Climate vulnerability assessment methodology

Agriculture under climate change
in the Nordic region

Lotten Wiréhn

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Author: Lotten Wiréhn

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Abstract

Food security and climate change mitigation are crucial missions for the agricultural sector and for global work on sustainable development. Concurrently, agricultural production is directly dependent on climatic conditions, making climate change adaptation strategies essential for the agricultural sector. There is consequently a need for researchers, planners, and practitioners to better understand how, why, and to what extent agriculture is vulnerable to climate change. Such analyses involve challenges in relation to the complex social–ecological character of the agricultural system and to the multiple conceptualizations and approaches used in analysing vulnerability.

The aim of this thesis is to identify how vulnerability assessments can be used to represent climate-related vulnerability in Nordic agriculture, in order to advance the methodological development of indicator-based and geographic visualization methods. The following research questions are addressed: *(i)* How can agricultural vulnerability to climate change and variability in the Nordic countries be characterized? *(ii)* How do selections, definitions, and emphases of indicators influence how vulnerability is assessed? *(iii)* How do estimates of vulnerability vary depending on the methods used in assessments? *(iv)* How can geographic visualization be applied in integrated vulnerability assessments? This thesis analyses and applies various vulnerability assessment approaches in the context of Nordic agriculture.

This thesis demonstrates that various methods for composing vulnerability indices result in significantly different outcomes, despite using the same set of indicators. A conceptual framework for geographic visualization approaches to vulnerability assessments was developed for the purpose of creating transparent and interactive assessments regarding the indicating variables, methods and assumptions applied, i.e., opening up the ‘black box’ of composite indices. This framework served as the foundation for developing the AgroExplore geographic visualization tool. The tool enables the user to interactively select, categorize, and weight indicators as well as to explore the data and the spatial patterns of the indicators and indices. AgroExplore was used in focus group settings with experts in the Swedish agricultural sector.

The visualization-supported dialogue results confirm the difficulty of selecting and constructing indicators, including different perceptions of what indicators actually indicate, the assumption of linear relationships between the indicators and vulnerability, and, consequently, that the direction of the relationship is predefined for each indicator. This thesis further points at the inherent complexity of agricultural challenges and opportunities in the context of climate change as such. It is specifically emphasized that agricultural adaptation policies and measures involve trade-offs between various environmental and socio–economic objectives, and that their implementation could furthermore entail unintended consequences, i.e., potential maladaptive outcomes. Nevertheless, it proved difficult to validate indicators due to, e.g. matters of scale and data availability. While heavy

precipitation and other extreme weather events are perceived as the most relevant drivers of climate vulnerability by the agricultural experts participating in this study, statistical analyses of historical data identified few significant relationships between crop yield losses and heavy precipitation. In conclusion, this thesis contributes to the method development of composite indices and indicator-based vulnerability assessment. A key conclusion is that assessments are method dependent and that indicator selection is related to aspects such as the system's spatial scale and location as well as to indicator thresholds and defined relationships with vulnerability, recognizing the contextual dependency of agricultural vulnerability. Consequently, given the practicality of indicator-based methods, I stress with this thesis that future vulnerability studies must take into account and be transparent about the principles and limitations of indicator-based assessment methods in order to ensure their usefulness, validity, and relevance for guiding adaptation strategies.

Sammanfattning

För jordbrukssektorn och global hållbar utveckling i stort är matsäkerhet och mitigering av klimatförändringar viktiga angelägenheter. Samtidigt är jordbruksproduktionen ofta direkt beroende av klimatförhållanden, vilket gör klimatanpassningsstrategier mycket centrala för sektorn. Forskare, planerare och aktörer behöver förstå hur, varför och i vilken omfattning jordbruket är sårbart inför klimatförändringar. Sådana analyser inbegriper även de utmaningar som skapas genom jordbrukets komplexa socio-ekologiska karaktär, och de många utgångspunkter och tillvägagångssätt som används för att bedöma sårbarhet. Syftet med denna avhandling är att identifiera hur sårbarhetsbedömningar kan representera klimatrelaterad sårbarhet i nordiskt jordbruk, och i och med detta har avhandlingen som avsikt att utveckla metodologin för indikatorbaserade- och geografiska visualiseringsmetoder. Följande forskningsfrågor avhandlas: (i) Hur kan det nordiska jordbrukets sårbarhet inför klimatvariation och förändringar karaktäriseras? (ii) Hur påverkar urval, definitioner och betoningar av indikatorer bedömningar av sårbarhet? (iii) Hur varierar uppskattningar med bedömningsmetod? (iv) Hur kan geografisk visualisering användas i integrerade sårbarhetsbedömningar? För att svara på dessa frågor analyseras och tillämpas olika tillvägagångssätt att bedöma sårbarhet inom nordiskt jordbruk.

Avhandlingen visar att olika metoder för sårbarhetskompositindex resulterar i signifikanta skillnader mellan index, trots att samma indikatorer och data används. Ett konceptuellt ramverk för sårbarhetsbedömningar där geografisk visualisering används, har utvecklats för att möjliggöra transparens avseende till exempel, vilka variabler, metoder och antaganden som används i kompositindex. Detta ramverk har följaktligen legat till grund för att utveckla ett geografiskt visualiseringsverktyg – AgroExplore. Verktyget möjliggör interaktivitet där användaren kan välja, kategorisera och vikta indikatorer, och dessutom utforska data och spatiala mönster av indikatorer och kompositindex. AgroExplore användes i denna avhandling för att stödja fokusgruppdialoger med experter inom den svenska jordbrukssektorn.

Resultaten från dessa workshops bekräftar svårigheten med att välja och skapa indikatorer. Dessa svårigheter innefattar olika uppfattningar om vad indikatorer representerar, antagandet om linjära samband mellan indikatorerna och sårbarhet, och följaktligen att sambandens riktning är fördefinierade för respektive indikator. Utöver de konceptuella och metodologiska utmaningarna med sårbarhetsbedömningar visar avhandlingen på komplexa svårigheter och möjligheter för jordbruket vid klimatförändringar. Särskilt framhålls att klimatanpassningspolitik och åtgärder inom jordbruket medför konflikter och avvägningar mellan olika miljö- och socio-ekonomiska mål. Implementering av sådana anpassningsåtgärder kan vidare innebära oönskade konsekvenser, så kallad missanpassning. Trots ökad kunskap gällande nordiska jordbrukets sårbarhet inför klimatförändringar har det visats sig vara svårt att statistiskt validera indikatorer på grund av, exempelvis, skalproblematik och datatillgänglighet. Samtidigt som experterna ansåg att kraftig nederbörd och andra extrema väderhändelser är de mest relevanta drivkrafterna till klimatsårbarhet

visar den statistiska analysen av historiska data på få signifikanta samband mellan förlorad skördeavkastning och kraftig nederbörd.

Denna avhandling bidrar till metodutveckling av kompositindex och indikatorbaserade metoder för sårbarhetsbedömningar. En viktig slutsats är att bedömningar är metodberoende och att valet av indikatorer är relaterat till aspekter såsom systemets utbredning och den spatiala skalan av bedömningen. Även indikatorernas tröskelvärden och hur deras relation till sårbarhet är definierade anses vara viktiga faktorer som påverkar hur indikatorer representerar sårbarhet, vilket visar på sårbarhetsbedömningars kontextuella beroende. I och med de rådande bristerna hos indikatorbaserade metoder, som bland annat har identifierats i denna avhandling, vill jag framhålla vikten av att sårbarhetsbedömningar bör vara transparenta gällande den tillämpade metodens principer, antaganden och begränsningar. Detta för att säkerställa användbarhet, giltighet och relevans, om metoden och bedömningen ska ligga till grund för anpassningsstrategier hos såväl politiker, planerare och lantbrukare.

List of papers

The thesis is based on the following papers, which are referred to in the text by the Roman numerals I–IV.

- I. Wiréhn, L. ‘Nordic agriculture under climate change: a systematic review of challenges, opportunities, and adaptation strategies for crop production’ (Submitted to *Land Use Policy*).
- II. Wiréhn, L., Danielsson, Å., and Neset, T.-S. (2015) ‘Assessment of composite index methods for agricultural vulnerability to climate change’, *Journal of Environmental Management*, 156:70–80. Published here with kind permission from Elsevier
- III. Wiréhn, L., Opach, T., and Neset, T.-S. (2017) ‘Assessing agricultural vulnerability to climate change in the Nordic countries – an interactive geovisualization approach’, *Journal of Environmental Planning and Management*, 60(1):115–134. Published here with kind permission from Taylor and Francis
- IV. Neset, T.-S., Wiréhn, L., Opach, T., Glaas, E., and Linnér, B.-O., ‘Evaluation of indicators for agricultural vulnerability to climate change: the case of Swedish Agriculture’ (Submitted to *Ecological Indicators*).

Author’s contributions to the appended papers

- I. Lotten Wiréhn is solely responsible for this article. Dr. Tina-Simone Neset, Prof. Björn Ola Linnér, Dr. Sirkku Juhola, Dr. Julie Wilk, and Dr. Mathias Fridahl, however, provided valuable comments on the manuscript.
- II. The study was planned collaboratively by the co-authors. Lotten Wiréhn carried out the data collection, conducted most of the analysis, and wrote most of the manuscript. The statistical analysis was conducted in collaboration with Dr. Åsa Danielsson.
- III. The study was planned together with the co-authors. Lotten Wiréhn together with Dr. Tina-Simone Neset designed the conceptual framework. Lotten Wiréhn collected and processed the data included in the tool. Dr. Tomasz Opach developed the tool and was responsible for the rapid prototype assessment. Lotten Wiréhn was responsible for most of the writing, but all authors collaboratively worked to finalize the manuscript.
- IV. The study was planned by Lotten Wiréhn in collaboration with the co-authors. Lotten Wiréhn together with Dr. Tina-Simone Neset held stakeholder workshops. In the manuscript writing, Lotten focused specifically on background, quantitative results, and discussion sections, though finalizing the complete paper was a collective effort.

Abbreviations

AR5	Assessment Report Five
CHES	Coupled human–environmental system
HPI	Heavy precipitation index
IPCC	Intergovernmental Panel on Climate Change
PCA	Principal component analysis
TAR	Third Assessment Report
VI	Vulnerability index
WGII	Working Group Two
YLI	Yield loss index

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With gratitude,

A handwritten signature in black ink, appearing to read "Helen Wille", written in a cursive style. The signature is positioned on a light gray rectangular background.

1 Introduction

Global temperature has increased for more than a century and the effects of climate change are currently obvious in natural and human systems around the globe (IPCC 2014a). Research into climate change vulnerability began in the 1990s (Hinkel 2011) in order to understand the extent and complexity of climate change and its effects, in the interest of developing policies and measures to reduce such vulnerability.

In Northern Europe, the trend indicates that the climate is becoming warmer and wetter, especially in winter. These trends are projected to continue in the future, in combination with more frequent extreme weather, particularly heavy precipitation (Kovats et al. 2014). Agricultural yields and production quality are directly dependent on climatic factors (EEA 2012), which makes the agricultural sector generally sensitive to climate variability and change. In general, climate scenarios for the Nordic region indicate that climatic conditions are expected to change considerably until the 2071–2100 period, involving, for example, earlier onset of spring, longer growing seasons, higher mean temperature, and more precipitation (Strandberg et al. 2014).

These climatic changes are often considered beneficial for agricultural production, implying that climate change will be advantageous for agricultural production in Northern Europe (IPCC 2007). However, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) presents a more critical discussion of climate change benefits for Northern European agriculture. It states that ‘there is diverging evidence concerning future impacts’ of climate change on agricultural production in Northern Europe (Kovats et al. 2014). For example, increased precipitation in autumn complicates the conditions for both sowing and harvesting (Rötter et al. 2012; Uleberg et al. 2014) and increased variation of temperature and precipitation could cause increased yield variability and loss. Accordingly, climate change in the Nordic region is likely to imply both challenges and opportunities. Regardless of climate impacts, adaptation policies and measures are essential to limit vulnerability and take advantage of opportunities presented by climate change. Increased crop yield potential (Olesen et al. 2002) may, for example, be realized only with adaptation responses such as changed timing of the planting of specific cultivars, erosion protection, increased fertilization, shifts in varieties, and protection of crops from plant pests (Olesen et al. 2011). Nordic agriculture is an interesting case of a sector traditionally considered a climate change ‘winner’ but in which obvious climate-related challenges exist, involving various interacting climate factors as well as non-climatic stressors related to, for example, the implementation of adaptation and mitigation policies and measures.

The wide scope of climate change research and the diversity of scientific traditions involved in vulnerability research have resulted in different definitions and theoretical

conceptualizations of the climate vulnerability phenomenon. Furthermore, this diversity of interpretations has led to numerous methods for operationalizing vulnerability as an analytical concept, i.e., frameworks and approaches for vulnerability assessments.

In vulnerability assessments, indicators are used to ‘measure’ and characterize the vulnerability of a system. Indicator-based assessment is one of the main approaches in vulnerability research. However, there is criticism of the approach, for example, regarding its lack of capacity to capture the complexity of a vulnerable system (Hinkel 2011). In agricultural vulnerability research, there appears to be a gap between large-scale studies of climate change impacts on agricultural production, which are typically model-based studies of crop growth, and local studies of farmers’ adaptation barriers, which typically have a qualitative profile (Simelton et al. 2012).

The great variety of existing vulnerability assessment approaches raises the question of how indicator-based assessments differ in their way of capturing and characterizing the phenomenon of vulnerability. In this thesis, I scrutinize vulnerability assessment methodology by applying various vulnerability assessment approaches.

Many of the factors influencing a complex vulnerable system such as the agricultural sector are spatially dependent. Geographic visualization could be used to assess climate vulnerability due to its ability to analyse and represent spatial data (MacEachren et al. 2004a). Visual representation by means of digital mapping is one method to manage the explicitly spatial information about climate vulnerability, forwarded as a potentially effective means of presenting assessments (Preston et al. 2011). However, how geographic visualization can contribute to an increased understanding of climate vulnerability, including its causes, consequences, and alternative responsive actions, still needs further investigation. This thesis addresses the methodological challenges of climate vulnerability assessments, especially those involving vulnerability indicators and static indices, in order to contribute to vulnerability assessment methodology. Geographic visualization allows to combine quantitative measures of vulnerability with a qualitative approach to assessing contextual vulnerability. This study explores the potential to develop the vulnerability assessment methodology by linking quantitative and qualitative approaches.

1.1 Aim and research questions

The aim of this thesis is to identify how assessments can be used to represent climate-related vulnerability in Nordic agriculture, to advance the methodological development of indicator-based and geographic visualization methods. In this thesis, ‘representation’ refers to the act of conveying characteristics and qualities of vulnerability, including how indicators and geographic visualization can be used to describe vulnerable systems.

The following research questions are used to address this aim:

1. How can agricultural vulnerability to climate change and variability in the Nordic countries be characterized?
2. How do selections, definitions, and emphases of indicators influence how vulnerability is assessed?
3. How do estimates of vulnerability vary depending on the methods used in assessments?
4. How can geographic visualization be applied in integrated vulnerability assessments?

While this thesis builds our knowledge of climate vulnerability assessment methodology, it is also intended to improve our understanding of climate vulnerability in Nordic agriculture and implications for future adaptation policies and measures. The vulnerability concept is central throughout the thesis. In this study, ‘agricultural vulnerability’ refers to the vulnerability of crop production and competitiveness of the agricultural sector, though production and competitiveness could of course be considered on different scales.

Theoretically, this thesis does not analyse the concept of vulnerability since the focus is on assessment methodology. Nevertheless, the lessons learned from operationalizing the vulnerability concept also contribute to the development of vulnerability theory.

This thesis examines different approaches to assessing agricultural vulnerability (papers II–IV). In parallel, climate stressors and contextual factors that can characterize vulnerability of Nordic agriculture are investigated (papers I and IV). Based on the results of the method assessments, an approach based on geographic visualization is developed and applied (papers III and IV).

This thesis addresses agricultural crop production but does not consider the vulnerability of livestock or dairy production. Crop production for feed is considered, however.

1.2 The thesis outline

Following this introduction, the second chapter of the thesis summarizes the state of the art of vulnerability assessment methodology as well as the anticipated impacts of climate change and variability on Nordic agriculture. Chapter two hence reflects upon the literature

that this thesis intends to address. Chapter three describes the analytical framework of the thesis, the foundation for relating the study to the concept of vulnerability, vulnerability assessment methodology, and geographic visualization. Chapter four summarizes the material and methods used in the appended papers, structured according to analytical methodology.¹ In chapter five, I present a synthesis of the findings related to the four research questions. These findings, as well as advantages and shortcomings of the present research approach, are discussed in relation to the existing literature in chapter six. Chapter seven presents the conclusions and the main contributions of this thesis.

¹ This refers to the different analytical methods applied in this thesis, i.e., not the vulnerability assessment methods applied but rather statistical analysis, literature review, and geographic visualization.

2 State of the art

2.1 Assessing climate vulnerability

In recent decades, vulnerability has emerged as a central concept in research into climate change. The United Nations Framework Convention on Climate Change (UNFCCC) refers to ‘developing country Parties that are particularly *vulnerable* to the adverse effects of climate change’, while developed country Parties are to assist particularly vulnerable developing country Parties to meet the costs of climate change adaptation (United Nations 1992). This triggered research into climate change vulnerability in the early 1990s (Hinkel 2011), and since 2006, the number of scientific publications on the topic has rapidly grown, as demonstrated by multiple reviews of this research field (Tonmoy et al. 2014; Wang et al. 2014; Giupponi and Biscaro 2015; McDowell et al. 2016).

This growth in research attention can be linked to the fact that adaptation strategies became a priority when climate change impacts started to be observed and were acknowledged by the IPCC in Assessment Report Four (AR4) (Hinkel 2011). Accordingly, vulnerability assessments ‘moved from being an academic exercise to being a political necessity’ (Hinkel 2011, p. 198). Climate change vulnerability assessments are conducted to address certain objectives, such as helping policymakers identify ‘hot spots’ in allocating adaptation resources, better communicating climate risks to the public, monitoring the effects of adaptation measures, and better understanding weaknesses in the socio–ecological² system that lead to vulnerability (Tonmoy et al. 2014). For example, the European Environmental Agency conducts climate change vulnerability assessments to identify European regions that are particularly vulnerable and to provide knowledge that can guide adaptation strategies on both the national and European levels (EEA 2012; 2017).

On the local level, assessments of vulnerability may be conducted to identify vulnerable entities, providing knowledge that can be integrated into comprehensive municipal plans (e.g., Staffanstorps Kommun 2011). However, if vulnerability assessments are based on climate change exposure but lack coverage of contextual factors,³ the relevance and

² ‘A system that includes societal (human) and ecological (biophysical) subsystems in mutual interaction’ is a socio–ecological system (Gallopín 2006, p. 296). The term ‘socio–ecological’ is used in this thesis to refer to the system type; in contrast, ‘socio–economic’ (e.g., Brooks et al. 2005; Simelton et al. 2009) is used to refer to a category of indicating variables capturing vulnerability or particular dimensions of vulnerability.

³ The county administrative boards in Sweden have conducted ‘climate and vulnerability analyses’ (author’s translation) of their counties. However, these consider only climate change exposure and in some cases impact-modelling results. The counties’ reports can be found at: <http://www.klimatanpassning.se/roller-och-ansvar/vem-har-ansvaret/lansvisa-klimat-och-sarbarhetsanalyser-1.25071> (accessed 2017-08-29). Several

robustness of the vulnerability assessments as a basis for adaptation strategies can be questioned (Carr and Owusu-Daaku 2016), because socio-economic aspects such as policies, equity, and power relations also influence climate change vulnerability (Sovacool and Linnér 2016).

The conceptualization and operationalization of ‘vulnerability’ have evolved through various research traditions. In the climate change vulnerability context, interdisciplinary approaches are often claimed to be essential in order to incorporate information about climatic, biophysical, and social processes and characteristics (e.g., Füssel and Klein 2006; Wilhelmi and Hayden 2010). The various scholarly traditions and the interdisciplinary approaches to operationalizing the scientific term ‘vulnerability’ have led to different interpretations of the concept (Wolf et al. 2013). It is generally accepted that there is a need for greater clarity concerning vulnerability and related concepts. Numerous studies have, due to the prevailing confusion, attempted to assess the various definitions and conceptualizations in order to identify and create overarching frameworks (Kelly and Adger 2000; Brooks 2003; Turner et al. 2003; Adger et al. 2004; Adger 2006; Eakin and Luers 2006; Füssel and Klein 2006; Gallopín 2006; O’Brien et al. 2007; Soares et al. 2012; Costa and Kropp 2013). However, a general conclusion of these conceptual studies is that the concept entails considerable confusion (Ionescu et al. 2009). On the other hand, it may not be possible or even desirable to create a unified and general vulnerability framework. Instead, it has been argued ‘that there is no single “correct” or “best” conceptualisation ... that would fit all assessment contexts’ (Füssel 2007, p. 155). Nevertheless, alongside discussion of the lack of consensus and constant evolution in vulnerability research, the fact remains that there is a demand to understand the influences of climate change on human–environmental systems, including the options to respond to and cope with the anticipated impacts.

While vulnerability is an inclusive concept that is appealing and interesting to apply (Polsky et al. 2007), this inclusiveness makes it complex to assess. The multiple interpretations of the components of vulnerability identified by various conceptual frameworks do not translate into distinct approaches or methodologies in assessing vulnerability (Costa and Kropp 2013). Although the conceptualizations of exposure, sensitivity, and adaptive capacity appear straightforward, it has proven difficult to operationalize them in climate vulnerability assessment studies (Ionescu et al. 2009). The longstanding confusion surrounding vulnerability and related concepts calls for greater emphasis on systematically assessing how vulnerability components are made operational (Costa and Kropp 2013).

The literature on vulnerability assessments of socio-ecological systems is highly diverse because of the numerous quantitative and qualitative approaches, and contexts of these

counties delimit the scope to ‘climate analysis’ alone, though it is of course possible that contextual factors of climate vulnerability are addressed in other parts of their work on adaptation strategies.

assessments. Since climate vulnerability is a theoretical concept, it cannot be estimated as can physical phenomena such as mass, energy, and temperature (Luers et al. 2003; Tonmoy et al. 2014); it has therefore been argued that the quantification of vulnerability should not be spoken of in terms of ‘measurement’ (Hinkel 2011). Nevertheless, because of the need to integrate knowledge of climate change vulnerability in decision making and planning, the processes that generate vulnerability need to be understood and therefore ‘measured’ in some sense (Luers et al. 2003).

2.1.1 Indicators

Indicator-based vulnerability assessment, among the most common assessment methods, makes use of variables that serve as operational representations of characteristics, qualities or properties of a system (Gallopin 1996) in order to make the vulnerability concept operational (e.g., Luers et al. 2003; Birkmann 2006; Tonmoy et al. 2014). The advantages of indicator-based assessments include the ability to merge knowledge from various sciences into a mathematically combined composite index, i.e., combining the multiple dimensions of a phenomenon that cannot be captured by a single indicator. This incorporation of socio-economic and biophysical competences is more difficult to achieve with other assessment methods (Tonmoy et al. 2014). Indicators could be seen as ‘weak’ models in which relationships with vulnerability are known or assumed but cannot be characterized with accuracy.

Concurrently, the indicator-based methodology for building and assessing vulnerability has been criticized, for example, for hiding the complexity of the phenomenon (e.g., Adger 2006) and regarding the selection, weighting and aggregation of indicators (e.g., Eriksen and Kelly 2007; Vincent 2007; Barnett et al. 2008; Binder et al. 2010). The different steps involved in building a vulnerability index have been reviewed and discussed in the vulnerability literature (e.g., Adger et al. 2004; Binder et al. 2010; Hinkel 2011; Tonmoy et al. 2014; Becker et al. 2015). Previously applied methodological approaches to building vulnerability indices vary considerably in their indicator-selection, variable transformation, scaling, weighting, and summarizing methods (Tate 2012). Knowledge of vulnerability indices’ robustness to various methodological choices is lacking, but ought to be increased to avoid planning based on methodologically fragile indices (Tate 2012). Nevertheless, since the complexities of socio-ecological systems and anthropogenic processes are difficult to model mechanistically, the aggregation of indicators becomes a reasonable option for quantitatively assessing vulnerability (Tonmoy et al. 2014).

Cutter et al. (2003), Birkmann (2007), Hinkel (2011), and Rød et al. (2012) exemplify scholars arguing that indicator-based assessments can serve as a good starting point for the discussion and analysis of vulnerability, especially if geographic visualization approaches are applied (Rød et al. 2014). Generally, geographic visualization allows the exploration of

complex spatial and temporal aspects of continuously changing multidimensional phenomena (Harrower et al. 2000). Since vulnerability to climate change is an example of such a phenomenon, the construction and presentation of multidimensional aspects of vulnerability can advantageously be represented in geospatial displays (MacEachren et al. 2004a). Moreover, communicating the complexity of vulnerability is arguably crucial in order to increase the ability to reduce vulnerability (Preston et al. 2011).

2.1.2 Geographic visualization

Most of today's digital information is geospatially referenced through, for example, geographic coordinates, addresses, or postal codes (Hahmann and Burghardt 2013). Mapping has historically been considered a fundamental geographic method for representing georeferenced data. Since the 1950s, researchers have recognized that the interpretation of geographic phenomena is dependent on visualization through maps, and in recent decades there has been an increased emphasis on the role of maps in research (MacEachren and Taylor 2013).

In terms of vulnerability, visualization can support the exploration and communication of multidimensional aspects of people's perspectives, data, and concepts at different conceptual scales (MacEachren et al. 2004a). Rød et al. (2014) noted that visualization, validation, and negotiation are three essential activities that vulnerability assessments must undertake. A geographic visualization approach can be argued to meet this demand, enabling a process by which scientific knowledge can be integrated with local expert judgement. In the field of climate adaptation and vulnerability, an increasing number of web-based geographic visualization tools is available (Neset et al. 2016). Most of these tools do not enable sophisticated interaction with the data and are therefore used mainly to view various types of climate-related data (Neset et al. 2016). Several tools address vulnerability, risks, and hazards, but few of them support data exploration and new knowledge creation (cf., Tate et al. 2011; Opach and Rød 2013; Neuvonen et al. 2015; Carter et al. 2016). Because of the wide-ranging confusion regarding the conceptualization of vulnerability (Ionescu et al. 2009) and the extensive range of methods used to assess it, geographic visualization tool developers must be cautious in endeavouring to support spatial planning or to explore and represent climate change interaction mechanisms (Preston et al. 2011).

2.2 Climate change and agriculture linkages in the Nordic region

Although the agricultural sector is influenced by various critical factors such as globalization and energy policy, climate is fundamental to the sector's production and competitiveness. Agriculture is therefore inherently sensitive to climate change and variability. Climate change has direct and indirect impacts on all aspects of agriculture, such as crop suitability, yields, environmental impacts, crop protection, livestock health, and the pattern and balance

of food trade (Bindi and Olesen 2011; Wheeler and von Braun 2013). However, the level of climate change impact is anticipated to vary regionally depending on initial conditions and the degree of temperature and precipitation change (Olesen et al. 2011; Iglesias et al. 2012).

Future outlooks for Nordic agriculture under climate change present divergent perspectives regarding opportunities versus challenges. Warmer temperatures and longer growing seasons are likely to benefit crop production in northern Europe compared with the rest of Europe (Bindi and Olesen 2011; Iglesias et al. 2011). Increased crop production potential (e.g., Olesen and Bindi 2002; Ewert et al. 2005), increased areas for cropping (Trnka et al. 2011), and the introduction of new suitable species (Tuck et al. 2006) are the most fundamental potential opportunities for Northern European agriculture under climate change. Nevertheless, the latest assessment report of the IPCC, Assessment Report Five (AR5) (Kovats et al. 2014), states possible challenges associated with the projected warmer, wetter, and more varied future climate. Challenges associated with pests and weeds are expected to increase with higher temperatures and changed precipitation patterns, but could also result from changed crop distribution in fields (Jordbruksverket 2012). More temperature variation in winter could increase the number of days with freeze–thaw events, leading to the de-hardening⁴ of plants or, together with increased precipitation, causing ice encasement (Høglind et al. 2007). Furthermore, these events could increase the risk of the frost-kill of perennial plants. Frost events and excess water content in the soil when the light and temperature conditions are otherwise suitable for the establishment of annual crops could have negative effects on germination (Jordbruksverket 2012). Increased variation in temperature and precipitation could threaten projected yields as a result of harvesting or soil management problems. Generally, both flooding and droughts are anticipated to constitute increased challenges for Nordic agriculture in the future climate (Bernes 2017).

There is currently a strong emphasis on research into developing global and regional impact scenarios for crop yield change. Recent results, however, indicate large ranges between different impact scenarios' estimated change in crop yields. Rötter et al. (2012) demonstrated that the estimates from two studies of barley yields in Finland ranged between approximately a 70% increase and a 5% decrease by 2050 relative to 2000 levels. The analysis resulting in a large yield increase took into account changes in climate, elevated carbon dioxide (CO₂), and technological progress, while the one resulting in a decrease excluded technical progress from its calculations. This illustrates how most of the difference among future yield projections can arise from assumed differences in technology (Rötter et al. 2012), indicating the importance of climate change adaptation strategies. Yield projections are usually based on crop-growth models, and these simulations usually do not

⁴Hardening enables plants to withstand temperatures below zero during the winter, even though such temperatures would kill the same plants in summer. De-hardening is the reverse process during spring and is brought on by rising temperatures (Dexter 1941).

capture management or extreme-weather-event factors (Trnka et al. 2011). It is apparent that impact assessments of crop yields are challenging and under development, and different regions with different soils and crops are certain to respond differently to climate change (Iglesias et al. 2007). However, it is common knowledge that a changing climate will impact on, and to some extent already has changed, the conditions for crop production in the Nordic region (EEA 2012; Jordbruksverket 2012).

Adaptation to climate change is not a goal in itself but a precondition for achieving other goals, such as increased agricultural production and competitiveness. This can be exemplified by the Swedish national adaptation goal for the agricultural sector, formulated by the Swedish Board of Agriculture. This goal states that the agricultural sector should ‘contribute to a long-term sustainable society via competitive agriculture that addresses climate change by reducing vulnerability and taking advantage of opportunities’ (Jordbruksverket 2017, p. 5, author’s translation). Research into agricultural vulnerability reflects a possible shift from ‘predict and adapt’ to enhancing resilience and adaptive capacity through diversifying systems (Rötter et al. 2013). For example, it has been demonstrated that Norwegian farmers are focusing on the ability to respond to annual or seasonal changes rather than to mean changes in temperature or precipitation (Kvalvik et al. 2011). This is sometimes associated with ‘no-regret’ adaptation options (see review by Preston et al. 2015) and referred to as an important element of ‘climate-smart agriculture’ (FAO 2013). However, a pertinent question is *who* will have no regrets, because few adaptation actions can be considered ‘no-regret’ options by all stakeholders (Preston et al. 2015).

The Nordic region appears to be less covered in the scientific vulnerability literature, like other regions generally considered ‘winners’ in terms of climate change. It seems too simplistic to describe Nordic agriculture solely in terms of opportunity gains from new climate conditions, and doing so could probably result in unpreparedness for future climate-related challenges. A compilation of climate change challenges and opportunities facing Nordic agriculture, identified from recent grey and peer-reviewed scientific literature (Paper I), is presented in Table 1 to provide the context of this thesis. The challenges and opportunities mentioned in this chapter and in Paper I, together with the rationale for the need for adaptive actions to facilitate the realization of these opportunities (Olesen et al. 2011), establishes a basis for the present examination of the Nordic region.

Table 1. Summary of climate-related challenges and opportunities facing Nordic agricultural production (adapted from Tables 1 and 2 in Paper I).

Climate change	Challenges	Opportunities
Increased temperature in autumn	Reduced hardening period leading to increased risk of frost damage ¹	Possibility of growing ryegrass where it has not been grown before ¹³
Increased temperature in winter (reduced snow cover)	Reduced winter fallow from snow cover ¹ ; shortening of vegetative period ²	
Increased <i>duration</i> of growing season and <i>temperature</i> during the growing season	Depending on the crop, will generally accelerate the phenological stages and shorten the growing period, ^{2,6} resulting in earlier harvests ¹⁵	Potential for new varieties and species ³ and increased productivity and quality, ^{7,15} particularly due to increased number of harvests; ¹⁶ spring cereals may be more competitive than winter cereals ⁶
Earlier onset of and increased temperature in spring	In the North, excessive soil water content due to snowmelt will be a limiting factor in exploiting the earlier spring; ¹² shortening of the vegetative growing period due to earlier flowering and maturity; ¹² combination of frost events and high soil water content leading to germination difficulties ⁹	Decreased exposure to frost damage ¹⁴ and better utilization of solar radiation in spring ⁶
Increased number of freeze/thaw events	Increased risk of ice cover and encasement leading to crop damage ¹	
Increased precipitation	Together with warmer conditions creates favourable conditions for pests, weeds, and diseases, leading to yield losses ^{2,9}	
Early season droughts	Increased mean precipitation anticipated for autumn and winter will probably not reduce the spring droughts demonstrated to lower yields ³	
Adequate spring precipitation comes as heavy rains	Leads to delayed sowing due to soil water saturation; heavy rain plus dry periods hamper seedling emergence; water logging and anoxia ³	
Extreme precipitation	Flooding, erosion, and soil compaction leading to yield variability ^{1,5}	
Summer drought and timing of drought	This risk in southern areas could counteract the increased yield potential	
Increased precipitation in autumn and winter	Complicating harvesting and sowing ^{1,4,10}	
Increased atmospheric CO ₂	Climate change exposure	CO ₂ fertilization; may compensate for climate-induced yield reduction ⁶

¹ Uleberg et al. (2014); ² Kristensen et al. (2011); ³ Hakala et al. (2012) ⁴ Rötter et al. (2011); ⁵ Rötter et al. (2012); ⁶ Olesen et al. (2005); ⁷ Olesen and Bindi (2002); ⁸ Tuck et al. (2006); ⁹ Jordbruksverket (2012); ¹⁰ Kvalvik et al. (2011); ¹¹ Trnka et al. (2011); ¹² Olesen et al. (2012) ¹³ Thorsen and Höglind (2010); ¹⁴ Kaukoranta and Hakala (2008); ¹⁵ Eckersten et al. (2012); ¹⁶ Höglind et al. (2013)

3 Analytical framework

3.1 The concept of vulnerability

Research into vulnerability theory has developed from the consideration of human–environment interactions in a socio–ecological system experiencing environmental and/or social stress (Adger 2006). Two major vulnerability research traditions have arguably been the source of ideas for research into integrated human–environment vulnerability, namely, analysis of vulnerability as (i) ‘lack of entitlements in livelihoods’, traditionally used to explain food insecurity, and (ii) social impacts of ‘natural hazards’, developed to explain commonalities between different types of natural catastrophes and their societal impacts (Adger 2006). However, the conceptual understandings of and methods for assessing vulnerability are not coherent in either climate change or other contexts. Many of the inconsistencies arise from the fact that conceptualizations of vulnerability have developed independently in various disciplines (e.g., political ecology, human ecology, physical science, and spatial analysis) (Cutter 1996). Theoretical definitions of vulnerability are often vague and there is a mismatch between these and operational definitions, which involve methodologies for assessing vulnerability (Wolf et al. 2013). It has therefore been argued that theoretical and operational definitions should be separated in vulnerability discussions (Wolf et al. 2013).

3.1.1 Theoretical definitions

Among the diversity of definitions, the IPCC’s conceptualization of vulnerability from the third and fourth assessment reports (TAR and AR4, respectively) of Working Group Two (WGII) (Kelly and Adger 2000; IPCC 2001, 2007; Fussler 2007) has dominated climate change-related studies over the last decade (Bassett and Fogelman 2013). Here, vulnerability is defined as ‘the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes’ (IPCC 2007, p. 883). The IPCC’s TAR and AR4 frame vulnerability as a function of a system’s exposure, sensitivity, and adaptive capacity. Soares et al. (2012) emphasized two other vulnerability definitions used in climate vulnerability studies, arguing that these three definitions together capture the range of views within the climate vulnerability community. The other two definitions are: ‘the degree to which a system is susceptible to injury, damage or harm’ (Smith et al. 2000) and ‘the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard (an extreme natural event or process)’ (Wisner et al. 2003). The Smith et al. (2000) definition is general in that it does not specify the subject of analysis or the source of harm, while the Wisner et al. (2003) definition specifies these as being the characteristics of

a social system and natural hazards, respectively. The IPCC (2007) definition is considered to have a broad scope in terms of the subject of analysis but is very specific in terms of the source of harm, i.e., climate change (Soares et al. 2012).

Besides the perspectives reflected in these definitions of vulnerability, several studies argue that two streams of vulnerability literature exist that are specifically relevant to climate change science (Costa and Kropp 2013; Giupponi and Biscaro 2015). One stream focuses on disaster and hazard-risk management and the other on climate change and adaptation. The climate change and adaptation stream is argued by Costa and Kropp (2013) to consist of two prominent conceptualizations of vulnerability, namely, those of the IPCC (2007) and Turner et al. (2003). Turner et al. (2003) stated that vulnerability is ‘the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress’. Costa and Kropp (2013) argues that the difference between the IPCC and Turner et al. (2003) conceptualizations is that the IPCC included adaptive capacity as one of the vulnerability components, whereas Turner et al. (2003) instead applied the resilience concept. Giupponi and Biscaro (2015) argue that the paper by Turner et al. (2003) has played a prominent role in bridging the literatures on hazard-risk and climate change vulnerability. Notably, however, is that Turner et al.’s (2003) theoretical definition is very similar to Smith et al.’s (2000) broad definition.

Even though the IPCC’s definition of vulnerability from TAR and AR4 has been commonly used, and its compiled dimensions have gained wide acceptance in climate change research over the last decade, the operationalization of exposure, sensitivity, and adaptive capacity in assessments has remained problematic (Tonmoy et al. 2014). The IPCC (2007) defines ‘sensitivity’ as the degree to which a system is affected by climate-related stimuli, and ‘adaptive capacity’ as the ability of a system to adjust to climate change. Although the IPCC has been consistent throughout its reports on how to define these two concepts, the climate change literature contains additional interpretations of the terms. The IPCC definition of ‘exposure’, however, changed from ‘the nature and degree to which a system is exposed to significant climatic variations’ (IPCC 2001, p. 987) to ‘the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected’ (IPCC 2014b, p. 1765). These two definitions mirror two streams of interpretations of the concept, i.e., (i) exposure as a manifestation of a hazard and (ii) exposure in terms of a geographical location (Räsänen et al. 2016). Consequently, as vulnerability is defined by imprecise terms (Wolf et al. 2013) that can be interpreted differently, it is up to individual researchers to operationalize these concepts in research practice as they consider appropriate (Delaney et al. 2014).

Since theoretical definitions of vulnerability are often vague, the small differences between them hide existing similarities (Wolf et al. 2013).⁵ Confusion regarding the definitions arises since the theoretical differences cannot be discussed in a precise way. Wolf et al. (2013) proposed that, on a theoretical level, there is no difference between what different scholars mean by vulnerability. They argued that the definitions all suggest that gradable properties (e.g., characteristics, states, conditions, or processes) of entities (e.g., persons, groups, or systems) will be harmed (e.g., in terms of impacts, effects, or loss of property or life) by stimuli in an uncertain future (e.g., described as ‘likely’ or ‘potential’, or using technical terms such as ‘exposure’ and ‘susceptibility’). Various stimuli are however included in all the definitions, for example, climate change, natural hazards, environmental change, and social change (Wolf et al. 2013).

In the latest Fifth Assessment Report (AR5) of the IPCC WGII, it became clear that the conceptual understanding of climate change vulnerability is undergoing continuous evolution. The revised IPCC definition has shifted the focus from climate vulnerability to climate change-related ‘risks’. With this development, climate research has to reassess the framework for vulnerability and how it is interpreted. The definition of vulnerability has changed to what WGII argues reflects the progress of science, being defined as follows: ‘the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt’ (IPCC 2014b). This broader take on vulnerability is in line with the recommendation of Wolf et al. (2013) that scholars should agree on a basic structure and theoretical definition as a common basis and later consider precise operational definitions for specific purposes, i.e., approaches to making the vulnerability concept operational by providing methods that associate measurements with the concept.

3.1.2 Operational definitions

Costa and Kropp (2013) reason that frameworks are useful for conceptualizing vulnerability but that the practical operationalization of vulnerability is closely associated with specific social or environmental contexts, as in ‘biophysical’ and ‘social’ perspectives on vulnerability (Brooks 2003). According to Brooks (2003), ‘biophysical vulnerability’ is a function of a system’s exposure and sensitivity to physical hazards (i.e., physical manifestations of climatic variability or change), while social vulnerability exists within the system independently of external hazards, i.e., is an inherent property of a system. Brooks argued that distinguishing between biophysical and social vulnerability could resolve the conflict between different formulations of vulnerability in the climate change literature. Biophysical vulnerability is referred to as comprising the impacts of hazards, which could be

⁵ For a compilation of vulnerability definitions, see, for example, Thywissen (2006).

measured in terms of the damage experienced from that hazard. Social vulnerability, on the other hand, is not a function of hazard severity or probability, but is nevertheless hazard specific in terms of, for example, indicator selection (Brooks 2003).

Kelly and Adger (2000) and O'Brien et al. (2007) proposed, in line with Brooks (2003), that there are two general approaches to vulnerability. The first approach is linear in nature, using projections of future emissions to create climate change scenarios as well as biophysical impact studies to identify adaptation options. This is referred to as 'end-point' or 'outcome' vulnerability (Kelly and Adger 2000; O'Brien et al. 2007). The second approach is broader and usually starts by identifying the limited capacity to respond to external stressors, striving to concentrate on the processes and the multiple dimensions of climate–society interactions. Kelly and Adger (2000) used the term 'starting point' to talk about this second approach, whereas O'Brien et al. (2007) referred to this interpretation of vulnerability as 'contextual'. Various characteristics of vulnerability assessments have been examined based on these frameworks, and the conclusions indicate that outcome vulnerability assessments are usually physical science based and employ quantitative methods, whereas contextual assessments generally have a social science theoretical basis and draw on qualitative methods (Pearson et al. 2011; Soares et al. 2012).

Yet another way to categorize the various vulnerability assessment approaches is based on their characteristics as 'future-explicit', 'present-based', or 'combined' assessments (Wolf et al. 2013). Future-explicit assessments contain impact scenarios for evaluating harms, and the aggregated harms together describe the vulnerability of the system. Present-based assessments are based on measurements of the present state of the social–ecological system, considering its vulnerability and/or adaptive capacity. Hazards may not be explicitly represented in present-based assessments, but they cannot be neglected since the capacity to adapt only becomes relevant with respect to a system's exposure. This links to Brooks' (2003) argument regarding social vulnerability and the necessity of being hazard specific. 'Combined assessments' merge the future-explicit and present-based methodologies, but how the two are combined differs between assessments (Wolf et al. 2013).

With a description of combined assessments, Wolf et al. (2013) argued that their categorization of approaches extends the previous literature on vulnerability assessment frameworks (cf. Kelly and Adger 2000; Brooks 2003; O'Brien et al. 2007). Nevertheless, such 'combined approaches' could resemble with the 'integrated' vulnerability concept (e.g., Füssel and Klein 2006). In climate change vulnerability research, studies often strive to have an 'integrated' perspective, to address both the biophysical and social dimensions of vulnerability in theory as well as in operationalization (e.g., Eakin and Luers 2006; Füssel and Klein 2006). Though Soares et al. (2012) have described this integrated perspective as the current paradigm of climate change vulnerability analysis, it has also been recognized as problematic due to its requirement to synthesize different methods of performing and

analysing vulnerability assessments. As with the vulnerability concept, ‘integrated’ vulnerability has various meanings and is operationalized differently in various studies (Füssel 2007).

One can discuss whether a junction of outcome and contextual vulnerability is the same as the operationalization of ‘integrated’ vulnerability, a relevant discussion since integrated vulnerability has been proposed to be the current paradigm for climate vulnerability assessments (Soares et al. 2012). O’Brien et al. (2007) claimed that it is problematic to conjoin the two interpretations due to their different framings. They argued that these approaches should instead complement each other, since they have different means of recognizing the linkages between climate change and society.

However, as outcome vulnerability is frequently equated with biophysical vulnerability and contextual vulnerability has been equated with social vulnerability (e.g., Soares et al. 2012; Wolf et al. 2013), an integration of biophysical and social vulnerability could be understood as identical to an integration of contextual and outcome vulnerability. According to Pearson et al. (2011), it is possible to integrate the two interpretations of vulnerability because the results of outcome assessments may serve as input to contextual assessments.

It is generally accepted that climate change vulnerability cannot be estimated by biophysical, social, economic, or political factors separately, but that these factors must be integrated. However, this is not necessarily the same as integrating different interpretations of vulnerability. In discussing integrated vulnerability, there must be a distinction between the integration of human–environmental aspects and the combination of vulnerability interpretations. In this thesis, ‘integrated vulnerability’ is understood as the integration of a system’s biophysical and socio–economic dimensions, which should not be confused with the integration of *approaches* (cf. Pearson et al. 2011). However, this thesis acknowledges that different assessment methods can be combined into hybrid approaches (Wolf et al. 2013; Tonmoy et al. 2014).

The interpretation of vulnerability within this thesis is guided by the understanding that vulnerability is created in an integrated human–environmental system as the sum of a system’s exposure, sensitivity, and capacity to adapt to climate change stimuli (IPCC 2001, 2007; Füssel and Klein 2007). *Exposure* is here understood as the manifestation of climate change (Räsänen et al. 2016) and, more specifically, as ‘the nature and degree to which a system is exposed to significant climatic variations’ (IPCC 2001, p. 987). This thesis defines *sensitivity* in line with the IPCC (2007, p. 881), as the ‘degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct ... or indirect’. The sensitivity of a system specifies whether or not it is sensitive to climatic or non-climatic stressors; it is interpreted as an inherent property of the socio–ecological system with system attributes existing before the stressor (e.g., Gallopín 2006).

To evaluate a system's vulnerability to climate change, assessments need to address the capacity for and likelihood of adaptation (Smit et al. 1999). This third component is the system's *adaptive capacity*, which is closely associated with terms such as 'coping capacity' (Turner et al. 2003) and 'capacity of response' (Gallopín 2006). Integrated vulnerability assessments assume that it is not the availability of adaptation options but the capacity to implement these options (Füssel and Klein 2006) or the avoidance of *maladaptive* outcomes (Juhola et al. 2016) that determine a system's vulnerability to climate change. The concept of maladaptation is explored in Section 3.2.1. 'Adaptive capacity' is the term used for the capacity and likelihood of adaptation in this thesis, and the IPCC's (2014a, p. 1758) definition is applied: 'The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences'. Adaptive capacity is, like sensitivity, a system characteristic that exists prior to climate stress.

Several other terms are consistently used throughout this thesis to describe a vulnerable system:

- *Stressor* – climate change events or trends (i.e., *climate exposure factors*) or non-climatic external factors influencing the human–environment system (e.g., O'Brien et al. 2004; Räsänen et al. 2016), in this thesis used interchangeably with *drivers* (IPCC 2014b)
- *Contextual factors* – factors that constitute the characteristics of the vulnerable system (O'Brien et al. 2007; IPCC 2014b), in this thesis used interchangeably with *underlying factors*
- *Vulnerability indicators* – observable variables functioning to indicate theoretical concepts, i.e., in the case of vulnerability; the function of variables indicating vulnerability, sensitivity, adaptive capacity, or exposure (Hinkel 2011)

3.2 Additional key concepts in vulnerability frameworks

3.2.1 Adaptation, maladaptation, and adaptation-induced trade-offs

In conjunction with the increased scientific evidence of inevitable climate change (IPCC 2007), *adaptation* became one of two fundamental response options to anthropogenic climate change, with the other being *mitigation*. Adaptation is a relatively new concept in climate science but has a longer history in, for example, ecology, natural hazard research, and risk management (Smit et al. 1999).

Climate change adaptation generally refers to adjustments in social–ecological systems that moderate the adverse effects of unavoidable climate change through actions targeting the vulnerable system (Smit et al. 1999), but it may also include actions to seize opportunities presented by climate change (Füssel and Klein 2006). This thesis understands adaptation as

response actions intended to reduce current and/or future climate vulnerability and to take advantage of opportunities arising from climate change.

Adaptation strategies or decisions are successful if they meet the objectives of the action, but the question of whether or not an adaptation action is successful also depends on the action's effect on others' ability to meet their adaptation goals (Adger et al. 2005). An assessment of adaptation is therefore dependent on the temporal and spatial scale (Adger et al. 2005) and should describe and specify: (i) the system, i.e., who and what adapts, (ii) the climate stressors, i.e., adaptation to what, and (iii) the process, i.e., how adaptation occurs (Smit et al. 1999). Adaptation can influence a system's vulnerability to climate change in various ways. Fussler and Klein's (2006) conceptual framework of vulnerability assessments illustrates that adaptation actions may reduce sensitivity or exposure, limit the impacts, or reduce the negative influence of non-climatic factors. Consequently, through these channels, vulnerability to climate change can be reduced. However, not all adaptation actions result in successful outcomes.

Adaptation actions that fail to reduce vulnerability are referred to by several scholars as *maladaptation* (e.g., Smit et al. 1999; Barnett and O'Neill 2010; Rickards and Howden 2012). Maladaptation has historically not been a widely-used concept in climate change research, but since 2010, a literature on empirical examples of maladaptive outcomes has emerged (Juhola et al. 2016). Juhola et al. (2016) identified three types of maladaptive outcomes from empirical examples: (i) *rebounding vulnerability* implies that an adaptation action increases the climate vulnerability of the implementing or targeted actor; (ii) *shifting vulnerability* implies that an adaptation action increases climate vulnerability for one or several external actors; and (iii) *eroding sustainable development* is when an adaptation action has negative impacts on environmental, social, and/or economic conditions. Based on the previous definitions and interpretations of the concept, Juhola et al. (2016, p. 139) defined maladaptation as 'a result of an intentional adaptation policy or measure directly increasing vulnerability for the targeted and/or external actors, and/or eroding preconditions for sustainable development by increasing society's vulnerability'. This is how the concept of maladaptation is interpreted within this thesis.

Another related term is *trade-offs*, which is used in various ways and contexts in sustainability and climate change vulnerability science. For example, trade-offs are presented as one of three foundational concepts of vulnerability research in sustainability science, with the others being the 'coupled human–environmental system' (CHES) and 'environmental services' (Turner II 2010). Turner II (2010) discussed how activities intended to improve certain environmental services may have repercussions throughout the CHES, reducing other environmental services and, accordingly, involving trade-offs. The IPCC's AR5 stresses that the central tenet of sustainable development is to resolve trade-offs among social, economic, and environmental goals (Denton et al. 2014). Research into

climate change vulnerability and response actions should therefore explicitly assess trade-offs between suitability goals (Turner II 2010).

Trade-offs is also used to describe interrelationships between adaptation and mitigation policies and measures (Landauer et al. 2015). Here, trade-offs arise when there is a desired balance between adaptation and mitigation but the integration partially or completely fails when it is impossible to achieve both aims simultaneously (Landauer et al. 2015).

Adaptation policies and measures frequently involve the balancing of factors that are not attainable simultaneously, or in combination, due to conflicting goals (Denton et al. 2014). This thesis accordingly understands ‘trade-offs’ in line with this broader view and does not limit the concept to the balancing between adaptation and mitigation.

3.2.2 Risk and resilience

The various scholarly traditions of sustainability science have resulted in an array of vulnerability-related terms defined and conceptualized in various ways. These involve, for example, resilience, transformation, adaptability, transformability, coping capacity, robustness, marginality, susceptibility, fragility, risk, drivers, stressors, hazard, harm, stimuli, exposure, and sensitivity. The relationships between these concepts are often imprecise, implying that the same term may have different meanings when used in different contexts, conceptual frameworks, or by different authors (e.g., Brooks 2003; Gallopín 2006; Füssel 2007; Miller et al. 2010; Soares et al. 2012; Costa and Kropp 2013). Füssel (2007) reasoned that the diverse conceptualizations of vulnerability should be accepted, that they reflect the wide range of valid perspectives on the integrated human–environmental system. Similarly, Berkes et al. (2003, p. 8) stated that ‘a complex social–ecological system cannot be captured using a single perspective’. Nevertheless, an assessment requires clear conceptualizations of the involved concepts and clear definitions of related terms if it is to have meaning (Füssel 2007).

Operationalizing the two theoretical concepts *risk* and *resilience* is not within the scope of this thesis. Nevertheless, since the research fields of vulnerability, risk, and resilience are so conceptually and methodologically close, I believe that the two concepts ought to be acknowledged in the field of climate vulnerability. This section describes how risk and resilience can be theoretically related to vulnerability, but also why this thesis does not analytically apply the two concepts. The contribution of this thesis is nevertheless intended to be relevant in the contexts of resilience and risk.

Risk

Risk is a widely and increasingly used term in climate change-related contexts (Räsänen et al. 2016). It generally refers to uncertain future events and the evaluation of uncertain losses, and sometimes gains, attributable to such events (Scholz et al. 2012). Risk is often

represented as the consequences of an hazardous event multiplied by the hazard's probability of occurrence (e.g., Kaspersen et al. 1988; IPCC 2014b). However, various definitions of risk exist and can be divided into two categories depending on whether they refer to the probability of occurrence of a particular hazard or the probability of its outcome (Brooks 2003).

Previous studies have noted that vulnerability research includes the 'risk reduction' and 'climate change adaptation' streams (Thomalla et al. 2006; Giupponi and Biscaro 2015), meaning that the notion of risk is central to one stream of climate change vulnerability research. Several studies have analysed the relationships between risk and vulnerability in terms of both conceptual and methodological interpretations (e.g., Brooks 2003; Birkmann 2007; Scholz et al. 2012). Jurgilevich et al. (2017) argued that the general conceptual understanding of risk in the climate change context draws heavily on the work of the IPCC. Consequently, as the IPCC's understanding of vulnerability has developed from a climate change adaptation framing of vulnerability to a disaster risk conceptualization (Oppenheimer et al. 2014), the notion of risk has become central to climate change research. In relation to that, it has been demonstrated that approaches and concepts typical of the disaster risk literature are spreading to vulnerability studies conducted by the climate change adaptation community (Giupponi and Biscaro 2015).

In the IPCC AR5 (2014) framework, climate risk is the result of interaction between hazard, exposure, and vulnerability. *Hazard* refers to a physical event, trend, or impact thereof, that has an effect on human or natural systems; *exposure* refers to the presence of people or another unit of interest in settings where there can be adverse effects; and *vulnerability* here refers to the system's sensitivity and adaptive capacity (IPCC 2014b). Hazard as a scientific term has its roots in the risk-hazard paradigm of the 1970s (Cutter et al. 2009). Although various definitions of the term exist, the disaster-risk community has traditionally referred to a hazard as a potentially damaging physical event, sometimes also limited to naturally induced events (Schneiderbauer and Ehrlich 2004). Since the term has been adopted in climate change risk research, the latest definitions also include 'physical trends' (e.g., IPCC 2014). The current climate change literature consequently defines 'hazards' similarly to what were previously referred to as 'stressors' in the climate change and adaptation literature (e.g., O'Brien et al. 2004).

It has been recognized that it could be confusing that vulnerability is now perceived as a component of risk in climate change research (Jurgilevich et al. 2017). Räsenen et al. (2016) noted that even though the term is commonly used in vulnerability studies, the IPCC climate risk framework has not been explicitly used. This is possibly because of the lack of conceptual clarity of the key concepts involved, though an additional factor could be that the climate risk framework is new and not yet widely established (Räsenen et al. 2016).

This thesis acknowledges the development of climate risk and vulnerability research, that the IPCC's risk framework is an attempt to link the earlier disaster risk management literature and the climate change vulnerability and adaptation literature (Jurgilevich et al. 2017). However, as this thesis applies the climate change and adaptation stream of vulnerability research, perceiving vulnerability as a function of exposure, sensitivity, and adaptive capacity, exposure being interpreted as the manifestation of hazards (IPCC 2001, 2007), the climate risk framework is not applicable. Nevertheless, even though the risk framework is not analytically applied here, the results of the thesis should be relevant to the climate risk context.

Furthermore, in this thesis I apply the term 'stressor' and not 'hazard' to avoid confusion regarding the conceptual framework, as the hazard terminology is associated with the disaster risk reduction conceptualization.

Resilience

As with the notions of vulnerability and risk, *resilience* is part of sustainability science and addresses threats to societal and life support systems, seeking to understand these threats and their implications, including these systems' capacities to cope and adjust to them (Turner II 2010). Both vulnerability and resilience are specific to the perturbations that affect the system (Gallopín 2006). A key difference is their scientific entry points: resilience originates from the ecological/biophysical perspective with exogenous influence of social perspectives, whereas the reverse is the case for vulnerability. The resilience concept emerged in ecology in the 1960s and has evolved in two directions, reflecting two aspects of system stability (Holling 1996; Adger 2000). It is considered either the ability to accommodate disturbances (Holling 1973) or the ability to return to a pre-existing state after a temporary disturbance (Holling 1996).

Resilience is a relatively new addition to research into socio-ecological systems under global environmental change (Eakin and Luers 2006). In the core stream of resilience research, humans were excluded or treated as external to the system. However, in the early 21st century, social scientists contributed diverse perspectives on the dynamics of socio-ecological systems, resulting in further evolution of the resilience concept (Folke 2006). Social resilience is defined as the ability of human communities to withstand external shocks, which could be either environmental or socio-economic (Adger 2000). The resilience concept in general, and the socio-ecological perspective on resilience in particular, is used as an approach to understanding system dynamics (Folke 2006). The IPCC and the climate change community at large have gradually incorporated this concept⁶ (e.g., Leichenko 2011; Maru et al. 2014).

⁶The IPCC (2014b, p. 127) defines resilience as 'the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their

While ‘resilience’ and ‘vulnerability’ may be conceived as linked (Turner et al. 2003; Gallopín 2006; Maru et al. 2014), their conceptual relationships are unclear. Resilience is sometimes described as the inverse of vulnerability (e.g., Adger 2000; Folke et al. 2004). Adger (2006, p. 269) reasoned that ‘vulnerability is influenced by the build-up or erosion of the elements of social–ecological resilience’. From this notion, vulnerability and resilience are loose antonyms (Adger 2000). Other definitions present resilience as a system’s capacity to cope with or respond to hazards (Turner et al. 2003; Gallopín 2006). Gallopín (2006) claimed that even though a resilient system is less vulnerable than a non-resilient one, the relationship between the two concepts is not symmetrical; instead, he argued that resilience is related to the adaptive capacity component of vulnerability, so resilience is less than the inverse of vulnerability.

The resilience and vulnerability perspectives could be viewed as constituting different but complementary framings of socio–ecological systems (Miller et al. 2010; Turner II 2010), as well as contributing to each other’s conceptual development (Miller et al. 2010). However, there is need for a common lexicon for vulnerability and resilience research to avoid conceptual fuzziness (e.g., Gallopín 2006; Miller et al. 2010). There has been a tendency in both the vulnerability and resilience research communities to redefine the other community’s scientific terms in their own language, which may have impeded collaboration between the two (Miller et al. 2010).

It is apparent that as the two concepts of resilience and vulnerability have evolved, it has become possible to establish more and clearer linkages between them. I recognize that ‘socio–ecological resilience’ and ‘integrated vulnerability’ are the results of the evolution of two concepts towards the same target, but from different perspectives and analytical approaches. While I acknowledge the relevance resilience research into socio–ecological systems under climate change, I regard it as a supplementary approach to vulnerability studies. As vulnerability is the conceptual point of departure of this thesis, which applies the IPCC AR4 interpretation stream emphasizing climate change and adaptation vulnerability, resilience is not part of the vulnerability framework and therefore not used.

3.3 Vulnerability assessment methodology

Indicators are functions that make theoretical concepts operational (Hinkel 2011), and several indicating variables are often needed to represent a theoretical concept. There are many existing approaches that incorporate various indicating variables to create qualitative or quantitative assessments of the processes and outcomes of climate change vulnerability

essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation’.

(Adger 2006). While various vulnerability assessment methods exist, indicator-based vulnerability assessment is one of the most common (Luers et al. 2003; Tonmoy et al. 2014).

Indicators that represent a system's vulnerability are assessed and can be mathematically combined into a single composite index (Adger et al. 2004; Tonmoy et al. 2014). The composite index approach has the advantage of capturing multiple dimensions of phenomena that cannot be captured by a single indicator (Nardo et al. 2008). It also allows knowledge from various sciences to be combined. Furthermore, it has been argued that indicator-based assessments are relatively easy to conduct (Tonmoy et al. 2014), that a single composite index may be easier to interpret than the trends of many separate indicators (Saisana et al. 2002), that indicators or indices are easy to communicate to the public and policy makers, and that indicators or indices enable users to compare complex dimensions (Nardo et al. 2008; Tonmoy et al. 2014), and can therefore serve as valuable tools for systematic evaluation and discussion (Birkmann 2007).

The indicator-based assessment method has nevertheless received considerable criticism regarding shortcomings that should not be neglected (e.g., Birkmann 2006; Eriksen and Kelly 2007; Vincent 2007; Hinkel 2011). To start with, vulnerability is a dynamic phenomenon (e.g., Leichenko and O'Brien 2002; Luers et al. 2003; Eriksen and Kelly 2007; Vincent 2007; Ionescu et al. 2009; Jurgilevich et al. 2017) comprising complex linkages between various factors. Indicators are used to reduce this complexity and describe systems in simpler terms; however, because of the inherent nature of indicators, they do not capture all the essential characteristics of climate change-vulnerable systems, involving nonlinearity, vulnerability thresholds, or 'tipping points' (e.g., Vincent 2007; Hinkel 2011). Aggregating indicators is an alternative to mechanistic modelling for the purpose of obtaining an overview of vulnerability when exact relationships between variables are unknown and consequently cannot be applied in equations or simulation models (Tonmoy et al. 2014).

A single quantitative vulnerability index may consequently hide a system's complexity (Adger 2006), inviting simplistic policy conclusions if one considers only the 'big picture' and not the separate indicators (Saisana et al. 2002). Furthermore, the indicator approach is said to result in a lack of correspondence between the conceptual definition and the resulting index (Luers et al. 2003) and there is uncertainty related to the validity and robustness of indicators and conceptual frameworks (Eriksen and Kelly 2007; Vincent 2007; Becker et al. 2015). In the case of vulnerability as a function of exposure, sensitivity, and adaptive capacity, it has been argued that the differences between the three components are increasingly blurred as assessments move away from outcome vulnerability towards contextual indicator-based assessment. Furthermore, as a result of that blurriness, many indicator-based assessments find it difficult to categorize the indicating variables into the three vulnerability components (Hinkel 2011).

The process of selecting indicators, weights, and aggregation methods when constructing vulnerability indices involves judgment calls. The development of vulnerability indicators can be based on arguments from scientific knowledge of existing theory, statistical models explaining observed impacts, expert judgements, and multivariate analysis to reduce the number of indicating variables (e.g., Adger et al. 2004; Vincent 2007; Binder et al. 2010; Hinkel 2011; Tonmoy et al. 2014; Becker et al. 2015). It is a recognized struggle, irrespective of research tradition, to find suitable indicators of vulnerability (Brooks et al. 2005; Adger 2006). Eriksen and Kelly (2007) have argued that in reality, due to data constraints, vulnerability studies often make use of the indicators for which data already are available.

An additional challenge is to choose appropriate weighting and summarizing⁷ methods. While deductive arguments based on existing theory are common in the selection of indicating variables, it is rare for such arguments to be available to guide the weighting and aggregation of indicators (Hinkel 2011; Tonmoy et al. 2014). The equal-weighting approach has been demonstrated to be the most common (Tonmoy et al. 2014), but is arguably too arbitrary (e.g., Brooks et al. 2005; Gbetibouo et al. 2010) as it is not based on a suitable rationale (Tonmoy et al. 2014). A methodological approach that uses expert judgment for weighting could, on the other hand, entail complications in reaching agreement among the experts (Brooks et al. 2005; Gbetibouo et al. 2010) and result in disputes between, for example, stakeholders emphasizing different regions of the assessment (Nardo et al. 2008). Descriptive techniques for assigning weights are based on the variability of the data for a given indicator, for example, using factor and principal component analysis (PCA) (e.g., Thornton et al. 2006; Cutter and Finch 2008; Deressa et al. 2008; Holand et al. 2011). However, such approaches could be inadequate since they do not reveal anything about indicators' influence on the overall vulnerability (Nardo et al. 2008; Hinkel 2011).

There is ongoing scientific discussion of shifting the focus from attempting to quantify the vulnerability of a place, instead focusing on selected variables of concern in vulnerability assessments (e.g., Luers et al. 2003). Crop yield is one main variable of concern for agricultural production and competitiveness. Several studies analyse historical, or simulate future, crop yield productivity responses to climate change as a vulnerability assessment approach. In these cases, vulnerability is analysed by quantifying climate change-affected yield in relation to adaptation responses (e.g., Antwi-Agyei et al. 2012; Soora et al. 2013; Dong et al. 2015), which is recognized as a simulation-based (Tonmoy et al. 2014) assessment of outcome vulnerability (O'Brien et al. 2006). It could be argued, however, that studies using crop models in assessing vulnerability lack the incorporation of adaptation

⁷This thesis uses 'aggregation method' interchangeably with 'summarizing method'.

aspects if only coarse hypothetical adaptation measures are included in the model (Kandlikar and Risbey 2000; Antwi-Agyei et al. 2012).

Another way to analyse contextual indicators of vulnerability is to use data on observed impacts and indicating variables to build statistical models that explain these observed impacts (Hinkel 2011). Attempts have been made to identify and analyse how indicating socio-economic variables and climate conditions interact and create crop yield vulnerability (e.g., Simelton et al. 2009; Simelton et al. 2012; Fraser et al. 2013). The results concerning indicating variables from such an inductive approach (Hinkel 2011) are valuable in terms of policy support and information about key drivers of change (Ramirez-Villegas et al. 2013). As dynamics of vulnerability are increasingly emphasized as an essential aspect of vulnerability assessments, and dynamics are often understood as changes in vulnerability over time (Jurgilevich et al. 2017), drivers of change must be identified in order to improve estimates of climate impacts and vulnerability (Ramirez-Villegas et al. 2013). The development of statistical models of climate change vulnerability is only feasible if systems can be described by a limited number of variables for which sufficient data exist (Hinkel 2011). This is a difficult task since integrated vulnerability per definition concerns the complexity of socio-ecological systems.

This thesis regards indicator-based methods as feasible for vulnerability assessments. I further recognize that indicator-based approaches can be divided into four categories: (i) simulation based, (ii) aggregation based, (iii) hybrid, and (iv) neither simulation nor aggregation based (Tonmoy et al. 2014). In line with Tonmoy et al. (2014), I regard simulation-based assessments as modelling the climate change impacts of state variables⁸ in the system (e.g., crop yield being affected by climate change). Aggregation-based assessments combine present-value data on socio-economic and biophysical indicating variables into an overall index of vulnerability. Hybrid approaches combine indicating variables of impacts or stressors from simulation outputs (e.g., climate change, growing season change, and crop yield change) with the present value of socio-economic and biophysical indicating variables. In assessments in which there is no simulation or aggregation, vulnerability indicators are presented and discussed qualitatively without combining them into a single index, but this type of indicator-based vulnerability assessment is rarely found in research (Tonmoy et al. 2014).

In this context, this thesis views simulation-based assessments as typically ‘future explicit’ and as assessing outcome vulnerability, while aggregation-based approaches are ‘present based’ and assess contextual vulnerability. Hybrid and non-aggregation approaches are not, however, clearly linked to assessing outcome or contextual vulnerability. However, since

⁸Based on Tonmoy et al.’s (2014) description, this thesis interprets ‘state variables’ as variables that describe the current socio-ecological system.

this thesis interprets outcome vulnerability as climate change impacts in relation to adaptation responses, hybrid assessments and non-aggregation approaches are arguably more closely related to contextual vulnerability than outcome vulnerability. This thesis analyses and develops methods for assessing contextual vulnerability through hybrid approaches using simulated climate change indicators for exposure and present-based indicators for sensitivity and adaptive capacity.

3.4 Geographic visualization for vulnerability assessments

Geographic visualization, also shortened to ‘geovisualization’, draws on the geographic and cartographic tradition when developing methods to cope with the rapidly increasing volume of georeferenced data in science and society (MacEachren and Kraak 2001). The present research integrates approaches from ‘scientific visualization’ and ‘exploratory data analysis’, and refers to the use of geospatial displays to explore heterogeneous data to gain new insights (MacEachren and Kraak 2001; Kraak 2003). Moreover, geographic visualization can integrate different types of information to facilitate problem solving, and again, support the development of new insights (MacEachren and Kraak 2001; MacEachren and Brewer 2004).

Climate change visualization is a research field that has developed from the need to understand and organize emerging information about climate change through capacity-building processes and decision-support tools addressing climate change (Sheppard et al. 2011). Since many climate change-related aspects are geospatially specific, climate change visualization is frequently related to geographic visualization (e.g., Neset et al. 2016), with maps being used to stimulate visual thinking or communication about geospatial patterns, trends, and relationships (Kraak 2003).

Geographic visualization methodology could be divided according to relevant analytical components, such as data setup, visual display methods, participatory methods, and analysis of participant responses to the content, form, and relevance of the visualization tool (Salter et al. 2009; Sheppard 2012; Bishop et al. 2013; Wibeck et al. 2013). This thesis separates the geovisualization methodology into *Data content and visual displays* and *Participatory method – analysis and evaluation*.

3.4.1 Data and visual displays

DiBiase (1990) framed a range of functions of visual methods and argued that geographic visualization is a tool to foster either ‘private visual thinking’ or ‘public communication’. Accordingly, private visual thinking includes data exploration and the confirmation of data relationships in a collaborative effort of individuals intimately acquainted with the subject. When fostering public communication, the emphasis of visualization is instead on communicating ideas to others in contrast to answering research questions. DiBiase (1990)

viewed the range of functions of visual methods as a sequence of research, starting with private data exploration and ending with the communication of information to the public.

Another aspect considered essential in applying geographic visualization is the human–map interaction. Instead of conceiving maps as static storage devices representing space with geographic features, in geographic visualization, maps are conceived as dynamic interactive spatial information tools that can include multiple interconnected geospatial data resources (MacEachren 1994; MacEachren and Kraak 2001) and that can be equipped with various interaction techniques, such as zooming or dynamic selection. The visual representation of geospatial information can enable collaboration (i.e., geocollaboration; MacEachren and Brewer 2004) and interaction through geospatial technologies. Such an approach draws on the principle of facilitating knowledge construction by means of visualization tools. For example, this can be performed by incorporating local knowledge with the visual representation of multiple perspectives (e.g., Burch et al. 2010; Sheppard et al. 2011; Bohman et al. 2014).

Building on DiBiase's (1990) research sequence for visual methods, MacEachren (1994b) developed a conceptual framework for visualization from the *map use* perspective. MacEachren (1994b) reasoned that map use could be conceptualized as a three-dimensional space depicting: (i) the level of human–map interaction; (ii) whether the map is used to present known information or to reveal unknown information; and (iii) whether the map is constructed for the constructor's own needs or made available to a wider audience. This conceptualization is recognized as the 'map-use cube' and has been further developed (e.g., MacEachren and Kraak 1997) and commonly applied (e.g., Schroth 2010; Bohman et al. 2014; Neset et al. 2016) since it was first established. It should be noted, however, that the map-use cube is not completely intuitive. For example, the audience/user dimension of the cube has been interpreted in various ways in the literature, and the public–private dimension of the user profile could instead be interpreted as a lay–expert user dimension (Neset et al. 2016). These interpretations may imply the same thing if the constructor/private user of the visual representation is the expert, though the meanings are complementary if the visual representation is constructed for the constructor's own needs but the user is an external expert in the subject.

MacEachren and Kraak (1997) argued that the map-use cube can be applied to determine the goals of using visual representations of geo-referenced data. The distinction between goals could accordingly be based on the three dimensions of the cube, placing the goal inside the cube. Objectives may, for example, be exploration, analysis, synthesis, or presentation. Data exploration is in the corner with high human–map interaction, visual representation constructed for private needs, and unknown relationships between the data. Presentation, or communication, is at the other end of the goal dimension (MacEachren and Kraak 1997; Bohman et al. 2014).

The functionality of geographic visualization can involve *multiple linked views*, also known as *coordinated and multiple views*, which in a single visual interface combine, for example, map displays dynamically linked with other data displays that present supplementary characteristics, or the same information but in different ways (Roberts 2005). Such interactive exploratory environments facilitate a hands-on approach to gaining insights into the multiple dimensions of a concept as well as the deeper understanding of underlying information (Roberts 2005).

In visualizing climate-related vulnerability, in which regions are assigned scores based on their relative vulnerability, *choropleth mapping* is suitable (e.g., Opach and Rød 2013; see Figure 1A). Choropleth maps are planimetric generalizations of geographical distributions, with the whole area being divided into unit areas with assigned categories (Jenks and Caspall 1971). These can be further dynamically linked with other visualization techniques such as *parallel coordinate plots* (Opach and Rød 2014) that represent multidimensional data. Such a combination can facilitate the understanding of the multivariable spatial characteristics of, for example, a composite index represented in a choropleth map (see Figure 1B). The respective polylines from the parallel coordinates can moreover be represented in tiny multivariate glyphs – *polyline glyphs* – to provide increased insight into similarities and differences between various multivariate signatures (Opach and Rød 2017; see Figure 1C). Another visualization technique that could beneficially be included in a visual environment with multiple linked views is the Sankey diagram, a flow diagram in which the widths of the flows represent quantities (Alemasoom et al. 2014). A map-based multiple view approach is feasible for visually representing vulnerability data (Opach and Rød 2013), and some examples of studies using such an approach are Rød et al. (2014), Neuvonen et al. (2015), and Carter et al. (2016).

Visualization can also involve a number of potentially negative consequences, such as low estimation accuracy for encoded data and cognitive overload. Some aspects of a visual representation are emphasized more than others, and it can be unclear how visuals are to be interpreted in terms of colour, size, and data relationships (Montello 2002). Moreover, the selection of visual representation could potentially be biased or doubtful. Nevertheless, existing theory considers how to address these potential consequences through the proper use of visual variables (Bertin 2011) or effective information design (Tufte 1990).

Figure 1. (A) Choropleth mapping. (B) Parallel coordinate plot in which each line represents a county. (C) The dotted-line box includes polyline glyphs for all municipalities and the solid-line box contains the polyline glyph for the municipality selected in the parallel coordinate plot (red arrow). These three visual representations are displays from the AgroExplore tool.

3.4.2 Participatory methodology

The engagement of stakeholders in visualization-supported participatory processes arguably facilitates collaboration, engagement, learning, and knowledge refinement through dialogues (e.g., Salter et al. 2009; Sheppard et al. 2011; Sheppard 2012). Geographic visualization tools are therefore argued to facilitate a participatory process that may support dialogue and collaboration among participants when geographic data are represented in visual interfaces and data exploration is enabled (MacEachren et al. 2004a). The selection of stakeholders for the participatory process depends on the goal that the visualization method is intended to achieve. Evoking DiBiase's (1990) framework, the participants need to be intimately acquainted with the subject for the visualization to support data exploration. When visualization serves as a mediator for communication, audience preconceptions of the subject and their perceived need for knowledge must be taken into account (Wibeck et al. 2013).

Geocollaboration is a concept developed to describe the process when visual representations of geospatial information enable collaboration through geospatial technologies (MacEachren and Brewer 2004). In a geocollaboration process, a visual interface therefore serves as a mediator for collaboration. The process could, for example, facilitate knowledge construction and refinement, design, decision support, and education – often with one specific issue in focus.

Participatory processes enabling geocollaboration could be performed in various settings, for example, through physical meetings including visualization-supported dialogues (Wibeck et al. 2013), participatory GIS (e.g., Krishnamurthy et al. 2011; Hung and Chen 2013), or web-based consultations structured around thematic data exploration (Rød et al. 2014). MacEachren and Brewer (2004) reasoned that different stages of collaborative work (1) generate or explore, (2) negotiate or analyse, (3) choose or synthesize, and (4) execute or present information. The task of each stage is dependent on the underlying goal of the visualization approach, whether it is to support decision making or to construct knowledge.

A participatory process may aim for collaborative learning. The notion of collaborative learning is repeatedly spoken of in relation to visualization (e.g., Isenberg et al. 2011), and could in that context be described as a process that engages and promotes exploration, concept development, elaboration, direct application, and assessment (MacEachren and Brewer 2004). Although collaborative learning is defined in various ways (Kreijns et al. 2003), it has several agreed-on general characteristics: learning is active; teaching and learning are shared experiences between the facilitator and audience/users; participants reflect on their own assumptions through the learning processes; and there is give-and-take consensus-building among participants (Kirschner 2001; Kreijns et al. 2003).

While ‘seeing’ is part of creating people’s perceptions, visualization tools can make issues such as climate change more obvious, and further be used to reduce perceptual barriers to mitigation and adaptation (Sheppard 2012). Another objective of a visualization-supported participatory process could be to gain knowledge (revealing unknowns) of the participants’ views of the discussed topics. However, for both these objectives, visual representations of scientific information are useful only if stakeholders consider them credible, salient, and legitimate (e.g., Sheppard et al. 2011; Tang and Dessai 2012). Since the data selection and visual displays influence user perceptions, these aspects need to be carefully considered when designing a visualization tool. The parameter selection is crucial for addressing the interests of the audience, and local anchoring of the visual representations helps make them concrete and relatable for users on a personal level (Sheppard et al. 2011; Wibeck et al. 2013). To be salient, the information must appear relevant to the stakeholders across spatial, temporal, ecological, and administrative scales (Tang and Dessai 2012).

Extensive research has explored people’s perceptions of climate change (e.g., Bord et al. 1998; Lorenzoni et al. 2007; Dessai and Sims 2010; Wibeck 2014); perceptions shaped by people’s previous knowledge and experience, everyday interactions with other people, as well as media, scientific, and political debate (Wibeck 2014). Research into climate change perceptions can be categorized as studies of *what* people think about climate change (i.e., what factors they focus on) and *how* people make sense of climate change (i.e., how their understandings form) (Wibeck 2014). Furthermore, there is scientific discussion of the implications of these perceptions for individual climate change responses or for barriers to responding to climate change (e.g., Dessai and Sims 2010; Sheppard 2012). However, in this thesis, the term ‘perception’ refers to trends and patterns of participants’ perspectives of agricultural vulnerability, identified in the thematic analysis of transcribed material. While I acknowledge that people’s perceptions influence participatory approaches, it is beyond the scope of this thesis to analyse why participants ‘perceive’ agricultural vulnerability as they do, or how they make sense of vulnerability.

Rød et al. (2014) emphasized the importance of the participatory validation of data, i.e., when stakeholders interact with the data and their judgements of parameters and indices serve to validate the content. This is considered as important as traditional validation, for example, using historical data, since the result of participatory validation supports the assessment of the usability and policy relevance of the data. When the validity of indicators is discussed in this thesis, it refers to the question of whether the indicating variables are feasible measures of vulnerability. However, this is not to state that there is a single correct set of indicators suitable for characterizing the phenomenon. Rød et al. (2012) argued that a participatory geovisualization approach to indicator-based vulnerability assessments could serve to close the gap between top-down and bottom-up approaches, since top-down assessments can form a basis for participatory vulnerability assessments.

Another phase of the geovisualization methodology involves the analysis of participants' responses to and interactions with the visual interface. This could, for example, be achieved through ex post surveys, interviews, or focus groups to analyse participants' perceptions of the relevance of the visualization and content (Wibeck et al. 2013). While the evaluation of visualization tools is essential, Bishop et al. (2013) recognized that it is a complex task, and only a few publications treat the subject. Various frameworks for visualization evaluation have been developed. Wibeck et al. (2013) reasoned that content, form, context, and relevance are aspects that should be included in both the design and evaluation of visualization tools.

Salter et al. (2009) categorized their analysis and evaluation based on the overall effectiveness of the geovisualization workshop, effectiveness of geovisualization tools and components, and responses to data and scenarios. However, regardless of the framework, the focus of the evaluation is dependent on the intended goal of the visualization method, whether it is to communicate effectively, gain scientific insight, or serve as decision support (Bishop et al. 2013). Retrospective evaluation of the geographic visualization approach is therefore essential in determining the effectiveness of the approach and in learning from experience (e.g., Bishop et al. 2013; Wibeck et al. 2013).

4 Material and methods

The research design of this thesis is problem oriented and has been implemented within an interdisciplinary research environment and PhD programme. In problem-oriented research, it is the societal problems that determine the research, which in the longer run should provide knowledge for stakeholders and decision makers (Kueffer et al. 2012). The underlying problems of this thesis are vulnerability to climate change as such and the struggle to reduce this vulnerability. However, the specific problem tackled is the need to understand how vulnerability can be represented by means of assessments in order to explain the characteristics and processes of the phenomenon and reduce vulnerability.

It has commonly been emphasized that research into complex socio-ecological problems requires interdisciplinary approaches (e.g., Thompson Klein 2004; Pohl 2005; Petts et al. 2008). The character of climate change vulnerability as integrating social and biophysical dimensions calls for interdisciplinary approaches to operationalizing the vulnerability concept (e.g., Füssel and Klein 2006; Wilhelmi and Hayden 2010). Given this, I consider it necessary also to use an interdisciplinary approach to explore how vulnerability can be assessed and characterized from various perspectives and frameworks, to develop a conceptual approach to interactive vulnerability assessments and to synthesize the results of different analytical methods. In other words, while analysing interdisciplinary methods for vulnerability assessments, the thesis is itself an interdisciplinary effort.

Since it is the ‘problem’ that is the focal point of this thesis, pluralistic approaches are required to derive knowledge of the problem. *Pragmatism* could be used to describe the philosophy of science applied here. Pragmatism is a philosophy that supports the integration of perspectives and approaches on the basis of what is feasible and pertinent in order to gain insight into or solve the research problem at hand (Creswell 2003; Johnson et al. 2007). As pragmatism offers an epistemological rationale for mixing methods (Johnson et al. 2007), I applied a mixed-methods approach to address the four research questions of the thesis (RQ1–4). A mixed-methods approach combines both quantitative and qualitative data analysis in a single study (Creswell 2003).

In reading the rest of this thesis, it is important to be aware of the distinction between the *analytical methods* applied to answer the research questions and the *vulnerability assessment methods*, which are study objects. The analytical methods include *literature review*, *statistical analysis*, and *geographic visualization*. Through this mixed-methods approach, complementary and converging findings are sought, and the results of one analysis are used in developing another. On a general level, this thesis follows a sequential mixed-methods design (Johnson and Onwuegbuzie 2004; Ivankova et al. 2006) in which the results of the

analysis of different vulnerability indices (Paper II) were fed into the development of a conceptual framework (Paper III) applied and analysed to improve our knowledge of agricultural vulnerability indicators while bridging quantitative and qualitative perspectives (Paper IV). I am aware that this sequential method design may create some biased results, since the first study influenced the output of the second. Nevertheless, I consider this approach to be pragmatic and to produce relevant findings. By reflecting on how the sequence can influence the results, the potential bias can be handled transparently. If so, the method has clear benefits in terms of effectiveness and congruence.

In addition to this sequential method design, the review of the literature on climate-related challenges and opportunities for Nordic agriculture (Paper I) was concurrently (Johnson and Onwuegbuzie 2004) integrated with the results of other qualitative and quantitative analyses when interpreting the results. Moreover, this thesis statistically analyses the relationships between heavy precipitation, crop yields, and previously applied indicator variables to further problematize the vulnerability assessment methodology.⁹ This triangulation from the literature review, geographic visualization (including a participatory approach), and statistical analyses encompasses the opportunities and challenges of vulnerability assessment methods from various analytical perspectives.

Although this thesis has a point of departure in quantitative methods, both in terms of statistics as an analytical method and in terms of vulnerability assessment methods, the results of both qualitative and quantitative analyses are considered relevant and important for a thorough assessment. With the mix of analytical methods, I intend to gain knowledge of several dimensions of vulnerability assessments (cf. Nightingale 2016). This knowledge would probably not be as comprehensive if a disciplinary approach were applied, due to the integrated social and biophysical dimensions of climate vulnerability. Important insights into how to advance vulnerability assessment methodology can therefore be targeted with this mixed-methods approach. However, it is beyond the scope of this thesis to identify a single ontologically or epistemologically ‘correct’ vulnerability assessment method.

This chapter outlines the three categories of methods that constitute the overall thesis: sections 4.1 ‘Literature review’, 4.2 ‘Statistical analysis’, and 4.3 ‘Geographic visualization as an analytical method’. Figure 2 presents the methods in relation to the addressed research questions and the studies in which the methods are applied. Note that geographic visualization comprises both the ‘visual display’ as well as ‘participatory methods’, in line with the outlined analytical framework for geographic visualization methodology (Section 3.4). It is also worth noting that the respective papers do not correspond to specific research questions or methods; rather, the questions are addressed in several papers and the papers

⁹These statistical analyses and their results are described and discussed only as a sub-study (S1) in the preamble of this thesis and not appended as a separate paper.

respond to one or several of the research questions. Geographic visualization was applied to answer all research questions except how estimates of vulnerability vary depending on method (RQ3); here, geographic visualization was not regarded as an applicable analytical method.

The material consists of peer-reviewed scientific papers and grey literature for the literature review, quantitative data on vulnerability-indicating variables for the statistical analyses and geographic visualization, and qualitative data from the transcribed dialogues of the visualization-supported workshops. The material is specified for each of the methods in the following sections, though detailed descriptions are found in the appended papers I–IV. In addition, an overview of all vulnerability indicating variables’ associated sources and data are described in the Appendix.

Figure 2. An overview of methods (lilac) used to address the research questions (RQs) (apricot) in the studies (blue) that constitute this thesis (papers I–IV) and the additional analyses of the relationships between heavy precipitation, crop yields, and indicating variables (S1). Note that geovisualization refers to data and visual display methods as well as to the participatory method.

4.1 Literature review

A literature review was conducted, along with other analytical methods, to address RQ1 in Paper I, and a less extensive review was conducted to outline different composite index methods used in previous climate change vulnerability assessments for agriculture. This was done to select methods to analyse when addressing RQ3 in Paper II.

The systematic literature review presented in Paper I is based on a five-step approach adopted from Khan et al. (2003). The steps of the review comprised framing structured questions before the review, identifying relevant work for the questions based on specified selection criteria, structurally assessing the studies, summarizing the evidence, and interpreting the findings (Khan et al. 2003). The aim of the review was to synthesize climate change opportunities, challenges, and adaptation policies and measures for the Nordic agricultural sector from the scientific peer-reviewed and grey literature (except for Iceland). The structured review questions were as follows: (i) How is climate change influencing and projected to influence agricultural crop production and management in the Nordic countries? (ii) What challenges and opportunities are highlighted? (iii) What required adaptation actions (i.e., policies and measures) are mentioned?

The systematic search¹⁰ of the scientific literature was performed in the databases ‘Web of science’, ‘Environmental Sciences and Pollution Management’, ‘Scopus’, ‘Agricola’, ‘Google scholar’, and ‘Norart’. National grey literature was accessed through Google searches. A first screening of search returns identified approximately 160 documents.¹¹ The titles and, when necessary, abstracts of these 160 publications were further screened to examine the publications’ relevance in relation to the focus of this study. Finally, 60 documents were included in the literature review.

The assessment was structured based on the climate challenges and/or opportunities recognized in the studies as well as on possible adaptation strategies or guidelines examined or suggested by them. Moreover, if a study addressed other climate-related stressors in combination with climate change, this was also noted in the review. The material was synthesized to improve our knowledge of what climate factors are likely to contribute to agricultural vulnerability in the Nordic region, but also to comprehend the adaptation actions necessary to limit the vulnerability and seize possible opportunities. Furthermore, from this

¹⁰(Agricult* OR Crop* OR farming) AND Climate AND (risk OR hazard OR stress OR impact OR vulnerability OR effect) AND (adaptation OR action OR response) AND (Nordic OR Scandinavia OR Norway OR Sweden OR Denmark OR Finland).

¹¹The search was performed by the Linköping University Library in 2014. Based on this screening of the >2000 search returns, a list of approximately 160 documents was compiled. The original search was performed in 2014 but additional searches were performed as time passed, to update the literature list.

synthesis, knowledge gaps on climate related and adaptation related challenges could be explored.

The less extensive literature review in Paper II functioned as the first phase of a sequential mixed-methods approach. The review was implemented in Paper II to study the composite index methods and vulnerability indicators applied in the existing scientific literature on agricultural vulnerability to climate change.

The search was conducted in ‘Academic Search Premier’ and ‘Scopus’.¹² Although a substantial amount of literature assessing aspects of agricultural vulnerability appeared to be available, the review was limited to studies using indicator-based methods to construct composite indices for climate change vulnerability in the agricultural sector. Furthermore, the methods had to be comparable in that they addressed vulnerability to ‘climate change’ and used an integrated vulnerability perspective to do so.

4.2 Statistical analysis

The statistical analyses of this thesis altogether address RQ1–3 and different methods for quantitatively estimating vulnerability are applied and analysed. The analysis of outcomes in Paper II specifically addresses RQ3. To further problematize the vulnerability assessment methodology, statistical analyses were conducted to evaluate the possible statistical validation of indicating variables (addressing RQ1 and RQ2) and to test a vulnerability index constructed from the relationships between climate stress and its effect on crop yield (addressing RQ3).

The literature review in Paper II identified three weighting methods and three summarizing methods for composite vulnerability indices in the literature on agricultural vulnerability to climate change. To evaluate how assessments of vulnerability vary depending on these weighting and summarizing methods, nine combinations of composite vulnerability index approaches were applied to Sweden and further statistically analysed (Paper II). The indicators were selected based on the reviewed literature and the corresponding data were assembled for Swedish municipalities (see Appendix).

Simple linear regression analysis was used to evaluate differences in vulnerability scores between the methods, since the objective was to identify systematic differences between methods of climate vulnerability assessment. Simple linear regression models were conducted for the relationships between all index methods given the population regression equation below. *SW* is the combination of a summarizing (*S*) method and a weighting (*W*)

¹² Vulnerability AND agriculture AND (index OR mapping) were searched for in title, abstract, and keywords (2012) and gave 83 returns in ‘Academic Search Premier’ and 176 returns in ‘Scopus’.

method, β_0 is the intercept of the line with the y-axis, β_1 is the slope of the line, and ε describes the random component of the linear relationship between S_iW_j and S_kW_l :

$$S_iW_j = \beta_0 + \beta_1 \cdot S_kW_l + \varepsilon$$

It was tested whether $\beta_1 = 1$ and $\beta_0 = 0$. A slope of 1 indicates equivalence in the way vulnerability is measured by the two methods S_iW_j and S_kW_l . A slope $\neq 1$ indicates a systematic difference, i.e., that vulnerability is under- or overestimated relative to the other method in the model, meaning that when the vulnerability estimated in one method increases, the vulnerability in the other method increases ($\beta_1 > 1$) or decreases ($\beta_1 < 1$). Significant differences in intercept and slope suggest that the two composite vulnerability index methods measure different things.

In addition to simple linear regressions, the municipalities' coefficients of variation were analysed to evaluate the differences between the indices (Paper II). The coefficient of variation is the standardized measure of standard deviation, i.e., a standardized measure of the amount of variation from the mean. This was a feasible measure since the standard division is scale dependent. Differences in vulnerability *ranks* were not statistically tested in Paper II, though the vulnerability ranks are visually represented in the preamble of this thesis to enable visual examination.

This thesis includes further statistical analyses in order to test and deliberate on an inductive approach to assessing vulnerability and developing vulnerability indicators. Previous studies have used similar methods to analyse agricultural crop production vulnerability to drought on a global scale as well as in developing regions (e.g., Simelton et al. 2009; Antwi-Agyei et al. 2012; Simelton et al. 2012). Inductive approaches to vulnerability indicator development typically use statistical models to analyse relationships between observed impacts and vulnerability-indicating variables (Hinkel 2011). This thesis focused specifically on the relationships between crop yield and heavy precipitation as well as on the relationship between yield loss and the indicating variables of contextual vulnerability (i.e., indicating variables of sensitivity and adaptive capacity) in Sweden. The objective was to test and evaluate alternative ways of assessing vulnerability and validating indicating variables in order to advance the methodological discussion of vulnerability assessment challenges.

Heavy precipitation¹³ was selected as the climate stressor in this analysis due to its likely negative impact on crop production in addition to its relevance to past trends and future climate change in Europe (Stocker et al. 2013). Monitored weather data were preferred for the analysis, since actual years with extremes should be compared with historical county

¹³ 'Precipitation' is any form of condensed water vapour that falls from the atmosphere, and when precipitation during the growing season is discussed in this thesis, it is considered to fall as rain. This thesis thus equates heavy rains and heavy precipitation during the growing season.

crop yield data. Historical stationary data on heavy precipitation were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The dataset contained data from all available Swedish weather stations from January 1990 to June 2013 with the corresponding number of days with ≥ 20.0 mm and ≥ 40.0 per month, year, and county.

Crop yield data were collected for 21 crop species¹⁴ but were available only on the county level, which meant that heavy precipitation data had to be converted into county values as well. The station with the maximum number of heavy precipitation days per month in a county was used as representative of the county, as it was considered important to avoid smoothing of extreme event data. The monthly county-representative values were summarized for March–October to represent the approximate number of days with heavy precipitation during the growing season for a county; this is called the *heavy precipitation index (HPI)* in this thesis.

Regarding statistical analyses of vulnerability-indicating variables, data were unavailable for the consecutive years 1990–2013 for several of the adaptive capacity and sensitivity indicators applied in papers II and III (Appendix). It therefore became infeasible to create statistical models that could explain the observed heavy precipitation impacts through indicating variables (i.e., sensitivity and adaptive capacity indicators) (cf. Simelton et al. 2012). Because of this data limitation, this statistical analysis of vulnerability and underlying factors of vulnerability was divided into (i) a historical time-series analysis of crop yield and heavy precipitation, (ii) an estimate of crop production vulnerability to heavy precipitation, and (iii) an analysis of differences in vulnerability-indicating variables for ‘current’ static values between counties that have experienced and not experienced yield loss.

Bivariate Pearson correlation tests and simple linear regressions were used to analyse possible relationships between the historical time series of crop yield, and heavy precipitation for the various crop types. Theoretically, for crops whose yields significantly correlate with heavy precipitation, an index for crop production vulnerability could be produced. This crop production *vulnerability index (VI)* is based on the research of Simelton et al. (2009, 2012). In this thesis, *VI* is described as the severity of heavy precipitation (*HPI*) relative to the loss of crop yield from climate stress (i.e., the *yield loss index*) for each county and year.¹⁵

¹⁴ Winter wheat, spring wheat, rye, winter barley, spring barley, oats, winter triticale, mixed grain, peas, broad beans, maize, table potatoes, starch potatoes, sugar beets, winter rape, spring rape, winter turnip rape, spring turnip rape, oil flax, and grass ley $\times 2$ (the first and second cuts of grasses are separated into two variables).

¹⁵ The crop production vulnerability index for county and year i : $VI_i = \frac{HPI_i}{YLI_i} = \frac{HPI_i}{Y_i}$

The *yield loss index (YLI)* is defined as the actual yield, Y , divided by the expected yield, $\hat{Y}$. The expected yields were calculated based on 15-year moving averages. $YLI < 1$ indicates years with crop yield losses, and the VI was calculated for these cases. Accordingly, the higher the VI , the higher the crop production vulnerability to heavy precipitation for a county in a specific year.

Since it was impossible to create statistical models to explain the observed impacts using indicating variables, another method, adopted from de Toro et al. (2015), was used to statistically validate vulnerability-indicating variables from papers II and III. Here static current values of the indicating variables were analysed in relation to the counties' levels of yield loss over time (1990–2013). See Appendix for the list of indicating variables included in this sub-study. The relative frequency of >30% yield loss ($RFYL$ ¹⁶) during the 1990–2013 period was used as the foundation for categorizing counties into two groups. Since spring barley has the widest production dispersion across Sweden, it was used to calculate counties' yield loss. The categorization for the two groups was based on $RFYL = 0$ and $RFYL > 0$, respectively. The vulnerability-indicating variables of sensitivity and adaptive capacity were analysed in t -tests based on this grouping.

Moreover, since the grouping based on the relative frequencies of >30% yield loss and the t -tests could only be performed for spring barley, the relative frequency of >10% yield loss for the individual crops was also analysed in relation to the individual indicating variables through simple linear regressions. The data for >10% yield loss provided larger sample sizes than did >30% yield loss and the simple linear regressions were not dependent on any categorization of groups. However, multiple regression analysis was not feasible due to multicollinearity.¹⁷ Hence, only the indicating variables' individual relationships with $RFYL$ could be considered, while comparisons between indicators were impossible.

4.3 Geographic visualization as an analytical method

Initially, geographic visualization was suggested and tested in Paper III as an approach to support the assessment of agricultural vulnerability, addressing RQ4. The approach was applied in Paper IV intending to support dialogues to increase our knowledge of expert practitioners' perspectives on Nordic agricultural vulnerability to climate change, addressing both RQ1 and RQ2. However, the tool's design and functionality for interactive vulnerability assessment were also considered from the workshop dialogues, contributing to RQ4.

¹⁶The relative frequency of yield loss for county i : $RFYL_i = \frac{n_i}{N} = \frac{n_i}{\sum_{j=1990}^{2013} n_j}$

¹⁷Correlation among the independent variables in multiple regression.

4.3.1 Data and visual displays

The initial selection of vulnerability indicators was based on the literature review in Paper II. However, some of the identified indicators of agricultural vulnerability were excluded due to irrelevance in a Nordic agricultural context. Original variable data for the indicating variables were obtained in various formats (e.g., NetCDF, raster dataset, and attribute data from statistical databases) and for various spatial resolutions.

The highest possible spatial resolution was the municipal level. The data for all indicating variables were thus processed into municipal mean values. In cases in which only county data existed, all municipalities in a county were assigned the same value. Raster data were aggregated into municipal attribute data by calculating the mean value using the ‘zonal statistics’ tool in the ArcGIS software. Climate change scenario data were obtained in NetCDF format, which can be opened in ArcGIS using a tool to create a feature or raster layer. However, due to the inherent constraints of the NetCDF data, the procedure was limited to the creation of feature point layers only. The point layers were further interpolated using natural neighbour interpolation, which in turn was used to calculate zonal mean values for the counties.¹⁸

The vulnerability composite indices from the different methods were presented in nine cartographic representations (Paper II). As cartographic representations provide geographic contexts in which to recognize spatial patterns and relationships, the vulnerability index methods were classified using equal intervals in choropleth maps in order to compare the relative vulnerability scores between the indices. Since cartographic representations facilitate the recognition of spatial patterns and relationships, it was possible, from these visuals, to analyse the various vulnerability distributions provided by the different composite index methods.

To make the index set-ups flexible and to enable data exploration (papers III and IV), an interactive vulnerability assessment tool – AgroExplore – was designed and developed as presented in Paper III. The tool offers high interactivity in terms of selecting, combining, and weighting indicators as well as in categorizing them into the sub-indices of exposure, sensitivity, and adaptive capacity. In addition, in AgroExplore, indicators and indices can be explored through various choropleth maps, parallel coordinate plots, ordinary tables, and Sankey diagrams. The multiple linked functionalities were developed to support the performance of highly personalized vulnerability assessments and the exploration of vulnerability-indicating variables – i.e., how various factors and composite index set-ups contribute to high or low vulnerability scores.

¹⁸ Here, counties were chosen due to the low resolution of the climate raster data.

In the map-use cube (MacEachren 1994), AgroExplore is situated in the lower-left corner, constituting a research tool for private needs, providing a high level of interactivity for the expert user, and with unknown data relationships. Accordingly, the goal with AgroExplore is ‘data exploration’ to reveal new perspectives on agricultural vulnerability and assessment methodology.

Figure 3. AgroExplore situated in the map-use cube (adapted from MacEachren 1994; MacEachren and Kraak 1997).

4.3.2 Participatory method – analysis and evaluation

Initially, the development of AgroExplore was driven by the requirement to open the ‘black box’ of vulnerability composite indices, addressing the need for transparency in the selection of vulnerability assessment methods (Paper III). The AgroExplore tool was further applied to support stakeholder dialogues to gain an increased understanding of stakeholder perceptions of agricultural vulnerability to climate change (Paper IV) and to assess how geovisualization can be used in integrated vulnerability assessments.

An initial evaluation of AgroExplore was arranged as a rapid prototype assessment (Robinson et al. 2005) to determine whether users found the tool understandable. The tool was tested by 11 students to obtain feedback on its design and effectiveness. In this evaluation, the students were asked to complete five short tasks and then answer five closed-ended questions (Paper III). This rapid prototype assessment was conducted to obtain feedback in order to optimize the tool before the participatory vulnerability workshops.

Although visual representations of vulnerability in AgroExplore are based on scientific knowledge, they should not be considered representations of reality but rather as various possible perspectives on vulnerability (cf. Rød et al. 2012, 2014). It was the users’

interaction and dialogues concerning these perspectives that constituted the participatory process in Paper IV.

The participatory method (Paper IV) drew on interactive vulnerability assessment (Rød et al. 2014) through focus group methodology (Wibeck 2010) in a visualization-supported set-up (e.g., Sheppard et al. 2011; Wibeck et al. 2013). This approach was a development from traditional focus-group methodology using visualization tools to facilitate engagement and dialogue. Interactive vulnerability assessment enables participant interaction to explore data and identify knowledge gaps and inconsistencies. Three workshops with four or five agricultural experts professionally active in south-east Sweden (e.g., county administrative board representatives and agricultural extension officers) were arranged in the Norrköping Decision Arena¹⁹ in spring 2015. The Norrköping Decision Arena is a research environment that allows immediate interaction in which participants' mobile units can be displayed simultaneously on a 360° screen. The Decision Arena enables inclusive workshops where participants are directly supported by data, which each participant can display, manipulate, and reflect on. Discussions of the tool's design and functionality for interactive vulnerability assessment were also considered even though the specific aim of the participatory process in Paper IV was to support explorative discussions to obtain expert practitioners' perspectives on Nordic agricultural vulnerability indicators.

The AgroExplore participatory approach provided both qualitative and quantitative data. Transcripts of the three audio-recorded focus group sessions constituted the qualitative empirical material, which was analysed by means of thematic analysis to identify possible trends and patterns in the dialogues (Kvale and Brinkmann 2009). In this thesis, participants' perceptions of vulnerability and vulnerability indicators are reflected in the trends and patterns of the discussed perspectives. The quantitative material constituted the participants' indicator selection, weighting, and categorization settings from their final individual agricultural vulnerability assessment. The various participants' settings reflect the potential for reflexivity incorporated into the AgroExplore tool, regarding how to represent vulnerability. As the sample size was too small for statistical analysis ($n = 11$), the setting data were presented in graphs to support the results of the qualitative thematic analysis.

4.4 Ethical considerations

Research ethics could be described as the 'appropriateness of your behaviour in relation to the rights of those who become the subject of your work, or are affected by it' (Saunders et al. 2009, pp. 183-184). Research ethics have been considered throughout this thesis, i.e., in the overall design of the research, data collection, and data processing and analysis as well as

¹⁹ <https://liu.se/en/research/the-norrkoping-decision-arena> (accessed, 2017-03-24)

in writing up and disseminating the research findings. In particular, the participatory research component of this thesis has been the object of ethical considerations.

When inviting stakeholders to take part in the visualization-supported workshops, the purpose of the workshop and the professional role of the invited stakeholders were described. The participants were contacted via individual email addresses, so that it would be impossible for them to discern who else was invited to participate. Participation was of course voluntary. As the participants were invited with regards to their professional role as agricultural experts, and the workshop discussions were not on a personal level, I consider it most unlikely that the participants perceived that they were exposed to any stress, discomfort, pain, or harm during the workshops. Moreover, the Norrköping Decision Arena is a workshop setting that creates a non-hierarchical and inclusive environment for dialogue.²⁰

To ensure participant privacy and anonymity, no personal information was included in the dialogue results. Furthermore, the quantitative data from the AgroExplore settings were coded. Participant well-being was unlikely to be negatively affected either during the workshops or in the way the findings were communicated. Generally, throughout this thesis, the highest possible level of objectivity in result interpretation, analysis, and discussion has been striven for. In this regard, I consider that the mixed-methods approach strengthened my ability to be an objective researcher.

4.5 Limitations and generalizability

While the vulnerability assessment methods applied and analysed in this thesis involve limitations, these are not the same as the limitations of my analytical approach. The limitations of the analysis involve, for example: delimitations regarding what was included in the literature reviews (papers I and II); difficulties reading documents in other Nordic languages than Swedish (Paper I); data for certain indicating variables used in analysing the composite index methods being available only on the county level (Paper II); the inclusion only of participants from Östergötland county in the workshops on agricultural vulnerability (Paper IV); and the poor historical data availability for socio-economic variables.

As the title and aim suggest, the regional context of this thesis is the Nordic region. Naturally, the state of the art regarding agricultural challenges and opportunities arising from climate change and variability was reviewed for the Nordic region (Paper I). However, due to limited time for data collection, the analysis of composite indices (Paper II) and the development of AgroExplore (Paper III) were conducted only for Sweden. The AgroExplore-supported stakeholder workshops therefore came to have a Swedish focus as

²⁰ <https://old.liu.se/forskning/climatevisualization/research-projects/nda?l=en> (accessed 2017-09-27)

well (Paper IV). Furthermore, the statistical analysis of relationships between crop yield and heavy precipitation required coherent historical data for the specific regions included in the analysis, which were unavailable. Nevertheless, since it is not the aim of this thesis to determine Nordic agricultural vulnerability, I believe that these limitations will not affect the generalizability of the methodological discussions included here. Rather, the discussions of composite indices, indicator selection, and indicator definitions could also be of importance for other sectors or regions.

Regarding the first research question – ‘How can agricultural vulnerability to climate change and variability in the Nordic countries be characterized?’ – I argue that the general aspects found in this thesis could be of value for the Nordic region as a whole. Possibly, it could also be of value for other parts of the northern hemisphere, although, this remains to be examined. Nevertheless, I do not attempt to present a conclusive list of indicating variables exclusively applicable to the Nordic region.

5 Results

This chapter summarizes the results of papers I–IV and of the additional statistical analyses, by synthesizing the findings for each research question. Accordingly, detailed descriptions of the papers' results are found in the respective papers, while this chapter contains four sections that specifically address the research questions of the thesis.

5.1 Nordic agricultural vulnerability

The review in Paper I demonstrates that the literature on Nordic agricultural vulnerability to climate change mainly involves crop productivity studies focusing on different climatic factors. The literature review signifies that both challenges and opportunities are anticipated to arise from a changed climate, but it was also evident that the opportunities could be limited by other expected climatic or non-climatic factors. Specifically, the results of this review identify a need to emphasize research into agricultural adaptation to climate change and possible trade-offs associated with adaptation actions. Agricultural adaptation actions were seldom the focal point of the reviewed studies but were instead discussed in terms of plausible responses to the analysed anticipated climate impacts.

Climate change-related challenges, opportunities (Table 1), and suggested adaptation actions (Table 2) are listed based on the literature review. Generally, the climate change exposure of Nordic agriculture is indicated by the frequency of heavy precipitation and drought, and level of increased precipitation and temperature. However, the results of the synthesized literature indicate that it is the timing and frequency of these stressors as well as the context of the exposed agricultural system that make these stressors critical. For example, crop yield is said to be particularly negatively affected by extreme precipitation in connection with sowing, first emergence, and harvest. With extreme precipitation, soils can become saturated and anoxic (e.g., Hakala et al. 2012), while another consequence is that soils become too wet for heavy machinery to sow or harvest in fields (Fogelfors et al. 2009; Uleberg et al. 2014).

Increased temperature and earlier onset of spring can be beneficial in terms of increased yield and opportunities to cultivate 'new' crops, but the same factors could be experienced as climate stressors if, for example: accelerated phenological stages shorten the vegetative growing period (Kristensen et al. 2011); winter crops become less hardened because of a shortened hardening period in autumn (Höglind et al. 2013; Uleberg et al. 2014); or soil temperatures are too low to permit cultivation in early spring due to decreased snow cover (Uleberg et al. 2014). These circumstances exemplify the complexities that make it impossible to define the general vulnerability situation of Nordic agricultural crop production and competitiveness, i.e., not only do climatic changes such as warmer climate

have positive consequences for Nordic agricultural production, but multiple other aspects need to be taken into account. However, the list of challenges and opportunities in Paper I demonstrates the vast number of possible climate change impacts that together can characterize the climate exposure component of Nordic agricultural vulnerability (these are summarized in Table 1).

The adaptation actions suggested in the literature are intended to reduce vulnerability or seize opportunities arising from climate change (Table 2). The results of the literature review indicate that the suggested adaptation actions are mainly farm based, grounded in farmers' rational self-interests and implemented by the farmers themselves. These actions involve, for example, cultivating new crops and varieties (Maracchi et al. 2005; Eckersten et al. 2012; Uleberg et al. 2014; Jordbruksverket 2017), increased fertilization (e.g., Maracchi et al. 2005; Eckersten et al. 2007; Fogelfors et al. 2009), increased crop rotation (Rötter et al. 2012; Jordbruksverket 2013; Uleberg et al. 2014), and improving sub-surface drainage in agricultural fields (Fogelfors et al. 2009; Hakala et al. 2012; Jordbruksverket 2013). Some adaptation actions that were listed in the literature were of a more policy driven character, for example, breeding varieties adapted to new conditions and improving policies and measures for the drainage system. However, the diversity of possible challenges and opportunities in the literature point towards uncertainty regarding how to adapt.

Table 2. Adaptation actions suggested in the literature on Nordic agriculture under climate change (adapted from Table 3 in Paper I).

Climate-related change	Adaptation action
Extended growing season and altered climate conditions	New crops or crop rotations. ²⁶ Northward expansion of crops and varieties: heat-demanding species; legumes and more productive forage grasses, vegetables, and grains; ¹ peas, faba beans, oil seed rape, soybeans, sunflowers, ² and maize ³
Increased atmospheric CO ₂ : new crops – new needs	Increased fertilization ^{2,4} Increased pesticide usage ^{2,5}
Accelerated phenological development of grain/take advantage of the shortened vegetative period ³	Delayed sowing of winter crops ⁶ Use of long-season varieties ² Use of spring-sown crops (less affected than winter-sown crops in Denmark) ⁷ Adjusted sowing dates in spring ^{2,8,9} Breeding new varieties in which the date of anthesis is less responsive to increased winter temperatures, or with extended vegetative growth that is more heat tolerant during anthesis and grain filling ^{6,10–12} Breeding varieties to make use of the unique Nordic light conditions ^{1,13}
Stress from drought periods	Enhance soil properties through, e.g., improved drainage ²⁴ and a greater focus on crop rotation ^{1,14,15} Develop irrigation systems and reservoirs (especially important for potatoes, sugar beets, vegetables, and fruits) ^{24,26,27} Identify current and future water withdrawal needs and available water resources ²⁷ Use of winter-sown crops ^{13,16}
Stress from increased precipitation	Enhance soil properties; ²⁴ greater focus on crop rotation; ^{1,14,15} intercropping; ²⁸ increased and improved drainage systems ²⁶

Delayed opportunities to exploit extended growing seasons	Use of winter-sown crops ^{13,24} and frost protection (e.g., cover potato plants in early spring) ²⁹
Excessive soil water content causing sowing and harvesting problems	Use of perennial crops ¹³
Heavy rains and excessive water on fields reducing yield and soil buoyancy	Reduce tile spacing in sub-surface drainage systems ¹⁵
	Minimize heavy machinery use in fields to avoid soil compaction ³¹
	Use cropping systems that enhance the soil structure and infiltration capacity ^{15,31}
	Improve the dimensioning and management of main drainage systems ^{15,31}
	Revise recommendations for drainage systems ¹⁵
	Improve knowledge of drainage on all agricultural levels through research and education ^{15,17}
	New drainage system policies ¹⁵
	Cooperation between administrative units and institutions ³⁰
	Breeding varieties with increased water-logging resistance ¹⁷
Nitrogen leaching	Reduce intensive tillage in autumn; liming; extend the period of green cover and active crop growth; plant grassland, catch crops, and winter-sown crops ^{13,18,19,32}
Increased risk of weeds, pests, and diseases	Increased need for crop protection and pest control products ^{2,5,12,13,20,21,26}
Increased risk of weeds, pests, and diseases, simultaneously with increased resistance to chemical plant-protection products	Varied crop rotations ⁵
	Earlier sowing (in case of potatoes) ²⁹
	Subsidies for non-chemical products ⁵
	Limit the production of winter-sown crops and potatoes ⁵
	Increase grassland production ^{5,19}
	Mechanical weed control ⁵
	Intercropping ²⁸
	Biological seed protection ⁵
	Revise guidelines on reduced soil tillage ⁵
	Introduce official import control of plants ²⁵
Vulnerability to more varied climate	Increased diversity in how crop genotypes respond to various climate conditions ^{14,17}
	Increased crop diversity; ²⁶ intercropping ²⁸
General climate change	Improved crop management and cultivar selection on suitable land ¹⁶
	Harvest loss follow-up system considering weather and economic loss ²⁴
	Implement increased extension to farmers regarding climate change impacts ²⁴
	Research to improve knowledge and develop approaches to adaptation planning ^{22,23}

¹ Uleberg et al. (2014); ² Maracchi et al. (2005); ³ Eckersten et al. (2012); ⁴ Eckersten et al. (2007); ⁵ Wivstad (2010); ⁶ Kristensen et al. (2011); ⁷ Olesen (2005); ⁸ Rötter et al. (2013); ⁹ Kaukoranta and Hakala (2008); ¹⁰ Olesen et al. (2012); ¹¹ Patil et al. (2010); ¹² Marttila et al. (2005); ¹³ Fogelfors et al. (2009); ¹⁴ Rötter et al. (2012); ¹⁵ Jordbruksverket (2013); ¹⁶ Rötter et al. (2011); ¹⁷ Hakala et al. (2012); ¹⁸ Jeppesen et al. (2010); ¹⁹ Reinfeldt and Erlandsson (2012); ²⁰ Gaasland (2004); ²¹ Peltonen-Sainio et al. (2010); ²² Bizikova et al. (2014); ²³ NOU (2010); ²⁴ SOU (2007); ²⁵ Andersson et al. (2015); ²⁶ Jordbruksverket (2017); ²⁷ Bastviken et al. (2015); ²⁸ Himanen et al. (2016); ²⁹ Pulatov et al. (2015); ³⁰ Jordbruksverket (2016b); ³¹ Jordbruksverket (2016a); ³² Huttunen et al. (2015)

Moreover, as different adaptation actions have different purposes, they may result in unintended negative consequences, i.e., being maladaptive in that they increase the vulnerability of the implementing actor, shift vulnerability to other adjacent systems, or

negatively affect the sustainability of the common pool (Juhola et al. 2016). The literature synthesis indicated that several of the suggested adaptation actions are in conflict with each other, entailing a risk of maladaptive outcomes. For example, increased tillage to enhance drainage capacity and reduce the risk of pests and weeds could instead increase the risk of nutrient leaching (cf. Fogelfors et al. 2009; Jeppesen et al. 2010; Wivstad 2010), thereby reducing the capacity for sustainable development. Another example is that the opportunities arising from climate change in the Nordic countries could lead to increased possibilities to cultivate winter crops and maize, while on the other hand, such adaptation could increase vulnerability due to increased need for fertilizers (Fogelfors et al. 2009) as well as enhanced risks of pest and weeds (Wivstad 2010).

The results therefore suggest that climate adaptation actions involve various trade-offs between individual adaptation actions as well as between adaptation actions and other environmental objectives. Specifically, the results point towards decision-making trade-offs between various adaptation guidelines concerning, for example, longer and warmer growing seasons, increased risks of pests, weeds, flooding, and droughts, as well as important trade-offs between adaptation guidelines and environmental policies concerning, for example, wetland protection, a non-toxic environment, and zero eutrophication (cf. Eckersten et al. 2007; Wivstad 2010; Jordbruksverket 2013).

The fact that different adaptation actions involve trade-offs between objectives which may lead to maladaptive outcomes, could influence the sensitivity of agricultural production and competitiveness on different spatial scales. For example, increased pesticide use to handle increased occurrence of pests and weeds could lead to pests and weeds developing immunity to the applied chemicals (Wivstad 2010). The review indicated little about the actual adaptive capacities, but the suggested adaptation actions and their purposes point to factors that could describe sensitivity, which in turn could be used to analyse the capacities needed to implement the suggested actions.

In addition to the results of the literature review (Paper I), the thematic analysis of the geovisualization workshop dialogues (Paper IV) as well provided results regarding how climate change-related vulnerability in Nordic agriculture can be characterized. The discussions involved participants' perspectives on the indicating variables already included in AgroExplore, and on the perceived relevance of these indicating variables depending on how they are defined, weighted, and categorized. The visualization-supported dialogues also revealed information about factors the participants perceived as indicating vulnerability but that were missing in the AgroExplore tool.

The agricultural practitioners intensively discussed various climate change exposure factors during the AgroExplore workshops, and concluded that extreme weather events were considered more important than annual or seasonal mean changes. Extreme weather events as well as political decisions, practices, and messages influencing agricultural practice were

examples of factors that participants perceived as not covered in AgroExplore. Table 3 summarizes the factors that participants perceived as indicating agricultural vulnerability but that were not included in the AgroExplore tool. These factors are relevant to future research into climate-related vulnerability in Nordic agriculture. The factors in Table 3 are categorized into vulnerability dimensions based on how the participants considered the factors²¹.

The results suggest that Nordic agriculture is indeed vulnerable to multiple stressors and, consequently, that these stressors require a portfolio of adaptation actions. However, the results also suggest that climate vulnerability could be characterized differently depending on perspectives regarding, for example, contextualization, spatial scale, and stakeholder perceptions.

Table 3. Factors identified in Paper IV perceived by the participants as influencing agricultural vulnerability.

Vulnerability dimension	Identified vulnerability factor
Climate exposure	Extreme weather: <i>e.g., heavy precipitation and frost</i>
	Climate variability
	Soil water content (<i>drought indicator</i>)
	Rain intensity
	Autumn temperature change
Non-climatic external stressors	Climate change impacts: <i>e.g., occurrence of pests and weeds</i>
	Political-economic conditions: <i>decisions, practices, messages and need for continuity, food prices, imports, exports, world market, external prices, need to produce food, and profitability</i>
Adaptive capacity	Lack of focus on agriculture in industrialized countries
	Access to pesticides
	Access to agricultural extension (<i>financial limitation</i>)
	Economic support: <i>e.g., distribution of EU subsidies</i>
Sensitivity	Age structure of employees
	Political readiness of future climate vulnerability: <i>e.g., rationalization, control measures, incentive structures, and food contingency</i>
	Wind: <i>i.e., influencing the efficiency of pesticide application</i>
	Field slopes (<i>indicator of drainage capacity</i>)
	Eccentricity and shapes of fields

In addition to the results of papers I and IV regarding how vulnerability can be characterized, the statistical analyses found that only few of the generic indicating variables previously used in agricultural vulnerability assessments could be statistically validated in relation to Swedish agricultural yield loss. The analysis of counties' relative frequencies of barley yield loss demonstrated that 10 counties have had no yield loss larger than 30%

²¹These categorizations were not explicitly introduced by the participants, but rather interpreted based on the discussions and the applied definitions of exposure, adaptive capacity, sensitivity and non-climatic external factors.

during the 1990–2012 period, whereas 11 counties²² have experienced yield losses >30%. The *t*-tests identified that three out of twelve indicating variables (three were excluded due to unequal variance) had significant differences in means ($\alpha = 0.05$) between the two groups of counties. These three indicating variables were *clay content*, *share of larger-scale farming*, and *P fertilizer use*. This implies that counties with a high soil clay content, a smaller share of large-scale farming, or higher phosphorus fertilizer use have experienced extensive yield losses to a greater extent; suggesting that high clay content, smaller-scale farming, and high P fertilizer use are three factors that characterize more vulnerable spring barley production. Interpreting these results further, the sensitivity of spring barley production to climate change decreases with lower clay content, whereas the adaptive capacity of such production systems increases with larger farm size and lower use of added P fertilizer.

The results of the simple linear regression models for the relative frequency of >10% yield loss for the cases in which significant correlations were identified between crops' RFYL (10%) and the individual indicating variables, are presented in Table 4. These results capture the individual indicating variables' relationships with crop yields, but it is impossible to relate the indicating variables to one another. Taking oats as an example, the relative frequency of >10% yield loss could be described by a linear model with either *erosion risk* or *nitrogen fertilizer use* as the independent variable. Hence, based on these linear regression models, nothing can be said about which of the variables influences the relative frequency of yield loss the most.

While the vulnerability-indicating variables used in this analysis constitute the type of generic indicators previously used in the literature as well as in papers II–IV, only a few could be statistically validated, and these were each validated for just one specific crop type and yield loss threshold. None of the crops in the analysis provided the same set of indicating variables that could significantly explain a crop's relative frequency of yield loss.

²²Counties with a relative frequency of >30% yield loss during the 1990–2013 period: Skåne, Blekinge, Halland, Kalmar, Kronoberg, Jönköping, Gotland, Jämtland, Västernorrland, Västerbotten, and Norrbotten.

Table 4. Simple linear regression models for counties' relative frequencies of >10% yield loss and climate change sensitivity and adaptive capacity indicating variables (see Appendix for sources and units of all variables). β_0 is the intercept of the regression line on the y-axis and β_1 is the slope of the line.

Dependent variable: counties' relative frequency of yield loss (>10%) for crop, y		β_0	p-value	β_1	p-value	R^2
Independent variable, x						
Spring barley	Arable land	0.243	<0.000	-0.004	0.003	0.371
	Diversification	0.09	0.006	0.003	0.001	0.44
	Employees in agriculture	0.278	<0.000	-0.012	0.032	0.219
	N fertilizer use	0.381	<0.000	-0.002	0.011	0.296
	Potential irrigated area	0.210	<0.000	-2.0 E-6	0.044	0.196
Grass ley, first-cut	Crop diversity	0.261	<0.000	-0.003	0.016	0.31
	Soil phosphorus	0.47	non-sign.	0.15	0.034	0.25
	Employees in agriculture	0.05	non-sign.	0.014	0.039	0.24
	Irrigation share of arable land	0.107	<0.000	0.993	0.016	0.313
Winter wheat	Clay content	0.053	non-sign.	0.005	0.047	0.290
	N fertilizer use	0.549	0.007	-0.004	0.042	0.302
Oat	Erosion risk	0.3	<0.000	-0.031	0.002	0.468
	N fertilizer use	0.464	0.001	-0.003	0.036	0.248

5.2 Development of indicating variables

Both the visualization-supported vulnerability assessment workshops (Paper IV) and the statistical analyses identified essential challenges for the validation and development of vulnerability-indicating variables.

Of the exposure indicators included in the tool, *spring and autumn precipitation change* was weighted the highest by the participants. In the discussions of sensitivity indicators, the physical condition of the soil was regarded as particularly important, and most participants agreed that the *soil organic matter* content serves as a good indicator of sensitivity. The indicators *crop yield* and *crop diversity* were both considered relevant and weighted highly. However, while they by default were categorized as indicators of sensitivity, two participants instead regarded *crop diversity* as an adaptive capacity indicator. Socio-economic variables were generally considered relevant as adaptive capacity indicators, but the relevance of the specific indicating variables in AgroExplore was intensively debated.

Farm income was the only indicating variable of adaptive capacity that all participants considered useful.

The participants of the AgroExplore workshops (Paper IV) argued that the thresholds for the indicating variables are crucial in terms of how the indicators are considered to influence vulnerability. For example, thresholds for small or large farm holding sizes were debated, and most participants argued that the small-holding size threshold should be at least 50 ha, not 2 ha, as in the AgroExplore tool. However, it was not obvious to the participants how to perceive that variable's relationship with vulnerability. Participants argued that smaller farms are less sensitive because they do not depend on agricultural production and their owners do not farm full time; on the other hand, larger farms have higher financial capacity and therefore have higher adaptive capacity. Furthermore, it was stated that the threshold for small farm holdings determines whether the indicator is perceived as increasing or decreasing sensitivity, i.e., the threshold for when the agricultural producer becomes dependent on agricultural production.

Although the statistical analysis (chapter 4.2) found significant differences between the two groups of counties for the indicating variables *clay content*, *share of larger-scale farming*, and *P fertilizer use*, these results were not supported by the findings of the thematic analysis of the AgroExplore workshop dialogues. For example, the participants generally weighted clay content low or deselected the indicator, mainly considering clay content a factor that reduces sensitivity during longer dry periods. Instead, the statistical analysis indicated that the sensitivity increases with higher clay content, since the group of counties with a relative frequency of 30% yield loss had significantly higher mean clay contents than did the counties not experiencing 30% yield loss. These results jointly illustrate how difficult it is to define indicating variables and that further contextualization is needed for the representation of characteristics, qualities or properties of the exposure, sensitivity and adaptive capacity of the agricultural system.

Similar to the results of the literature review, the participants of the workshops stressed that the timing, frequency, and intensity of weather events are of particular importance in determining whether or not exposure to a climate change factor should be considered a stressor. Precipitation was discussed as an example, and the timing was argued to determine whether a weather event should be considered to increase or decrease climate exposure. Nevertheless, sudden changes were generally considered to increase rather than reduce vulnerability. Extreme precipitation was considered particularly important since it could undermine the entire planning of agricultural production.

The issue of the spatial scale of the data was a main theme in the workshop discussions. Several participants argued that municipal-level data (as in AgroExplore) were difficult to relate to, as there may be large differences between farms in the same region.

The analysis of the relationships between heavy precipitation and crop yields exposed difficulties in statistically validating the anticipated exposure indicator, as a climate stressor. The results identified that, of the 23 crops included in the analysis, only county yields of rye, spring barley, winter triticale, broad beans, table potatoes, winter rape, and the first cut of grass ley were significantly correlated with the county heavy precipitation index (*HPI*; $\alpha = 0.05$). However, the yields of rye, winter triticale, and winter rape were positively correlated with *HPI*, contrary to what was hypothesized. The result for table potatoes could not be considered valid, since the data collection and sampling method changed in 1999, resulting in overall lower potato yield values. Figure 4 presents scatterplots and simple linear regression models for yields of spring barley, broad beans, and grass ley, all relative to *HPI*.

Figure 4. Bivariate scatterplots for yields of spring barley (kg ha^{-1}) (A), broad beans (kg ha^{-1}) (B), and grass ley (kg ha^{-1}) (C) relative to the heavy precipitation index (*HPI*) (i.e., number of days with >40 mm precipitation during the growing season) for county values, 1990–2012.

According to the statistical analysis results, it is impossible to draw any conclusions regarding the particular importance of heavy precipitation as a climatic stressor. However, this is not to say that heavy precipitation is *not* a relevant climate stressor and indicator of vulnerability. The current analysis was based on the best available data for heavy precipitation and crop yield; however, for the statistical analysis of weather events that are local and rare, the spatial resolution of the data can be considered too low.

5.3 Vulnerability assessment variations

This section presents the results of the analysis of how assessments of vulnerability vary depending on selected composite index methods (Paper II) and in relation to the index constructed based on the relationship between heavy precipitation (*HPI*) and spring barley yield loss (*YLI*) (chapter 4.2).

The results of statistical analyses of weighting and summarizing methods for the composite indices (Paper II) demonstrate that the choice of method has considerable impact on the vulnerability score. More specifically, 34 out of 36 method combinations were found to differ significantly from one another in either intercept or slope in the simple linear regression models, indicating systematic differences in what the methods measure.

The results demonstrate that the coefficients of variation for nine method combinations ($S_{1-3}W_{1-3}$) are largest in mid-southern Sweden. The highest coefficient of variation is 94% and the lowest is 10%. Moreover, the different visual representations of the vulnerability distributions in Sweden (Figure 1 in Paper II) also illustrate the difference in municipal vulnerability scores between methods. However, while Paper II presents the relative vulnerability scores, the municipal vulnerability rankings are not explicitly presented in the paper. Therefore, Figure 5 presents the rankings with equal interval classes to visualize the different methods and their outcomes in rankings. However, the representations of the rankings of municipal vulnerability for the various composite indices do not indicate as strong a difference between the indices as do the vulnerability scores. Nevertheless, the mean of all municipal differences between the highest and the lowest rankings is 70 (290 municipalities in total). A representation with equal intervals and five classes hides some of the ranking variations between the methods.²³ The most extreme case is Gotland, which is ranked as the 62nd, 91st, 92nd, 101st, 115th, 136th, 214th, 218th, or 232nd most vulnerable municipality, depending on the composite index method. Conclusively, in addition to the systematic differences between methods identified by the regression analyses of the scores, these ranking differences further challenge the composite index method of representing

²³The reason for having five classes was to make the representation comparable to the representations of the vulnerability scores in Paper II.

vulnerability. The results of this thesis do not indicate whether one composite index method is preferable to another, but rather highlights the great variability between methods.

Figure 5. Municipal vulnerability ranking from highest (1) to lowest (290) vulnerability for nine method combinations based on three summarizing and three weighting methods. The same weightings are shown vertically (equal weights = $S_1 - S_3W_1$, component score loading of absolute PC1 = $S_1 - S_3W_2$, and aggregated scorings of principal components with eigenvalues greater than one = $S_1 - S_3W_3$) and the same summarizing methods are shown horizontally (weighted mean including all indicators = $S_1W_1 - W_3$, weighted average of exposure/sensitivity and adaptive capacity separately and further summed into one index = $S_2W_1 - W_3$ and standardization method = $S_3W_1 - W_3$). For further description of the methods, see Paper II.

In addition to the composite indices, yet another way to calculate an index was tested, in this case, to represent agricultural production vulnerability to heavy precipitation based on the relationship between heavy precipitation and crop yield loss. This vulnerability index gave the same vulnerability distributions for vulnerability scores and rankings in equal interval classes. As this method provided a vulnerability score for each year, Figure 6 presents ranking based on the mean of all vulnerability scores for the studied 1990–2012 period. A sound comparison with the composite indices (Paper II) is impossible since this assessment was only achievable on the county level due to the above-mentioned data resolution restrictions; nevertheless, similar patterns regarding higher vulnerability in northern regions, modest vulnerability in central and western regions, and lowest vulnerability in southern and south-eastern regions can be noted.

Figure 6. Ranking of the mean value of the annual vulnerability indices from the relationship between heavy precipitation and spring barley yield loss for the 1990–2012 period. The counties are ranked from highest to lowest vulnerability.

5.4 Vulnerability assessments through geographic visualization

To address the limitations identified with vulnerability assessments through static composite indices (Paper II), a conceptual framework for interactive vulnerability assessment was developed using a geographic visualization approach (Paper III).

Three themes of requirements were identified based on existing literature and the results of Paper II. To address these themes, the conceptual framework suggests that three

corresponding components should be applied in vulnerability assessments. First, vulnerability needs to be defined and conceptualized since the specification affects what aspects to include and how to include them in assessments. Second, transparency regarding the selection and definition of vulnerability assessment method could address the limitations of different methods providing different results. Lastly, reflexivity in conveying vulnerability results would enable user feedback and facilitate exploration of the vulnerability assessments. The results of Paper II motivate the need for reflexive use of vulnerability indices, which generally is held back by lack of transparency and the exclusion of stakeholders' perspectives. Accordingly, this thesis supports arguments for developing a conceptual framework of interactive vulnerability assessments in which a geographic visualization approach allows the personalized selection of indicators, the interactive classification of indicators into a defined conceptualization of vulnerability, electable method steps, knowledge acquisition and construction, and collaborative learning (Figure 7).

Figure 7. The conceptual framework developed for interactive vulnerability assessments (VA) through geovisualization (Redrawn from Figure 1 in Paper III).

This framework was applied to support the design and development of the AgroExplore tool (Figure 8). The rapid prototype assessment of the layout and functionality found that the participants mainly had positive attitudes towards the visualization tool (Paper III). All participants in the rapid prototype assessment agreed or strongly agreed that the design of the tool was successful and that its various interactive functions were well integrated. Most also stated that the tool was easy to use. While the general result of the rapid prototype assessment indicated that the layout and functionality of the tool were properly designed, this does not necessarily imply that the tool is easy to learn. Paper III concluded that tutorials and technical support are desirable to ensure that the full potential of AgroExplore can be realized.

Figure 8. The AgroExplore interface featuring one possible setting. In the top three displays, the vulnerability sub-indices are created and the exploration of spatial differences is enabled. The lower-left display shows the resulting vulnerability index, which can be manipulated by changing the proportions of the sub-indices in the final vulnerability index (to the far left). To the right of the vulnerability index, a municipality's vulnerability score can be explored relative to those of other municipalities. This can be done in a data view, in a parallel coordinate plot, or, as shown in this interface, in a Sankey diagram.

The participatory process confirmed that the spatial scale is problematic in regional mapping (Paper IV), as hypothesized in Paper III. The dialogues regarding AgroExplore as a facilitating tool revealed difficulties with the spatial scale of the assessment. Furthermore, participants said that it could be difficult to interpret and develop adaptation measures based on municipal mean values and that the mean values of some indicating variables were irrelevant since there may be huge differences between farms within a single municipality.

Regarding the settings of the indicators, some participants commented that they were uncertain whose perspective they were supposed to apply when they selected and weighted indicators. In relation to that, the absence of regional settings was considered an issue, in that AgroExplore users make their selections and weightings from specific regional perspectives, but those settings are then applied to the entire country. One participant discussed the effect of selecting many indicators, noting that, even if weights are adjusted, individual indicators become less important (i.e., have less influence on the final composite vulnerability index) as more indicators are selected.

A final remark from the participants was that interaction with the tool was complex and therefore time consuming, i.e., more time was needed to explore the indicating variables. It was also considered a barrier that the tool was available only in English at the time of the workshop.

Although Paper IV did not conduct a usability evaluation as such, the results of analysing the transcribed workshop dialogues indicate a rich discussion and evaluation of indicating variables of Swedish agricultural vulnerability. The objective of AgroExplore and the visualization-supported approach applied in Paper IV was to facilitate ‘data exploration’ to reveal new perspectives on agricultural vulnerability (Figure 3). For this purpose, the geographic visualization approach presented in this thesis is considered to have achieved its goal.

6 Discussion

In this thesis, I apply and analyse vulnerability assessment approaches to Swedish agriculture in order to develop the methodology and improve our understanding of climate vulnerability in Nordic agriculture. The research questions address this objective from different angles through a novel interdisciplinary and mixed-methods approach involving a literature review, geographic visualization, and statistical analyses. In this chapter, the findings of this thesis are interpreted and discussed while considering the strengths and weaknesses of the study in relation to the state of the art of vulnerability assessment methodology and climate-related vulnerability in Nordic agriculture.

Although vulnerability assessment methods are problematized in this thesis, developing such methods is regarded as essential for assessments to improve our understanding of how, why, and to what extent agriculture is vulnerable to climate change. Key results indicate that there is great variance between the vulnerability assessment outcomes of different indicator-based methods and that geographic visualization can enable enhanced transparency in vulnerability assessment processes, to facilitate collaborative learning between stakeholders and researchers. This chapter discusses the difficulties in developing vulnerability indicators and assessments, the role of geographic visualization, and the complexity of the agricultural system under climate-related stress, involving possible trade-offs between different climate adaptation and socio-ecological objectives.

6.1 Reflecting on vulnerability assessment methodology

This section discusses the various processes involved in developing vulnerability assessments, such as indicator selection, defining and validating indicating variables relative to a vulnerability conceptual framework, and aggregating normalized indicator variables with different summarizing and weighting methods. The results of the statistical analyses and the AgroExplore workshops identify a number of critical challenges in vulnerability assessment methodology. While recognizing the necessity of using vulnerability indicators due to their inherent measurability, this thesis contributes to the scientific discussion of difficulties and dilemmas associated with the selection and definition of indicating variables (cf. Eakin and Luers 2006; Hinkel 2011; Birkmann 2012; Delaney et al. 2014). Based on the results of this thesis, I argue that previously applied generic indicators require reconsideration and that the outcomes of vulnerability assessments are largely method dependent.

6.1.1 Indicator selection

In the composite index analysis (Paper II) and in AgroExplore (papers III and IV), indicators were defined individually and correlations with vulnerability were assigned to the respective indicators. While other methods exist to assign correlation direction (e.g., principal component analysis), these were not applied here, which might constitute a limitation. The AgroExplore workshops nevertheless included discussions of defining and validating indicating variables in relation to a vulnerability conceptual framework. The discussions of, for example, the importance of the timing and frequency of weather events and how to define small- or large-scale farming revealed that a specific threshold might influence whether and how an indicating variable could be perceived as indicating vulnerability – and therefore influence how to categorize indicators according to the vulnerability dimensions and, subsequently, influence whether it is perceived as increasing or decreasing vulnerability.

While this thesis addresses its research questions using various analytical approaches, both the literature review and the visualization-supported workshop dialogues pointed at the importance of extreme weather events, in particular, heavy precipitation. However, since heavy precipitation, for most of the included crops, could not be statistically validated as having a negative effect on crop production, different ways of constructing the heavy precipitation index²⁴ were evaluated in bivariate correlation analyses. Nevertheless, no conclusion regarding differences between the indices could be drawn from these analyses. The lack of significant results could be due to a methodological weakness in the statistical evaluation through bivariate correlation, considering the range of the different regions' crop yields and the assumed linear relationships between the two factors of crop yield and heavy precipitation. In a test to limit the regional differences, the county of Östergötland was selected for the 1965–2012 period, but this analysis found no significant correlation between the heavy precipitation index and any crop's yield.

Previous studies have obtained comparable findings for other regions or sectors (e.g., Adger et al. 2004; Brooks et al. 2005) and the difficulty of statistically validating vulnerability indicators has previously been addressed (e.g., Hinkel 2011). Brooks et al. (2005) studied the statistical relationships between mortality and indicating variables of vulnerability in order to identify key vulnerability indicators. In their analysis, GDP was not found to be a significant indicating variable of vulnerability, but they asserted that this may be because GDP does not capture the aspects of the economic environment that make people vulnerable. Poverty was, however, considered an important indicator of vulnerability. Similarly, from the AgroExplore workshops (Paper IV) and literature review (Paper I), heavy precipitation was

²⁴ Aggregated by the county mean values (HPI2) and by the county maximum (HPI3) and mean values (HPI4) and weighted by the total number of stations per county. Different periods of the season were also tested.

identified as an important climate stress factor even though it cannot be statistically validated as an indicating variable. Given this lack of statistical validation and the anticipated increase in heavy precipitation events with climate change, there is a need for future research into the impact of heavy precipitation on crop production. Bearing in mind the importance of the timing and frequency of weather events, this thesis' results concerning missing relationships between crop yield and heavy precipitation may be a result of infeasible thresholds for the heavy precipitation index in its role as an indicator of climate stress. However, these results could also be consequences of an insufficient number of observations or insufficient data resolution, as discussed later in this chapter.

The role and importance of thresholds in vulnerability assessments (e.g., Adger 2006; Eakin and Luers 2006; O'Brien et al. 2006; Ionescu et al. 2009; Tonmoy et al. 2014) have been discussed in relation to the assumption of linear relationships between indicators and vulnerability – in other words, the disregard of the possible nonlinearity of vulnerability. For example, in the framing of vulnerability as susceptibility to damage, Luers et al. (2003) referred to 'thresholds of damage', i.e., the point at which the system experiences damage to which it is susceptible. This notion is linked to the concept of 'ecological threshold', defined as 'an abrupt change in a quality ..., property or phenomenon or where small changes in a driver ... may produce large responses in the ecosystem' (Groffman et al. 2006, p. 2).

This thesis recognizes the importance of this discussion of vulnerability thresholds, but considers it specifically important for outcome vulnerability assessments. In contextual vulnerability assessments, on the other hand, it may be difficult to account for vulnerability thresholds due to the lack of mathematical relationships between all factors. Therefore, based on the results of this thesis and on the ongoing scientific discussion of the nonlinearity of vulnerability, I stress the essentiality of valid thresholds for the indicating variables, i.e., concerning how to define *variable thresholds* for indicators used in contextual vulnerability assessments. It is worth noting that this goes beyond the discussions of threshold values for climate stress factors, but concerns all dimensions of vulnerability.

As the generic vulnerability indicators were difficult to validate despite using both statistical and participatory methods, I argue that vulnerability needs to be assessed by means of new indicating variables. By 'new' I do not only refer to the indicators in Table 3 but also to the fact that the commonly used indicators need to be redefined, as they often are too generic and do not sufficiently represent exposure, sensitivity, or adaptive capacity. Thus, the results imply that these indicators are too blunt and do not adequately characterize vulnerability. I therefore call for increased contextualization and narrower variable thresholds in the development of agricultural vulnerability indicators. However, this should be linked to a discussion regarding for whom the indicators are selected and assessments are conducted. A general question is whether it is at all feasible to create national or international indicators of agricultural vulnerability. The Swedish action plan for climate adaptation in the agricultural

sector (Jordbruksverket 2017) asserts that a great number of indicators from various agricultural-relevant dimensions are needed in order to produce relevant assessments of adaptation needs in the agricultural sector. However, the results of this thesis indicate that the generalizability of such national indicators comes with the trade-off that the relationships between these indicators and overall vulnerability cannot be validated.

Furthermore, this thesis confirms that the matter of spatial scale of analysis is central to several aspects of the vulnerability assessment methodology (cf. Birkmann 2007; Vincent 2007; Binder et al. 2010), specifically concerning the loss of information when aggregating higher-resolution data on the municipal and county levels. While these settings are often selected to enable the comparison of administrative entities as well as the linking of biophysical and socio-economic variables, the aggregated level proved difficult for the agricultural practitioners. It is a well-known limitation of any geographical visual representation that spatial information is lost when being generalized (e.g., De Gruijter et al. 1997; Antunes et al. 2001), for example, when higher-resolution data are aggregated to the municipal level.

The issue of scale was discussed during the AgroExplore workshops in which participants argued that there can be significant differences between farms located in the same municipality, and that it would be more relevant to explore vulnerability on the farm level. For example, biophysical variables indicating sensitivity, such as *clay content*, *phosphorus content*, and *pH*, were weighted low by the agricultural practitioners because of the lack of contextualization and the fact that such indicators were considered irrelevant as regional mean values. It has previously been stated that there is a need to understand vulnerability to climate variability and change within communities and households, at the scale at which most adaptation decisions are made (Carr and Owusu-Daaku 2016). However, farm-level assessments may not be suitable to guide policy, which links back to the discussion of the purpose of assessments. For policy support, indicators that require high contextualization, for example, soil quality, might not be relevant. On the other hand, to support farmers in their development of adaptation strategies, such indicators might be appropriate, at least for higher resolution assessments than on the municipal level.

The issue of data resolution was also noted when analysing the relationship between heavy precipitation and crop yield (see Chapter 5.2). The analysis was conducted at the county level, since that was the highest accessible resolution for yield data. For heavy precipitation, the best available data were stationary data. However, the stationary data were unevenly distributed within the counties and it is problematic to construct aggregated county values for extreme values based on these data. Moreover, the fact that heavy precipitation events are often local means that crop yield losses will be local as well, according to the hypothesis that heavy precipitation affects crop production. Similarly, de Toro et al. (2015) found that it was unusual for extreme weather to have large regional effects on crop yields in Sweden

during the 1965–2014 period. However, on the farm level, their analysis demonstrated that crop yield losses could be related more to weather events that could not be identified from the county crop yield statistics. Further research into statistical relationships between heavy precipitation and crop yield would preferably involve other types of climate data than stationary weather data and use crop yield data at a higher resolution than the county level. Regarding precipitation data, one possibility could be to use data from weather radars, a matter to be evaluated in future research.

The above-mentioned considerations regarding the need for increased contextualization of indicators and the challenge of the spatial scale of vulnerability assessments fuel the claim that indicator-based vulnerability assessments are only appropriate for local-scale analysis and carefully defined systems (e.g., Barnett et al. 2008; Hinkel 2011). Moreover, these aspects are linked to the argument that local vulnerability indicators cannot be generalized because of their context-specific characteristics (O'Brien et al. 2007). While I would not go as far as claiming that indicators are not applicable on a regional level, I argue that there are trade-offs concerning spatial scale and variable thresholds in terms of developing vulnerability indicators and vulnerability assessment approaches. These spatial scale-related trade-offs concern the circumstances that (i) comparative analysis requires lower-resolution normalized indicator data, (ii) the presentation of user-relevant data requires higher-resolution data, (iii) making vulnerability indicators generalizable for a larger region and/or sector requires broader variable definitions, and that (iv) statistical or participatory stakeholder validation requires more narrowly defined variables and systems. If these spatial scale-related trade-offs are acknowledged, the best possible indicator-based assessment could be prepared.

Various vulnerability outcomes attributable to different indicator selections have not been analysed here, but it has previously been argued that the selection stage of the vulnerability assessment methodology is the most critical stage in determining what places are to be considered vulnerable (Jones and Andrey 2007). The different outcomes arising from the agricultural practitioners' selections of indicators were not evaluated in Paper IV due to the focus on how vulnerability could be represented through vulnerability indicators. Moreover, statistical analyses of vulnerability scores from the participatory settings were limited by the small number of observations (i.e., participants).

6.1.2 Index design and uncertainty

The design and temporal scale of vulnerability assessments often involve data-associated problems. It has previously been stressed that it is important to be clear on whether vulnerability assessments refer to the potential impact of current or future conditions (e.g., Jurgilevich et al. 2017). Tonmoy et al. (2014) argued that the time-frame of the assessment should reflect the time when indicating variables are measured. The focus of this thesis on

indicator-based vulnerability assessment methodology limits the selection of adaptive capacity and sensitivity data to being historical or current, whereas the data used for climate change exposure are modelled future data. While this aggregation of simulation-based data and current situation data could be regarded as a ‘hybrid’ or ‘combined’ indicator-based vulnerability assessment approach (Wolf et al. 2013; Tonmoy et al. 2014), it could also be criticized since a generalized measure of vulnerability needs to account for dynamics (e.g., Jurgilevich et al. 2017). What is vulnerable in one period may not be vulnerable in the next (Adger 2006). However, in light of the uncertainties of vulnerability assessment methods demonstrated in this thesis, projecting all indicating variables into the future would probably increase the uncertainty of the results even more. I agree with previous research (e.g., Tonmoy et al. 2014) that the temporal time frame should be specified, but argue that in this type of aggregated or hybrid approach, a system’s vulnerability can be interpreted as *the current contextual condition of a system vulnerable to future exposure to climate change (or additional stress factors modelled for the future)*.

While there is a well-established discussion of how to weight indicators in the scientific literature, Paper II contributes with a novel analysis and visualization of the differences between methods. The finding that the decision on how to weight the selected indicators in an indicator-based vulnerability assessment has great consequences for the resulting vulnerability score and rank, argues for the insufficiency of using a single composite index to represent agricultural vulnerability. Since the vulnerability score of a region changes considerably with the use of a composite index method, the vulnerability classification changes, or even becomes inverted, with the use of another method. These challenges to the construction of indices become even more problematic if indices are used or communicated without taking into account case specific assumptions and aggregations.

In addition to the uncertainty of vulnerability assessments stemming from various composite index methods, assessments are influenced by the uncertainty of the data for the indicating variables. This uncertainty varies depending on how the original measurements and regional aggregations have been conducted. However, as this study does not aim to reveal *the* actual vulnerability but rather explore assessment methods and aspects that can characterize vulnerability, the inherent data uncertainties for the applied indicating variables have not been evaluated here.

The constructed vulnerability index, based on the relationship between heavy precipitation and crop yield loss (Figure 6), cannot be classified according to the indicator-based vulnerability assessment categorization of Tonmoy et al. (2014). It is rather similar to a ‘simulation-based method’ in that it can be used to generate indicators as outputs of the assessment (cf. Simelton et al. 2012). Even though this method is methodologically different from the aggregation-based vulnerability assessment method (papers II and III), some similarities concerning the vulnerability distribution of Swedish agriculture can be noted

(Figures 5 and 6). Although the differences between the various composite indices have been emphasized in this thesis, the results imply that, on a very general level, the methods provide similar results that confirm certain regional trends. The analysed assessment methods may therefore be feasible for presenting general indications concerning vulnerable regions, though the outcome becomes uncertain on the municipal or county level. This means that even though an indicator-based vulnerability assessment is applied on the municipal level, the results should not be interpreted as specific for the municipal level but rather as regional trends.

Previous studies have emphasized that background information is required in order to avoid misinterpretations of indicator-based assessments as they inherently reduce the complexity of the vulnerable system (e.g., Hinkel 2011). Moreover, the composite index method as such lacks transparency and requires a clear description of applied methods in order to support the proper use of the approach (Ramieri et al. 2011). I argue that the great variance between the methods identified in this thesis, together with their inherent lack of transparency, calls for advancement in the use of composite index methods.

6.2 Developing assessment methodology through geographic visualization

This thesis proposes that several drawbacks of composite indices could be addressed through geographic visualization in which the consideration of participant perspectives is expanded by exploring the indicators' functions and the indicator variable data. By means of interactivity, methodological choices can also be made electable in order to assess vulnerability based on the participants' perspectives, enabling the exploration of differences in local and national vulnerability depending on the chosen method. The challenges associated with composite vulnerability index methods that call for transparency in terms of methods, underlying variables, weights and assumptions are aspects that geographic visualization can address.

The technique by which the vulnerability scores are classified also influences the choropleth map (Figure 1A) representation of vulnerability. For example, Paper II demonstrates that several municipalities can each be placed into different vulnerability classes by different classification techniques depending, in this case, on whether the classes are based on equal intervals or quintiles. This indicates the essentiality of cautious reflexivity when determining the class interval technique for choropleth map representation, which has been discussed in traditional cartography literature (e.g., Jenks and Caspall 1971; Evans 1977; Armstrong et al. 2003; Xiao and Armstrong 2006).

The conceptual framework for interactive vulnerability assessments developed here is not an alternative to previous vulnerability assessment frameworks (cf. Turner et al. 2003; Füssel and Klein 2006; O'Brien et al. 2007). Rather, it suggests that, by means of geographic

visualization, the relevance of the vulnerability assessment can be increased through transparency and reflexivity.

AgroExplore's high level of interactivity in terms of selecting, categorizing, and classifying indicators as well as assigning the shares to the vulnerability dimensions have, to my knowledge, not previously been included in any other vulnerability assessment tool (cf. Opach and Rød 2013; Carter et al. 2016). As AgroExplore has been developed to fit this specific research design, it is a complex tool that targets agricultural experts and participatory research processes, which makes the tool unique in terms of its highly interactive features.

The participatory workshops in which AgroExplore was applied included an open and rich dialogue on agricultural vulnerability. The geographic visualization approach created a two-way dialogue process, facilitating collaborative learning. The collaborative learning process both enabled exploration of agricultural vulnerability assessments for the participants as well as contributed new knowledge and understanding of different dimensions of vulnerability, based on practitioners' interaction with and dialogue about the tool. In particular, the expert assessments facilitated through geographic visualization enabled the identification of 'new' aspects of vulnerability as well as the validation (or rejection) of already applied indicators and their indicating variables. Furthermore, by means of AgroExplore, the quantitative data on personalized indicator-selection, categorization, and weighting settings complemented the qualitative dialogue data.

The conceptual framework developed here can facilitate novel design approaches that combine outcome and contextual methods to assess vulnerability in which the results of an outcome assessment, through, for example, participatory modelling, serve as input to a contextual assessment. Whether or not the vulnerability assessments start with an outcome assessment, geographic visualization enables mixed-methods approaches for assessing contextual vulnerability. Based on the results of this thesis, I suggest that geographic visualization approaches advance the vulnerability assessment methodology in terms of enabling combined quantitative and qualitative assessment methods and revealing knowledge of different indicators' roles in shaping vulnerability depending on the context and spatial scale. In the developed conceptual framework, pluralistic views of what vulnerability is and how it can be assessed are allowed. By means of geographic visualization, a combination of methods with epistemologically different entry points could be incorporated into the research design (cf. Nightingale 2016). I would argue that a mix of perspectives and approaches to vulnerability assessments is beneficial in order to achieve as deep and broad an understanding of vulnerability as possible.

In light of the many existing conceptualizations and operationalizations of vulnerability, I argue that indicators will play an even greater role in future vulnerability assessments while aggregated vulnerability indices will become less important. For example, in the Swedish

action plan for climate adaptation in the agricultural sector (Jordbruksverket 2017) and the European Environmental Agency's report 'Climate change, impacts and vulnerability in Europe' (EEA 2017), indicator development is described as essential in order to conduct relevant assessments. Geographic visualization tools, such as AgroExplore, could support this increased emphasis on indicator development. As vulnerability is a complex phenomenon that conceptually involves various dimensions, geographic visualization can facilitate potentially holistic mixed-methods approaches centred on indicators. The interactivity in geographic visualization tools can enable exploration of agricultural vulnerability under climate change at different scales, such as the farm or national level, thereby contributing to the development of indicators to support farmers or policymakers.

I nevertheless agree with Nightingale (2016) that mixed-methods research will not solve the challenge of comprehending an entire problem at once, since this can be regarded as impossible. However, the use of different conceptualizations and operationalizations of vulnerability could instead be considered valuable rather than problematic. Yet with conceptually diverse and epistemologically plural research designs, the requirement of defining the applied conceptualization, being transparent regarding the method and also reflexive regarding the interpretation and conveying of results (Paper III), becomes increasingly important.

In addition to discussions of agricultural vulnerability, the AgroExplore workshops enabled the research team to collect feedback on the tool. One key criticism raised by the participants was that they considered it a drawback that the entire studied region (i.e., Sweden) was assigned a uniform weighting. They argued that the uniform weighing creates an unfair basis for comparison, as the indicators are context dependent and should be weighted accordingly. This is in line with previous findings emphasizing the need for caution when applying uniform weightings of indicators across countries (e.g., Adger et al. 2004). However, as the purpose with vulnerability assessment involves identification of hot spots and understanding of spatial differences, it needs to be comparative for the entire region examined. Approaches to addressing the problem of uniform weightings in regional vulnerability assessments appear however to be lacking.

Similarly, the challenge associated with predefined assumed correlations between indicators and vulnerability could be resolved by making the correlation alternatives electable. However, such added functionality depends on the specific purpose of the tool. Incorporating electable correlation alternatives into AgroExplore could strengthen it as a research tool, facilitating even better discussions; however, this could make the tool too complex, and AgroExplore, even in its present form, might be too complex to facilitate adaptation strategies.

Although AgroExplore is targeting experts in the agricultural sector, the workshop participants found that additional time was required to get acquainted with the various

functionalities of the tool and related documentation. The Decision Arena setting, however, enabled an inclusive discussion, supporting dialogues around personalized settings and overall assessments.

6.3 Climate-related vulnerability in Nordic agriculture

In relation to this section's discussion of climate-related vulnerability, I would like to start by emphasizing that vulnerability is just *one* of several concepts that can be used to understand a socio-ecological system that experiences environmental and/or social stress. Although a mixed-methods approach by means of geographic visualization is suggested as a way forward in vulnerability assessment, I do not attempt to demonstrate that any single specific epistemology of vulnerability assessments is theoretically or methodologically correct.

Similarly, I perceive 'risk' and 'resilience' as two other ways of conceptualizing and understanding a socio-ecological system under stress. In my view, these concepts are all tools with which to understand important aspects of a phenomenon, in this case, agricultural vulnerability to climate change. The same aspects that can characterize vulnerability could also be translated into a risk or resilience framework. For example, the socio-economic and biophysical indicating variables for sensitivity and adaptive capacity in the vulnerability framework (Füssel and Klein 2006) could describe the 'vulnerability component' of a risk framework (Oppenheimer et al. 2014), whereas the climate change variables defined as exposure in the vulnerability framework could be described as hazards in a risk framework. Furthermore, the non-climatic external factors or stressors could, in a risk framework, be categorized as socio-economic process components. Methodological discussions of indicator-based assessments are therefore applicable to both resilience and risk assessments, and results on aspects characterizing Nordic agricultural vulnerability to climate change could be translated to other conceptualizations as well.

Both the AgroExplore workshops and the literature review improve our knowledge of factors and processes that can characterize vulnerability to climate change in Nordic agriculture. The literature review synthesizes the challenges as well as opportunities that climate change may bring to Nordic agriculture. The results indicate that opportunities typically involve higher crop yield potential and the introduction of new crops due to increased temperature and prolonged growing seasons. The challenges include negative impacts on production, but also the possibility that the anticipated positive effects could be limited by other climate change factors or policies and measures.

It is worth noting that both the peer-reviewed and grey literature tends to focus on the Nordic agricultural challenge of excess water. However, climate change is also anticipated to increase the challenges associated with summer droughts in some regions, for example, in southeast Sweden as a result of increased evaporation and increased precipitation variability

(Bernes 2017). No indicator of drought was included in the analysis of composite indices (Paper II) or in AgroExplore (papers III and IV), but an inclusion of such an indicator would possibly have changed the regional trends, for example, regarding southeast Sweden, which is the least vulnerable agricultural region in the composite indices presented in Paper II.

Both the literature review (Paper I) and the results of the AgroExplore workshops (Paper IV) pointed to the importance of extreme weather events as critical factors. However, the statistical analysis of the relationship between heavy precipitation and crop yield losses was not cogent. Nevertheless, even though only a few crops displayed significant correlations between yield and exposure to heavy precipitation (by means of the heavy precipitation index), heavy precipitation and other extremes were considered ‘participatory validated’ and confirmed as important aspects in the existing literature (de Toro et al. 2015; Jordbruksverket 2016a, b). As discussed in section 6.1, this signifies a need for future research into the impact of extreme weather on crop production to further investigate indicating variables for extreme weather exposure.

The outcomes of the participatory workshops suggested that different aspects of agricultural vulnerability would differ in importance depending on the participants’ perspectives on region, farm, and crop type. It should be noted, however, that all practitioners came from the same region in Sweden. Although this thesis does not analyse why agricultural experts perceive vulnerability the way they do or how they make sense of vulnerability, these aspects can be regarded to have influenced the AgroExplore workshop discussions. Participants’ personal opinions, previous knowledge, expertise, interactions with other people and exposure to media, as well as scientific and political debates may together form perceptions of climate-related vulnerability (cf. Wibeck 2014).

Moreover, previous studies have demonstrated that perceptions of climate change are often malleable and not fully formed and fixed (Weber 2016) and that interactions between focus group participants shape the participants’ representations (Wibeck 2014). The level of participants’ familiarity with climate change and the notion that people have a finite pool of ‘worry’ or ‘concern’ are other aspects said to influence their perceptions of climate change-related risks (Weber 2010). One example of how participants’ perceptions may have influenced the results is related to the weather conditions²⁵ when the workshops were conducted. The AgroExplore workshop discussions tended to focus too much on water, and this might have played out differently if the weather had been dry instead of normal or above normal in precipitation during the study period (cf. Dessai and Sims 2010; Weber 2016).

²⁵ Weather in Sweden spring 2015: <https://www.smhi.se/klimat/klimatet-da-och-nu/arets-vader/varen-2015-regnig-och-blasig-1.89471> (accessed 2017-08-28)

While the literature review reveals that it is not obvious whether climate change will present mainly challenges or opportunities for Nordic agriculture, plausible adaptation strategies involve a great number of perspectives. By synthesizing the literature, I could, among other things, demonstrate that policies and measures for, for example, climate change adaptation, wetland protection, non-toxic environments, and decreasing eutrophication may have conflicting outcomes if not implemented sensibly. I argue that adaptation policies or measures may counteract one another or involve trade-offs with other objectives, and that there is a knowledge gap regarding this issue in the current literature for Nordic agriculture under climate change.

This could possibly be explained by the epistemological challenge of framing vulnerability (Carr and Owusu-Daaku 2016). Carr and Owusu-Daaku (2016) reasoned that an exposure-led epistemology of vulnerability (referred to as ‘outcome vulnerability’ in this thesis) presents a limited view of the different ways in which vulnerability emerges. Most reviewed studies of Nordic agriculture under climate change were ‘impact assessments’ that mentioned possible adaptation actions only in their discussion sections. Even though a shift from ‘predict and adapt’ to enhancing resilience and adaptive capacity has been discussed in research (e.g., Rötter et al. 2013), I cannot detect this shift in the literature on Nordic agriculture (with some exceptions, e.g., Kvalvik et al. 2011).

A reason why adaptation-induced trade-offs are noticeable in the literature synthesis (Paper I) may be that the reviewed papers discuss and suggest adaptation policies and measures based solely on meeting targeted needs (cf. Carr and Owusu-Daaku 2016). While such studies are valuable in order to understand potential impacts of climate change, more holistic approaches are probably needed to comprehensively assess vulnerability and make better-informed recommendations and decisions for adaptation. Before deciding on an adaptation strategy, knowledge of why, how, and when adaptation actions become maladaptive is essential. Although challenges, opportunities, and adaptation actions are reviewed in this thesis, the identified challenges associated with adaptation-induced trade-offs make it infeasible to suggest a general path for prioritizing particular adaptation actions. I stress that there is a need in future research to conduct contextual vulnerability assessments to further assess possible trade-offs regarding how to adapt and what to prioritize in order to suggest robust adaptation strategies. Furthermore, I suggest research into how geographic visualization can be used to gain new insights into the choices and consequences involved in such trade-offs.

This discussion of Nordic agricultural vulnerability to climate change can be related to further discussions of whose responsibility it is to limit or reduce this vulnerability. As most of the actions suggested in the reviewed literature were ‘farm-based adaptation’ and fewer were ‘policy-driven adaptation’, the responsibility for climate adaptation in Nordic agriculture could be interpreted as more in the sphere of action of individual farmers than of

policy makers. Nevertheless, the effort of addressing environmental quality objectives on the policy level should guide farmers in their work. Moreover, adaptation measures taken on the policy level could often be considered a necessity for farm-based adaptation to take place. For example, the cultivation of new suitable crops or varieties to some extent requires that resources are invested in research into the breeding of crop varieties that can cope with accelerated climate development and the unique Nordic light conditions (e.g., Fogelfors et al. 2009; Uleberg et al. 2014). Another example is the development of main drainage systems and related policies that are needed in order to allow for new or improved drainage on farmland. In this context, policy makers play an essential role to enable farmers to adapt, whereas farmers have the responsibility to implement adaptation actions on the farm level. The Swedish action plan for climate adaptation in the agricultural sector (Jordbruksverket 2017) describes the Board of Agriculture's responsibility, but barely mentions farmers' responsibility to adapt, which points towards the need for a government-led action plan for climate adaptation in the agricultural sector with a focus on farm-level adaptation.

In relation to the idea that policy-driven adaptation may be necessary for farmers to adapt, several AgroExplore workshop participants pointed out politics and administration rather than climatic conditions as the most important stressors that agriculture is exposed to and must cope with. Previous Nordic studies (O'Brien et al. 2006; Kvalvik et al. 2011) have obtained similar results, i.e., that in order to assess and address vulnerability to climate change, there is a need to better understand indirect effects and critical interactions with economic, social, demographic, and cultural changes (O'Brien et al. 2006). The workshop dialogues revealed critical limitations of the current indicators in AgroExplore and pointed at aspects concerning, for example, extreme weather events, policy implications, and teleconnections (e.g., Benzie et al. 2016) as important additional factors to be included in agricultural vulnerability assessments. The practitioners pointed to the need to include external factors when assessing agricultural vulnerability, for example, measures to assess the teleconnections between global food demand, trade patterns, and climate change impact on agricultural production in other exporting countries. In deliberating on the reasons behind the practitioners' view that politics and administration, rather than climatic conditions, are the most important stressors to which agriculture is exposed, the notion of a 'finite pool of worry' (Weber 2010) may be germane. For example, if climate change is not considered an immediate stressor but rather a future and geographically distant stressor (e.g., Weber 2010), policies might occupy a larger place in the 'finite pool of worry'.

7 Conclusions

This thesis set out to identify how climate-related vulnerability in Nordic agriculture could be represented through vulnerability assessments in order to advance methodological development of indicator-based and geographic visualization methods. The main conclusions in response to the four research questions guiding this thesis are presented below.

The first question (RQ1) concerns how agricultural vulnerability to climate change and variability in the Nordic countries can be characterized. It was found that Nordic agriculture under climate-related stress constitutes a complex vulnerable system with numerous underlying contextual factors exposed to various stressors. I argue that it is not obvious which stressors characterize exposure, and moreover, how and to what extent Nordic agriculture is vulnerable to them. What can be determined is that a broad range of contextual aspects needs to be considered to ensure the robustness and relevance of vulnerability assessments. The literature review results indicated that the climate change adaptation actions proposed in the recent literature on Nordic agriculture involve trade-offs between different adaptation purposes or different socio-ecological goals. The actions may therefore result in maladaptive outcomes and increase the vulnerability of the focal system or other external systems. The uncertainty regarding the possible consequences of climate change for Nordic agriculture, together with plausible adaptation-induced trade-offs and maladaptive outcomes, creates an uncertain basis for adaptation strategy development. Furthermore, this uncertainty leads to difficulties regarding how to include adaptation or adaptive capacity in vulnerability assessments. The question is whether the advanced assessment potentials of vulnerability indicators realized through geographic visualization can assist in making these trade-offs observable.

The large number of climate change vulnerability conceptualizations and assessment methods served as the basis for inquiring into whether and how vulnerability assessment estimates are dependent on quantification methods (RQ3). In this thesis, the commonly applied indicator-based vulnerability assessment methodology was analysed in its application to Swedish agriculture under climate change. By applying the same set of indicators but with different weighting and summarizing methods, this thesis determines that there is great variance between composite index methods in terms of what they measure and, consequently, in their resulting vulnerability scores and ranks. As an alternative to the composite index, a method that determines an index based on the relationships between weather anomalies (heavy precipitation in this study) and crop yield losses was tested. The resulting vulnerability index presented yet another perspective on vulnerability, focusing specifically on crop productivity. Through the application of this method, challenges related

to spatial scale and variable thresholds for the indicating variables could be explored, underlining the context and scale dependency of indicators in terms of their representation of vulnerability.

The diversity of quantitative approaches to assessing vulnerability and the variance in the results of different methods called for transparent demonstrations of how vulnerability is assessed and for reflection on how vulnerability is represented and communicated to increase the relevance of these assessments. The fourth research question enquires into how geographic visualization can be applied in integrated vulnerability assessments (RQ4). This thesis advances the indicator-based composite index methodology by developing a conceptual framework for interactive vulnerability assessments. The conceptual framework suggests that transparent indicator selection, definition, and emphasis could be achieved by means of geographic visualization. The AgroExplore geovisualization tool was developed to enable an interactive assessment of vulnerability in a geovisualization environment, as well as to support the dialogue on agricultural vulnerability.

The AgroExplore workshops were designed to study how the selection, definition, and emphasis of vulnerability indicators influence how vulnerability is assessed (RQ2). The moderated dialogues and interactive assessments by means of AgroExplore involved open and rich discussions and contributed to new knowledge of agricultural practitioners' perspectives of climate-related vulnerability, allowing the validation of variables and their thresholds as well as discussion of their relevance to agricultural vulnerability. Based on these results, I argue that a geographic visualization approach to interactive vulnerability assessment can facilitate the inclusion of expert perspectives and validations and thus contribute with valuable input to the field of vulnerability research. Specifically, this approach provides knowledge of how indicating variables can and cannot be defined and how definitions can affect the indicators' roles in describing the vulnerable system. In order for the indicators to adequately represent climate-related vulnerability in agriculture, this thesis identifies a need for increased contextualization of indicators, involving valid definitions of variable thresholds. Moreover, this thesis stresses the need for careful consideration of the spatial scale of data while considering the spatial scale-related trade-offs between different purposes of assessments. The findings indicate that geographic visualization permits the assessment of dimensions that cannot be captured by a single vulnerability index, contributing to the important validation of indicators that represent the vulnerable system.

In conclusion, the main contribution of this thesis lies in its comprehensive study of composite climate vulnerability indices and how the associated methodological challenges can be addressed. Based on triangulating the results of a literature review, statistical analysis, and participatory process, the indicator development was problematized and the sequential mixed-methods approach identified ways forward for indicator-based vulnerability

assessments by means of geographic visualization. Starting from a review of the literature on Nordic agricultural vulnerability, the thesis further identified shortcomings of composite indices as a vulnerability assessment method. This motivated the development of a vulnerability assessment method through geographic visualization that enabled expert assessments which further contributed to new knowledge. I argue that future vulnerability studies ought to be aware of and transparent about the principles and limitations of indicator-based assessment methods in order to ensure their usefulness, validity, and relevance in guiding adaptation strategies.

This thesis outlines the benefits of using geographic visualization to include three perspectives that are often treated separately, (i) outcome-contextual vulnerability, (ii) integration of socio-economic and biophysical dimensions, and (iii) analysis of both quantitative-qualitative data. While this thesis constitutes a first attempt, its analysis points to a need for future research to develop capacity to assess vulnerability. For example, this thesis has put less emphasis on qualitative socio-economic aspects of the contextual assessments. Regarding indicator development, future vulnerability research ought to explore and develop frameworks for selecting indicators and defining variable thresholds while accounting for the need for contextualization and trade-offs between different spatial assessment scales. These future vulnerability research pathways are recommended in order to obtain more legitimate and comprehensive, potentially holistic, vulnerability assessments that could provide a more effective, robust, and reliable knowledge base for adaptation priorities.

8 References

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Appendix

Original data and sources for the vulnerability indicating variables included in the quantitative analyses of this thesis. S1 refers to the sub-study on statistical relationships between indicating variables and crop yield losses, and crop yields and heavy precipitation, included in the preamble of this thesis.

^a – Ensemble mean of six general circulation models downscaled with SMHIRCA30 A1B scenario.

^b – The change between 2021–2050 compared with 1961–2000

Variable	Description	Source	Study
Annual temperature change (°C)	Modelled ^a annual temperature change ^b	SMHI	Paper II and III
Spring temperature change (°C)	Modelled ^a spring ^c temperature change ^b	SMHI	Paper IV
Summer temperature change (°C)	Modelled ^a summer ^d temperature change ^b	SMHI	Paper IV
Winter temperature change (°C)	Modelled ^a winter ^e temperature change ^b	SMHI	Paper IV
Annual precipitation change (kg m ⁻² s ⁻¹)	Modelled ^a annual precipitation change ^b	SMHI	Paper II, III and IV
Autumn precipitation change (kg m ⁻² s ⁻¹)	Modelled ^a autumn ^f precipitation change ^b	SMHI	Paper II, III and IV
Spring precipitation change (kg m ⁻² s ⁻¹)	Modelled ^a spring ^c precipitation change ^b	SMHI	Paper II, III and IV
Growing season change (days)	Modelled ^a change ^b in days per year with average temp ≥5°C	SMHI	Paper II, III and IV
Change in autumn frost days (days)	Modelled ^a change ^b in days with min temp <0°C, max temp >0°C in autumn ^f	SMHI	Paper II, III and IV
Change in spring frost days (days)	Modelled ^a change ^b in days with min temp <0°C, max temp >0°C in spring (May in Paper II and III; March-May paper IV)	SMHI	Paper II, III and IV
Snow depth change (Snow water equivalence)	Modelled ^a snow depth change ^b in snow water equivalence	SMHI	Paper II
Historical heavy precipitation (days)	Stationary data, for all available Swedish weather stations, on the number of days with ≥ 40.0 mm. For the period: January 1990-June 2013	SMHI	S1
Arable land (%)	Arable land divided by total land area ^g	(SCB 2016)	Paper II, III, IV and S1
Crop diversity	Land-use data ^g (ha) with crop diversification formula in Bhatia (1965)	(SCB 2016)	Paper II, III, IV and S1
Irrigated land (%)	Area possible to irrigate (2007) (ha) divided by arable land	(Persson 2012a), (SCB 2016)	Paper II, III, IV and S1
Mean crop yield (kg ha ⁻¹)	Mean yield of all crops ^g	(SCB 2016)	Paper II, III and IV
Mean crop yield of spring barley (kg ha ⁻¹)		SCB (2016)	Paper II
Historical crop yield data (kg ha ⁻¹)	Crop yield data for the period 1990-2013 for 22 crop species	(SCB 2016)	S1
Clay content (%)	Interpolated measurements of clay content in topsoil	(Swedish board of Agriculture 2014)	Paper III, IV and S1
Erosion risk (t ha ⁻¹ yr ⁻¹)	RUSLE model	(Panagos et al. 2012)	Paper II, III, IV and S1
Soil organic matter (%)	Interpolated measurements	SLU; (Eriksson et al. 2010)	Paper II, III, IV and S1
Soil phosphorus (mg/100 g)	Interpolated Ammonium lactate-acetate soluble phosphorus (<i>P-AL</i>) in the topsoil	SLU; (Eriksson et al. 2010)	Paper II, III, IV and S1

Variable	Description	Source	Study
Soil pH	Interpolated pH-H ₂ O in the top soil	SLU ; (Eriksson et al. 2010)	Paper II, III, IV and S1
Employment in agriculture (%)	Temporary and permanent employed in agriculture (2010) divided by total working population	(Persson 2012b), (SCB 2016)	Paper II, III, IV and S1
Population density (pop km ⁻²)	Population density in 2012	(SCB 2016)	Paper II, III and IV
Unemployment rate (%)	Unemployed people (aged 16–64 years) seeking a job (2011)	(AMS 2012)	Pape II, III and IV
Older employees (%)	Share of 55-65 of the 22-65 years old working population	SCB (2016)	Paper II
Social welfare payments (SEK/capita)	Economic assistance (2009)	(SCB 2016)	Paper II, III and IV
In-migration (%)	Immigrated minus emigrated divided by total population (2011).	SCB (2016)	Paper II
Farm holdings smaller than 2 ha (%)	Eight classes from <2 ha to >100 ha. Number of farm holdings <2 divided by total number of farms (2007)	(SCB 2016)	Paper II, III and IV
Mean farm holding size	8 classes from <2 ha to >100 ha. A weighted mean value.	(SCB 2016)	Paper II
Share of small scale farming (%)	Eight classes from <2 ha to >100 ha. Number of farm holdings <50 divided by total number of farms (2007)	(SCB 2016)	S1
Share of larger scale farming (%)	Eight classes from <2 ha to >100 ha. Number of farm holdings >100 divided by total number of farms (2007)	(SCB 2016)	S1
Farm income (SEK)	Farmer income (SEK/household) (2010)	(SCB and Jordbruksverket 2012)	Paper II, III, IV and S1
Ground water availability (dimensionless)	Categorized data	© SGU (2012)	Paper II
Fertilizer consumed	A standardised sum of N+P+K, added manure and fertilizer (kg ha ⁻¹) (2011)	(SCB 2016)	Paper II, III and IV
N fertilizer use (kg ha ⁻¹)	Added Nitrogen from manure and fertilizer	(SCB 2016)	S1
P fertilizer use (kg ha ⁻¹)	Added Phosphorus from manure and fertilizer	(SCB 2016)	S1

Papers

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