind with such comprehensive ambitions, it is perhaps not surprising that previous research has argued that the BiSOS data contain numerous inaccuracies. There are two main critiques of the data. First, BiSOS systematically and substantially underestimates arable land and agricultural production. Second, researchers have critiqued the differences in methodology used by the various regional Husbandry Societies (Sw. *Hushållningssällskap*) that were responsible for collecting the data. This does not imply errors per se, but does introduce some possible heterogeneity. Both these issues were investigated by Svensson (1965), who argued that the problem of underestimation diminished over time but that the problem of heterogeneity largely did not. The problem of underestimation has been argued to be relevant mainly for arable acreages as well as total production at a given moment in time (Hallberg et al. 2022a). However, the main interest in this thesis is year-to-year variations and less in the estimation of absolute output. If underestimation systematically decreases over time, this could nonetheless cause distortions during the analysis, such as spurious correlations. This is addressed by detrending all the series analyzed from BiSOS. Heterogeneity within data collection methods by the various regional Husbandry Societies, which operated at the county level, is less of a concern for this thesis since the data is not aggregated across counties.

Similar to tithes, the BiSOS data is based on volumes and not weights. This is a potential issue because a grain of inferior quality weighs less. BiSOS does have some average county level figures regarding the relative weights of the harvested grains. While these figures are less exact than the seed and harvest volumes, they do give a rough idea of the variability in the weight of harvested grain for a period of roughly 25 years (almost 40 years for Jämtland).[18] A comparison of the reported weights of the harvested grain types in Scania during the years 1885–1911 shows small year-to-year differences, even in relatively bad years.

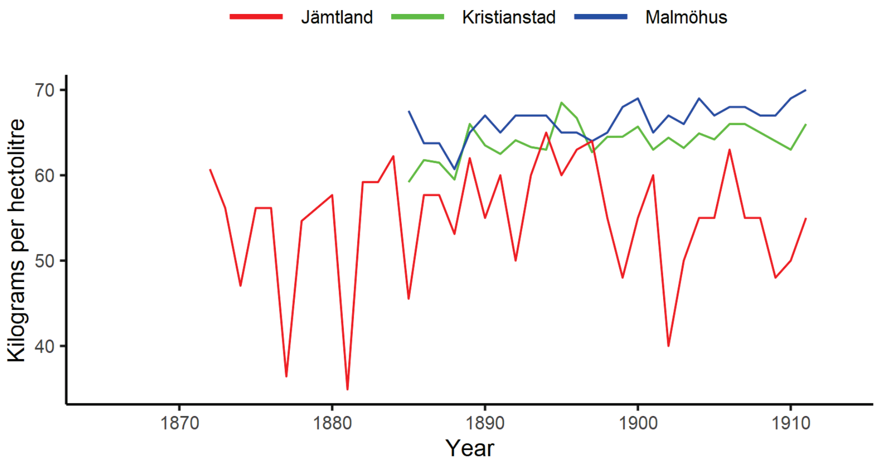

Figure 10. Average weight of harvested barley in Jämtland, Kristianstad and Malmöhus Counties, 1872–1911. Source: BiSOS (1872–1911).

If we look at the corresponding figures from Jämtland, harvest weights exhibit much greater variability. During the worst years, the weight of the harvested grain dropped by more than 30 per cent compared to the previous years. Furthermore, almost all outliers are negative, indicating that in terms of the weight of grains, harvests tended to be either normal or really severe. This further implies that the risk of non-weight harvest measures underestimating bad harvests is larger in Jämtland than in Scania. It seems likely that this would pertain to earlier periods as well, like in the tithe series used for earlier centuries in Paper III. However, while volume-based measures do not explicitly account for weight, the weight is clearly related to the volume. After detrending the series using a 10-year high-pass filter, the correlation coefficient between barley weight and barley harvest volume in Jämtland between 1872–1911 is $r = 0.86$ ($p < 0.01$). All in all, the risk for an underestimation bias during bad years in volume-based harvest data

[18] For Scania weights are often given in a range; e.g., between 60–65 kg. In such cases I used the middle value, here 62.5 kg.

appears negligible; however, the available data is not sufficient for a definitive evaluation.

5.3.2 County governors harvest reports

Official reports on harvests, often labelled subjective harvest assessments, began already in the 1740s (Hellstenius 1871; Utterström 1957:194). As their label implies, the reliability of these harvest assessments has been questioned in previous research, mainly concerning their tendency to underreport actual quantities (Erikson 2018:98–99). Since harvest assessors lacked complete information on actual harvest conditions across their provinces, they had to subjectively estimate the "average" harvest conditions of that year. Presumably, there was a bias here whereby the central areas of the province with the best communications were more accurately represented. Nonetheless, previous research has demonstrated that the reports correspond quite well with other harvest indicators, like tithes (Olsson & Svensson 2010). Over time, these reports were increasingly standardized. Edvinsson (2012) collected reports from county governors between 1818–1870, showing estimated yield ratios for the most important crops. This material showed good correspondence with tithes (Paper III), and was utilized in both Papers II and III. In Paper III, it was shown that the correlation between yield ratios from Edvinsson (2012) and tithes in Jämtland was $r = 0.62$. In terms of climate-harvest relationships, these yield ratios showed similar results as other materials, including tithes and BiSOS (Papers II and III). Given the similarities between BiSOS and the county governor harvest reports, and the fact that both sets of data can be aggregated to the county level, these data were combined to construct consecutive series of yield ratios covering the years 1818–1911 in Papers II and III.

5.4 Climate data

Two categories of climate data are used in this thesis: (early) instrumental meteorological observations of temperature and precipitation, and climate reconstructions of temperature and hydroclimate. These are each described below.

5.4.1 Early meteorological observations

Systematic instrumental meteorological observations began in the second half of the 17th century although surviving records from that century are few. In the subsequent century, there is a vast surviving record from a multitude of sites, mostly in Europe and North America (Brönniman et al. 2019a). This rich record is a result of an intensive and widespread interest in the natural sciences, including meteorology, during that period. This early period of instrumental measurements is usually described as the Early Instrumental Period (EIP) (Brönniman et al. 2029a). However, the extent of reliable and continuous records starting in the 18th is quite thin, especially from the early parts of that century. The publication of the first homogenized and continuous temperature records covering central England since the year 1659 began in about the 1970a. This work has been followed by others, including Paris (1658-), De Bilt (1706-), Berlin-Dahlem (1719-), Uppsala (1722-), and Stockholm (1756-), to give a few examples. The city of Lund in southwestern Scania has a more or less continuous daily record of temperature, air pressure and precipitation going back to 1747. The person responsible for these measurements was the *astronomie observator* of Lund University, but the actual measurements appear as a rule to have been taken by assistants. The instruments and their location, and of course the responsible and actual observers, changed over time. Schalén et al. (1968) and Bärring et al. (1999) have outlined many details of this station history. However, there are still some remaining uncertainties regarding the earliest part of the station history. More details would surely surface after a deeper investigation of the extensive primary material in the archives.

Bärring et al. (1999) homogenized the air pressure record going back to 1780, excluding the earlier period due to the larger uncertainties surrounding the measurement context. Neither the temperature nor the precipitation series have been subjected to similar attempts at homogenization, although they have been employed in several historical studies, including Mattsson (1986) and Palm (1997:161–166). Tidblom (1876) published the EIP temperature series in the form of pentad-averages and did apply some manual corrections. These series are employed in Paper I and III, where in Paper I the temperature series was converted to monthly means and homogenized using a network of homogenized monthly mean temperature series across northwestern Europe, as well as the software ACMANT (see section 4.1). Thus, the Lund EIP-series is complemented by series from central England (1659-), De Bilt

(1706-), Berlin-Dahlem (1719-), Uppsala (1722-), Stockholm (1756-) and Copenhagen (1768-) (Labrijn 1945; Manley 1973; Parker et al. 1992; van Engelen 1995; van Engelen et al. 2001; Bergström & Moberg 2002; Moberg et al. 2002; DWD 2018; Cappelen et al. 2019). Monthly precipitation data from Lund (1747-) was also employed. No homogenization similar to that of the temperature data was possible (see section 4.1). Moberg et al. (2003) proposed that there may be an issue undercatch in the EIP precipitation series from Swedish cities, specifically Stockholm and Uppsala, but could also show that this issue was less prominent during the summer months.

For Paper III, homogenized and continuous temperature series from Trøndelag (1762-) were utilized (Lawrimore et al. 2011; Durre et al. 2008). Other available EIP-series from the region (Jämtland County) are of insufficient length to be particularly useful. Continuous series are available from the 1860s from Östersund; however, the Trøndelag series is arguably more reliable, since it has been subjected to homogenization efforts. The correlations of monthly mean temperatures between the two regions are very high, with $r > 0.9$ throughout the year. Thus, the Trøndelag series can be considered reliable and useful for studying conditions in Jämtland.

5.4.2 Climate reconstructions

The research field of historical climate reconstruction is constantly evolving, with new and improved reconstructions constantly becoming available. This carries with it new opportunities, in terms of what is possible to study. Seventy years ago, when Utterström (1955; 1957) was doing historical research on climate and society, there were no relevant climate recon-structions available, and certainly none with the type of precision available today. Forty years later, Palm (1997:161–166) still had to rely almost exclusively on unhomogenized temperature and precipitation series from Lund and Copenhagen to study agrometeorological conditions in Halland. Yet another decade later, Edvinsson et al. (2009:117–118) had to rely on a summer temperature reconstruction from Torneträsk in northernmost Sweden and Finland to estimate past summer temperatures in large parts of Sweden, most of it well to the south of Torneträsk.

In contrast to the instrumental record, year-by-year seasonal climate reconstructions go back well beyond the limits of the study period of this thesis (ca 16th through the 19th centuries). Climate reconstructions are employed in all four papers of this thesis. For Papers I and II, a Standardized

Precipitation Evapotranspiration Index (SPEI) reconstruction covering southern Sweden by Seftigen et al. (2017) was employed, together with a May through July precipitation reconstruction (MJJ_{pr}), which also covers southern Sweden (from 1798-) (Seftigen et al. 2020). The SPEI is based on the amount of precipitation once potential evapotranspiration has been taken into account. The SPEI-reconstruction, here called ScandH17 following Seftigen et al. (2017), is based on tree rings from a carefully selected group of Scots pine (*Pinus sylvestris* L.) growing in dry environments in southern Scandinavia (Seftigen et al. 2015; Seftigen et al. 2017). The MJJ_{pr} is based on Blue Intensity and partial ring widths from a subset of samples used in the ScandH17 (Seftigen et al. 2020). For Paper III, two growing season temperature reconstructions based mainly on tree-ring maximum latewood densities (MXD) covering central Scandinavia were used (Gunnarson et al. 2011; Linderholm & Gunnarson 2019). Paper IV employed six temperature reconstructions altogether, as well as six hydroclimate reconstructions of annual or seasonal resolution.

There are some limitations to these data that are important to consider. Usually, they cover seasonal windows, such as AMJJAS or JJA, thus missing out the detailed day-to-day variation in weather that can be of crucial importance to agriculture (Bell et al. 2014; de Toro et al. 2015). Currently available climate reconstructions still leave a significant amount of unexplained variation when compared with instrumental measurements (Christiansen & Ljungqvist 2017; Ljungqvist et al. 2019). Spatial coverage is usually adequate for aggregated regional studies, but limited cross-sectional coverage puts constraints on the analysis of differences between localities within regions. All the climate reconstructions employed here are predominantly based on tree-ring records, using tree-ring widths (TRW) or maximum latewood densities (MXD). Similar to documentary sources, sample depth tends to increase over time, meaning that there is a larger degree of uncertainty the further back in time one goes. The value of tree-ring based proxy reconstructions is to a large degree determined by how dominant a single indicator is in shaping tree growth. For example, in colder regions with short growing seasons, like northern Sweden, growing season temperatures alone explain a very large part of the variation in tree growth (Gunnarson et al. 2011). By contrast, in southern Sweden, a more complex combination of wetness, radiation, wind strength and direction, as well as temperature, determines tree growth, making it more difficult to isolate the effects from wetness alone.

How reliable are climate reconstructions in terms of accurately portraying agriculturally relevant climatic information? Considering ScandH17, there were two main uncertainties. First, the correlation with instrumentally-based SPEI-values in the 20th century was good for southern Scandinavia as a whole, but weaker for Scania in particular. Secondly, even though the sample was carefully selected from a series of dry sites, interpreting results using the indicator is complicated by the fact that it can be expected to contain not only precipitation, but also other climatic signals like temperature (Seftigen et al. 2017). The MJJ_{pr} from Seftigen et al. (2020), based on a subset of the same tree-ring data, shows much stronger associations with instrumentally observed precipitation in Scania. In other to reduce uncertainties, these hydroclimatic reconstructions were mainly used in addition to instrumentally-based data from Lund (in Papers I and II).

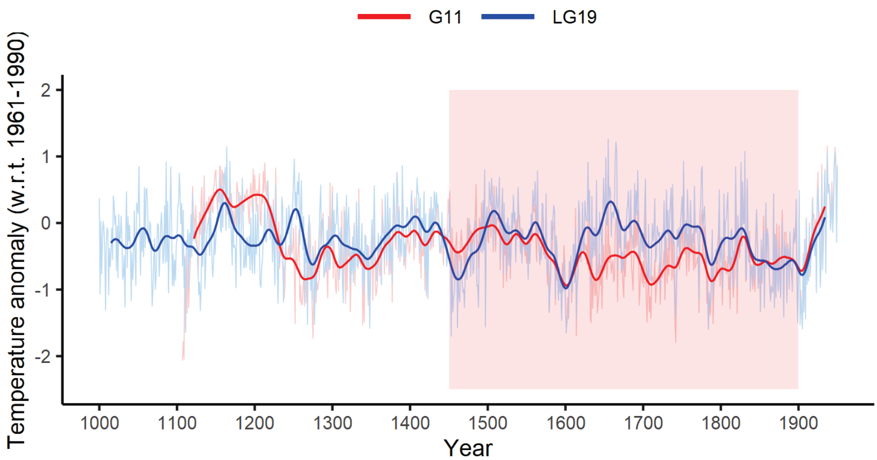

Figure 11. Mean growing season temperatures (anomalies w.r.t. the 1961–1990 mean) in central Scandinavia, 1000–1950. Shaded blue and red lines show annual variation whereas marked lines show 31-year moving averages. Shaded red area denotes the period of the LIA (1450–1900) in central Scandinavia, as defined by Linderholm & Gunnarson (2019).

The first reconstruction, here called G11 (Gunnarson et al. 2011), includes timber from buildings at lower elevation sites, potentially biasing the sample that otherwise is based on trees at higher altitudes (Zhang et al. 2015). At the same time, as argued in the paper, this bias potentially makes the reconstruction more relevant for agriculture, given that agriculture was mainly practiced at these lower elevations. Furthermore, G11 has a larger sample depth during the 17th and 18th centuries. Importantly, the two series diverge in their reconstructed temperatures during this period; see Figure 11. In order to account for this uncertainty, a newer tree-ring MXD reconstruction, LG19, based solely based on records from trees at higher altitudes, was also employed (Linderholm & Gunnarsson 2019). Two other notable temperature reconstructions exist for the area. The first, by Zhang et al. (2016) was deemed too similar to the more recent LG19, and hence not employed. The second, by Fuentes et al. (2018), is based on samples from the mountaineous areas of Härjedalen, and thus less relevant compared to G11 and LG19 that are centered closer to the studied areas. Similar to Papers I and II, instrumental measurements were also utilized (see section 5.3.1.).

6. Summary of papers

6.1 Paper I: Climate variability and grain production in Scania, 1702–1911

Paper I focuses on the first research question: how did the climate and variability thereof affect agricultural production in Scania during the 18th and 19th centuries? It also sheds some light on research question 2; i.e., what was the main agrometeorological threat in Scania? Up until the second half of the 19th century, farmers in Scania primarily cultivated varieties of barley, rye, and oats more similar to those cultivated further north in Fennoscandia than those to the south across the Baltic. This hardy crop mix was paired with a favorable agroclimatic context, including the longest growing season and some of the best agricultural soils in Scandinavia, making 18th and 19th century Scania a particularly interesting case study for the relationship between pre-industrial agriculture and climate.

Numerous sources were employed in the study, including a network of early instrumental temperature measurements across northwestern Europe, most prominently the Lund early instrumental temperature series (1753-), the *Historical Database of Scanian Agriculture* with data on Scanian farms during the 18th and 19th centuries, and agricultural data based on more than 80,000 tithe observations. Furthermore, the study also includes hydroclimate reconstructions based on tree rings in southern Sweden (Seftigen et al. 2017; 2020). The Lund early instrumental temperature series were homogenized and gaps were reconstructed using a network of instrumental temperature series across northwestern Europe, as well as the homogenization software *ACMANT*. Results from the homogenization were then compared with the station history, to cross-check identified statistical breaks with changes in instrument, instrument location, or observer (described in Appendix A in Paper I).

Farms were aggregated at the village level and clustered using hierarchical cluster analysis in order to avoid biases introduced by relying on *a priori* historical categorizations and to obtain clearer signals. To increase interpretability, results from clustering were compared with historical categorizations and geographical characteristics. Relationships between grain production series at the cluster level and climatic indicators were explored using correlation analysis. June and July showed the highest and most consistent correlations, with a negative association between grain production and temperatures (i.e., warmer temperatures = lower harvests) and a positive association between grain production and precipitation (i.e., more rain = larger harvests). Reconstructed May through July precipitation and summer SPEI-values also exhibited positive relationships with grain production.

Taken together, the results showed that grain production fared better during wetter and colder summers, and worse during warmer and drier summers, indicating a vulnerability to drought. Spring or autumn frosts did not appear as a systematic threat to arable agriculture in Scania. The average start and end of the frost seasons lay well outside the main cultivation and harvest period. Spring, autumn, and winter temperatures and precipitation yielded practically no statistically significant results. The results largely confirmed research on other parts of southern Sweden during the 18th, 19th, and early 20th centuries that had also identified positive precipitation and negative temperature summer signals. Repeating a similar analysis using late 19th century official statistical data yielded almost identical results, with the difference that autumn rye harvests contained no clear climatic signal. This was explained by the introduction of new cultivars around the end of the 19th century with different phenological requirements from the old cultivars.

The paper further demonstrated the utility of various climatic and agricultural data in estimating agrometeorological relationships, such as tithes and tree-ring-based hydroclimate reconstructions, even in a central agricultural area like Scania.

6.2 Paper II: The impact of drought in northern European pre-industrial agriculture

The second paper also revolves around the province of Scania, partly building on the results obtained in Paper I. This paper answers research question 2 more conclusively, and finds that summer drought was the dominant agrometeorological threat to Scanian agriculture. It also focuses on research question 3: what was the history and frequency of drought, and to what degree were the farming systems of Scania resilient to drought?

Drought, or agricultural droughts, takes center stage in the paper, which starts of by defining the concept of drought and subsequently establishes a systematic chronology of agricultural droughts from the 18th to the early 20th centuries in Scania, using a variety of sources. Specifically, the drought chronology is based on early summer (May-June) or high summer (June-July) precipitation droughts. Having provided such a history, I investigate how different types of farms and crops were impacted by droughts over various time scales.

Specifically, the impact of these droughts is estimated using Superposed Epoch Analysis (SEA). Prior to SEA, specific farm-level relationships between tithes and various climatic indicators are estimated and then aggregated into three clusters using K-means clustering. While June-July temperature and precipitation, as well as reconstructed May through July precipitation and SPEI, are the most consistent and significant climatic indicators in these relationships, the strength of these signals varies by cluster, with one cluster having the strongest climatic signals, one being the "middle" cluster, and one cluster having the weakest climatic signal. Farms are also aggregated using historical categorizations, i.e., types of farming districts. Droughts from the established drought chronology are used as event years in the SEA. In line with previous research, the SEA demonstrates the presence of large-scale harvest losses affecting all samples, even the cluster with weak climatic signals. Summer droughts are established as the dominant climatic shock in large-scale harvest losses. In contrast, no systematic positive or negative effects are found concerning extremely cold springs or summers.

Even though the impacts of drought were far-reaching, intensities varied over time and space. Forest district farms are found to have been most sensitive to climatic fluctuations, compared with brushwood and plains district farms, whereas no large differences were found based on property rights regimes. Differences became most clear when considering not only the impacts during the year of a drought, but also how harvests were affected in subsequent years. Plains district farms experienced large and significant rebound effects in the year after a drought; i.e., harvests were larger than usual during these years, and in total the harvest rebounds were larger than the harvest losses in the previous drought year. Similar effects are found when considering specific crops. Surprisingly, harvests of rye, usually seen as the more drought-resilient crop when compared with spring crops, were characterized by the largest drops during drought years, at least up until the second half of the 19th century. However, rye harvests were more consistent in exhibiting significant rebounds in the years after a drought, compared with other crops. Regarding 19th century harvest yield data, more clear divergences between crops are found, where the drought effect on autumn-crops diminished, whereas large and significant negative effects are consistently found for spring-crops.

6.3 Paper III: Farming at the margin: Climatic impacts on harvest yields and agricultural practices in Central Scandinavia, c. 1560–1920

Paper III is another region-based study, focusing on the province of Jämtland located on the northern edge of the inland agricultural zone in Sweden. It focuses mainly on research questions 1 and 2; i.e., how did climate and the variability thereof affect agriculture in Jämtland? What was the main agrometeorological threat in the region? An important contribution of this paper is the collection and reconstruction of historical time series on sowing, hay-cutting and harvesting dates in the Lake Storsjö District covering roughly two "long" centuries from the late 17th century to 1920. Similar to the first two papers, the paper also relies on published tithe databases, supplemented with additional tithe data from archival research, allowing the study to reach deeper back in time, as well as to fill in some gaps in previous research. The methodology is broadly similar to that developed in Paper I, including quantifications of linear relationships and the combination of algorithmic and source critical approaches to the evaluation and homogenization of historical data.

The paper stands in contrast to the two first papers in that the region studied offers quite a different context in regards to climate and agricultural possibilities, not least for grain production. As Jämtland is located in the most northerly part of the temperate climate zone, agriculture in the region exhibits aspects of a marginal agricultural area, while still practicing a mixed farming system similar to those prevalent in large parts of agrarian Scandinavia. Results show that growing season temperatures had the largest effects on agriculture during the study period, although they were mediated by farming practices and other localized conditions. Parishes around Lake Storsjön, as well as parishes in the eastern parts of Jämtland, exhibited a smaller dependence on growing season temperatures compared to northern parishes and parishes in the mountainous areas in the western parts of Jämtland and in Härjedalen in the south, see Figure 12.

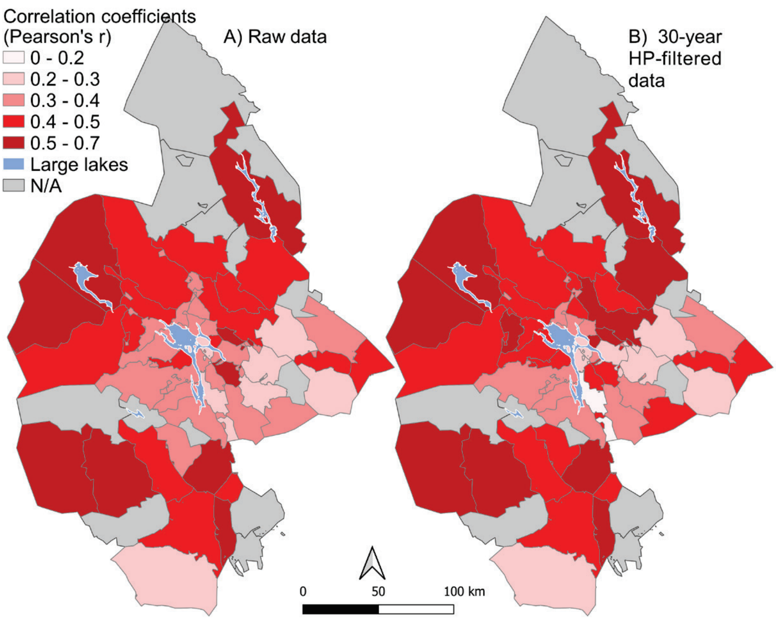

Figure 12. Spatial representation of correlation between parish-level tithes and mean growing season temperatures. A) shows results from raw non-detrended tithe data between the years 1565–1779 and B) shows results from 30 years of High-Pass filtered tithe data during the same years. Parishes vary in their temporal coverage. Lake Storsjön is visible in the center of the map. Reworked figure from Paper III.

There was a large degree of co-dependent relationships between farming practices in the form of agricultural dates; however, many of these effects diminished when controlling for growing season temperatures. The harvest and autumn frost seasons partly overlapped in large parts of Jämtland and Härjedalen. This could also be seen in the correlation and regression analysis, where the single most important month for the date of the harvest, as well as the harvest yield, was August.

One aspect where the agency of farmers remained important even when controlling for the effects of climate, and specifically temperature variability, was the timing of sowing, which affected subsequent agricultural dates as well as the final harvest output. Somewhat surprisingly, hay-cutting dates not only exhibited dependence on growing season temperatures, but were also positively correlated with sowing and harvesting dates. This was explained by the overall "tightness" of work during the spring and summer seasons, where the decision to sow on a particular date, mostly in May, delayed the general seasonal work schedule, including the start of hay-cutting in July. Hay-cutting itself was such a time- and labor-consuming task that it in turn had noticeable effects on the harvest in August or September. Here, elements of risk-taking and prioritization were involved. Whether or not to initiate the hay-cutting season would involve not only considerations of current vegetative growth and weather, but also other important tasks that had to be performed by the household. Since the start of the autumn frost season could not be known beforehand, even a single day of delay to the overall seasonal work schedule involved prioritizations and risk-taking in relation to the devastating autumn frosts. The sensitivity of agriculture to temperature variations during the growing season were of similar magnitude to those identified in northern Finland during similar periods.

6.4 Paper IV: Climatic signatures in early modern European grain harvest yields

Paper IV investigates the associations between climate variability and grain harvest yields in early modern Europe, focusing on research question 1; i.e., how did climate and variability thereof affect agriculture in different parts of Europe? Specifically, a large network of harvest time series in large parts of Sweden, Switzerland, and Spain are analyzed in relation to seasonal and annually resolved climate reconstructions during the period 1500–1800. The paper first presents previous research relevant to the subject, and then attempts to delineate expectations in terms of relationships between harvests and various climate indicators. Secondly, the harvest and climatic data is presented and various critical aspects are discussed, including issues such as gaps in the historical harvest data or areas and periods where the climatic reconstructions studied are less skilled. Following this, the methods employed by the paper are introduced. Two detrending methods were utilized; namely, linear detrending and Gaussian high-pass filtering (10-year). Linearly detrended data is argued to be slightly better at capturing low-frequency variability than the High-Pass filtered data, especially with the specific structure of the raw data. Two methods for assessing statistical significance are also employed: first, the Student's *t*-statistic. Secondly, a phase-scrambling-based method that accounts for the degrees of freedom when performing many pair-wise correlations and serial correlations is present in the time series. The second method is more conservative and was thus expected to give fewer spurious results. A final method utilized in the paper is the Granger causality test, which can help determine which variable is influencing or causing the correlation found between two variables and in the context of this study helped to mitigate the possibility of spurious correlations.

Overall, the identified climatic signatures in grain harvests were weak; they were even weaker than those found in historical grain prices. However, the strength of the obtained associations was similar to those found in studies of 20th-century conditions. Several factors that could affect the strength (and the direction) of the resulting coefficients are then discussed. Firstly, both the climate and harvest yield data contained limitations. During the study period most climate data is derived from proxy-based reconstructions. Tree-ring-based methods are mainly limited to the summer or spring-summer season, and in many cases do not give a perfectly isolated and definable climate signal, even though one type of signal usually dominates in higher quality reconstructions. The issue of spatio-temporal biases in the climate data is further aggravated when attempting to establish a satisfactory spatio-temporal match with the harvest yield data. The harvest yield data also contained additional uncertainties. For example, given the influence of societal factors on harvest yield data, it is considered less able to capture low-frequency signals.

Nonetheless, despite these uncertainties, several agrometeorological patterns could be distinguished. Similar to previous studies, a negative summer temperature signal of moderate strength was obtained from the harvest yield data (i.e., warmer summers = smaller harvests) from southern

Sweden. Furthermore, summer soil moisture indicators exhibited positive relationships with harvest yield data (i.e., wetter soils in the summer = larger harvests). Winter temperatures were consistently positive for harvest yields (i.e., warmer winters = larger harvests) in Switzerland, whereas summer temperatures and winter precipitation were either not significant or negative (i.e., warmer summers or wetter winters = smaller harvests). In Spain, relationships were more heterogeneous. The most common relationship was a negative one between annual or spring temperatures and harvest yields (i.e., warmer temperatures = smaller harvests), indicative of a drought signal. The Granger causality tests showed that highly significant results were in the expected direction. For Spain, the Granger causality tests gave less support to the harvest-climate relationships compared with Sweden and in particular Switzerland, for which the support was the strongest. The results generally indicated that climate-harvest signals could potentially vary by frequency, although additional research is needed to establish such discrepancies more clearly.

7. Discussion

This thesis has studied relationships between climate and pre-industrial agriculture in several regions in Europe. The main focus has been on the two Scandinavian regions of Scania (Paper I and II) and Jämtland (Paper III). Large parts of Spain, Switzerland and southern Sweden (excluding Scania) were also considered (Paper IV). All the included papers investigated how agricultural production, mainly crop production, was affected by climatic variability, and thus have been able to illustrate some of the main agrometeorological threats in each region under investigation. Paper II also delved deeper into the particular agrometeorological risk of drought in Scania during the 18th and 19th centuries, chronicling the history of droughts and examining to what extent the grain harvests and prices were affected by drought. The following parts of this section will discuss these results in more depth. First will come a discussion of agrometeorological relationships and the threat of drought in Scania, one of the main regions studied. Second, a review of the general effects of cold on harvests in several European regions in the context of the LIA will be offered. Third will be a discussion of agriculture operating at the very margins of the growing season constraint, namely in Jämtland. Fourth, changing risk patterns over time will be considered. Did agriculture in these regions become more or less resilient to climate and weather risks when agricultural practices or the type of crops grown changed? Fifth, methodological limitations and future prospects in the field will be elaborated upon. Finally, sixth, comes a conclusion summarizing the main results of the thesis and their implications.

7.1 Agrometeorological relationships in Scania

Scania presents an especially interesting case study for investigating historical relationships between climate and agriculture. Scania possesses a mild climate, a large proportion of high-quality soils, and a moderately diversified mixed farming system where barley and rye were the most prominent grains, followed by oats, and to a lesser extent other cereals like the more temperature-sensitive wheat. While a reading of Swedish-language publications would suggest that agriculture was mainly constrained by precipitation in the summer, a reading of English-language publications would probably lead one to conclude that growing season temperatures and late-spring or early-autumn frosts were the main constraints (Edvinsson et al. 2009:122–126; White et al. 2018b:339; Pfister & Wanner 2021:282).

What were the main agrometeorological patterns in Scanian agriculture in the last centuries of the pre-industrial period? Paper I demonstrated that neither autumn nor spring frosts constituted a systematic threat to cereal cultivation. This is not to say that cereals were immune to frost or that there was never any frost damages to crops. But such events were rare enough that there was no statistical indication of their presence. What did give indications of its presence, however, was the possible threat of summer droughts. While Paper I did not specifically study individual years, and did not define or consider the effects of droughts specifically, it could demonstrate that grain harvests were positively associated with June and July precipitation (i.e., less rain was associated with smaller harvests) and negatively associated with June and July temperatures (higher temperatures were associated with smaller harvests). An additional finding in Paper I when homogenizing the early instrumental temperature measurements from Lund was that summers and springs in the last decades of the 18th century were not as cold as suggested by previous research (Mattson 1986).

The study of agrometeorological relationships up until the 1860s in Paper I was based on clusters, where farms were clustered according to their differences in rye production over time, based on tithe observations from the HDSA. From the mid-1860s, the study relied on official statistics on harvest data (BiSOS) that are available until 1911. Relationships obtained in the analysis were consistent across samples, even when considering different subsets of years with a drier or wetter hydroclimate, except for autumn crops in the later period where climate signals were absent. The absence of signals in that case was explained with reference to the introduction of new cultivars with different crop phenology; these, notably, were more temperature-sensitive varieties, which obfuscated the overall signal. The consistency in signals between the two different materials, tithes and BiSOS, give credence to their reliability in covering year-to-year variations and in estimating agrometeorological relationships.

As pointed out in section 2.3.2, Edvinsson et al. (2009:125–126) found very similar agrometeorological relationships in southern Sweden during more or less the same period. One difference was that those authors found positive correlations between barley harvests in Sweden (aggregated nationally) and mean temperatures during the spring months, and no significant correlations with summer temperatures, during the period 1803–1955. This disparity can probably be accounted for by the level of aggregation that analyzed Sweden as a whole, including the northern half where cold was the main threat — even for spring crops — as well as by the slightly later study period (see Paper III, section 3.4.1). A similar obfuscation by aggregation can arguably be seen in Holopainen et al. (2012).

The results from Paper I give further support to the notion that pre-industrial agriculture in southern Sweden was mainly constrained by too little rain and *too much warmth*, rather than excessive cold. However, further exploration of the specific impact of droughts and answering research questions 2 and 3 were beyond the scope of Paper I. Paper II picked up this thread by establishing the first regional drought chronology for Scania in the 18th and the 19th centuries, and then by estimating the impact of these specific droughts on agricultural production. Paper II showed, firstly, that though periods with very low amounts of precipitation almost never lasted more than 60 days, there were multiple times in the historical record when the absolute volume of precipitation in periods lasting 60 days were low enough to be considered (agricultural) droughts that severely reduced agricultural output. Comparing the drought of 2018 to this drought chronology reveals that the summer of 2018 was nearly unprecedented, although years such as 1783 or 1826 come close.

How resilient or vulnerable to drought were the farming systems of Scania? Superposed epoch analysis showed that harvests on nearly all types of farms were negatively affected by drought years, which manifested in average reductions in aggregate harvest output or yields of up to 20 per cent, although in many instances reductions were significantly lower than that. This is consistent with previous research, which found that there were agricultural risks that were large-scale in character (Nyström 2019). Paper I and II could show that these large-scale risks were not generic extreme weather events; rather, they were predominantly summer drought events (Paper II). It could be argued that until the late 19th century, summer droughts in Scania with very little rain and extreme warmth in the months of June and July, possibly (but not necessarily) combined with an excessively rainy harvest season, constituted a comparable cocktail of meteorological shock factors to that of wet winters and extremely cold and wet springs and summers in central Europe (Pfister 2018b:126).

Previous research from England has highlighted how spring crops were commonly singled out in contemporary sources for being particularly sensitive to droughts (Pribyl 2020; Pribyl & Cornell 2020b). Similarly, the documentary material from *Tabellverket* in Scania regularly associated drought-induced crop losses with spring crops. The empirical analysis in Paper II showed that the rye crop, which was overwhelmingly cultivated as an autumn crop in Scania, suffered even larger losses during drought years. However, rye harvests rebounded in the year following a drought, an affect that was much less apparent in barley harvests. Rebound effects were additionally more apparent on plains district farms compared with brushwood or forest district farms. The fact that some crops or some types of farms experienced a rebound has important implications with regards to concepts such as resilience and vulnerability. Following the IPCC (2018) definition of resilience, namely, "to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure", it could well be argued that the intensive form of grain production taking place on the plains was more resilient, given the rebound effect. The grain production system certainly appears quite resilient if it can recover fully within just one year following the type of climatic event to which it is most sensitive.

Within a broader European context, Scanian agriculture appears to belong to the more climate-resilient examples. The systematic threat of large harvest losses induced by autumn frosts was largely absent in Scania, whose frost season lay well outside the normal harvest season. Colder conditions were generally not detrimental to grain production. In fact, cooler temperatures during the summer appear to have been beneficial. Single monthly or seasonal climatic indicators explained at most about 10 per cent of variations in harvests over time, again comparable to conditions in central agricultural areas in England or the Low Countries (Brunt 2004; 2015; Bekar 2019; Soens 2022). In terms of resilience, it could be further argued that, in a northern European context, being constrained by drought is better than being constrained by growing season temperatures, given that precipitation in northern Europe is more stochastic and exhibits a shorter climatic memory compared with temperature (Bunde et al. 2013). In other words, the probability of drought year clusters is lower than that for clusters of very cold years. Nonetheless, there were periods when Scania experienced what might be termed clusters of drought years, notably in the late 1750s, the years around 1820, as well as the years 1834–1837.

The relative agro-climatic resilience of Scanian agriculture can be explained in terms of both intensification and diversification. In terms of intensification, the two-row barley varieties that became increasingly common from at least the 18th century in southern Sweden were higher yielding as well as more resistant to spring frosts (Leino 2017:203). Furthermore, improvements in drainage suggested that less water was being stored in the top layers of the soil and more water reached lower layers, thus reducing evapotranspiration (Nyström 2019). Finally, with higher total levels of grain production, the potential trade-off between consumption and saving seeds for sowing in the subsequent year was less of an issue (Pfister & Wanner 2021:257). In terms of diversification, it was shown that there were differences between crops. For the barley crop, there were indications of persistence, or at least a lack of recovery, in harvests after drought years. However, considering that other crops rebounded, particularly the important rye crop, there are good reasons for arguing that there was resilience in grain production and that this resilience was achieved partly through diversification (Paper II). There were also differences, albeit small ones, in the specific seasonal windows within which crops were more susceptible, thus spreading out risk (Paper I). A more differentiated picture would probably emerge when considering the resilience of households or broader societal resilience. For example, landless laborers could be more vulnerable to short-term shocks, something less evident in this thesis, which has mainly focused on the direct impact of climatic shocks on harvests and crop yields (Dribe et al. 2017a). However, in Paper II, the impact of drought on grain prices appeared significant. Oat prices experienced the largest price hikes during drought years, followed by barley and rye in descending order. This indicates important second or third order impacts in terms of the effects on regional prices, seasonal employment and possibly even mortality (see section 1.3 for references and a brief description of the impact order model). Farms with more intensive forms of production were better situated to benefit from such price hikes, compared with farms that had more extensive and diversified forms of production. Considering the various aspects of diversification and intensification, it seems that intensification was the main driver of resilience in Scanian pre-industrial agriculture, although diversification also played a role. Further exploration of these issues remains an important topic for future research (Ljungqvist et al. 2021).

Scanian agriculture was not unique in pre-industrial Europe in being vulnerable to drought. Paper IV was able to show that several counties in southern Sweden exhibited similar agrometeorological dependencies to parts of central Europe (e.g., many locations in Switzerland). In Switzerland, however, agriculture also appears to have been much more dependent on winter and spring conditions, where colder winters and springs were detrimental to grain harvests. This stands in stark contrast to Scania, where there were almost no agrometeorological signals for these seasons. Another relevant example when discussing droughts is Spain. Intense summer droughts were the norm in Spain, leading to winter and spring being the preferred period for cereal cultivation. The regularity of drought in Spain can also be seen in the institutionalized forms of religious prayer with long historical roots that were meant to counter drought (and to a lesser extent excessive rainfall) (Tejedor 2019). In Paper IV, there were indications of a spring drought signal in wheat yield ratios from most locations in the Spanish central plateau region, except in Guadalajara. The magnitude of that particular threat appeared comparable to or even lower than that of summer droughts in central Europe and southern Scandinavia. One obvious reason for this, as pointed out in the paper, is that the spring season was actually colder in most parts of Spain than the main growing season in Switzerland or Sweden. Furthermore, the cereal growing season in Spain lay largely outside the dry period.

7.2 The cold of the LIA

The vulnerability to summer drought in areas north of the Alps is consistent with studies of grain prices that have found them to be at least as responsive to drought in northern as in southern Europe (Esper et al. 2017). However, when looking at longer time scales, colder temperatures appear to have been a more important driver of grain price variations than hydroclimate (Ljungqvist et al. 2022). The mechanisms behind this divergence remain largely unclear. Certainly, the threat of colder temperatures has been one of the most common themes in climate history (Holopainen et al. 2009; White 2017). A particular type of climatic shock identified within several European societies during the LIA are periods with cold winters combined with cold and wet springs and summers. In light of the research questions posed in section 1.1, especially the second research question, it seems relevant to discuss the responsiveness of Scanian harvests to conditions of extreme cold. While most of the larger harvest losses in Scania occurred during drought years, excessive cold did cause large-scale harvest losses on at least two occasions, namely in 1739 and 1740. An aspect of uncertainty here, however, is the fact that the overall sample in the HDSA is very small for those two years. Given the paucity of such examples, and the complete absence of such agrometeorological patterns in aggregate or average figures, it seems fair to argue that they are the exception that proves the rule; namely, that cold was not a common threat to Scanian agriculture (Olsson & Svensson 2017). Similar to the reasoning of Bohman (2017a; 2017b) regarding ecological crises in Scania in the 18th and 19th centuries, it could be said that extreme cold was only a local and conditional threat to Scanian agriculture during the study period.

Regarding Swiss conditions, the results from Paper IV show that harvests exhibited a positive relationship with spring and especially winter temperatures, with more pronounced effects in the cantons of Zurich and Schwyz. Furthermore, increased winter precipitation appears to have negatively affected harvests across Switzerland. On the other hand, summer precipitation appears to have been beneficial for crops, at least in the cantons Vaud and Bern in the western parts of the country. These two cantons also exhibited agrometeorological relationships similar to those of southern Sweden, with harvest yields and summer temperatures being negatively correlated (i.e., colder summers = larger harvests, or vice versa). In Spain, there were few indications of sensitivity to cold, except for oats in the Castille-La Mancha region. Overall, the negative impact of cold and wetness, assessed using linear correlation analysis, is only apparent for winters and springs in Switzerland. Certainly, extreme years such as 1739–1741 or the Great Frost of 1709 have been shown to have negatively affected harvests and societies in many parts of Europe (Béaur & Chevet 2017; Pfister et al. 2018a:269; Kelly 2021). However, based on previous research and the results obtained in this thesis it seems inaccurate to state that cold was problematic in general (e.g., Soens 2022). As discussed in sections 3.2 and 3.3, in many instances colder temperatures can be beneficial, as they may reduce the risk of drought or allow crops to take full advantage of the cereal growing season (with the exception of marginal cases where colder temperatures directly shorten the cereal growing season, as in northernmost Europe) (Edvinsson et al. 2009:122–126; Aslan et al. 2015; Lundström et al. 2018). An important area for future research in this regard is the investigation of agrometeorological relationships in other parts of Europe. Poland and other areas in eastern Europe are especially interesting in this regard, considering their role in the medieval and early modern grain trade. The livestock sector is also of particular interest. For example, in an early exploratory study de Vries (1981:29–30) found that milk yields were negatively affected by cold March temperatures. Crop production was dependent on livestock production in the mixed farming system, not least for the provision of fertilizer in the medium to long term. If livestock production can be found to have been systematically negatively affected by colder temperatures, this might be an important part of the puzzle to explain the negative effect of colder temperatures on grain prices in the medium to long term (Esper et al. 2017; Ljungqvist et al. 2022).

7.3 The growing season temperature constraint in northern(most) European agriculture

If agriculture in Scania and parts of Switzerland were better adapted to wetter and colder summer conditions, agriculture in Jämtland represents the opposite, at least when it comes to the warm-cold spectrum: agriculture there fared better during warm growing season conditions. Paper III was able to show that cereal cultivation was very sensitive to growing season temperature fluctuations in Jämtland, except for a few notable parishes around Lake Storsjön. Severe harvest losses or even near-failures have been described as a common, almost systemic, feature of agriculture in the region (Lindegren 2011:96). One of the most striking constraints of agriculture in Jämtland was the near overlap between the harvest season and the autumn frost season. The mean harvest date during the years 1701–1920, as reconstructed in Paper III, was very close to the mean date for the first autumn frost in the reference period 1961–1990 (SMHI 2023). Given the year-to-year variability in both these variables, autumn frost appears to have very much been a *systematic* threat to agriculture in central Scandinavia.

Advocates for agricultural reform and improvements in 19th-century Jämtland believed that these reforms would release agriculture from the chains imposed by the harsh climate and allow it to achieve the potential promised by soils that were perceived as particularly rich (von Törne 1829:40–46). More widespread introduction of autumn rye cultivation was one potential improvement that authorities were particularly interested in promoting (Wichman 1968:20). Paper III demonstrated that autumn rye was, if anything, more vulnerable to the climatic conditions in Jämtland. While agrometeorological patterns in Scania appear to have undergone a shift in the late 19th century with the introduction of new varieties of autumn crops, in Jämtland it seems that the potato brought the biggest change in agrometeorological dependencies, even though excessive cold continued to present a threat.

The documentary evidence abounds with references to grain being damaged or destroyed by frost, similar to conditions in Finland (Wichman 1962b:136–146; Myllyntaus 2009:80–81; Holm 2012:23; Huhtamaa et al. 2015). For several parishes studied in Paper III, mean summer temperatures alone explained a third or more of the variation in harvests. This was most clear in parishes located in the more mountainous or rugged parts of Jämtland and Härjedalen, as well as in the northernmost parishes. However, in some central parishes in the Lake Storsjö District, such as Hackås, Norderön, Frösö and Rödön, harvests were much less dependent on mean summer temperatures alone, even though they were still certainly constrained by temperature (i.e., warmer temperatures were associated with larger harvests). By all accounts, autumn frost played a central role in the relationship between growing season temperatures and harvests. As could be seen in 19th and early 20th century yield ratios, mean August temperatures yielded the strongest correlations with harvests, although temperatures during all months from at least March until September appear to have been important. The combination of the central role played by August temperatures and that the date of the harvest was one of the strongest factors affecting crop yields is indicative of the role played by autumn-frosts.

Furthermore, Paper III could demonstrate that harvest dates were even more dependent on growing season temperatures than harvest output or yields. Mean spring temperatures explained about 16 per cent of variation in harvests dates, whereas mean summer temperatures explained up to 52 per cent. The latter number is about the same or even lower than corresponding figures from central agricultural areas of Europe like southern Germany/Switzerland (also 52 per cent) or England (up to 62 per cent) (Wetter & Pfister 2010; Pribyl et al. 2011). Why weren't growing season temperatures more important in the marginal agricultural area of Jämtland, compared to these other central agricultural areas? One probable agent here is, again, frost. While growing season temperatures were crucially important for agriculture in Jämtland, and more important than they were for agriculture in southern Germany or England, an early occurrence of frost could force a premature harvest, thus overriding part of the effect from growing season temperatures.

Paper III also introduced long time series of sowing dates, with an almost continuous record between 1699–1920, as well as of hay-cutting dates between 1762–1920, both types of series being extremely rare if not altogether unprecedented in European historiography. Sowing dates were, as might be expected, dependent on spring temperatures. Up to 27 per cent of the variation in sowing dates could be explained by mean spring temperatures alone. Perhaps more surprisingly, hay-cutting dates were also dependent on spring and summer temperatures, where about 22 per cent of the variation in hay-cutting dates could be explained by mean spring and summer temperatures, respectively. There were also relationships between the various agricultural dates, where later sowing dates tended to delay hay-cutting and harvests. The effect of a delayed hay-cutting on the harvest date was especially strong: up to 53 per cent of the variation in harvest dates could be explained by hay-cutting dates. Overall, these relationships show that there was a comprehensive dependence on growing season temperatures for all the agricultural indices under consideration. However, they also show that there was considerable scope for other factors determining variations in harvests and agricultural dates. Combining climatic and agricultural indicators generally increased the explanatory power of all models. For example, mean summer temperatures in tandem with hay-cutting and sowing dates could explain up to 70 per cent of variations in harvest dates, whereas temperatures alone, as already noted, explained about 53 per cent. The apparently climate-independent relationships between the various agricultural dates indicate that there was a scope of decision-making based on priorities and perception of risk on the part of farming households.

Regarding the climate-agriculture relationships in central Scandinavia, it is also important to bear in mind that the cultivation of crops, while important, probably took second place to livestock production. The cutting of hay generally took eight weeks, almost twice the amount of time dedicated to harvesting crops (Wichman et al. 1968:56, 59). Furthermore, the relationship between hay-cutting and harvest dates could be interpreted as being partly caused by farmers prioritizing hay-cutting over the harvest and thus allowing the hay-cutting to delay the grain harvest. The same climatic conditions that delayed hay-cutting could also be responsible for delaying the grain harvest; however, these two explanations are not necessarily mutually exclusive. The dependence of livestock production on climatic variability is an understudied subject in European historiography (White 2014b), and it is arguably an especially important topic for areas more oriented towards livestock production like central Scandinavia or the *Hirtenländer* of Switzerland (Pfister 1983; Larsson 2009:56). Unfortunately, most of the data utilized for Paper III only highlighted conditions for crop cultivation (with the important exception of hay-cutting dates); thus, considering the livestock sector was largely outside the scope of the paper.

7.4 Methodological limitations

An important factor to bear in mind when considering the agrometeorological relationships identified in all the four papers is that the evidence was mainly obtained through linear analyses like parametric regression models or correlation analysis. While this type of analysis usually has more statistical explanatory power, such models or methods do not give a full picture. Most relationships between crop yields and meteorological indicators are only linear within certain parameters. When including the full range of outcomes in, for example, correlation analysis, the results by themselves do not let us know whether droughts played an outsized role in determining these associations. Nor do they directly reveal to what extent the associations were just as much the result of crop production being *favored* by cold and wet conditions, as it was negatively impacted by warm and dry conditions. Controlling for one factor or the other implies a loss of degrees of freedom by, for example, only considering dry or wet years, as in Paper I. Such approaches can still be useful if used in combination with other statistical methods, as in Paper II when the specific impact of drought could be demonstrated through compositing (SEA) in tandem with correlation analysis (Brás et al. 2021). Another important constraint is that available cross-sectional data is limited. For Scanian agriculture, one of the regions with the best coverage in Europe, such data is only available after ca 1700 (Olsson & Svensson 2010). For climate indicators, cross-sectional local-level data is unfortunately even more limited. Doing panel-based regressions of agriculture-harvest relationships is therefore limited to including climate as a time-variant but individual-invariant variable (Hsiang 2016; Bekar 2019). If more standardized indicators across regions could be obtained, a possible approach here for future research could be to use aggregated data at, for example, county or subregional levels and estimate panel-based models of larger regions (Burke & Emerick 2016).

7.5 Conclusion

This thesis has investigated how pre-industrial agriculture in different parts of Europe was affected by climate variability and change during the period ca 1500–1920. A particular focus has been directed towards Scania in southernmost Scandinavia and Jämtland in central Scandinavia during the years ca 1700–1910 and 1560–1920, respectively. Spain, Switzerland, and other parts of southern Scandinavia during the period ca 1500–1800 have also been considered. The thesis has concentrated on three research questions, distributed among the included papers, namely: (1) how did the climate and variability thereof affect agricultural production in different parts of Europe, and Scandinavia in particular, during the study period ca 1560–1910? (2) What were the main agrometeorological risks in each region studied? (3) What was the history and frequency of these risks during the study period, and to what degree were pre-industrial farming systems resilient to these risks? The first research question was addressed in all papers. The second research question was mainly addressed in papers II–III and to a lesser extent in papers I and IV. The third and final research question was primarily addressed in papers II and III.

In relation to research question 1, there were notable differences in the most readily identifiable agrometeorological relationships across the regions

Included in the study. For Scania, it was demonstrated that June and July were the most important months, with harvest showing a positive correlation with precipitation and negative correlation with temperatures in those months (i.e., higher temperatures = smaller harvests and more rain = larger harvests). No other significant agrometeorological relationships could be distinguished in the region. Rather, farms mostly differed in their degree of dependence on meteorological conditions in June and July.

Identified associations in central agricultural areas were generally quite weak – but in line with expectations – where single monthly or seasonal climatic indicators explained about 10 per cent, frequently less, of historical harvest variations. In marginal agricultural regions like Jämtland, single climatic indicators explained at least twice as much of the historical harvest variations. In Paper III, a clear temperature signal was present in the variation of all the agricultural indicators in Jämtland under consideration, where colder/warmer temperatures were associated with smaller/larger harvests, and later/earlier onsets of sowing, hay-cutting, and harvesting.

In Switzerland, winters and spring temperatures were positively related to harvests; i.e., colder winters and springs were associated with reduced harvests. Similarly, wet winters were also associated with reduced harvests. Harvests in parts of Switzerland showed similarities to southern Sweden in terms of exhibiting a negative association with summer temperatures (i.e., warmer summers = smaller harvests) at inter-annual time-scales, albeit with a weaker effect. Conditions in Spain were more heterogeneous, consistent with the diversified climate of the Iberian Peninsula and the prevalence of different irrigation regimes. Wheat tithes in Andalusia, as well as wheat yield ratios from the central plateau region, exhibited a drought signal (i.e., warmer and drier conditions = lower harvests), with the difference between Spain and Sweden being that this signal was relegated to the spring season. Conversely, harvests in Guadalajara exhibited a reverse climatic signal (i.e., warmer and drier conditions = larger harvests), especially for oats, which appeared to be the most climatically sensitive crop, probably due to its cultivation on more exposed and marginal plots.

Regarding research questions 2 and 3, Paper II demonstrated that droughts constituted the main agrometeorological threat in Scania, with drought being the main culprit behind large-scale harvest losses in the region, affecting both spring and autumn crops on different types of farms, as well as grain prices, at least until the late 19th century. In the late 19th and early 20th centuries, the introduction of new autumn crop varieties shifted agrometeorological patterns, with autumn crops no longer being as vulnerable to drought, possibly becoming more susceptible to conditions of extreme cold instead. Spring crops in Scania continued to be vulnerable to drought throughout the study period. In the years subsequent to a drought, harvests and yields of autumn crops generally experienced a rebound effect, recovering the losses from the previous drought year, while spring crops generally experienced a reduced rebound or even suffered persistent harvest losses in the year following a drought.

Cold was not a systematic threat in either Scania or southern Sweden as a whole, although episodes of extreme cold conditions could lead to local harvest losses. In contrast, in the northern two-thirds of Sweden, roughly the regions above the *limes norrlandicus*, cold was very much a systematic threat. Agrometeorological differences between northern and southern Sweden were in general not a matter of degrees (although to some extent it was), but rather one of opposites, where agrometeorological relationships tended to go in opposite directions. In Jämtland, cold springs and summers, as well as autumn frosts, were clearly the main agrometeorological threats, and remained so throughout the study period. These vulnerabilities were partly mitigated by the rapid increase in potato cultivation in the 19th century.

Even though climatic signal in central agricultural areas was spread out over a wider range of possible meteorological outcomes, and each specific signal (e.g., growing season temperatures) was thus weaker, drought during the main cereal growing period appeared to be the main (Sweden, Spain), or one of the discernable (Switzerland), agrometeorological risks in most central agricultural areas. In such areas, harvests at inter-annual time-scales tended to be negatively correlated with growing season temperatures (i.e., warmer growing seasons = smaller harvests) and in the case of Sweden and Spain, positively correlated with summer or spring precipitation (i.e., more rain = larger harvests), respectively. Conversely, in marginal farming areas risks were more concentrated, with colder growing season temperatures being the dominant agrometeorological threat.

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Popular science summary

Throughout the history of agriculture, farmers have been acutely aware of their reliance on the unpredictability of weather. Additionally, farmers have had to constantly adjust their agricultural practices to accommodate long-term weather patterns, or the climate. One such significant climatic period was the Little Ice Age, which occurred roughly from 1300 to 1850 and featured lower average temperatures. This era posed specific challenges to agriculture in Europe. However, after the Late Medieval Agrarian Crisis of the 14th and early 15th centuries, many European regions witnessed substantial population growth and a marked increase in agricultural production.

This thesis investigates how specifically agriculture was affected by climate variability in different parts of Europe during the perod 1500–1920, what the main weather- and climate related risks facing farmers were, as well as how impactful and frequent these threats were. Scania in southern Scandinavia and Jämtland and Härjedalen in central Scandinavia receive special attention, while large parts of Switzerland, Spain and other parts of Sweden are also considered.

The first paper, paper I, employs climate reconstructions from southern Sweden, early instrumental precipitation data from Lund as well as harvest yield and tithe harvest data from Scania to study the relationship between climate and grain production during the 18th and 19th centuries. Furthermore, a network of early instrumental temperature observations are employed to homogenize the early instrumental temperature record from Lund. Results show that June and July were clearly the most important months. Cooler and wetter summers were generally beneficial to grain harvests, whereas warmer and less rainy summers experienced smaller harvests, especially of the historical varieties of barley and rye cultivated before the late 19th century.

Paper II built on Paper I and establishes the first systematic chronology of summer droughts in Scania during the 18th and 19th centuries using early instrumental precipitation records, hydroclimate reconstructions and documentary evidence. The specific effects of summer droughts are then investigated using statistical analysis. Summer droughts are shown to have negatively influenced harvests of most crops throughout the region, leading to reduced harvests and large increases in the price of grain. Even harvests of autumn-rye, supposedly one of the more drought-resilience crops, were severely impacted by summer droughts. At the end of the study period, new varieties of autumn-rye and autumn-wheat were becoming less susceptible to drought, like the one in 1868, but more susceptible to extreme cold conditions in the spring, like in the spring of 1867.

Paper III focuses on Jämtland and Härjedalen in central Scandinavia. Here, growing season temperature was the predominant constraint facing farmers. The decision to start sowing, hay-cutting or harvesting was to a large degree dependent on how warm or cold the spring or the summer was. However, farmers could not blindly follow weather patterns but had to make decisions based on the perception of risk and prioritization between hay-cutting, harvesting and other important agricultural tasks. In mountainous areas, farmers experienced the largest dependence on climate and weather, at least when it came to the cultivation of cereals, whereas farmers around Lake Storsjön and parts of eastern Jämtland were less dependent on growing season temperatures alone. Farmers mainly cultivated barley. Other crops like rye were even more vulnerable to shifts in growing season temperatures, while the potato contributed to increased resilience by being less vulnerable in that regard.

Paper IV investigates how harvest yields in large parts of Switzerland, Spain and southern Sweden (excluding Scania) were affected by climate variability using an unprecedentedly large collection of harvest yield and climate data and a consistent statistical framework. In southern Sweden, the clearest relationship between harvests and climate indicators was that between reconstructed hydroclimate (for example soil moisture) and harvests, where wetter conditions were generally beneficial to harvests. Cooler summers were also beneficial to harvests in the southernmost counties, similar to conditions in Scania. In Switzerland, precipitation and temperature patterns during the late autumn and winter had the largest effect on harvests, with wetter and colder conditions generally being detrimental.

Cooler summers were in contrast generally beneficial to harvests, similar to conditions in southern Sweden. In Spain, relationships were more complex, owing to the heterogeneous climate present there. Nonetheless, spring drought appeared as the most prominent threat facing farmers in Spain.

In general, harvests in central agricultural areas, for example Andalusia in Spain or Scania in southermost Sweden, tended to be larger during cooler years. Only in marginal agricultural areas like Jämtland and Härjedalen in central Scandinavia did an opposite signal prevail. In other words, by the early modern period, if not earlier, agriculture in large parts of Europe appears to have been well adapted to the lower average temperatures of the Little Ice Age.

Populärvetenskaplig sammanfattning

Genom hela jordbrukets historia har jordbrukare varit beroende av väderförhållanden som är svåra att förutse. Vidare har jordbrukare ständigt behövt anpassa sina jordbruksmetoder för att svara på klimatets skiftningar. En sådan betydande klimatperiod var Lilla istiden, en period med bland annat lägre genomsnittstemperaturer som inträffade mellan ca 1300 och 1850. Även om denna period ställde jordbruket i Europa införsärkilda utmaningar, så kom många europeiska regioner att uppleva betydande befolkningstillväxt och ökning av jordbruksproduktionen i efterdyningarna av den senmedeltida jordbrukskrisen på 1300- och 1400-talet.

Denna avhandling undersöker specifikt hur jordbruket påverkades av klimatvariationer i olika delar av Europa under åren 1500–1920, vilka de främsta väder- och klimatrelaterade riskerna för jordbruket var, samt vilken betydelse och frekvens dessa risker hade. Särskild uppmärksamhet ägnas åt Skåne samt Jämtland och Härjedalen, medan stora delar av Schweiz, Spanien och andra delar av Sverige också ingår i avhandlingen.

Den första artikeln, artikel I, använder klimatrekonstruktioner från södra Sverige, tidiga instrumentella nederbördsdata från Lund samt olika skördedata, exempelvis tiondeobservationer, från Skåne för att studera sambandet mellan klimatet och spannmålsproduktionen under 1700- och 1800-talen. Dessutom används ett nätverk av instrumentella temperaturobservationer för att homogenisera de tidigaste instrumentella temperaturmätningarna från Lund. Resultaten visar att juni och juli var klart de viktigaste månaderna. Kyligare och regnigare somrar gynnade generellt spannmålsskördarna, medan varmare och mindre regniga somrar resulterade i mindre skördar, särskilt av de historiska spannmålssorterna av korn och råg som odlades före sent 1800-tal. Artikel II bygger på Artikel I och etablerar den första systematiska kronologin över sommartorkor i Skåne under 1700- och 1800-talen med hjälp av tidiga instrumentella nederbördsdata, hydroklimatiska rekonstruktioner och andra historiska källor. De specifika effekterna av sommartorkor undersöks sedan med hjälp av statistisk analys. Sommartorkor visade sig ha negativt påverkat skörden av de flesta grödor i hela regionen, vilket ledde till minskade skördar och kraftiga ökningar av spannmålspriserna. Även skördarna av höstråg, som antogs vara en av de mer torktåliga grödorna, påverkades påtagligt av sommartorkor. I slutet av studieperioden blev höstråg och höstvete mindre mottagliga för torka, som t.ex. 1868 års torka, men mer mottagliga för extremt kalla förhållanden på våren, som på våren 1867. Detta skifte förklaras med introduktionen av nya spannmålssorter och förbättrade jordbruksmetoder.

Artikel III fokuserar på Jämtland och Härjedalen i centrala Skandinavien. Här var temperatur under växtsäsongen den främsta begränsningen för bönderna. Beslutet att börja så, inleda slåttern eller kornskörden var till stor del beroende av hur varm eller kall våren eller sommaren var. Dock kunde bönderna inte blint följa vädermönster utan var tvungna att fatta beslut baserade på riskkalkyler och prioriteringar mellan slåttern, skörden och andra viktiga jordbruksarbeten. Fjälltrakternas bönder var mest beroende av växtsäsongens temperaturer, åtminstone när det gällde odlingen av säd, medan bönderna i delar av Storsjöbygden och delar av östra Jämtland var mindre beroende av enbart växtsäsongens temperatur. Bönderna i Jämtland och Härjedalen odlade främst korn. Andra grödor som råg var än mer sårbara för temperaturväxlingar, medan potatisen bidrog till ökad motståndskraft genom att vara mindre sårbar i det hänseendet.

Artikel IV undersöker hur skördar i stora delar av Schweiz, Spanien och södra Sverige (med undantag för Skåne) påverkades av klimatvariationer med hjälp av en stor samling av skörd- och klimatdata och en konsekvent statistisk analys. I södra Sverige var det tydligaste sambandet det mellan hydroklimat (t.ex. markfuktighet) och skördar, där blötare förhållanden generellt var gynnsamma för skördarna (eller torrare somrar generellt var negativt för skördeutfallet). Kyligare somrar var också fördelaktiga för skördarna i de sydligaste länen. I Schweiz hade nederbörds- och temperaturmönster under senhösten och vintern störst effekt på skördarna, där blötare och kallare förhållanden generellt var ogynnsamma. Kyligare somrar var å andra sidan generellt fördelaktiga för skördarna, vilket påminner om förhållandena i södra Sverige. I Spanien var de agrometeorologiska relationerna mer komplexa på grund av Spaniens heterogena klimat. Trots det framstod vårtorka som det mest framträdande hotet mot jordbruket i Spanien.

Generellt sett tenderade skördarna i centrala jordbruksområden, till exempel Andalusien i Spanien eller Skåne i södra Sverige, att vara större under kallare år. Endast i marginella jordbruksområden som Jämtland och Härjedalen i centrala Skandinavien dominerade en motsatt klimatsignal. Med andra ord verkar jordbruket i stora delar av Europa från den tidigmoderna perioden, om inte tidigare, ha varit väl anpassat till de lägre genomsnittstemperaturerna som rådde under Lilla istiden.

Papers

I

Clim. Past, 18, 405–433, 2022
https://doi.org/10.5194/cp-18-405-2022

Climate of the Past
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Climate variability and grain production in Scania, 1702–1911

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Received: 29 April 2021 – Discussion started: 10 May 2021
Revised: 27 November 2021 – Accepted: 15 December 2021 – Published: 4 March 2022

Abstract. Scania (Skåne in Swedish), southern Sweden, offers a particularly interesting case for studying the historical relationship between climate variability and grain production, given the favorable natural conditions in terms of climate and soils for grain production, as well as the low share of temperature-sensitive wheat varieties in its production composition. In this article, a contextual understanding of historical grain production in Scania, including historical, phenological, and natural geographic aspects, is combined with a quantitative analysis of available empirical sources to estimate the relationship between climate variability and grain production between the years 1702 and 1911. The main result of this study is that grain production in Scania was primarily sensitive to climate variability during the high summer months of June and July, preferring cool and humid conditions, and to some extent precipitation during the winter months, preferring dry conditions. Diversity within and between historical grain varieties contributed to making this risk manageable.

Furthermore, no evidence is found for grain production being particularly sensitive to climate variability during the spring, autumn, and harvest seasons. At the end of the study period, these relationships were shifting as the so-called early improved cultivars were being imported from other parts of Europe. Finally, new light is shed on the climate history of the region, especially for the late 18th century, previously argued to be a particularly cold period, through homogenization of the early instrumental temperature series from Lund (1753–1870).

1 Introduction

In recent years, numerous studies have explored the relationship between grain yields, prices, and climatic change in medieval and early modern Europe. The fundamental assumption underlying these studies is that grain production to a substantial degree was affected by variability in temperature and precipitation (Edvinsson et al., 2009; Holopainen et al., 2012; Camenisch, 2015; Esper et al., 2017; Pribyl, 2017; Ljungqvist et al., 2021a, b). Most of these studies have either focused on particularly temperature-sensitive grain types like wheat or temperature-sensitive agricultural regions, like Finland or the Scottish Highlands (Parry and Carter, 1985; Brunt, 2015; Huhtamaa and Helama, 2017a). In these historical contexts, cold conditions become the “grim reaper” (Holopainen and Helama, 2009). However, in the long term, grain farming even in the northern border regions of European agriculture has shown considerable adaptability and resilience (Solantie, 1992; Huhtamaa and Helama, 2017b; Degroot, 2021). Diversified grain production has been identified as an important aspect of this resilience (Michaelowa, 2001). In this article, I argue that an understanding of the impact of climatic variability and change on agriculture as well as explanations of resilience in terms of grain diversity need to be grounded in an understanding of the phenology of historical grain varieties.

Attempts to account for the resilience, or the ability of early modern farmers and farming systems to cope with climate variability in intensive grain farming areas of Europe north of the Alps like northern France and England, have remained mainly hypothetical (Michaelowa, 2001; Tello et al., 2017). Early modern Scania offers an especially interesting case in this regard. The climate of Scania is mild, hosting a continental climate stabilized by the proximity to the Baltic Sea. From an agronomic viewpoint, it is often stressed that Scania has the longest vegetative period of present-day Sweden (Osvald, 1959; Persson, 2015). Moreover, the southwestern half of Scania, roughly the extent of the historical county of Malmöhus, contains large areas of soils of exceptionally high quality (Lantbruksstyrelsen, 1971). For most of the historical period, Scania was an important surplus producer of grains in the Kingdom of Denmark and from 1658 in the Kingdom of Sweden (Åmark, 1915; Bohman, 2010). At the same time, since at least the 17th century up until the end of the 19th century, Scanian farmers relied on Scandinavian grain varieties adapted to cooler and humid climates with short growing seasons, i.e., conditions often prevalent at the northern limits of arable agriculture (Lundström et al., 2018; Larsson et al., 2019).

The aim of this article is to study the relationship between climate variability and grain production in Scania during the period 1702–1911. The study period is divided into the early study period (1702–1865) and the late study period (1865–1911). Given that the role of climate cannot be conceptualized in a simplistic or deterministic manner, it has to be contextualized in the specific agrarian and ecological context (Haldon et al., 2018; van Bavel et al., 2019; Degroot, 2021). Accordingly, this article starts out by contextualizing the study and setting the historical background, particularly detailing historical grain production in Scania during the study period. Following this is a conceptual and theoretical discussion of the relationship between crop production and climate as well as the concept of resilience. Subsequently, I present and discuss the climate and agricultural production data and the employed methods. Finally, results are discussed in relation to the historical context as well as to previous research.

1.1 Background

Scania is situated at the southernmost tip of the Scandinavian Peninsula in the borderlands between Sweden and Denmark. The farming districts on the plains of Scania have, and continue to be, some of the most productive arable farming regions in Scandinavia, owing mostly to its mild climate and rich soils. In the Danish and Swedish historiography, Scania is commonly referred to as a *kornbod* (roughly translated as "breadbasket"). Adam of Bremen in his Gesta Hammaburgensis ecclesiae pontificum from ca. 1075 CE describes Scania as the most prosperous of the provinces in the Danish kingdom (Bremensis, 2002). However, the natural geography of Scania is and was not uniform (Svensson, 2016). Besides the arable plains, Scania was constituted by a diverse landscape of forests, disparate but mostly hospitable coastal areas, lakes, and hills with different soils and natural conditions (Lidmar-Bergström et al., 1991). Farming was to some extent adapted to this variability in natural conditions, especially in the period prior to the late 19th century (Dahl, 1989; Gadd, 2000; Bohman, 2010). During the years ca. 1750–1850, Scania underwent what has been called the agrarian revolution, implicating a general transformation of agriculture as well as dramatic and sustained increases in production (Olsson and Svensson, 2010). Subsequently, Scanian agriculture has continued to sustain its growth trajectory, intermittently inter-

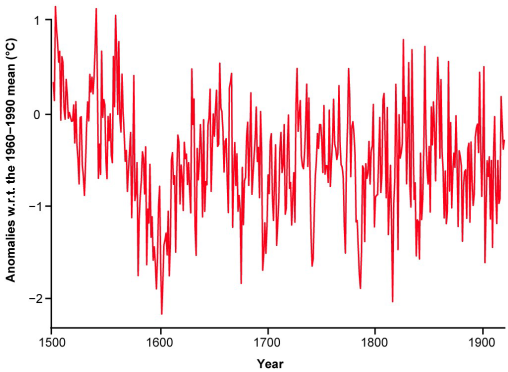

Figure 1. The 1500–1920 summer (JJA) temperature reconstruction from Ljungqvist et al. (2019) based on a grid cell at 12.5° E and 57.5° N, roughly corresponding to Mark Municipality in southern Västra Götaland. Source: Ljungqvist et al. (2019).

rupted by various agrarian and economic crises (Myrdal and Morell, 2013). Scanian farmers also faced challenges. Situated between two rivalling kingdoms, Denmark and Sweden, the fertile plains of Scania have been fought over and acted as a battleground in numerous wars. After 1711, there were fewer conflicts compared to the preceding centuries (Frost, 2000).

Like in other parts of Europe, colder climatic conditions prevailed in Sweden and Scania for most of the second half of the 16th century and throughout most of the 17th century. The period ca. 1560–1630 was particularly cold and experienced overall increased climatic variability (see Fig. 1). In the 1690s, there was also a recurrent span of cold years with late springs in the Baltic area, culminating in the disastrous years of 1695–1697 and leading to mass mortality throughout the region, especially in northern Sweden, Estonia, and Finland (Dribe et al., 2015; Lilja, 2008). Reconstructions of winter ice severity from the western Baltic indicate that the period experienced greater volumes and persistence of winter ice compared to preceding and subsequent periods, and the sound between Scania and Zealand was covered with ice for most of the years 1694–1698 (Speerschneider, 1915; Koslowski and Glaser, 1999).

During portions of the 18th century, there was a "return" to milder temperatures, albeit with some notable exceptions with especially cold periods in the early 1740s and 1780s. The most notable challenge in terms of natural conditions pointed out in previous research is the increasing degree of sand drift and soil erosion in Scania during the later parts of the 18th century and early 19th century (Mattsson, 1987). As Bohman (2017a, b) has shown, these agro-ecological crises were mostly local and temporary, counteracted by land management policies at the local and regional level. The main causes behind the increasing soil erosion and sand drift have been framed as anthropogenic through deforestation and intensified land use practices. Mattsson (1987), relying on instrumental and observational meteorological records from Lund, argued that another underlying factor behind these agro-ecological issues was climatic variation in the form of the generally colder conditions during the Little Ice Age (LIA) and increased heavy winds and storms, particularly easterlies, during the latter half of the 18th century.

In the following century, the 1810s and the 1840s stand out for being cold (Tidblom, 1876; Cappelen et al., 2019). In general, the 19th century was one of great transformation and expansion for agriculture in Scania, making it difficult to identify any prolonged climatic periods that were beneficial or detrimental for agriculture. Nonetheless, there certainly were years that experienced particularly bad agrometeorological conditions like summer droughts, for example in 1811, 1822, 1826, 1837, 1868, 1870, and 1899 (Tidblom, 1876; SMHI, 2021). The 1868 summer drought was particularly bad since it followed a year of severe crop failures in northern Sweden that had already depleted much of the grain stocks available for aid (Dribe et al., 2015; Västerbro, 2018). According to Utterström (1957) and Edvinsson et al. (2009), lack of precipitation and drought during the summer were the main agrometeorological risks in southern Sweden in the 18th and 19th centuries.

1.2 Farming in Scania

Descriptions of agriculture in Scania during and subsequent to the study period have relied on the ethnographic and geographical categorizations made by Campbell (1928), who outlined three different types of farming districts: the plain, the intermediate (or "brushwood", sw. *risbygd*), and the forest districts (Dahl, 1989; Svensson, 2013). Villages in the plain districts generally practiced a three-field farming system and were characterized by their specialization in grain production (Campbell, 1928). In the intermediate districts, villages had a higher share of livestock production and often practiced a one-field farming system (Bohman, 2010). Finally, the forest districts had the most diversified economy with handicrafts and forest-related industries complementing grain and livestock production (Svensson, 2016). Bohman (2010) estimated that during the 18th century and the first half of the 19th century, crop production constituted roughly 90 % of the total production value in the plains district and somewhere around 80 % in the intermediate and forest districts. Controlling for price changes, crop production increased its share of overall production value at least until the 1860s.

Despite the fact that the types of farming districts varied in their respective specializations, practically all farming in Scania was performed in a mixed farming system, wherein livestock husbandry and grain production were integrated and mutually dependent (Bohman, 2010; Myrdal and Morell, 2013). Until the 19th century, most farms in Scania belonged to a village where farming operated under an open-field system (sw. *tegskifte*) with a mixture of private and communal management. Limited enclosure reforms, *storskifte*, were introduced starting in 1757, followed by radical enclosure reforms in 1803 (*enskifte*) and 1827 (*laga skifte*). These latter reforms involved the breakout of the individual farms from the communal management, effectively privatizing land ownership and management. Implementation of these reforms was gradual and intermittent (Gadd, 2011, 2018). Hence, for large parts of the study period, decision-making regarding grain production was largely mediated through the institutions of the village.

1.3 Grain crops

Rye, barley, and oats dominated the composition of grain production during the study period and had done so since the Viking Age, albeit with much internal variation over time. For example, oats production saw a large increase in its share of overall grain production during an export boom in the 19th century (Welinder, 1998; Bohman, 2010). In the late 19th century and early 20th century, the new so-called improved cultivars (mainly in the form of autumn rye and autumn wheat) increasingly took the place of the most dominant grain crops (Leino, 2017). Given their dominance in a historical perspective, this study will mainly be limited to analyzing the production of barley, rye, and oat varieties. Wheat varieties will also be included in the later study period (1865–1911).

In previous research, the type of farming district and soil types have been seen as the primary factors determining differences in crop composition (Dahl, 1942, 1989). Wheat and barley were more dominant in the arable plain districts. The share of oats was lowest in the forest districts, and the share of rye was roughly the same in the different types of districts. Regarding soil types, Bohman (2010) found that barley and oats (and wheat) were more dominant on high-quality soils and rye was more common on poorer soils and that in relation to animal production. He also argued that vegetable production increased its share throughout the 18th and the first half of the 19th century as a supply-side response to increasing prices. The share of the total value of agricultural production constituted by vegetable products ranged between 61 % and 97 % through the 18th and 19th centuries depending on decade and parish (Bohman, 2010).

1.4 Rye varieties

Leino (2017) has studied some of the historical grain varieties in Sweden. Examples of rye varieties prevalent in Scania were late rye (sw. *senråg*), St. Laurentius Day rye (sw. *larsmässoråg*), sand rye (sw. *sandråg*), and spring rye (sw. *vårråg*). Swidden rye (*svedjeråg*) was most likely also grown, especially in the forest districts. Scanian farmers preferred to grow their rye on sandy soils or other well-drained soils (Dahl, 1989; Gustafsson, 2006). Leino (2017) notes that in historical sources, late rye is often characterized as allowing very late sowing, all through December in Scania (in some extreme cases this nominally autumn crop was apparently sown in early spring). According to Leino (2017), this type of late sowing of late rye offered the possibility to incorporate autumn rye into a two- or three-field system without the need for a full year of fallow after the preceding harvest. This somewhat blurred line between spring and autumn rye is consistent with genomic studies of Scandinavian rye landraces (Hagenblad et al., 2012). More detailed sources on sowing dates are difficult to find. By all accounts sowing dates varied locally. In parish descriptions from Malmöhus county in the early 19th century, sowing dates for autumn rye vary from the middle of August until early October, although the most commonly noted sowing period was the latter part of September (Bringéus, 2013). Spring rye appears to have been sown after barley sometime in May, depending on the village. Autumn rye is noted to have been harvested earlier than other crops, although all harvesting of rye is reported in either late July or August.

In a broader context of European rye landraces in the pre-1900 period, Fennoscandian landraces have been found in genomic studies to belong to a particular and separate metapopulation of rye landraces, distinct from landraces in continental Europe. Furthermore, even southern Scandinavian rye landraces have been found to have more in common genetically with landraces from northeastern Europe than those from maritime western Europe (Larsson et al., 2019).

1.5 Barley varieties

Southern six-row barley (sw. *sydsvenskt sexradskorn*) was common in Scania, especially in the forest districts, even in the late 19th century. It was sown late, often well into June, due to its sensitivity to frost and its rapid growth, allowing ripening despite late sowing. Two-row varieties like Scanian two-row barley (sw. *skånskt tvåradskorn*) were also grown, at least during the 19th century but probably earlier as well. Two-row varieties required more intensive agricultural practices, longer growth periods, and richer soils but offered better resistance to frost and often gave larger yields compared to six-row varieties. In the previously mentioned parish descriptions from the early 19th century, sowing dates for barley range from late April to early June, while harvesting is mostly described as taking place sometime in August (Bringéus, 2013).

Similar to rye, genomic evidence for barley landraces from Scandinavia and southern Scandinavia in particular indicates spatial and temporal consistency from the 17th century up until the late 19th century (Lundström et al., 2018). A distinctive feature of these Scandinavian barley landraces in terms of genetic markers is the prevalence of the nonresponsive ppd-h1 allele, which prolongs the flowering during periods of increasing daylight, prolonging the vegetative state and potentially increasing yields in cooler and wetter conditions (Jones et al., 2012; Aslan et al., 2015). An allele is one of several possible expressions of a given gene. The ppd-h1 allele is the nonresponse expression of the ppd-H1 (Photoperiod-H1) gene (Turner et al., 2005). It has been suggested that selection and maintenance of barley seed with this particular allele were part of a long-term adaptation process by early farmers (Cockram et al., 2007).

1.6 Oat varieties

Historical oat varieties can be grouped into two broad categories: white oats and black oats. Generally, white oat varieties were grown on poorer, and especially wet, soils. According to Campbell (1950), they were better suited for making bread compared to the fodder-oriented varieties that became increasingly more common during the course of the 19th century. Black oat varieties were more resistant to droughts and were preferably grown on richer, manured soils. Campbell (1950) argued that Nordic white oats (sw. *nordisk vithavre*) were the most common variant in Scania. It is more uncertain whether black oat varieties were grown, although they were grown in all neighboring provinces (Halland, Blekinge, and Småland), which suggests, together with the fact that there was a widespread trade in seed grains, that black oats were at least grown locally and intermittently (Campbell, 1950; Leino, 2017). Oats appear to have been sown about 1–3 weeks prior to barley and spring rye and harvested at about the same time as, or shortly before, barley (Bringéus, 2013).

According to Dahl (1942), oat farming in Scania was *not* an adaptation to local climate like in parts of northwestern Europe. Rather, it was other natural conditions, primarily the type of moraine soil common in some areas around the Baltic like Denmark, Scania, and northern Germany (sw. *baltisk morän*), as well as local hydrological conditions, namely on soils that were poorly drained, that were decisive for oat cultivation. It is important to note that Dahl (1942) conceptualized natural conditions and climate as something static and that the only secular changes that occurred in natural conditions were due to human intervention, for example by not investing in drainage or through over-cropping. However, given that the climate actually varied over time, one would expect climate effects interacting with factors like soil and the type of cultivated crop. For example, periods of a wetter climate should have had more negative impacts on crops grown on poorly drained soils, whereas crops cultivated on well-drained soils should have been more exposed to drought periods (Osvald, 1959; Weil and Brady, 2017).

2 Crop diversity, resilience, and adaptation

This brief overview of the diversity of grain varieties to be found in early modern Scania suggests a flexible farming system in terms of sowing and harvest dates as well as the ability to produce grains under differing agrometeorological conditions. It is important to note in this context the inherent capacity of crop varieties to adapt to local environmental conditions (including local farming practices) that over time should have led to much greater variety, and indeed resilience, than this brief overview suggests (Leino, 2017; Aslan et al., 2015). In the context of historical grain production, I define resilience as the ability of a production system to maintain itself over a longer period through a combination of biological and institutional flexibility and durability in the face of a variable environment. When discussing adaptation I refer to how a given crop or farming practice performs in a given set of environmental circumstances. I subsume the concept of exaptation (passive or accidental adaptation) under adaptation, given the difficulty in disentangling the two. For example, a particular crop may perform better during colder periods, increasing the production of the crop, which could be due to farmers *actively* adapting to changeable circumstances or the crop being more adapted (passively) relative to the other crops being cultivated. Moreover, even if farmers are actively increasing the production of a given crop, it can still be very difficult to establish whether it is due to adaptation to environmental change, a response to shifting market demands, technological innovation, or cultural trends.

Previous research has stressed that, at least in relation to climate “extremes”, diversified crop production including both spring and autumn crops of different varieties was more resilient in areas of Europe north of the Alps (Michaelowa, 2001; Ljungqvist et al., 2021a). Michaelowa (2001) partly blamed the excess specialization towards autumn wheat for the relatively poor performance of French agriculture compared to English agriculture during the 18th century; the latter was more diversified, cultivating autumn wheat, autumn rye, and spring barley and oats.

Utterström (1955) and Michaelowa (2001) argued that colder periods in the early modern period, specifically in the late 17th and 18th centuries, led to reductions in livestock production in France, England, and Sweden, and in response grain production usually increased with the intention to fill in the nutritive gap. If such adaptations took place, they must have been difficult to implement in the short term and were probably also insufficient given that grain production was also vulnerable to spats of cold weather. Pfister (2005) showed how cold and wet conditions during the different seasons of the year were detrimental to livestock production in the Swiss Alps as well as the difficulties of the local communities to adapt given that the cultivated grains and vines were also vulnerable to cold and wet conditions. Grain shortages, sometimes resulting in famines, were common in many parts of Europe up until at least the 19th century (Appleby, 1980; Dribe et al., 2015; Esper et al., 2017).

There have been attempts to detail the relationship between grain production and climate variability in northern Europe during the early modern period in more detail. Brunt (2004) found that English wheat yields during the 1770s were mainly sensitive to temperature and to a lesser extent precipitation, depending on local soil conditions. Especially important were summer temperatures. Cooler summer temperatures through the month of July benefited wheat yields, supposedly by prolonging the grain-filling period. A warm and dry August was then beneficial by allowing the crops to dry for the coming harvest. Ideally, rainfall would be spread out over many days during the early summer months. Concentrated rainfall during a short time span risked ruining the crop, with the harvest month of August being especially vulnerable (Brunt, 2004). In a later study, Brunt (2015) found that wheat yields were significantly affected by weather shocks throughout the ca. 1690–1850 period (to the extent that they obfuscated subsequent estimations of long-term productivity trends), with the 19th century largely conforming to the 1770s as to the effects from temperature and precipitation during summers.

Pei et al. (2016) studied the relationship between yield ratios and temperature at a continental scale and proposed that European farmers during the period ca. 1500–1800 used crop management as a mechanism for climate adaptation. Specifically, farming systems drifted towards increased rye production during colder periods, which the authors argue was a more cold-resistant crop. In an earlier study, Pei et al. (2015) asserted that extensification of land use was the most prominent strategy in mitigating climatic stress during the same period. However, given differences in soil, climate, available grain varieties, and other factors, it seems more reasonable to expect more heterogeneous and contextually dependent adaptation practices at the local and regional level (van Bavel et al., 2019; Ljungqvist et al., 2021a). While rye was almost certainly more cold-resistant than wheat, in relation to oats the same seems to be true only when we exclude wetter climatic areas (e.g., western Sweden or parts of Scotland). In relation to barley there is limited evidence indicating that rye was the more cold-resistant grain *overall*. For example, in northernmost Sweden and Finland grain production was limited almost exclusively to barley. An important caveat in making these types of comparisons is the fact that rye was mostly grown as an autumn crop, whereas barley and oats were exclusively grown as spring crops and that in many agricultural areas of northern Europe they were more often supplementary than rival crops (Huhtamaa and Helama, 2017b).

Considering Sweden, and southern Sweden in particular, one finds a composition of grain production that was diversified and comparable to that of England in the 18th century described by Michaelowa (2001), with the important exception of wheat, which in Sweden was only a marginal crop. Utterström (1957) argued that for grain production in northern Sweden, temperature was the most important climatic variable, whereas it was precipitation for southern Sweden. Using more up-to-date climate and grain harvest data, Edvinsson et al. (2009) largely confirmed the stipulations made by Utterström (1957), at least from 1724 up until the late 19th century, finding a negative association between subjective harvest assessments and June and July temperatures and a positive association with precipitation in the same months and November and December temperatures. After ca. 1870, Edvinsson et al. (2009) found a shift in the relationship. Precipitation in the summer, including the month of May, was still positively correlated with the harvest assessments. However, summer temperatures were no longer statistically significant, whereas the first 4 months of the year (JFMA) showed positive associations with harvests assessments. A short digression is in order here. Compared to summer and spring temperatures, relationships with winter temperatures are more difficult to explain, given that they are indirect, occurring before the growing season for spring crops. Temperature and precipitation during the winter months do affect the overwintering autumn crops by facilitating or inhibiting the survival of the grains themselves, as well as fungi, soil bacteria, and other various grain pests (Holopainen and Helama, 2009; Osvald, 1959). In addition, the nutritive balance of the soil is affected (Aðalsteinsson and Jensén, 1990). Again, it is quite difficult to establish, both empirically and theoretically, the mechanisms and links between these relationships and the subsequent grain harvest. It should be noted that these "indirect" effects are also at play during the other seasons. For example, de Vries et al. (2018) found that summer droughts have different effects on soil bacteria and fungus and that these effects have long-term consequences for vegetation growing on the soil.

Returning to the discussion of the results from Edvinsson et al. (2009), they argued that the overall relationship between climate variability and grain harvests was weak, partly explained by the lack of detail in climate data. Furthermore, they found that the magnitude of the relationships increased in the period 1871–1955 compared to the previous roughly 150 years, which they primarily explained in terms of the increasing shift towards higher-yielding and more temperature-sensitive wheat production. More controversially, they also hypothesized that climate variability itself was less important to harvest in pre-industrial agriculture due to chronic seed shortages and more risk-averse behavior on the part of farmers.

With respect to the differences between different grains, Edvinsson et al. (2009) employed aggregate official statistics at a national level for the period 1803–1955 (with a gap between the years 1821 and 1859). They found that wheat and rye harvests were positively correlated with October through April temperatures, that barley harvests were positively correlated with temperatures in April, May, and August–September, and finally that oat harvests were negatively correlated with June–July temperatures. Harvests of all the mentioned grains were positively associated with increased precipitation in May through July. Wheat and rye harvests were negatively associated with increased precipitation in March, whereas the same was true for barley and oat harvests in relation to precipitation in September. These results are possibly skewed towards the late 19th century and especially the first half of the 20th century considering the gap between 1821 and 1859 as well as the dramatic shifts in the types of cultivated grain varieties that Sweden underwent in the late 19th century (Leino, 2017). Beside the study from Edvinsson et al. (2009), Palm (1997) tried to estimate the relationship between the yields of various grains at a farm in Halland between ca. 1750 and 1870, with limited results.

The division of Sweden into a southern and northern half in regards to the main agrometeorological constraints for agriculture and grain production made by Utterström (1957) and later affirmed by Edvinsson et al. (2009) arguably needs to be complemented. As discussed by Huhtamaa and Ljungqvist (2021), the relationships between climate and agriculture in Scandinavia vary from region to region. From an agronomic perspective, southern Sweden is a diverse place in terms of natural geography. Northwestern Scania and the provinces further north on the west coast (Bohuslän, Halland, Västra Götaland) are wetter and colder than most of Scania, whereas most of the east coast of southern Sweden is drier (especially during spring and autumn) and experiences on average a few hundred extra hours of sun each year (Persson et al., 2012). As mentioned previously, Scania stands out relative to the rest of southern Sweden in terms of the duration of the growing season (Osvald, 1959). Huhtamaa and Ljungqvist (2021) propose that in neighboring Denmark hosting similar conditions for grain production, the shortening of the growing season during wetter and/or colder years might not have led to major issues related to frost. Important additions to these considerations of natural geography include the question of what types of grain varieties were cultivated and in what type of farming system.

In the following sections, I attempt to estimate the relationship between climate variability and grain production in Scania during the period 1702–1911, divided into an early study period (1702–1865) and a later study period (1865–1911). First, I describe and discuss the sources and methods employed, followed by a presentation and a discussion of the results. Finally, I conclude the article by interpreting and contextualizing the obtained results.

3 Sources and methods

3.1 Sources on agriculture and grain production

Scania stands out in the Swedish context regarding the availability and extent of specific historical source material, namely the priestly tithes (sw. *prästetionde*), which in many parts of Scania remained flexible and proportional to output throughout the 18th and 19th centuries (Olsson and Svensson, 2010). Using surviving tithe records from 36 parishes in Scania, Olsson and Svensson have produced a database, the Historical Database of Scanian Agriculture (HDSA), with roughly 85 000 unique farm-level observations covering the period 1702–1881, wherein one observation is one farm's production in 1 year (Olsson and Svensson, 2017b). The structure of the HDSA is that of an unbalanced panel and includes, besides production data on crops and animals, data on farm size and household characteristics, land tenure and other institutional factors, soil quality and land size, geographical factors, and relative crop and animal prices.

The soil data in the HDSA are based on modern soil grading. Previous historical studies have relied on modern soil grading, arguing that it better captures the "natural" fertility of agricultural landscapes compared to those found in historical sources. For instance, Brunt (2004) used national survey data from the 1950s and 1960s in his study of historical grain production in England. The English national soil survey was predominantly based on geological and climatological indicators (Gilg, 1975). Bohman (2010) used data from Göransson (1972), who performed a local study of soils in Scania based on the gradient system established by the Swedish national soil survey published in 1971, which was based on a mix of geological, yield, and price data as well as local expertise (Lantbruksstyrelsen, 1971). The data from Göransson (1972) have subsequently been incorporated into the HDSA. The soil grading system was based on 10 levels; 1 denotes the lowest and 10 the highest-quality soils. According to the national survey, Scania was the only region in Sweden with grade 10 soils (Lantbruksstyrelsen, 1971).

Constructing grain production series for the earlier period 1702–1865 from the HDSA involves attempting to solve some issues. Firstly, there is an issue related to how the tithe was collected, i.e., that it was collected before threshing, and the amount of seed that was obtained by threshing the same type of grain differed across parishes and farming districts. Therefore, all crop production series are adjusted to local threshing coefficients based on actual threshing accounts in different parishes, in line with Olsson and Svensson (2017a).

Secondly, there are issues of nonstationarity in grain production time series, particularly in the 18th century and beyond, requiring detrending methods in order to obtain reliable and linear estimations of relationships (Jörberg, 1972; Huhtamaa, 2015; Shumway and Stoffer, 2017). At the same time, detrending risks removing information related to the long-term effects of climate variability on grain production (see Esper et al., 2017, and Ljungqvist et al., 2021b, for a discussion of this in the context of historical grain prices). I estimate normalized production anomalies (NPAs) in line with Beillouin et al. (2020) by employing a locally weighted scatterplot smoothing (loess) for each grain as well as total grain production in the HDSA. Beillouin et al. (2020) used the term normalized yield anomalies, but given that this study mainly relies on production or harvest data, the term yield has been substituted with the term production to avoid confusion (since, for example, sowing intensity per area unit can vary, it is often important to distinguish the *harvest* from *yield* in general when discussing agricultural production). A common smoothing span of 0.25 is used for all series. The formula for the NPA is

$$\widetilde{a}_t = \frac{(Y_t - \mu_t)}{\mu_t}, \quad (1)$$

where $\widetilde{a}_\mathrm{t}$ is the normalized production anomaly for a given grain in a cluster or aggregate region at each t year. Y_t is the average of the observed annual production outcome for the specific grain. μ_t is the expected production outcome according to the loess fit.

Thirdly, there is the issue that the HDSA panel is *unbalanced*. Similar to, for example, tree-ring-based temperature reconstructions, with the number of tree rings available for the reconstruction usually declining further back in time (Esper et al., 2016), the number of farms in the HDSA is lower in the early decades of the 18th century (the number of farms also goes down in the final decades of the database coverage). This introduces an increased risk of sampling bias. This problem is partly counteracted by the loess detrending and partly by clustering the data into most similar clusters using hierarchical cluster analysis, as described in Sect. 2.2.

Grain production data are only available up until 1865 in the HDSA. After 1865 there are instead official statistics on grain production on the county and parish levels based on reports from the local rural societies (sw. *Hushållningssällskapen*) up until 1911, henceforth referred to as the BiSOS data (SCB, 2021). I rely on county-level data only. The 19th century Swedish official statistics have been subject to some important criticisms. The manner in which the data were collected varied to some extent locally as it was up to the local representatives in the rural societies to establish data collection procedures (Svensson, 1965). This is less of an issue considering that I do not compare different parishes with the BiSOS data. Moreover, it is commonly argued that total crop production and the amount of arable area are systematically underreported and underestimated in the official statistics. Again, this is not an issue to the extent that I am principally interested in the variations in output over time that are associated with climate variability. There are no obvious reasons to suspect that this part of the variation in output is related to the general underestimation in official statistics. BiSOS data are detrended by applying the same technique as for the HDSA, namely with estimations of NPA (see Eq. 1).

3.2 Clustering

Considering the institutional and geographical diversity of Scania, aggregating the data risks masking location- or type-specific relationships between agriculture and climate or, conversely, some localized trends distorting the overall picture. To homogenize data from the HDSA, obtain clearer signals, and reduce the risk of introducing a geographical or institutional bias by grouping the data by parish, type of farming district, or cadastral status, all villages in the sample are divided into three different clusters using a hierarchical cluster analysis (HCA).

HCA is an algorithmic-based method that clusters the data into "most similar" groups based on a chosen parameter in the data, in this case threshing-adjusted rye production over time on the village level (see Sect. 2.1). Rye was one of the two most important grains during the study period, and since it was mainly grown as an autumn crop it required some specific management practices at the village level and therefore serves as a more appropriate distinguisher than barley or oats. I use an agglomerative HCA, whereby each village initially forms a cluster by itself, pairing up with other villages as the hierarchy "moves up" (Day and Edelsbrunner, 1984). Distances between groups are estimated using the Ward's D method and Euclidean distances. Euclidean distance is the straight line between two points in classical metric space (Howard, 1994). In HCA the true or optimal number of clusters is not known and the number of clusters is therefore determined by some metric or criteria determined by the researcher. Multiple such criteria have been suggested in the literature, often relating to the largest visible or measurable distances between the branches in the cluster dendrogram. One of the most common such metrics is the gap statistic (Tibshirani et al., 2001). Specifically, I use the clusGap function in the factoextra package in R, setting the maximum number of potential clusters at 10 and running 100 bootstrap samples (Kassambra and Mundt, 2020).

Some descriptive and interpretative issues come with this approach. If a resulting cluster consists of several different types of farming districts and administrative units, e.g., parishes, separated into different clusters, then describing, interpreting, and contextualizing results become difficult. In order to reduce the descriptive and interpretative issues related to the HCA, the clustering results thus obtained are contextualized using the most common historical categorizations found in the historical literature when discussing regional specialization in agricultural production, namely the type of farming district (see Sect. 1.3). Clusters are also described in terms of cadastral status and soil characteristics using information available in the HDSA.

3.3 Grain production clusters

Figure 2 shows the cluster dendrogram obtained using the method described in Sect. 2.2, cut at three clusters. Describing these clusters in terms of historical and geographical categorizations, some distinguishing patterns emerge.

Figure 3 reveals that all clusters are represented by villages in the northernmost parishes of Hjärnarp and Tostarp, the forest and mixed farming districts centered around Billinge and Kågeröd parishes, and the parishes located in the forest and mixed farming districts around lake Vomb in southern Scania. Cluster 1 is most heavily represented by the parishes in the proximity of Billinge and Kågeröd as well as around lake Vomb. Cluster 2 is the most geographically spread, covering all of the areas of the total sample, except the plain district parishes around Malmö and Lund. Finally, cluster 3 is mostly concentrated on the parishes around Malmö and Lund, with some villages in parishes around Röstånga and Kågeröd as well as around the southern edges of lake Vomb.

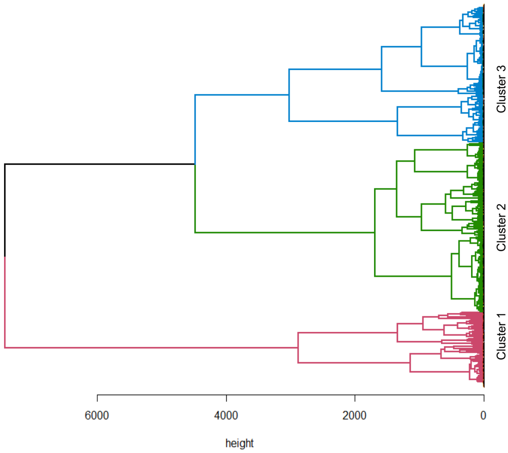

Figure 2. Cluster dendrogram illustrating the sorting process leading to three most similar clusters. Source: HDSA.

Table 1 shows the outcome from the clustering in terms of proportion of arable land in each grade. Cluster 1 has the largest share of the low-quality soils (grade 1 to 4) of roughly 39 %, as well as the least amount of high and moderately high-quality soils (grade 7–8 and 9–10). Cluster 2 has the largest variance in terms of shares in different types of soils as well as the largest share of moderately high-quality soils of ca. 54 %. Finally, cluster 3 has the largest share of the highest-quality soils at 16 %, as well as the largest amount of moderate soils at 44 %.

Figure 4 below shows the number of villages from each type of farming district in the three clusters as well as the institutional make-up in terms of property rights regimes of each cluster (i.e., freehold land owned and managed by peasant farmers, crown land owned by the state but managed by tenants, and manorial land owned by the nobility but managed by their tenants). Cluster 1 is more mixed, with farms in all three different types of farming districts, albeit with most farms in the intermediate and forest districts, with a moderate share of peasant-owned and managed farms. Cluster 2 has the largest number of manorial farms and almost all farms are located in the intermediate and forest districts. The largest number of plain district farms can be found in cluster 3, which also has the largest number of crown and peasant-owned farms. Furthermore, cluster 3 contains almost no intermediate district farms and a moderate number of farms in the forest districts.

In terms of grain production, cluster 3 has the largest average production of all grains over time as well as the largest

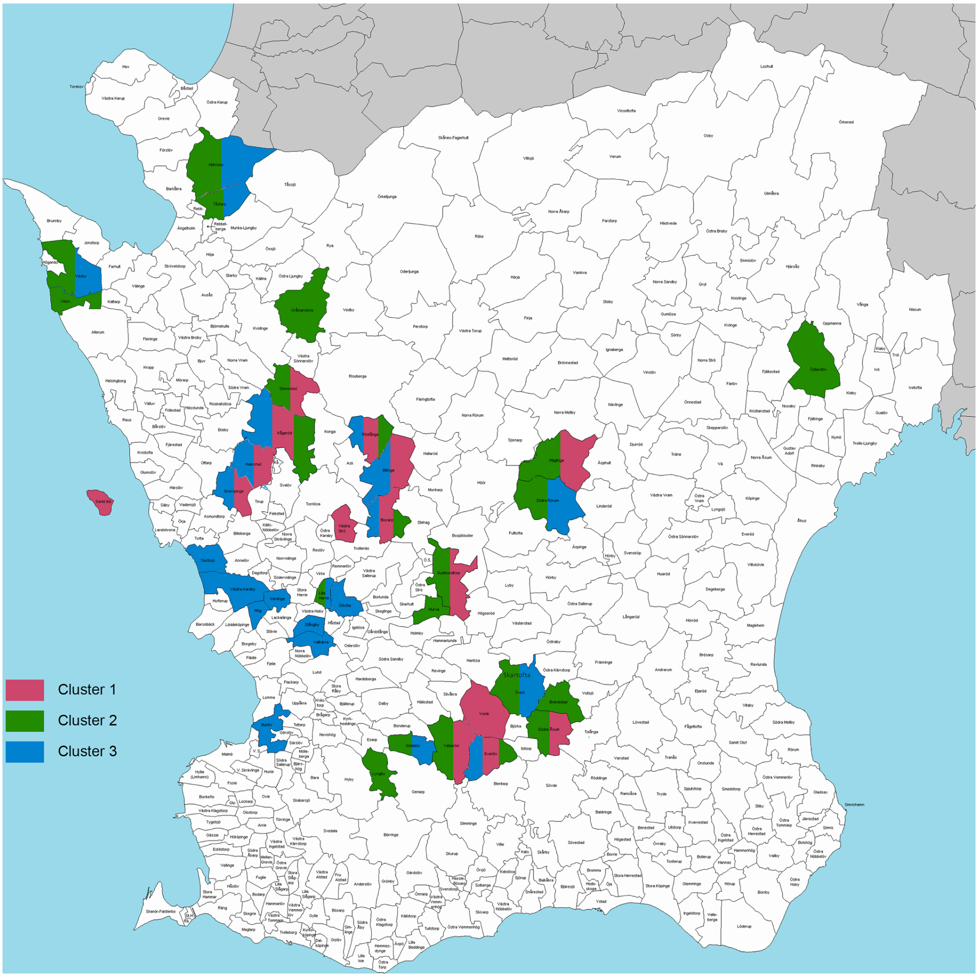

Figure 3. Geographical and administrative (parish) representation of each cluster. Source: author's own edit of the parish map of Scania from Wikimedia Commons (Mrkommun, 2010).

share of rye and barley in its production, which is not surprising given that it has the largest share of plain district villages as well as the largest share of the highest-quality soils, as shown in Fig. 5. Cluster 2 has similar average production levels as cluster 3 in the first decades of the 18th century, followed by a slight stagnation for the rest of the century, then by large increases in production of all grains, in particular oats, during the first half of the 19th century. The cluster with the lowest-quality soils, cluster 1, also has the lowest average production levels, although it shows continual increases throughout the period 1702–1865.

To summarize, cluster 1 is institutionally mixed and has the lowest-quality soils; cluster 2 is more manorial, has the largest share of soil grades 6–10 of all the clusters, and is the most geographically spread cluster. Finally, cluster 3 is mostly peasant-owned or managed and has the largest share of the highest-quality soils (grade 8–10) and lands in the plain districts, notably in the plains around Lund. Average production levels increase in ascending order from cluster 1 (the lowest) to cluster 3 (the highest), although there is some variation over time.

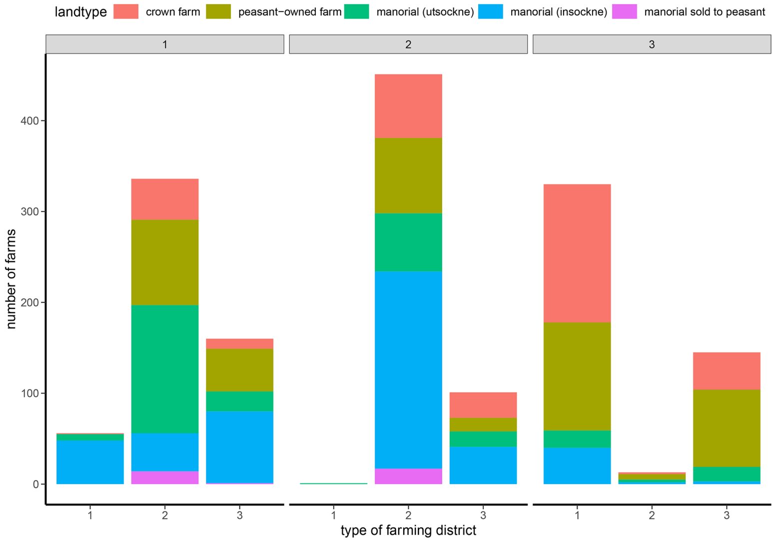

Figure 4. Institutional status of farms, including type of farming district. Each bar plot represents a cluster with each cluster denoted in the grey-marked area. 1 denotes plain districts, 2 mixed districts, and 3 forest districts. Source: HDSA.

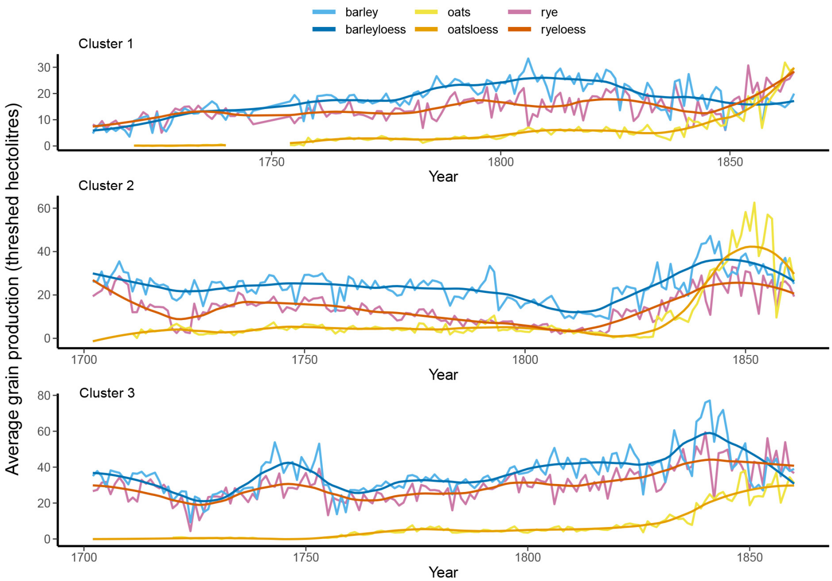

Figure 5. Average grain production (threshed hectoliters) in each cluster over time, including estimated loess. For cluster 1 the years 1743–1746 are covered by only one farm, heavily skewing the average for those years. Therefore, I have substituted the values for rye and barley for the years 1743–1746 with values obtained from a linear estimation of the relationship between the production of that farm and the average production in the cluster in the years 1727–1742. Source: HDSA.

Table 1. Descriptive statistics for each cluster, including proportions of soils of different qualities.

Clusters 1–3	1	2	3
Years covered	1711–1864	1702–1861	1702–1860
Villages	173	137	71
Village-level observations	8511	4311	5551
Farms	481	514	389
Farm-level observations	32 420	22 054	31 432
Soil grades by proportion in each cluster			
1	0	0.001	0
2	0	0.001	0
3	0.16	0.04	0.01
4	0.23	0.11	0.08
5	0.15	0.12	0.25
6	0.16	0.16	0.19
7	0.15	0.38	0.10
8	0.07	0.15	0.21
9	0.02	0.04	0.01
10	0.06	0	0.15

Note that there are no grade 1–2 soils in the sample, whereas the amount of the highest-grade (8–10) soils is quite large. Source: HDSA.

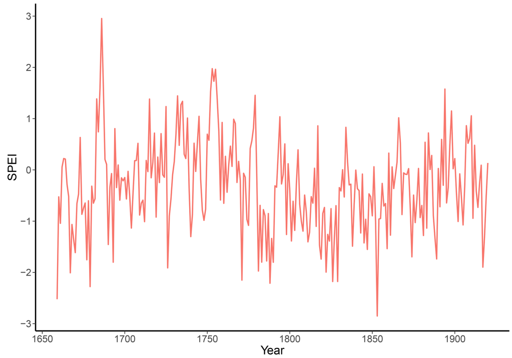

Figure 6. Reconstruction of southern Scandinavian SPEI, 1659–1920. Source: Seftigen et al. (2017).

3.4 Sources on the climate

Temperature is one of the most important agrometeorological indicators, especially during the growing season. Instrumental temperature measurement data are available from the city of Lund from the year 1753. The series contains gaps and has several noted inhomogeneities in the form of instrument relocations, instrument replacements, and changes in observers (Tidblom, 1876). For the purposes of this study, the temperature series was homogenized and gaps were filled using adapted Caussinus–Mestre algorithm (ACMANT) software relying on the target unhomogenized temperature series as well as a network of homogenized temperature series (Domonokos and Coll, 2017). The homogenization procedure is further detailed in Appendix A. Results of the homogenization procedure are also presented and discussed in Sect. 3.2 and 3.4. I use a homogenized monthly temperature time series centered on Lund from 1702–1865, including infilling of gaps between 1702–1752 and 1820–1833.

I also use precipitation data from Lund, available from 1748, as well as the number of rainy days per month (Tidblom, 1876). Hydroclimate is much less spatially coherent compared to temperature; hence, a similar homogenization approach in line with the temperature series is not suitable. Therefore, I supplement the instrumental precipitation data with regional hydroclimate reconstructions. I use three hydroclimate reconstructions. The first, from Cook et al. (2015), is a Palmer Drought Severity Index (henceforth, PDSI) reconstruction from the Old World Drought Atlas, covering the entire study period; I use the grid cell centered at 55.75° N, 13.75° E, roughly corresponding to east-central Scania. The second is a reconstructed standardized precipitation–evapotranspiration index (henceforth, SPEI) for southern Scandinavia compiled by Seftigen et al. (2017), which also covers the whole study period (see Fig. 6). These two reconstructions are independent and based on mutually exclusive data. The third and final hydroclimate reconstruction is a May through July precipitation reconstruction (henceforth, MJJ*pr*) by Seftigen et al. (2020) based on the wood densitometric indicator referred to as blue intensity (BI), covering the period after 1798. The second and third reconstructions are not strictly independent given that they are based on the same tree-ring data, although they are extracted using different methods and the MJJ*pr* is more oriented towards capturing high-frequency variability (Seftigen et al., 2020).

For the period after 1865, I use monthly average, minimum, and maximum temperatures and monthly accumulated precipitation instrumental data, also from Lund, available at the Swedish Meteorology and Hydrology Institute (SMHI, 2021), as well as the hydroclimate reconstructions mentioned above. I also use daily air temperature data from Lund during the period 1863–1911 to calculate the average occurrence of the first autumn frost and last spring frost. Given that ground temperature can vary from air temperature, I use a slightly conservative estimate; days with 1 °C or less in average temperature between January and May are considered days with spring frosts and between June and December are autumn frosts. These estimates are then compared to estimations made by SMHI for the period 1960–1990.

Some studies employ climate variables based on annual change, month-to-month changes, or anomalies from some long-term or moving trend when estimating the relationship between historical grain production and climate (Brunt, 2004; Edvinsson et al., 2019; Bekar, 2019). However, the evidence of any potential information added by increasing the complexity of the climate variable involved has been limited (E. Vogel et al., 2009; M. M. Vogel et al., 2019). Thus, I follow the example of Beillouin et al. (2020) and use "simple" climate variables.

3.5 Estimating the relationship between grain production and climate

The main analysis is based on cluster-wise Pearson correlation analysis of pairs of variables. I estimate correlation coefficients between annual normalized yield anomalies of rye, barley, oats, total grain production, and climatic variables on a monthly and seasonal basis using HDSA for the early study period 1702–1865 and the BiSOS data for the later period 1865–1911. Given that harvesting was usually completed in late August or during September, I have used lagged (i.e., the values from the previous year) climatic variables for the autumn and early winter months (OND). In addition, I estimate the same relationships during drier and wetter years, respectively. Wet and dry years for the HDSA are defined according to the 33rd (dry) and 67th (wet) percentiles of the SPEI during the period 1651–1951. For the HDSA period, this translates to 58 dry years and 55 wet years (see Tables B1 and B2 in Appendix B). Due to the low n in the latter period 1865–1911 ($n = 47$), I split the data into two halves, each representing the lower (drier, $n = 23$) and higher (wetter, $n = 24$) halves of the SPEI during those years (see Tables B3 and B4 in Appendix B).

4 Results

4.1 Estimations of past temperatures and frequencies of growing season frosts in Scania

In this section, I present the results from the estimations of two agrometeorological indicators, both specifically related to temperature. First, I present the main results from the monthly temperature series homogenization for the early study period. Second, I describe the results regarding the average occurrence of the first autumn frosts and last spring frosts during the late study period.

4.1.1 Monthly temperature series homogenization

After homogenization of the Lund monthly temperature series, the largest corrections occur during the summer (JJA) and autumn (SON) months, with temperatures adjusted upwards, especially during the late 18th century (see Figs. 7 and 8). There is a slight tendency for upwards adjustments for the spring (MAM) and winter (DJF) temperatures as well, although it is comparably small. Several breaks were detected in the temperature series, almost exclusively at points in time when there was a change in observer and change in observation location (see Appendix A). The largest breaks occurred in the late 18th century, and smaller inhomogeneities were detected throughout the early instrumental period, except for the 2 earliest decades, 1753–1774, when no significant breaks were detected. The homogenization process is discussed in more detail in Appendix A.

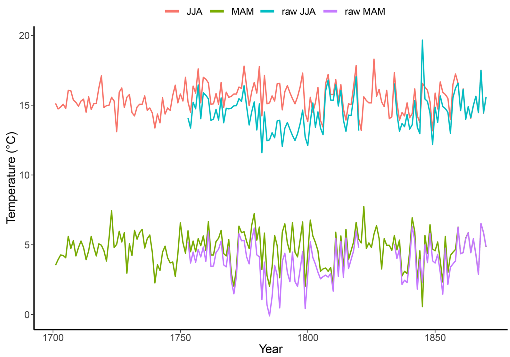

Figure 7. Raw and homogenized seasonal JJA and MAM mean temperatures at Lund, 1701–1870. Sources: Copenhagen (Cappelen et al., 2019), Berlin–Dahlem (DWD, 2018), De Bilt (Durre et al., 2008; Lawrimore et al., 2011), Lund (Tidblom, 1876), Uppsala (Bergström and Moberg, 2002), and Stockholm (Moberg et al., 2002; Moberg, 2021). Note: see Appendix A for a further discussion of the homogenization process.

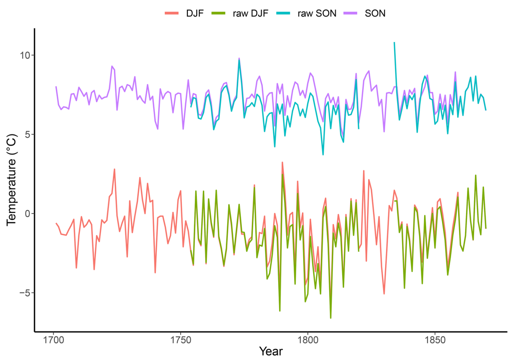

Figure 8. Raw and homogenized seasonal DJF and SON mean temperatures at Lund, 1701–1870. Sources: Copenhagen (Cappelen et al., 2019), Berlin–Dahlem (DWD, 2018), De Bilt (Durre et al., 2008; Lawrimore et al., 2011), Lund (Tidblom, 1876), Uppsala (Bergström and Moberg, 2002), and Stockholm (Moberg et al., 2002; Moberg, 2021). Note: see Appendix A for a further discussion of the homogenization process.

4.1.2 Average occurrence of the first autumn frost and last spring frost, 1863–1911

The average date for the last spring frost during the 1863–1911 period was 15 April. In almost half (44 %) of these years, there were no occurrences of temperature measurements below 1 °C. Only 2 years experienced late spring frosts in May, namely the years 1864 and 1867, in which the latest estimated spring frost was 24 May in 1867, a year which is known for its exceptionally cold spring (Västerbro, 2018). The average date for the first autumn frost was 8 November. The earliest estimated autumn frost occurred on 16 October 1879. These dates are similar to those estimated by SMHI using data from the 1960–1990 period, for which the average date for the first spring frost was between 1 and 15 April in the western and southwestern edges of Scania, between 15 April and 1 May for the rest of western and southern Scania, and finally between 1 and 15 May in northern and northeastern Scania (SMHI, 2017a). The average date for the first occurrence of autumn frosts follow a similar geographical pattern, e.g., between 15 November and 1 December for the western edges of Scania to between 1 and 15 October for the northernmost forested areas bordering Småland (SMHI, 2017b).

4.2 Relationship between climate variability and grain production

In this section, I present the correlation results between climate and grain production indicators in the early and late study periods, respectively. Furthermore, I present correlation results of restricted samples with years including dry or wet summers analyzed separately.

4.2.1 Grain production and climate variability 1702–1865

During the bulk of the period of 1702–1865, there is a negative association between summer temperatures and grain production in all three clusters, with July and June producing the strongest signal, as shown in Fig. 9. May yields low negative correlation coefficients for rye in clusters 1 and 3, and August yields a low negative coefficient for barley in cluster 1. Overall, the signal obtained from the oats series is weak and mostly divergent from the other grains, except for its strong positive association with a higher SPEI, i.e., wetter summer conditions, which it has in common with the other grains. The seasonal temperature indicators largely correspond to monthly indicators, with JJA consistently showing strong negative associations with total grain production in all clusters. Except a low positive association between oat production and spring temperatures in cluster 3, monthly and seasonal temperature indicators for the spring and autumn give almost no statistically significant results.

The results revealed by Fig. 10 for monthly summer precipitation show the inverse of those of temperature and hydroclimate: strong positive correlations with grain production. In addition, there are more differences between the various clusters and grains. There are no significant correlations between rye production and the instrumental summer precipitation variables, although in clusters 2 and 3 there is a positive correlation with reconstructed MJJ. On the other hand, there is a negative association between January (and February in cluster 1) precipitation and rye production in all clusters. Barley, oats, and total grain production all show large positive correlations with June and July precipitation and with reconstructed MJJ. The number of rainy days in June and July produce a strong positive signal in relation to almost all grain production, especially barley production, in clusters 2 and 3. There is also a positive, albeit weak, association between the number of rainy days in May and oat production in cluster 2 and rye production in cluster 3.

Overall, the magnitude of the correlations are similar across grains and climate indicators, except correlations involving barley production that provide the strongest effects. Cluster 3 stands out in relation to the other clusters in producing a stronger signal between most grain production and precipitation.

4.2.2 Grain production and climate variability 1865–1911

The results from the later study period, depicted in Fig. 11, are for the most part consistent with those of the earlier period using the HDSA data, although only for the spring grains (excluding spring rye and spring wheat). Notably, the coefficients are much higher for the latter period compared to the earlier period: roughly double in magnitude. May and to a larger extent June and July temperatures are negatively associated with the series for oats, barley, and mixed grain. Furthermore, maximum and minimum June temperatures also yield negative coefficients. Similar to the 1702–1865 period, the SPEI is positively correlated with the spring grains. The related MJJ*pr* yields positive coefficients which are strong (between $r = 0.46$ for barley and $r = 0.57$ for oats). June precipitation is positive for the three spring grains, whereas no statistically significant results are obtained for July, which is surprising considering the importance of July precipitation in the period 1702–1865. Autumn rye and autumn wheat only show one statistically significant relationship each, with November precipitation for autumn rye ($r = -0.41$) and with MJJ*pr* for autumn wheat ($r = 0.46$).

4.2.3 Grain production and climate variability during years with dry and wet summers

Repeating the analysis on restricted samples for which only the years with the driest and wettest summers are included, the direction of the relationships remains consistent. Figure 12 shows the results of the correlation analysis in the early period considering only dry years (as defined by the SPEI). The magnitude of the negative association between summer temperatures and all grain production except for oats increases, yielding correlation coefficients between -0.3 and -0.52.

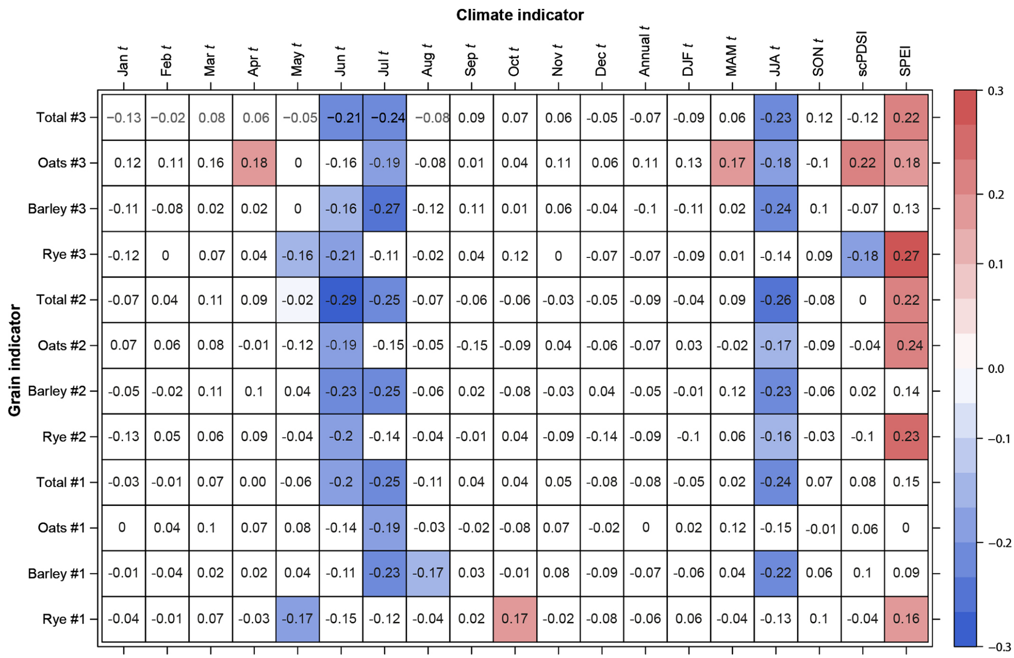

Figure 9. Correlations of grain series vs. temperature and hydroclimate indicators, ca. 1702–1865. Note: only statistically significant ($p \leq 0.05$) correlations are colored. Clusters are signified by number. Sources: HDSA, Cook et al. (2015), Seftigen et al. (2017), and the homogenized monthly temperature series (Appendix A).

There is no statistically significant effect from monthly summer precipitation except for the MJJ*pr*, which shows a positive association with most grain production in all clusters except oats in clusters 2 and 3. Considering only wet years in the early period (Fig. 13), summer temperatures are still negatively associated with grain production in all clusters, especially cluster 1. Additionally, there is a positive association between rye production and September temperatures in clusters 2 and 3 in wet years. Notably, the highest correlation coefficients are obtained by the correlation between grain production and precipitation during June, and especially July, during wet years in the early 1702–1865 period (r between 0.31 and 0.78).

5 Discussion

The main result obtained in this study was the negative association between all grain production and summer temperatures as well as a corresponding positive association with summer precipitation, especially during the high summer months of June and July, in the early study period (1702–1865) and for spring crops in the late study period (1865–1911). Another important finding was the lack of signal for autumn grains in the late study period as well as the weak relationship between autumn and spring temperatures and grain production during the whole study period. Finally, during homogenization of the monthly temperature series from Lund a cold bias was identified in the late 18th century and multiple statistically identified breaks, almost all of which could be associated in time with changes in observers and/or instrument locations. In the following sections, all these results are discussed in more detail.

5.1 The relationship between temperature, precipitation and grain production across the seasons

For roughly 2 centuries, between the early 18th and early 20th centuries, the results of this study show that Scanian grain production had a reversed relationship to temperature compared to other parts of Scandinavia, as well as other parts of Europe (Esper et al., 2017; Pribyl, 2017; Brunt, 2015; Holopainen et al., 2012; Waldinger, 2012; Holopainen and Helama, 2009). This merits some further discussion.

Precipitation and drought during the growing season were pointed to by Utterstörm (1957) and later by Edvinsson et al. (2009) as the primary agrometeorological constraints for

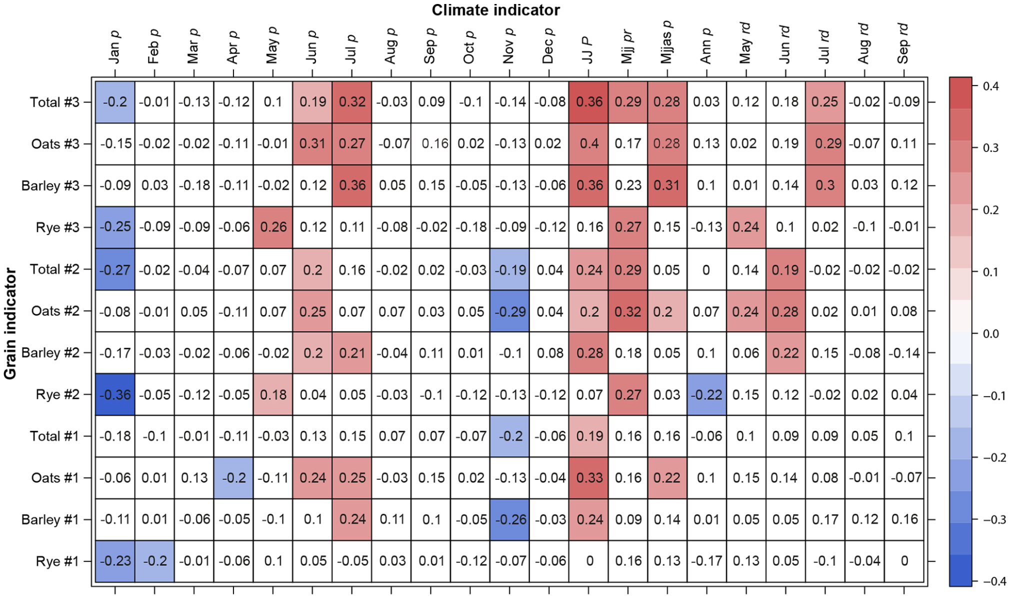

Figure 10. Correlations of grain series vs. precipitation indicators, ca. 1748–1865. Note: only statistically significant ($p \leq 0.05$) correlations are colored. Clusters are signified by number. Sources: HDSA, Sefitgen et al. (2020), and Tidblom (1876).

pre-industrial agriculture in southern Sweden. Much of the arable land in Scania, as elsewhere in southern Sweden, was situated on well-drained and elevated soils, whereas meadows were often on more low-lying and wet soils (Dahl, 1942; Gadd, 2001). These circumstantial factors, combined with the consistent findings of negative associations with June and July temperatures and positive associations with precipitation in June and July, indicate that summer drought was the greatest agrometeorological risk to grain production. Relative to the benefits of intensive grain production in the region, this was by all accounts a risk worth taking. Indeed, most of the land improvements that occupied farmers in the 19th century after enclosures were about transforming wetter lands to well-drained arable lands, primarily through ditching, rather than efforts to preserve soil moisture (Bohman, 2010).

Nonetheless, it is worth considering what farmers could do to mitigate the risk of drought: in regards to the grain cultivation on well-drained soils, probably very little. It was after all the very same characteristics in the soil that increased the risk of drought that also made a large production of grains possible. Grain production in the cluster with the best soils in this study, cluster 3, showed a relationship with climate variability that was of similar or greater magnitude than the other clusters. Cluster 3 also has the largest share of peasant-owned and crown-owned farms. Theoretically, it can be expected that with increased private ownership of farms, risk-taking will also increase in comparison with tenant farms. One concrete example of such risk-taking would be to make long-term land improvements in the form of drainage. A version of this argument is commonly made in reference to enclosure. Nyström (2018), for example, found that enclosed farms experienced more risk in agricultural production compared to non-enclosed farms in Scania during the period 1750–1850. The results obtained here support the notion that privately owned farms engaged in greater risk-taking. However, a more conclusive affirmation of this hypothesis in the Scanian context would require a more in-depth study of farms with similar soil characteristics but different property rights regimes.

The extensive land reclamation efforts that took place during the 18th and 19th century could have helped mitigate drought as an unintentional and temporary side effect by making new lands of variable qualities, not least in terms of drainage, available (Håkansson, 1997). A diversified composition of grain production also helped to some extent to make grain farming more resilient in Scania. The slight but important variation *between* the grains in terms of their relationship to summer temperatures and precipitation, with oats and rye more sensitive to variation in May and in particular June and barley more sensitive to variation in July, accordingly spread out risks. Diversity *within* each grain variety would also have been helpful in mitigating the risk to drought or other cli-

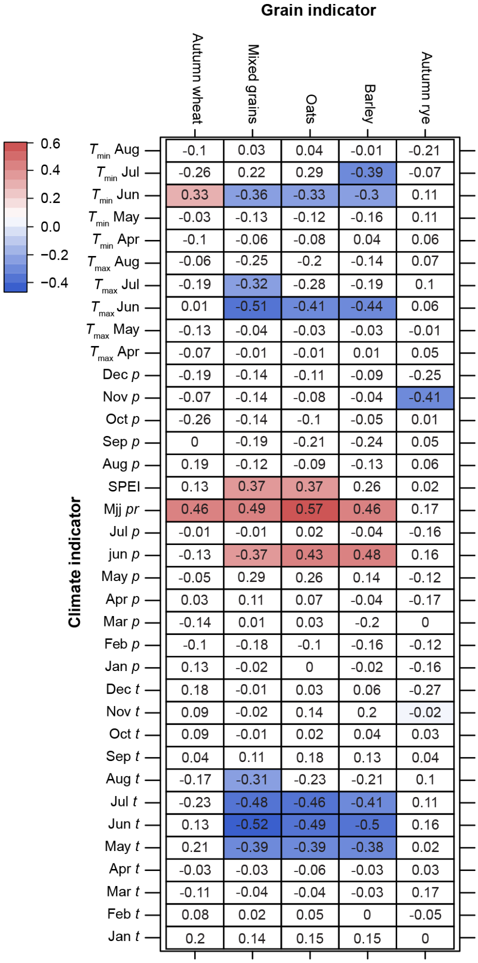

Figure 11. Correlations of grain series vs. climate indicators 1865–1911. Note: Only statistically significant ($p \leq 0.05$) correlations are colored. Sources: SCB (2021), Seftigen et al. (2017, 2020), and SMHI (2021).

mate anomalies (Hagenblad et al., 2012, 2016; Leino, 2017; Lundström et al., 2018).

As noted in Sect. 1.4, Edvinsson et al. (2009) suggested that before the agrarian transformations in the 18th and 19th centuries, yields were in general so low as to lead to a chronic shortage of seeds, which they suggested overrode the effects from climate variability and hence the weak relationship between temperatures and grain yields. Theoretically, low yields leading to low seed quantities could obfuscate the effect of temperature, necessitating some kind of control for the previous year's weather. For example, Bekar (2019) found that English manorial harvests in the 13th and 14th centuries were persistent, i.e., subpar harvests, partly induced by "weather shocks", persisted into the subsequent year for both wheat and other grain crops like barley and oats. Notwithstanding these results, the relevance of 14th century England for 18th century Scandinavia is arguably limited. In instances in which one might assume persistent harvests would be more apparent (although it is arguably an understudied phenomenon), like northern Finland, one still finds strong current-year temperature effects on grain yields and production during the early modern period (Huhtamaa and Helama, 2017b; Huhtamaa, 2015; Solantie, 1988). Having limited amounts of seed did not obfuscate or exclude the effects from weather. Rather, the evidence seems to suggest it made farmers more vulnerable and the effects more apparent. There are few reasons to suspect that chronic seed shortages were a major issue in 18th century Scania, given that it was mostly an exporter of grains and experienced more or less ongoing increases in production during the period (Olsson and Svensson, 2010).

In relation to this argument, I would highlight another important result of this study, namely the absence of a climate signal in the spring and autumn months, as well as the last summer month of August to some extent. In the neighboring lands of Denmark, Huhtamaa and Ljungqvist (2021) suggest that it is possible that frosts were not a major problem, even in the wetter and colder periods of the LIA. The results from Sect. 3.1.2 show that the average date for the first occurrence of autumn frost in Lund was 8 November and not earlier than October in the northernmost areas of Scania, well after the harvest month of August as well as the sowing of autumn rye. In many years there were no spring frosts later than March, whereas in those years when they occurred after March the average date was 15 April in Lund. In the highlands in the north, spring frosts on average occurred later. Nonetheless, spring frosts, when they occurred, generally did so just before or at the start of the growing season. Thus, the results in this study point to spring and autumn frosts not being a systematic threat to grain production, except in localized conditions. An implication of this is that the combination of the climate in Scania with the farming systems Scanian farmers adhered to offered good margins for the spring and autumn agricultural work seasons, for example by allowing for delays in sowing and harvesting.

Based on the findings in this study, I would revise the notion forwarded by Utterström (1957) and Edvinsson et al. (2009). It was not only precipitation but rather the combination of temperature and precipitation during the summer that constituted the main constraints for the production of spring grains during the whole study period and for all grains in the early study period. Furthermore, I would not only frame the relationship in the form of constraints and risks. Grain farming in Scania was adapted to, and benefitted by, cool and humid summer conditions. Even in years

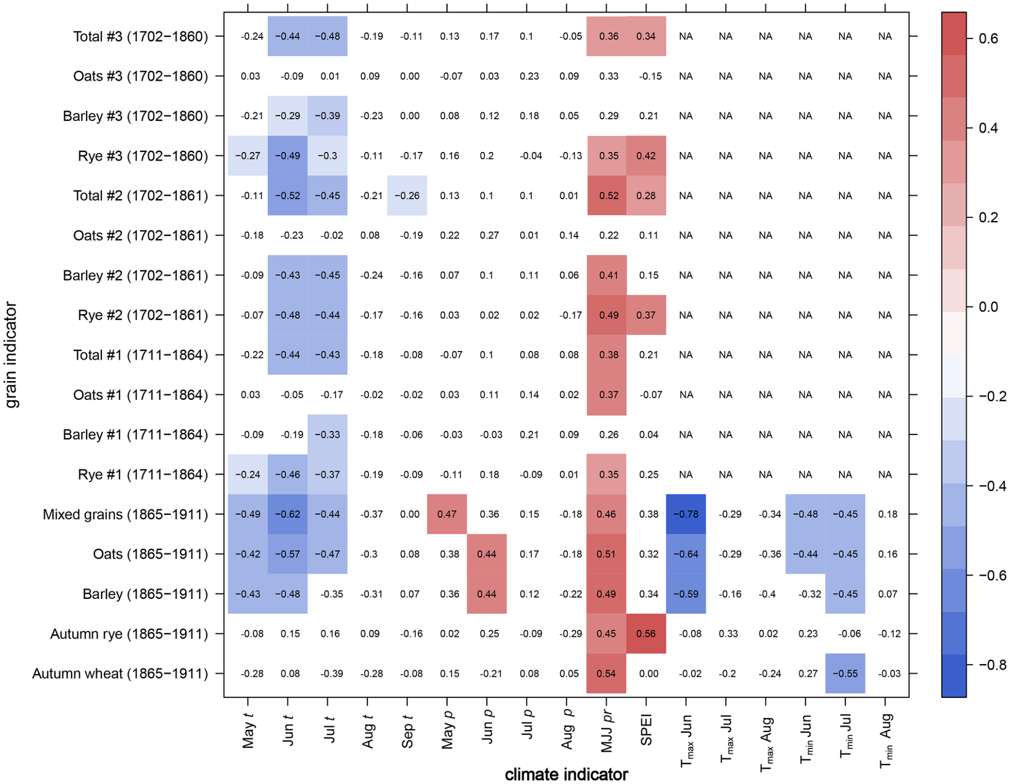

Figure 12. Correlations of grain series vs. climate indicators ca. 1702–1865 and 1865–1911 during relatively dry years. Note: only statistically significant ($p \leq 0.05$) correlations are colored. Clusters are signified by number. Sources: HDSA, SCB (2021), Tidblom (1876), Seftigen et al. (2017, 2020), SMHI (2021), and the homogenized monthly temperature series (Appendix A).

with wet summers there was a positive association between grain production and summer precipitation and a negative association between the former and summer temperatures. This would likely also be the case in other parts of southern Sweden where similar grain varieties were cultivated in the same type of farming systems on well-drained soils. In the later study period, both maximum and minimum June and July temperatures were negatively correlated with the production of spring grains, suggesting an optimal temperature range for these crops during these months and that the occurrence of extreme cold and heat had some detrimental effect.

5.2 The role of grain varieties

An account of the relationship between grain production and climate variability has to account for the type and varieties of grains being cultivated as well as the farming system more broadly. In Scania in the late 19th century, new autumn grain varieties, similar to those on the European continent, gradually replaced the old varieties that were more similar to those in other parts of Fennoscandia. I argue that this, rather than changes in the climate, was the most likely cause behind the diminished signal in the relationship between climate variability and autumn grains in the latter study period, given that the relationship with climate variability remained intact for most of the spring crops. Edvinsson et al. (2009) also argued that the shift towards new grain varieties changed the underlying relationship between grain production and climate variability from a negative to a positive association with temperatures, especially in the spring and early summer. The farming systems of Scania likewise underwent changes whereby arable lands were expanded and intensified with new crop rotations, land improvements, increased drainage, external sources of fertilizer, and burgeoning mechanization. All these changes created conditions that were more favorable for the new grain varieties.

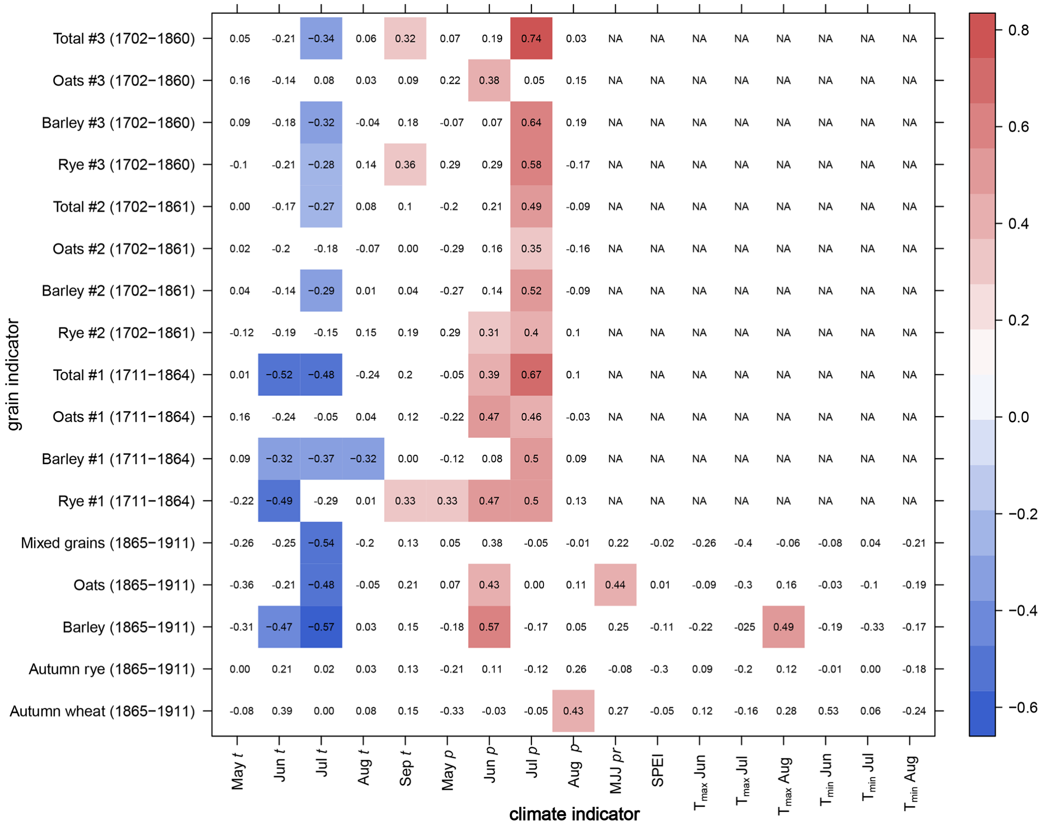

Figure 13. Correlations of grain series vs. climate indicators ca. 1702–1865 and 1865–1911 during relatively wet years. Note: only statistically significant ($p \leq 0.05$) correlations are colored. Clusters are signified by number. Sources: HDSA, SCB (2021), Tidblom (1876), Seftigen et al. (2017, 2020), SMHI (2021), and the homogenized monthly temperature series (Appendix A).

Nonetheless, it is possible that climate changes over a longer timescale were an active driver in the relationship between climate variability and grain production, considering that the historical grain varieties were changeable and adapted to changing circumstances, not least climate variability at different timescales (Leino, 2017). It can be argued that farming in Scania during the 17th up until the late 19th century had adapted over time to a more cool and humid summer climate, having experienced multiple cold years and extended periods with reduced average temperatures during the LIA in the 16th and 17th centuries, possibly earlier as well. Current evidence suggests that the grain varieties cultivated during these centuries were similar to or of the same group of varieties grown in more northerly and cold latitudes. For example, in regards to rye, Larsson et al. (2019) found through genetic analysis of preserved Fennoscandian rye seeds that they all belonged to the same meta-population of rye landraces that had been stable for at least the last 350 years. Similarly, Aslan et al. (2015) found that barley landraces from Fennoscandia form a homogenous group of barley landraces, distinct from other parts of Europe. This particular group of northern European barley varieties carries the nonresponsive ppd-H1 allele that prolongs flowering when exposed to periods with increasing daylight hours. Presumably, this would be beneficial during cooler and wetter periods by taking full advantage of the extended growing season. Studies of modern Finnish barley cultivars have shown that yields for most varieties are negatively correlated with excess rain or drought around the sowing season and positive in the subsequent stages of crop development, whereas they are negatively correlated with temperature at most stages of crop development, especially before heading (Hakala et al., 2012). The homogeneity of barley landraces over time in southern Sweden was confirmed by Lundström et al. (2018), who traced it back to at least the late 17th century. While Lundström et al. (2018) argued that such homogeneity was maintained *despite* repeated crop failures in southern Sweden between the 1700s and the 1900s, I would argue, at least when considering Scania, that such homogeneity was probably maintained because of the *lack* of repeated crop failures.

The discussion of the results on the relationship between specific grains and climate variability should also be put in a broader perspective. In terms of crop composition and the type of field system (a Swedish variant of the open-field systems called *tegskifte*), the farming systems of Scania remained more or less the same until the 19th century, when enclosure and new crop rotation systems started to be introduced, starting in the plains districts. All the same, even after the introduction of new crop rotations, which normally meant increasing shares of fodder crops, in Scania grain production continued to retain its primacy, at least in the plains districts (Bohman, 2010). This motivates the argument that the farming systems of Scania overall were resilient to colder conditions, at least until the late 19th century, given the importance of grain production. However, the relationship between livestock production, total agricultural production, and climate variability would require a study of its own.

5.3 Implications of the late 18th century cold bias and ACMANT detected breaks

Previous research that identified increasing soil erosion and sand drift in Scania during the 18th century partly blamed the coldness of the last 4 decades of the 18th century as indicated by the instrumental temperature measurements taken in Lund (Mattsson, 1987). After homogenization of the Lund temperature series 1753–1870, the largest corrections due were for upwards adjustments for summer temperatures in the same period, i.e., the late 18th century. In other words, the results suggest that the ca. 1770–1800 period was not as cold as suggested by Mattsson (1987) or the unhomogenized Lund temperature series. While these findings speak against a regional climate-driven ecological crisis, they do align with the results of Bohman (2017a, b), who downplayed the spatial scale of the ecological crisis, emphasizing its local and conditional character, as well as the counteracting efforts by local communities and authorities.

The breaks detected through the ACMANT procedure could almost all be associated with changes in observers and/or instrument location. While there is uncertainty in the number of times the instruments were replaced, those known could not be associated in time with the detected breaks. This suggests that the human factor, i.e., the degree of consistency in training, skills, and interest in observers, was the primary determinant in measurement quality and homogeneity. Faulty instruments or station location biases could in the end only be perceived, understood, and subsequently corrected or adjusted for by the human observer. The first decades, 1753–1774, can be considered a period of more competent (meteorological) observers, followed by the period after ca. 1850 when training and methodologies in meteorological observations had improved. Nonetheless, for most of the homogenization period there were issues of inhomogeneity requiring corrections.

5.4 Hydroclimate and historical grain production

Three different hydroclimate reconstructions were employed for this study. In the early period (1702–1865) very few and mostly inconsistent results were obtained using the scPDSI from the OWDA (Old World Drought Atlas), and no statistically significant results were found for the late period (1865–1911). The SPEI from Seftigen et al. (2017) was found to be positively associated with most grain production except barley, consistent over different samples and periods as well as with results from instrumental precipitation. The results of the MJJ*pr* and SPEI could be interpreted as more important for estimating hydroclimatic conditions relevant for grain production in the early summer (May and June, in particular). This is supported by the lack of statistically significant effects found between May and June climate variables and barley production as well as the fact that the most important month for barley seems to have been July, at least in the early period. This also offers an explanation as to why sorting dry and wet periods with the SPEI indicator led to much larger associations between precipitation and temperature in June and July with grain production. If conditions were wet or dry in the early summer, the effects from subsequent temperature and precipitation later in June and especially July would theoretically have been amplified. A similar argument was made by Brunt (2004), who showed that it was more beneficial to have precipitation spread out during the growing season. An important caveat to these interpretations is that a large degree of uncertainty remains as to what specific hydroclimate effects are captured by or represented in these reconstructions, beyond MJJ or JJA averages. Nonetheless, there does seem to be a relationship between the conditions for tree growth in southern Sweden as represented in these reconstructions and grain production in Scania during the study period. Seftigen et al. (2015) asserted that even though most high-resolution climate proxies in northern-latitude regions are temperature-based, there is also a need for precipitation-based proxies due to the importance of precipitation patterns for economic sectors such as agriculture. The results obtained here confirm both the importance of precipitation patterns for agriculture and the relevance of the proxy reconstructions in studying that relationship.

6 Conclusions

This article demonstrates the possibilities of estimating the relationship between climate variability and grain production in Scania during the pre-industrial period using available grain production data, climate reconstructions, and the network of early instrumental records. Grain production in Scania did not show any systematic relationship or vulnerability to climate variability in the spring and autumn seasons, whereas a more clear signal could be detected between grain production and climate variability during the summer season, especially in the months of June and July. Until the introduction of new varieties of autumn crops in the late 19th century, grain production was benefitted by cool and wet conditions throughout the summer, although there was a slight but important differentiation between rye and oats, which were more sensitive to conditions in May and June, and barley, which was mostly sensitive to conditions in July. The most apparent agrometeorological risk was summer drought. However, severe droughts like the one in the summer of 2018 were rare in Scania and the diversification within and between historical grain varieties cultivated meant that, by and large, this risk was manageable, especially when compared to the benefits of intensive grain production in the region. Scania largely conforms to the previous, albeit sparse, picture in the Swedish historiography of the relationship between historical grain production and climate in southern Sweden. At the same time it stands out compared to studies of other parts of Scandinavia and continental Europe wherein positive associations between grain production and summer temperatures have been identified.

The results obtained here should be further developed by integrating them into a broader model of the impacts of climate variability on agriculture, with other factors, e.g., market prices and access as well as institutional and other geographical factors like soil conditions, formally accounted for. This need is not least implied by the fact that even in the confined geographical area of Scania there was differentiation among sets of villages in regards to the relationship between their grain production and climate.

Appendix A: Homogenization of the Lund temperature series

Daily meteorological observations began in Lund in 1740, spearheaded by the professor of mathematics Daniel Menlös. Systematic instrumental meteorological observations began in 1747 for precipitation and late 1752 for temperature and air pressure under the responsibility of a formally appointed observer. Naturally, these observers changed over time. Instruments were also replaced or upgraded on a few occasions. More problematic from a perspective of consistency and reliability, the location of the instruments also changed multiple times. There is also a gap in (quality) temperature measurements between the years 1821 and 1833 as well as some other minor gaps over the period 1753–1870 (see Fig. A1). Issues relating to the nonhomogeneity of these meteorological series, not least the temperature series, were already

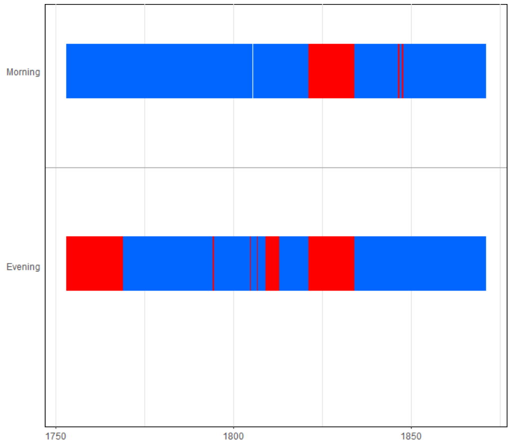

Figure A1. Gaps in the Lund temperature series, 1753–1870. Source: Tidblom (1876). Note: blue signifies available data and red signifies a gap. Measurement units are in the form of pentad (5 d) averages.

partly identified and discussed in the 19th century by Tidblom (1876). Schalén et al. (1968) and Bärring et al. (1999) also discussed inhomogeneities in the series relating to the station history.

Tidblom (1876) published the Lund temperature series in the form of pentad averages. He removed the daytime measurements and used only the morning and evening measurements, arguing that these were less affected by the location of the thermometer. He also did some minor manual corrections for September through December in 1834 and individual days in June in 1842 and 1843. Overall, the adjustments made by Tidblom (1876) should be considered minor and it seems probable that inhomogeneities remain in the series. Nonetheless, the temperature series have subsequently been employed in at least a few historical studies. For example Palm (1997) used the series to estimate the impact of temperature variations on grain yields on a farm in Halland, southwestern Sweden, during the years 1758–1865. To fill in the gaps Palm bridged the Lund series with data from Copenhagen using average differences. Mattsson (1986) observed the trends in the Lund series and argued that a reduction in temperatures in the last 3 decades of the 18th century, combined with changes in wind patterns, contributed to widespread soil erosion in Scania during the 18th and early 19th centuries. Using inhomogeneous data sets carries many important drawbacks, not least the risks of spurious and unreliable results (Aguilar et al., 2003). Hence, it is necessary for the purposes of this study to homogenize the temperature series.

Given that the exact location and relocations of the measurements for the period up until 1780 are unknown, it is difficult to identify periods of measurement error and estimate correction coefficients manually. The most tested approaches for homogenization of temperature series involve using interpolation techniques relying on homogenized data from nearby stations or networks of stations (Venema et al., 2012). It is generally advisable to use more than one station for interpolation since it reduces the probability of a single station bias as well as the general reliability of the interpolation (Conrad and Pollak, 1950). Again, applying interpolation manually is problematic since it risks introducing new biases for the less detailed parts of the Lund measurement station history. There are also computational difficulties in manually interpolating from a network of stations. Therefore, I employ the adapted Caussinus–Mestre algorithm for homogenizing Networks of Temperature Series (ACMANT) software. ACMANT relies on a homogenized network of stations and a computationally efficient algorithm for homogenizing climate data and data infilling.

I use a network of homogenized monthly temperature series located in the northwestern part of Europe for the homogenization process, namely Berlin–Dahlem (from 1719 with a gap between 1722–1727), central England (from 1659), Copenhagen (from 1768 with gaps between 1777–1781 and 1789–1797), De Bilt (from 1706), Stockholm (from 1756), and Uppsala (from 1722) (DWD, 2018; Bergström and Moberg, 2002; Cappellen et al., 2019; Moberg et al., 2002; van Engelen et al., 2001; Labrijn, 1945; Parker et al., 1992; van Engelen, 1995; Manley, 1973). Given that spatial correlations in temperatures on a daily or weekly basis are lower across the network region compared with monthly or seasonal averages and that daily temperature series are not available at all network stations, I employ monthly averages for homogenization. The ACMANT homogenization procedure requires spatial correlation coefficients of at least 0.4 with network stations and a minimum of four network time series. Spatial correlation coefficients are calculated from the increments in the time series after monthly climatic means have been removed (Domonokos and Coll, 2017). Table A1 shows the descriptive statistics of the network stations, including monthly correlations and spatial correlations.

A1 Detected breaks and station history

The ACMANT homogenization procedure detects eight breaks in the Lund temperature series. These breaks can be interpreted in light of what is known about the station history. Figure A2 shows known or suspected relocations and changes in observers between 1753 and 1870 as well as the detected breaks (Nenzelius, 1775; Tidblom 1876; Schalén et al., 1968; Bärring et al., 1999).

For the first 22 years, no breaks are detected, even though there is one change in observer (1763) and several replacements of instruments. The location of the instruments appears to have been constant. Furthermore, in 1770 there was a Royal Ordinance that the results from all monthly meteorological observations were to be sent in to the Swedish Royal Academy of Sciences. The first 2 decades of measurements were published by the Swedish Royal Academy of Sciences (Nenzelius, 1775). It is possible that the attention and interest given to meteorological observations as a preeminent scientific venture at this particular moment in time led the first two observers, Nils Schenmark and Olof Nenzelius, to make serious efforts to make sure the series was consistent or as correct as possible. Tidblom (1876) argued that were was no reason to suspect that the instruments or observers were lacking in quality or skill, at least during Schenmark's time (1753–1763). In the 1770s, there are some intermittent notes from this period of corrections to faulty instruments, something that is much sparser in the subsequent period (Tidblom, 1876).

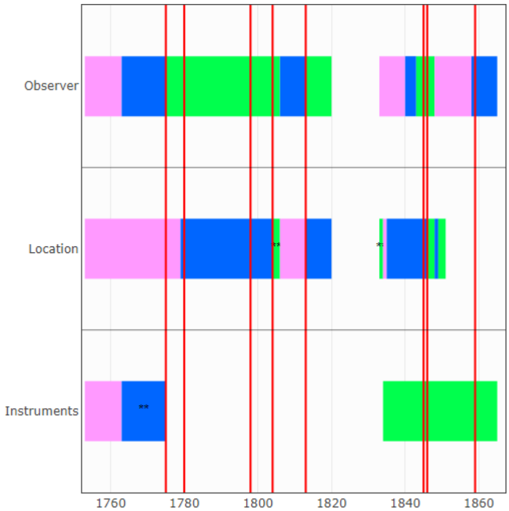

Figure A2. Station history and ACMANT-detected breaks, 1753–1870. Sources: Tidblom (1876), Schalén et al. (1968), and Bärring et al. (1999). Note: each colored area represents a distinct period location, observer, or set of instruments. ∗∗ denotes multiple changes during the indicated period. Detected breaks are shown by the vertical red lines. Gaps in white signify missing data.

The first detected break occurs in 1775, the same year in which Anders Lidtgren and his assistant Pehr Tegman took over observation responsibilities. It is possible that the thermometer also changed location at this time. Another break occurs in 1780, approximately coinciding with the change in location for the instruments in late 1779 to the upper story of Kungshuset. In 1798, 1804, and 1813 there are further breaks detected in the series. Nothing formally appears in the station

Table A1. Correlations between monthly temperatures in Lund and other network series.

	Copenhagen	Central England	Uppsala	Stockholm	Berlin–Dahlem	De Bilt
January	0.93	0.73	0.85	0.88	0.83	0.82
February	0.95	0.78	0.84	0.87	0.89	0.86
March	0.93	0.80	0.83	0.86	0.90	0.88
April	0.77	0.66	0.72	0.71	0.77	0.80
May	0.69	0.43	0.72	0.70	0.76	0.60
June	0.40	0.16	0.55	0.51	0.53	0.45
July	0.56	0.32	0.59	0.57	0.61	0.49
August	0.64	0.41	0.71	0.70	0.66	0.59
September	0.45	0.31	0.60	0.58	0.64	0.47
October	0.70	0.51	0.73	0.75	0.85	0.79
November	0.83	0.41	0.73	0.77	0.83	0.76
December	0.93	0.76	0.86	0.88	0.89	0.80
Annual	0.51	0.67	0.72	0.72	0.77	0.80
Spatial correlation	0.94	0.62	0.83	0.84	0.84	0.75

Sources are as follows: Central England (Manley, 1973, Parker et al., 1992), Copenhagen (Cappelen et al., 2019), Berlin–Dahlem (DWD, 2018), De Bilt (Durre et al., 2008; Lawrimore et al., 2011), Lund (Tidblom, 1876), Uppsala (Bergström and Moberg, 2002), and Stockholm (Moberg et al., 2002; Moberg, 2021). Note that spatial correlation coefficients are obtained by ACMANT, with increment series correlated after monthly climatic means have been removed (Domonokos and Coll, 2017).

history that could explain the 1798 break. However, the responsible observers, A. Lidtgren and P. Tegman, were both increasingly occupied with other duties, suggesting that actual meteorological observations were undertaken by some other unknown assistant. P. Tegman became a professor of mathematics in 1787, was awarded membership in the Royal Swedish Academy of Sciences in 1795, and was awarded membership in the board of mathematics in 1798. Furthermore, he was appointed dean of Lund University in 1795 and became responsible for a church deanery in 1797. A. Lidtgren was also awarded membership in the board of mathematics in the Royal Swedish Academy of Sciences in 1798 (Ståhl, 1834; Dahlgren, 1915). A. Lidtgren was recognized for his work in astronomy and astronomical observations, whereas much less is known about his work with meteorological observations (Dahl, 1948). Unlike their predecessors, neither P. Tegman nor A. Lidtgren made any publications regarding meteorological observations.

Both the 1804 and 1813 breaks occur during times of more apparent and known changes in the station history. In 1804 the instruments changed location several times, and in 1813 there was a change in observer to Adolph Frederic Knieberg, who supposedly also relocated the instruments to his living residence (Tidblom, 1876). Finally, there are detected breaks in 1845, 1846, and 1859. Between the 1820s and mid-1830s the instruments changed location on a number of occasions (leading to the gap in the temperature series between 1821 and 1833 due to the low quality of the temperature data in that period). The location of the instruments is then not mentioned in the records until 1846 when they again appear to have changed location. In 1858, there was a change in observers, but there are no changes in location close in time to the 1859 break.

Thus, almost all detected breaks occur in the same year as or the subsequent year to a change in observer or station location. Furthermore, almost all known changes in station location and observers are detected as breaks, at least in the 18th century. The largest exception is the break in 1845 that occurs more than a year after the latest known change in the station history, which is when there was a change in observer in 1843. However, in 1846 there is both a station relocation and a detected break. The latest detected break occur in 1859, shortly after a change in observers in 1858.

Overall, the change in instruments appears to have been a less important factor in causing inhomogeneities in the series compared with changes in observer and instrument location. Not one of the known changes in thermometers occurred at a point in time proximate to a detected break. Presumably, if an instrument was faulty the more skilled observers, as is noted on several occasions in the station records, could correct for this. Similarly, an unskilled or careless observer would have been less likely to identify faulty instruments, accurately read and note down observations, and appreciate the consequences of moving the instruments to a particular location (see Pfister et al., 2019, who discuss issues related to the maintenance of reliable and consistent observers).

A2 The late 18th century cold bias

As shown in Figs. 7 and 8, the largest corrections in the homogenization procedure occurred during the summer months and to a lesser extent spring months of the last decades of the 18th century, signified by the two detected breaks in 1775 and 1780 (Fig. A2). Other studies attempting to homogenize early instrumental temperature series have also found summers to be a larger source of measurement bias com-

Table A2. Average time of day for morning and evening measurements, 1753–1870.

Period (morning)	1753–1774	1775–1806	1807–1849	1850–1858	1859–1870
January	08:24	08:00	07:54	06:00	08:00
February	07:36	07:06	07:30	06:00	08:00
March	06:48	06:00	06:54	07:00	08:00
April	06:42	05:12	06:18	07:00	08:00
May	06:36	04:36	06:12	07:00	08:00
June	06:42	04:30	06:12	07:00	08:00
July	06:30	04:24	06:06	07:00	08:00
August	06:36	04:42	06:12	07:00	08:00
September	06:42	05:30	06:18	07:00	08:00
October	07:06	06:36	06:36	07:00	08:00
November	07:54	07:36	07:12	07:00	08:00
December	08:30	08:12	07:36	07:00	08:00
Period (evening)	1769–1791	1792–1820	1834–1849	JF 1850	M 1850–1870
	21:54	20:30	21:48	22:00	21:00

Source: Tidblom (1876). Note: single letters in the “Period” row denote months; e.g., JF denotes January–February.

pared with the other seasons. For example, when performing manual testing during homogenization of the Stockholm instrumental temperature series (beginning in 1756) Moberg et al. (2002) noted, in line with Modén (1963), that the largest discrepancies due to station location were to be observed during the summer months. Dobrovolný et al. (2010) also found a similar seasonal pattern in their study of early instrumental temperature series in central Europe. They argued that thermometers, which during the late 18th and early 18th century were mostly placed in a north-facing direction and without proper sheltering, were subject to a systematic summer season warm bias. They also conceded that this bias differed for different stations, depending on latitude, altitude, and other station-specific conditions.

In the Lund early instrumental period, particularly in the late 18th century, it appears conditions were reversed from those in central Europe; namely, there is a *cold* bias during the summer season as well as the during the growing season (AMJJAS) as a whole. Across the entire homogenization period, there is a slight correction upwards for spring and summer temperatures, which can be explained by the use of morning and evening observations, excluding daytime observations. To explain the much larger corrections made from 1775 until 1804 one has to consider the specifics of the station history during that period. During the years 1775–1806, the average time of the morning observations occurred up to 2 h earlier during the months of MJJA compared to the previous period 1753–1774. For the other months of the year the differences were much smaller; see Table A2. Furthermore, in late 1779 the thermometer was moved to the upper room of the Kungshuset, located at an altitude of 61m. Bärring et al. (1999) argue that these facilities probably were unheated until the 1830s. Given these conditions, it is feasible that the thermometer location between 1779 and 1804 was colder than the preceding and succeeding locations.

Thus, a consideration of the specifics of the station history, notably the change in observers, observation practices, and station relocation, in combination with the homogenization results, suggests that the Lund temperature series exhibits a cold bias in the last decades of the 18th century. This result has bearing on historical climate reconstructions generally, but also for the agrarian and climate history of Scania and southwestern Sweden, specifically, as discussed in Sect. 4.3 (Mattsson, 1986; Palm, 1997; Bohman, 2017a, b).

Appendix B

Table B1. Years at or below the 33th percentile of SPEI (drier conditions) during the years 1702–1865.

1704	1709	1712	1719	1726	1727	1740	1741
1747	1748	1749	1771	1774	1775	1781	1782
1783	1784	1785	1786	1787	1788	1789	1790
1798	1801	1803	1807	1808	1810	1811	1812
1816	1818	1819	1820	1821	1822	1823	1824
1825	1826	1827	1828	1829	1838	1843	1845
1846	1847	1850	1852	1853	1854	1855	1857
1859	1861						

Source: Seftigen et al. (2017).

Table B2. Years at or above the 67th percentile of SPEI (wetter conditions) during the years 1702–1865.

1706	1707	1708	1713	1715	1717	1718	1720
1722	1725	1730	1731	1732	1733	1734	1735
1736	1737	1738	1742	1744	1745	1750	1751
1752	1753	1754	1755	1756	1757	1759	1761
1763	1764	1765	1766	1767	1769	1776	1777
1778	1779	1793	1794	1797	1799	1805	1815
1817	1834	1835	1851	1860	1862	1865	

Source: Seftigen et al. (2017).

Table B3. Years below the median of SPEI (drier conditions) during the years 1865–1911.

1868	1873	1874	1875	1876	1877	1879	1880
1881	1883	1887	1888	1889	1891	1893	1895
1896	1901	1902	1904	1905	1906	1911	

Source: Seftigen et al. (2017).

Table B4. Years above or at the median of SPEI (wetter conditions) during the years 1865–1911.

1865	1866	1867	1869	1870	1871	1872	1878
1882	1884	1885	1886	1890	1892	1894	1897
1898	1899	1900	1903	1907	1908	1909	1910

Source: Seftigen et al. (2017).

Data availability. The original data used for this article can all be obtained through publicly available repositories, except for the historical temperature data from Copenhagen, which since 2019 is only available upon request; see below. The homogenized monthly mean temperature series compiled as part of this paper is available through request to the author.

HDSA data and related files can be obtained from the repository website of the Department of Economic History at Lund University; see https://www.lusem.lu.se/economic-history/databases/economic-history-data/historical-database-of-scanian-agriculture (last access: 26 January 2022). See also as Olsson and Svensson (2017a; https://lup.lub.lu.se/record/94f24113-f810-4c1d-bd34-22405e41185b, last access: 23 April 2021) for a detailed description of the data.

Lund temperature and precipitation data are available in published format in Tidblom (1876) and are also available in digitized format upon request to the author. Furthermore, monthly precipitation data for Lund are available at the SMHI open data repository, https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=precipitationMonthlySum,stations=all,stationid=53430 (last access: 26 January 2022, SMHI, 2021).

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Competing interests. The contact author has declared that there are no competing interests.

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Special issue statement. This article is part of the special issue "International methods and comparisons in climate reconstruction and impacts from archives of societies". It is not associated with a conference.

Acknowledgements. I would like to thank the anonymous referees and the editor for their valuable comments.

Review statement. This paper was edited by Chantal Camenisch and reviewed by three anonymous referees.

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Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2023:56

This thesis examines relationships between agriculture and climate in central and southern Scandinavia, Switzerland, and Spain during the years 1500–1900. The period constituted large parts of the 'Little Ice Age', a climatic period that presented particular challenges to agriculture. Mainly quantitative methods are employed, applied to a large set of climate and agriculture data, including long time series of harvests and agricultural calendar dates, early meteorological data and climate reconstructions.

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ISSN 1652-6880
ISBN (print version) 978-91-8046-164-1
ISBN (electronic version) 978-91-8046-165-8