Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production

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The Nordic countries' agricultural sector is potentially considered both a winner and loser in relation to climate change. With effective adaptation management, climate change could lead to increased agricultural productivity. Yet if concurrent challenges are left unaddressed, productivity losses may impede gains. Thus, adaptation to climate change is key both to avoid negative consequences and to benefit from opportunities. This paper conducts the first systematic literature review of scientific and grey literature on climate change related opportunities and challenges in Nordic agriculture, resulting in a complex overview of required adaptation actions. The synthesis on suggested adaptation policies and measures shows that farm based adaptation measures appear to be more abundant and more discussed than policy driven adaptation in the scientific literature. This paper identifies a knowledge gap regarding the complexity of adaptation needs and trade-offs in the Nordic agricultural sector. In conclusion, although the agricultural sector in the Nordic region is facing certain benefits from climate change, this review demonstrates profound challenges related directly to climate change. The synthesis of suggested adaptation actions furthermore indicates that adaptation involve trade-offs, however, increased knowledge on this subject is required. Failing to address these challenges might impede Nordic agriculture's potential gains from climate change in a long-term perspective.

Keywords

Adaptation; Agriculture; Climate change; Climate change impacts; Crop production; Nordic

1 Introduction

Nordic agricultural production is relatively small. The total wheat production of the Nordic Countries (Denmark, Norway, Sweden, Finland and Iceland) corresponds to only 5% of the total European wheat production (FAO, 2015), despite being one of the main cultivated crops. Climate change is generally anticipated to increase the food production potential in the Nordic countries (e.g. Maracchi et al. 2005; Olesen et al. 2007), and the degree to which climate change may cause increases in future agricultural production has even been equated to that of liberalization and trade (Fogelfors et al., 2009). Nevertheless, in the near future, agricultural policy and market conditions are anticipated to influence the Nordic agriculture to a greater extent than climate change (Jordbruksverket 2017; Juhola et al. 2017; Woods et al. 2017). Even though the prospects for future Nordic agriculture and their inter-linkages with climate change are highly complex, the relative importance of Nordic agriculture in global food production is likely to increase in the future (Fogelfors et al., 2009).

While many consider Nordic agriculture a potential winner of climate change, others stress the challenges for the region. On the one hand, if managed properly, climate change is projected to have positive effects on agricultural productivity (Olesen and Bindi 2002; Rötter et al. 2011), while on the other hand, agricultural production will face climate change induced challenges requiring adaptation (Olesen et al. 2011). The existing scientific and grey literature, thus, gives voice to diverging perspectives on the potential for Nordic agriculture in future climate conditions.

In this context, adaptation to climate change is key, both to avoid negative effects and to benefit from opportunities. Hence, this paper understands adaptation as actions intended to reduce vulnerability to and/or take advantage of opportunities arising from current or future climate change (Burton and Lim, 2005; Howden et al., 2007). Two levels of agricultural adaptation are often discussed; farm-based measures and policy-driven adaptation, the former grounded in farmers' rational self-interests and the latter in collective needs (Iglesias et al. 2009; Iglesias et al. 2012b). Since literature reviews on agricultural vulnerability and adaptation generally tend to focus on broad regional assessments or on challenges to the most vulnerable countries (e.g. Iglesias et al. 2012b; Anwar et al. 2013; Locatelli et al. 2015), the diversity of opportunities, challenges, and various required adaptation actions are not fully captured in syntheses involving the Nordic region.

This paper is the first systematic literature review on opportunities, challenges and adaptation actions to climate change in Nordic agricultural crop production. While opportunities for Northern European agricultural production are often highlighted in a larger regional contexts (e.g. EEA 2017), the study addresses the need for increased reflexivity about the geographical and socio-economic context when assessing climate change opportunities. The aim of this paper is to identify and synthesise opportunities, challenges and adaptation policies and measures from a systematic review of the scientific and grey literature on the Nordic countries' agricultural sector. Based on this synthesis, the intention is to identify important knowledge gaps within the research field of agricultural adaptation to climate change.

In section two, the analytical method of the systematic literature review is described. Section three presents the result of the review; summarising the opportunities, challenges and adaptation actions identified in the literature. Section four discusses knowledge gaps as identified in the synthesis. Section five concludes, inter alia, that there is a lacking amount of studies focusing specifically on adaptation in Nordic agriculture and that adaptation-induced trade-offs make it unclear how to adapt and what to prioritize.

In the following, a short background of the projected climate changes in the Nordic region is provided based on an ensemble-mean of nine of Global Circulation Models downscaled with Rossby centre's regional climate model RCA4 for the RCP4,5 scenario[1] (Strandberg et al., 2014). The projected changes described, are the differences between 2071-2100 compared to 1961-1990.

Of great importance for agricultural production is that the vegetation period is projected to start 10-50 days earlier and end 5-50 days later, depending on the region. The southern parts of the Nordic countries are projected to experience the greatest change in spring whereas Norway, southern Finland and mid-east Sweden are anticipated to have the greatest prolongation in autumn. The average temperature is projected to increase 1-3 °C during spring, summer and autumn, with different regional variations depending on season but generally the greatest temperature increase is in the northern parts. In winter, the temperature is projected to increase 2-8 °C, with the greatest increase in the very north of Norway and Sweden and northern half of Finland (6-8 °C). Mean precipitation is generally projected to remain stable or increase throughout the region, with up to 30% increase in northern half of Sweden during spring.

[1] http://www.smhi.se/klimat/framtidens-klimat/klimatscenarier (accessed: 2017-06-21)

These projected climate changes have commonly been argued to give rise to higher agricultural production potentials (e.g. Maracchi et al. 2005; Olesen et al. 2007). Improved conditions in northern Europe are thought likely to support a shift from spring-sown to winter cereals, which will allow higher yields (Trnka et al., 2011). This was also the main message that was communicated in Swedish farming magazines in year 2000-2009, favouring opportunities rather than challenges (Asplund et al. 2013).

Nevertheless, climate change will likely involve increased weather variation and more frequent extreme weather events (IPCC, 2012). The number of days with heavy precipitation is projected to increase for the whole Nordic region with about 2 days increase per season, while the western Nordic region is projected to have an increase of up to 6 days per season (except spring). However, despite a mean increase of annual precipitation and heavy precipitation events, droughts are anticipated to be prolonged with 1-2 days per year in the very south of Sweden and Norway and all over Denmark.

The projected warmer and wetter conditions as well as more frequent extreme weather events in Northern Europe might pose a number of challenges for agriculture (Kovats et al., 2014). Extreme weather events could cause yield losses in northern Europe if effective adaptation actions are not implemented (Rötter et al., 2013). Although projections indicate that the frequency of extreme weather events will increase in Europe (Kovats et al., 2014), aspects of extreme weather events are often omitted from yield models (Rötter et al., 2012).

2 Systematic literature review

The method of this study draws on a five step approach for systematic literature review developed by Khan et al. (2003). This method of a systematic review involves framing of structured questions, identifying relevant work based on a selection criteria, structurally assessing the studies, summarizing the evidences and interpreting the findings.

The following three structured questions were specified prior to the review work and further kept in mind when reviewing the literature: *(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 (polices and measures) are mentioned?

The second step of the systematic literature review involves the identification of relevant publications. This study covers a substantial body of peer-reviewed articles and some essential grey literature (reports from e.g., government, public authorities, county administrative boards, and research institutes). To include as many relevant publications as possible, the search[2] was performed in the databases: 'Web of Science', 'Scopus', 'Agricola', 'Google Scholar', 'Environmental Sciences and Pollution Management', and 'Norart'. In addition, a Google search was conducted in the Nordic languages to cover essential national grey literature.

This initial search was performed by the Linköping University Library in 2014 and resulted in >2000 search returns. The library conducted a first screening which resulted in a list of about 160 publications. Titles and, when necessary, abstracts, for these 160 publications were examined in order

[2] Search string: ((Agricultur* 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))

to determine the potential relevance in relation to the objective of this paper. The criteria to be included in the review were that the publication had to address one or several of the Nordic countries as well as agricultural issues in combination with climate-related impacts and/or adaptation. Iceland was excluded from the review since their agricultural production mainly is related to sheep and dairy production (Farmers Association Of Iceland, 2009). The original search, which was performed in 2014, was complemented by an additional search in June 2017 to add the most recent publications. Moreover, the systematic search has been complemented with studies identified from in-text citations and recommendations. Finally, 60 studies were included in the review (see Appendix).

The literature was assessed based on the (i) regional scope of the study, (ii) identified climate related challenges, (iii) opportunities, (iv) adaptation strategies or guidelines and (v) climate change adaptation experiences. The results were further coded for each climate factor mentioned in the assessed literature and synthesised for the three categories opportunities, challenges and adaptation actions to interpret the results of the review. In order to systematically synthesise adaptation actions and identify adaptation-related knowledge in the literature, adaptation actions were categorized for two levels of adaptation; farm-based and policy-driven.

Challenges related to impacts of climate change and the required adaptation actions are of course dependent on biophysical factors other than climate change, such as agro-climatic zone (Iglesias et al., 2012a) and soil type. This review does not structure results based on such preconditions but rather clarifies and synthesises relevant challenges and opportunities depending on various factors related to climate change. Nevertheless, the results of this paper can be used in combination with identified preconditions to determine the relevance of a challenge or opportunity to a specific case.

3 Results

3.1 Opportunities and challenges associated with impacts of climate change

The following sub-sections provide an overview of climate change opportunities (

Table 1), challenges (**Table 2**) and adaptation actions (**Table 3**) identified from the reviewed literature. While the projected climate changes in the Nordic regions presented in the introduction are the common background to many of the reviewed studies, the results of this paper are not discussed in terms of a specific climate change scenario or socio-economic pathway.

3.1.1 Opportunities

The reviewed material indicates an increase in production potential in the Nordic region due to a warmer climate in combination with other factors. Opportunities generally refer to possibilities to increase yields or introduce new varieties or crops.

Increased yield potential is mainly modelled as a result of an extended growing season, with temperature in particular being the limiting factor in northern regions (Himanen et al., 2013; Torvanger et al., 2004; Uleberg et al., 2014). The opportunities vary depending on the specific region and crop, but for grasslands there is potential to increase yields through an increased number of harvests per season (Fogelfors et al., 2009; Höglind et al., 2013; Uleberg et al., 2014). In the southernmost Nordic regions, future climate change may lead to a growing season lasting almost all year-round. This would suggest increased opportunities to grow two crops in one year, for example, winter rape followed by a crop with short cultivation time (Fogelfors et al., 2009). It has generally been demonstrated that earlier sowings will have little effect on yields in the near future, but a greater effect in the second half of the century (Rötter et al., 2013). Two possible reasons for this are that frost on snow-free ground could make the soil temperature too low for sowing, even though the air temperature is sufficient (Uleberg et al., 2014), and that excessive snowmelt water will cause problems for drainage (Olesen et al., 2012). Another possible limiting factor for early spring growth is 'day length'. Though, a model on growth of spring barley in Finland has shown that the short days in early spring has a minor effect on the development rate (Kleemola et al., 1995). The increase in future yield potential in northern Europe is commonly said to relate to three main factors: changed climate conditions, increased atmospheric CO_2 concentrations, and progress in agricultural technology (Kristensen et al., 2010; Maracchi et al., 2005; Olesen, 2005; Rötter et al., 2012, 2011). Leaving technological development aside, the source of increased yield potential comes mainly from elevated atmospheric CO_2 concentrations that effectively fertilize the crop. Some projections imply that elevated CO_2 concentrations could compensate for the yield decrease caused by accelerated phenological development from higher temperatures (Gaasland, 2004; Maracchi et al., 2005; Olesen, 2005; Rötter et al., 2011).

A longer growing season and a higher mean temperature will likely permit the northward expansion of currently produced crops and provide opportunities to cultivate new varieties or crops. For example, the current growing conditions for maize are marginal, often resulting in poor-quality grains. Future conditions could, on the other hand, create opportunities to grow silage maize with sufficient quality (Eckersten et al., 2012). Higher temperatures could also improve overwintering conditions for some crops, as it might become possible to grow perennial ryegrass in locations in Norway where it was not previously possible (Thorsen and Höglind, 2010).

Table 1 provides an overview of the identified climate change-related agricultural opportunities identified in the literature.

Table 1 Overview of general agricultural opportunities related to climate change

Area	Specific opportunity	Climate change driver	Source
Yield	Increased number of harvests per year	Prolonged growing season and higher mean temperature	1–4
	Increased quality	Climate change; combined aspects	5
	Compensate for climate change challenges	Elevated atmospheric CO_2 concentration	6,7
	Favour perennial crop production	Climate change; combined aspects	3,8
	Favour spring-sown crops in southern Nordic region	Temperature increase	7,9
	Shift from spring- to winter-sown crops in nemoral zones	Climate change; combined aspects	10,11
	General crop yield opportunities	Climate change scenarios, specifically earlier sowing and increased number of growing degree days	3,8,12–14, 19
New crops or varieties and northward expansion of current crops	Maize expansion	Climate change; combined aspects	4,5,15
	Ryegrass expansion	Increased winter temperature	16
	Winter wheat (and other cereals) expansion	Climate change; combined aspects	4,15,17
	Increased opportunities to grow peas, faba bean, oilseeds, soybeans, sunflowers, and C3 plants in general	Increased mean temperature and elevated atmospheric CO_2 concentration	3,18

1. Uleberg et al. (2014); 2. Höglind et al. (2013); 3. Fogelfors et al. (2009); 4. Eckersten et al. (2007); 5. Eckersten et al. (2012); 6. Rötter et al. (2011); 7. Olesen et al. (2005); 8. Rötter et al., (2013); 9. Olesen et al. (2012); 10. Trnka et al. (2011); 11. Peltonen-Sainio et al. (2010a); 12. Rötter et al. (2012); 13. Kaukoranta and Hakala (2008); 14.

Torvanger et al. (2004); 15. Elsgaard et al. (2012); 16. Thorsen et al. (2010); 17. Marttila et al. (2005); 18. Maracchi et al. (2005); 19: Lehtonen (2015)

3.1.2 Challenges

The reviewed literature shows that climatic challenges for Nordic agriculture are related to warmer and wetter conditions as well as extreme weather events (**Table 2)**. In terms of extremes, a Swedish study showed that drought periods during the growing period, and heavy precipitation during the harvesting period, are the two weather-related factors that historically have had greatest negative impact on yield (de Toro et al. 2015). Furthermore, additional studies demonstrate that precipitation is negatively correlated with yield for various regions and crops, although most markedly for barley and potatoes (Himanen et al., 2013; Kristensen et al., 2010; Torvanger et al., 2004). Excessive soil moisture and resulting 'drowned crops' (Jordbruksverket, 2013) likely explain the projected negative correlation, but it has also been suggested that diminished solar radiation could limit production in periods of high precipitation (Torvanger et al., 2004). Another possible explanation is that certain diseases could benefit from wetter conditions; for example, *Septoria* leaf spot outbreaks are correlated with high rainfall during May and June (Kristensen et al., 2010). Increased precipitation in autumn, winter, and spring complicate sowing and harvesting and could therefore hamper the exploitation of an extended growing season in spring. Additionally, excessive snowmelt water and low soil temperatures could limit the sowing opportunities presented by an extended growing season (Uleberg et al., 2014) and delayed tillage in spring could in turn create an undisturbed and therefore favourable environment for pests and weeds (Fogelfors et al., 2009). Nevertheless, for some southern regions, e.g. southeast of Sweden, where the runoff, groundwater levels and soil water content is projected to decrease in spring, the possibilities to exploit the extended growing season are anticipated to be advantageous (Bastviken et al. 2015).

Another highlighted challenge posed by increased precipitation, especially during the vegetation-free period, is the increased risk of nitrogen and phosphorus losses from leaching and erosion (Eckersten et al., 2007, 2001; Fogelfors et al., 2009; Jeppesen et al., 2010).

Barley yields are negatively affected by heavy rainfall both before and after sowing due to, for example, delayed sowing, water logging, and anoxia (Hakala et al., 2012). In contrast to increased precipitation in spring, early-season droughts might also pose a challenge to crop production. Projections indicate that the proportion of dry days in the April–June period will increase slightly in the Nordic region (Trnka et al., 2011), affecting barley cultivars, which are negatively affected by early-season droughts (Rötter et al., 2013). Moreover, even with sufficient *mean* precipitation in spring, there would be a problem if it falls as heavy rains (Hakala et al., 2012).

In the southern Nordic region, summer drought is a risk that will likely increase with climate change (Trnka et al., 2011), simultaneously as heavy summer rains and floods are projected to become more frequent (Jordbruksverket, 2013). These summer challenges, leading to flooding, erosion, drowned crops, and soil compaction, could counteract the increased yield potential in Northern Europe (Rötter et al. 2012; Trnka et al. 2011; Uleberg et al. 2014). Water-saturated topsoils should be drained within three days if roots and shoots are to recover (Jordbruksverket, 2013).

Even though a warmer climate creates opportunities connected with a longer growing season, the scientific literature revealed that higher temperatures are also related to challenges in all seasons. While overwintering conditions for perennial grasses are projected to be more favourable (Rötter et al., 2013), there is a risk that this potential could be limited by increased ice-encasement because of reduced snow cover (Thorsen and Höglind, 2010). The growing zone for ryegrass may not expand northwards as much as expected because of a shorter hardening period and the consequent risk of frost damage (Höglind et al., 2013). Crops could be less hardened due to a lower hardening capacity and shortened hardening period, decreasing the winter tolerance (Uleberg et al., 2014). Results for Norway indicate, however, that a reduced hardening period results in a frost tolerance decrease of less than 3°C, which is anticipated to be sufficient (Thorsen and Höglind, 2010). However, ice cover, ice encasement, and frost burn are risks that accompany more frequent freeze–thaw events (Fogelfors et al., 2009; Uleberg et al., 2014).

Another challenge associated with higher temperatures is accelerated phenological development. Increased temperatures in winter and spring stimulate the earlier appearance of final leaves in winter crops (Kristensen et al., 2010). Studies assert that elevated summer temperatures above crop optima in the Nordic region accelerate the phenological stages, i.e., reduce the duration to maturity and therefore reduce yields (Laurila, 1995; Maracchi et al., 2005; Peltonen-Sainio et al., 2010b). The duration of the grain-filling phase is often the limiting factor, but maintenance of a long grain-filling phase is only beneficial if droughts are avoided (Olesen et al., 2012). In the southern Nordic region, winter wheat is projected to be particularly negatively affected by accelerated phenological development (Kristensen et al., 2010; Maracchi et al., 2005; Olesen, 2005). Spring barley and potato yields may also be affected, although with smaller yield reductions than in winter wheat (Olesen, 2005).

Increased temperatures, especially during milder winters, enhance the risk of pest and weed infestation (e.g. Eckersten et al., 2007). Warmer winters could permit the northward expansion of weeds that are not hardy in the current climate but could overwinter in a changing climate (Wivstad, 2010). Moreover, a longer growing season with warmer and wetter autumns would make it possible for winter annual weeds to complete their lifecycle and establish strong populations (Wivstad, 2010). Weed productivity is promoted by CO_2 fertilisation but root establishment could benefit at the expense of aboveground growth. Along with higher CO_2 concentrations, the latter would make weeds less sensitive to herbicide treatments (Wivstad, 2010), making future weed control a twofold challenge.

Higher winter temperatures are anticipated to increase the contamination pressure from fungal diseases. For example, higher soil contamination with late blight is expected to give rise to earlier attacks on potato (Wivstad, 2010). Certain fungal diseases benefit from warmer conditions and others benefit from humid conditions. *Pucciniomycotina*, a fungal disease that benefits from warmer conditions, is projected to increase in coming decades. Fungal diseases that benefit from humid conditions are projected to be a problem in coming decades but of less importance later in the century as summers are projected to be progressively drier (Wivstad, 2010).

A warmer climate is also anticipated to increase insect and virus infestations as well as the opportunities for *new* pest and insects to establish (Eckersten et al., 2007; Fogelfors et al., 2009; Uleberg et al., 2014; Wivstad, 2010). More than one generation could breed per season, for example, in the case of aphids, adult insects instead of eggs could overwinter, resulting in active insect pests during winter and attacks in early spring when crops are in a more sensitive phenological stage (Wivstad, 2010).

Table 2 Overview of general agricultural challenges related to climate change

Area	Specific challenge	Climate change driver	Source
Growth productivity	Less hardy plants; frost damage	Increased autumn temperature; delayed start of autumn	1,2
	Poorer winter survival (ice cover, encasements, and frost burn); limited root development; fungal diseases	More frequent freeze–thaw events; reduced snow cover; precipitation during autumn and winter	1,3,4, 25
	Accelerated phenological development and decreased yield (winter-sown crops)	Earlier onset of spring (earlier sowing–earlier harvests); increased winter and growing season temperature (grain-filling period)	3,5–11, 24
	Decreased protein content (cereals)	Increased atmospheric CO_2 concentration	12
	Decreased yield in general	Increased precipitation (potato and barley yields negatively correlated with precipitation); heavy rains before and after sowing; early-season droughts, summer droughts, and critical timing of droughts; increased frequency of extreme precipitation	1,5,7,13–15, 22, 23
	Complicated conditions for harvesting and sowing	Increased precipitation in autumn and spring	1,6,13,16, 22, 26, 27
	Decreased grassland growth potential	Summer droughts	12
Harvest loss	Saturated soils, drowned roots, and anoxia	Sufficient precipitation in spring falls as heavy rains; extreme precipitation during growing season, steady rain periods	1,3,13,16,17, 26,27
	Increased risk of pests and weeds	Milder (especially in winter and early growing season) and wetter conditions; extended growing season; increased CO_2 concentration (increased root establishment makes weeds less sensitive to herbicides)	1,3,4,12,18,19, 28
Obstacles to exploiting the extended growing season	Soil temperature too low for earlier sowing	Extended growing season (frost on snow-free soil)	1
	Excessive water in soil	Increased rainfall in spring, when snowmelt water still to be drained	3,9,13
Agricultural practices	Nitrogen leaching and phosphorus loss through erosion	Increased precipitation in autumn, winter, and spring; extreme precipitation	3,4,12,20,21
	Soil erosion	Extreme precipitation, flooding	1,3,16
	More difficult to till soil in spring	Decreased soil freezing in winter	3,4
	Soil compaction	Extreme precipitation; decreased ground frost in winter – decrease of natural soil improvements; heavy machinery on wet soils	1,16, 23, 26

1. Uleberg et al. (2014); 2. Thorsen and Höglind (2010); 3. Fogelfors et al. (2009); 4. Marttila et al. (2005); 5. Kristensen et al. (2010); 6. Rötter et al. (2013); 7. Olesen (2005); 8. Laurila (1995); 9. Olesen et al. (2012); 10. Eckersten et al. (2012); 11. Maracchi et al. (2005); 12. Eckersten et al. (2007); 13. Hakala et al. (2012); 14. Peltonen-Sainio et al. (2010b); 15. Torvanger et al. (2004); 16. Jordbruksverket (2013); 17. Rötter et al. (2012); 18. Gaasland (2004); 19. Wivstad (2010); 20. Jeppesen et al. (2010); 21. Eckersten et al. (2001); Jordbruksverket (2017); 22: de Toro et al. (2015); 23: Bastviken et al. (2015); 24: Ozturk et al. (2017); 25: Sharif et al. (2017); 26: Jordbruksverket 2016a; 27: Jordbruksverket 2016b, 28: Peltonen-Sainio et al. (2016)

3.2 Adaptation strategies

In this section, the identified adaptation actions are described and structured based on implementation level, **Table 3** lists a summary of these adaptation actions.

3.2.1 Farm-based adaptation

Most of the adaptation actions featured in the scientific literature are measures to be implemented at the farm level. Farm-based adaptation includes a great diversity of possible actions, many of which entail adjusting the timing of sowing and harvest (Eckersten et al., 2007).

Generally, climate change will create a need to change the species and varieties grown in order to reduce vulnerability in the future and to exploit new crop production potential. As presented in section 3.1.1, a warmer climate and extended growing season will likely create opportunities for the northward expansion of crops and the introduction of 'new' crops and varieties. This includes opportunities to plant more productive varieties or crops (Uleberg et al., 2014), such as perennial grasses (Rötter et al., 2013; Thorsen and Höglind, 2010) and maize (Eckersten et al., 2012).

The reviewed literature presents various examples of the extended use of winter vs. spring crops. Warmer conditions and an extended growing season are sometimes said to favour winter-sown crops, to make use of an extended growing season while avoiding moisture-related tillage problems in spring (Fogelfors et al., 2009). Winter crop production is described as one possible measure for adapting to new climate conditions in Finland (Rötter et al., 2011) although winter wheat is more vulnerable to accelerated phenological development and decreased yield than spring wheat (Olesen, 2005). Additionally, the choice regarding winter vs. spring wheat is influenced by the potential risk of droughts. Winter wheat is favoured from a summer drought perspective: spring crops are more affected by summer droughts, due to difficulties in becoming established under dry conditions, while winter wheat could be harvested before the summer dry period begins (Eckersten et al., 2007; Fogelfors et al., 2009). While the occurrence of droughts is expected to be an enhanced problem in the future, especially in the southern regions, higher temperatures, extended growing season and a possibly changed crop production (e.g. to forage maize) will increase the need for irrigation (Bastviken et al. 2015). This could create a situation where surface water resources for irrigation may be limited simultaneously as irrigation purposes could come in conflict with other water-use purposes (Bastviken et al. 2015; Jordbruksverket 2017).

A main farm-based adaptation measure involves crop-, soil-, and water management. One suggested adaptation option for the cropping system is to advance sowing in spring and delay it in autumn. With an earlier onset of spring, the sowing date needs to be adjusted in accordance with the growing season (Kaukoranta and Hakala, 2008; Uleberg et al., 2014), which, in combination with longer-season cultivars, will arguably increase the yield potential (Maracchi et al., 2005). Depending on geographic location, crop type, and climate scenario, an adjusted sowing may be a sufficient adaptation measure (Rötter et al., 2013), while in other situations, adaptation through earlier sowing will not prevent the negative impacts of increased temperature and hastened maturity (Rötter et al., 2011).

Adaptation involving improved water management and drainage systems is essential and mentioned in several publications (Fogelfors et al. 2009; MMM 2014; Hildén et al. 2005; Hakala et al. 2012; Jordbruksverket 2013; Jordbruksverket 2016a; Jordbruksverket 2017; Uleberg et al. 2014). Improved drainage will be needed in order to cope with increased mean precipitation and heavy rains, to make use of earlier springs through increased buoyancy. Moreover, improved drainage also decreases the drought sensitivity of crop production (Jordbruksverket 2013).

At farm level, key drainage adaptation measures are to increase the capacity of the sub-surface tile system or to invest in water installations on productive land that is currently drained naturally. On low-productive land it may be more profitable to change the land use type rather than to invest in drainage systems (Jordbruksverket, 2013). In existing systems, reducing the tile distance from 15 m to 12 m can increase the drainage capacity by approximately 45% (Jordbruksverket, 2013). Farmers are further advised to use cropping systems that improve the soil structure and infiltration capacity (Jordbruksverket, 2013). Moreover, increased precipitation and runoff will increase the risk of nutrient leaching from the agricultural soil and increase the nutrient loading to water basins (e.g. Huttunen et al. 2015). Reduced soil tillage in autumn is discussed and recommended as an adaptation measure to limit this risk (Fogelfors et al., 2009; Jeppesen et al., 2010).

Plant protection is anticipated to be a key adaptation measure in the Nordic region (e.g. Jordbruksverket 2017; MMM, 2014; NOU; 2010). The use of chemical plant protection may increase considerably, especially for grains and potatoes (Gaasland, 2004), as a result of an increased risk of weed, disease, and insect infestations. Simultaneously, there is a general desire to reduce the use of pesticides, fungicides, and insecticides, as in the Swedish example, to promote achievement of the 'non-toxic environment' objective. Varied crop rotations and limited use of crops that conventionally need intensive protection are ways to limit the exposure to these threats. Potatoes and winter wheat are examples of crops that need intensive protection. The planting of autumn-sown crops such as winter wheat could increase the risk of pest and weed overwintering, leading to stronger establishment in a warmer and wetter climate. Grassland production, on the other hand, results in lower usage levels of chemical plant protection. For example, one calculation indicates that replacing winter wheat with grassland in southern Sweden under future climate conditions could demand approximately 30% less fungicide and 20% less insecticide use (Wivstad, 2010).

3.2.2 Policy-driven adaptation

Plant breeding is one of the most frequently discussed and essential adaptation actions for addressing several of the climate change challenges facing agriculture (e.g. Hildén et al. 2005; MMM 2014). New crop varieties in the future could better make use if the longer growing season and unique light conditions accompanying climate change (Fogelfors et al., 2009; Uleberg et al., 2014), minimize hastened maturity and decreased yield (Kristensen et al., 2010; Olesen et al., 2012; Patil et al., 2010; Rötter et al., 2011) and have increased water logging resistance (Hakala et al., 2012). Consequently, breeding research programmes (Fogelfors et al., 2009; Uleberg et al., 2014) and targeted breeding to support autonomous adaptation on farms (Himanen et al., 2013) are suggested adaptation actions.

Subsurface drainage systems on arable land require properly functioning main drainage systems. Thus, in combination with farmers' individual investments, improvements in the main drainage systems are required. Reconstructing these systems to accommodate increased precipitation and water flows requires major investments. In many cases, the dimensions of current water installations will have to be enlarged, though, the most appropriate dimensioning for a 50–100-year period is uncertain. For example, in Sweden, 28 % of the arable land needs new tile drainage or refurbishment of the existing tile drainage system, still, only 6% of the arable land is planned for refurbishment or new system installation within the next five years (Jordbruksverket 2014). Unless current drainage systems are excessively poorly dimensioned, it is not economically viable to update the main drainage system before its technical lifetime has expired, making it difficult to justify investments and to adapt to future climate conditions. A less costly, though still essential, adaptation measure is regular and structured maintenance of open ditches. Vegetation causes increased friction and results in higher ditch water levels in summer than in winter, and the water flow capacity of an open ditch can be approximately 30% less in summer than winter. In combination with more frequent heavy rains in summer, this means that vegetation growing in ditches should be kept low to control water levels (Jordbruksverket 2013, Jordbrukvserket 2016a).

The improvement of existing drainage installations and implementation of new ones are sometimes limited by existing policies. In Sweden, Jordbruksverket (2013) advocates policy revisions to simplify the process of changing existing drainage installations, at least in non-sensitive natural areas. Moreover, the allocation of responsibility for drainage systems is currently a problem. Community associations are often the owners of water installations, but these associations are seldom active and cost allocations are not updated to accommodate new land ownership patterns. New drainage policies are needed to govern the registering and archiving procedures for water installations (Jordbruksverket 2013). In addition to such new drainage policies, increased drainage research and education are of importance to, for example, identify areas which drainage systems, identify need for improvement in current systems, analyse sustainable development consequences and to outline incentives to realise desired development (Jordbruksverket, 2013). Current drainage guidelines are based on research from the 1960s and therefore require revision especially in light of climate change projections (Jordbruksverket 2013).

Table 3 Adaptation actions mentioned in the literature (F-level = farm-based adaptation measures; P-level = policy–driven adaptation)

Purpose of adaptation	Adaptation action	Level
Make use of 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]	F
Increased atmospheric CO_2: new crops – new needs	Increased fertilization [2,4]	F
	Increased pesticide use [2,5]	F
Cope with accelerated phenological development of grain/take advantage of the shortened vegetative period [3]	Delayed sowing of winter crops [6]	F
	Use of long-season varieties [2]	F
	Use of spring-sown crops (less affected than winter-sown crops in Denmark) [7]	F
	Adjusted sowing dates in spring [2,8,9]	F
	Breeding new varieties: in which the date of anthesis is less responsive to increased winter temperatures; with extended vegetable growth, that are more heat tolerant during anthesis and grain filling [6,10–12]	P
	Breeding varieties to make use of the unique Nordic light conditions [1,13]	P
Prevent stress from drought periods	Enhance soil properties through e.g., improved drainage [24]; greater focus on crop rotation [1,14,15]	F
	Develop irrigation systems and reservoirs (especially important for potato, sugar beet, vegetables and fruits [24, 26, 27]	F, P
	Identify current and future need for water withdrawal and water resources available[27]	P
	Use of winter-sown crops [13,16]	F
Prevent stress from increased precipitation	Enhance soil properties [24]; greater focus on crop rotation [1,14,15]; intercropping [28]; increased and improved drainage systems [26]	F, (P)
Delayed opportunities to exploit extended growing seasons	Use of winter-sown crops [13,24], frost protection (e.g. cover potato plants in early spring)[29]	F
Sowing and harvesting problems due to excessive water	Use of perennial crops [13]	F
Prevent decreased yield and increase soil buoyancy after heavy rains and excessive water on fields	Decrease tile distance in sub-surface drainage systems [15]	F
	Minimize the heavy machinery on the field to avoid soil compaction[31]	F
	Use cropping systems that enhance the soil structure and infiltration capacity [15, 31]	F
	Improve dimensioning and management of main drainage systems [15, 31]	P

	Revise recommendations for drainage systems [15]	P
	Improve knowledge of drainage at all agricultural levels: research and education [15,17]	P
	New drainage system policies [15]	P
	Cooperation between administrative units and institutions[30]	
	Breeding varieties with increased water-logging resistance [17]	P
Prevent nitrogen leaching	Reduce intensive tillage in autumn; liming; extend the period of green cover and active crop growth: grassland, catch crops, winter-sown crops [13,18,19,32]	F (P)
Cope with increased risk of weeds, pests, and diseases	Increased need for crop protection and pest control products [2,5,12,13,20,21,26]	F (P)
Cope with increased risk of weeds, pests, and diseases *simultaneously with increased resistance to chemical plant protection products*	Varied crop rotation [5]	F
	Earlier sowing (in case of potato)[29]	F
	Subsidies for non-chemical products [5]	P
	Limit the production of winter-sown crops and potatoes [5]	F
	Increase grassland production [5,19]	F (P)
	Mechanical weed control [5]	F
	Intercropping[28]	F
	Biological seed protection [5]	P
	Revise guidelines on reduced soil tillage [5]	P
	Introduce official import control of plants [25]	P
Reduce vulnerability to more varied climate	Increased diversity in how crop genotypes respond to various climate conditions [14,17]	P
	Increased crop diversity[26]; Intercropping[28]	F
General climate change	Improved crop management and cultivar selection on suitable land [16]	F
	Harvest loss follow-up system on weather and economic loss [24]	P
	Implement increased extension to farmers regarding climate change impacts [24]	P
	Research: improve knowledge and develop approaches to adaptation planning [22,23]	P

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. (2010); 7. Olesen (2005); 8. Rötter et al. (2013); 9. Kaukoranta and Hakala (2008); 10. Olesen et al. (2012); 11. Patil et al. (2010); 12. Mattila 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. (2010a); 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 (2016a); 31: Jordbruksverket (2016b); 32: Huttunen et al. (2015)

3.3 Knowledge gaps

This systematic literature review indicates that opportunities and challenges with climate change for crop production contain a complex set of factors, which are relevant in order to assess agricultural vulnerability to climate change. Several of the reviewed studies (40 out of which 28 are peer-reviewed scientific papers) are impact assessments focusing on biophysical impacts of climate change and/or adaptation on crop production, while fewer specifically address adaptation issues (13 out of which four are peer-reviewed scientific papers), and only two studies (Kvalvik et al. 2011; Juhola et al. 2017) specifically address contextual vulnerability in the agricultural system. This indicates a significant knowledge gap regarding contextual vulnerability to climate change, specifically related to the sensitivity of the agricultural system, but also related to adaptive capacity. Some of the studies addressing adaptation strategies do however consider aspects in relation to adaptive capacity. Furthermore, the synthesis indicates important interlinkages between (biophysical) impacts, even though these do not appear to be addressed in the reviewed literature, since frequently only single impact factors are included in the assessed studies.

As many of the reviewed studies are biophysical impact assessment, these studies mention adaptation measures in their discussion or include selected adaption options in the impact modelling rather than specifically assessing adaptation capacities, barriers, strategies and consequences. This literature review further indicates that there are significant challenges and opportunities that require adaptation, which calls for an advancement of climate adaptation research for the Nordic agriculture. Few of the reviewed papers account for that successful adaptation involves balancing of factors which that are not attainable in parallel or in combination, and none of the reviewed papers systematically analyses such adaptation-induced trade-offs. However, the systematic review of suggested adaptation actions indicates that, since adaptation actions serve different purposes, they may result in consequences that counteract other socio-ecological goals. The challenge of such compromises or conflicts between individual adaptation practices or between adaptation and other practices, becomes evident when aligning possible outcomes of actions. This paper thus highlights the essential knowledge gap regarding the understanding of adaptation-induced trade-offs in the literature on Nordic agriculture under climate change.

4 Discussion

This review of climate related challenges and opportunities as well as suggested adaptation policies and measures in Nordic agriculture, outlines a complexity of interacting factors that have to be addressed when developing adaptation strategies. In general, in climate change research, trade-offs are discussed as a form of inter-relationship between adaptation and mitigation (Tol, 2005) or as conflicts between different environmental, social and economic goals (Denton et al. 2014). The Intergovernmental Panel on Climate Change (IPCC) highlights the need for increased research about relationships between adaptation, mitigation, and sustainable development, and to consider potential trade-offs within and across land-use sectors for various objectives (Denton et al. 2014; Smith et al. 2014). The latest IPCC assessment report (AR5) discusses in particular trade-offs that may arise from mitigation actions in terms of balancing between mitigation and, for example, food security, natural resource use, livelihoods, emissions, environmental sustainability, and social, economic and environmental costs; where social, institutional, economic, and environmental goals could be conflicting (Smith et al. 2014). The adaptation-induced trade-offs are not as extensively covered by the IPCC as the mitigation-induced, but the need to consider potential synergies and trade-offs between adaptation, mitigation and development strategies is stressed (Denton et al. 2014). Nevertheless, the positive consequences of adaptation actions on mitigation, i.e., positive synergies, are emphasised in the chapter on 'Agriculture, Forestry and Other Land Use' within Working Group III's Fifth Assessment Report of the Intergovernmental Panel on Climate Change, while examples of adaptation-induced trade-off are not discussed (cf. Smith et al. 2014, p. 846). The report states that 'most categories of adaptation options for climate change have positive impacts on mitigation' (Smith et al. 2014, p. 847). Adaptation and mitigation synergies involve e.g. measures to improve the soil water holding capacity by adding crop residues or manure, measures that reduce soil erosion, or measures that reduce leaching of nitrogen and phosphorus (Smith and Olesen, 2010). Generally, if these measures are properly applied they might contribute to improved nitrogen use efficiency and improved soil carbon storage (ibid).

This paper does not answer whether there are more trade-offs than positive synergies regarding adaptation and mitigation, but demonstrates the specific knowledge gap regarding adaptation-induced trade-offs. The synthesis indicates that decisions regarding trade-offs require careful consideration on the balancing of factors. Three categories of trade-offs for climate adaptation could be outlined from the synthesis (*i*) climate adaptation vs. environmental objectives (limit eutrophication, wetland protection, limit toxic environments); (*ii*) climate adaptation vs. climate change mitigation; and (*iii*) climate adaptation vs. agricultural management (production efficiency).

One of the dominant issues in the reviewed studies is the need for adaptation to increased precipitation and changed precipitation patterns. While one measure in relation to this challenge is enlarged and improved drainage systems, such measures could however influence aquatic environments. In 1994, land drainage was prohibited in Sweden in response to previous wetland destruction (Jordbruksverket, 2013). Since the 1980s, Swedish policies have focused on maintaining sustainable aquatic environments rather than using arable land for food production – making it difficult to develop drainage systems (Jordbruksverket, 2013). This poses a trade-off in relation to the first category (*i*) between adaptation to future precipitation conditions through expanded drainage systems and wetland protection, and further indicates the need to review the possible trade-offs between environmental policies and possible adaptation options for drainage in order to make appropriate policy changes. The first trade-off category also involves the prospect that crop composition could be altered in the future to capitalize on new climatic conditions. It is likely that the share of winter crops and maize will increase at the expense of grassland to exploit a longer growing season. Such changes will however increase the need for chemical fertilizers (Fogelfors et al., 2009), herbicides and fungicides (Wivstad, 2010) with detrimental environmental effects (linked to category (*i*)). Expanding the grassland production could, on the other hand, be a measure to reduce both the risk of nutrient loss and the need for chemical plant protection (Fogelfors et al., 2009). This creates a trade-off between the choices of adapting to new climate conditions or preventing increased leaching and toxic environments (category (*i*)). Moreover, there is a risk that an increased use of pesticides and herbicides will result in target immunity (Wivstad, 2010), which implies that a scenario with increase production of winter wheat and maize could lead to double failure in terms of an even greater need for chemical plant protection in order to be effective (category (*i*)). Furthermore, an expansion of maize production to make use of new climatic conditions would also involve a trade-off in relation to category (*ii*). When maize is produced at the expense of grassland it is expected to reduce the soil humus content through increased CO_2 emissions from soil organic material (Fogelfors et al., 2009; Qin et al., 2016), counteracting mitigation.

A milder climate demands adaptation to increased risk of pests and weed infestations, flooding and nutrient leaching. However, increased risk of pest and weed infestation could also be an effect of adaptation to new climate condition through the cultivation of "new" crops. Such adaptation measures would imply conflicting choices facing the individual farmer, regarding for example tillage, year-round production and plant protection (linked to category (*i*) and (*iii*)). The trade-offs specifically include measures to reduce soil tillage in autumn and keep a green cover year-round to limit nutrient loss or adapt to increased risk of pest and weeds that comes with climate change. Soil tillage increases the infiltration and drainage capacity but on the other hand, increases leaching (category (*i*)). Yet, reduced soil tillage increases the risk of weeds and pests through providing them with undisturbed environments (category (*i*) and (*iii*)) (Wivstad, 2010). It has previously been reasoned, for the case of Sweden, that the environmental objectives of a 'non-toxic environment' and 'zero eutrophication' could come into conflict over the specific means used to achieve sustainable agriculture (Eckersten et al., 2007). With climate change and the related adaptation practices, it will be increasingly important to find ways to keep pesticide, fungicide, and insecticide use at low levels while minimizing nutrient loss (category (*i*)) (Wivstad, 2010).

The farmer's choice of whether to change or maintain current soil tillage practices also involves adaptation – mitigation trade-offs (category (*ii*)). Soil tillage promotes well-drained soils and simultaneously prevents pest and weed establishment but on the other hand, it causes nutrient loss and CO_2 emissions from the soil. CO_2 is mainly emitted during soil management, for example, due to ploughing or harvesting. A recommended way to reduce emissions from the soil is to reduce tillage and plant catch crops (Reinfeldt and Erlandsson, 2012). Again, this would be in conflict with suggested adaptation actions to promote better-drained soils and mechanical plant protection (category (*ii*)).

Trade-offs can also relate to farmers' choices regarding improvement of production efficiency under current conditions and enhanced challenges under a future climate (category (*iii*)). Farmers will possibly invest in heavy machinery to meet agricultural structures and policies to be efficient in production (Kvalvik et al., 2011). Yet, wetter conditions and heavy rains increase the risk of soil compaction, which probably will enhance the management challenges for farmers in the future. Thus, in times when agriculture needs to adapt to wetter conditions and increased soil compaction, heavier equipment instead enhances such management challenges (category (*iii*)).

In line with the present paper, Juhola et al. (2017) argue that farmers' decision-making processes on adaptation measures consist of making trade-offs between various adaptation measures. As the adaptation policies and measures discussed here only describe potential adaptation measures, the actual strategy directions could result in greater or weaker trade-offs. Furthermore, the trade-offs indicated in this section are certainly a small fraction of all inter-linkages between possible outcomes of adaptation and other agricultural measures. Nevertheless, the present review of suggested adaptation actions, points towards important challenges related to trade-offs between adaptation and *environmental objectives*, *climate change mitigation*, and *agricultural management for efficient production*. The IPCC AR5 reports discuss that mitigation actions involve trade-offs with other social, institutional, economic, and environmental goals. In the climate adaptation literature for Nordic agriculture, conflicting environmental goals seem to be more visible than social, institutional or economic, however, this is possibly a result of the types of studies being biophysical impact studies and not integrated contextual studies focusing on adaptation. In order to design and implement sustainable adaptation strategies for agriculture while minimising negative environmental effects and counteracting mitigation efforts, adaptation-induced trade-offs needs to be addressed.

5 Conclusion

This paper demonstrates that the agricultural sector in the Nordic region is facing certain benefits with climate change, along with essential challenges related directly to climate change as well as in relation to adaptation-induced trade-offs. While climate change in Nordic agriculture is anticipated to result in more important opportunities than challenges (e.g. Jordbruksverket 2017), this paper shows that there are important challenges that require recognition and analysis, and that potential adaptation-induced trade-offs need to be accounted for in order to develop sustainable adaptation strategies.

Several knowledge gaps related to how to adapt to specific challenges have been identified, for example, accelerated phenological development, difficulties of tilling in spring, and increased exposure to summer drought. While some conflicts and compromises related to how to adapt to challenges and opportunities are noted in the reviewed literature, this paper also identifies a knowledge gap regarding climate adaptation-induced trade-offs within agriculture, also involving environmental effects.

Many of the recommended adaptation actions may involve outcomes in addition to the intended ones, causing a situation where adaptation choices are not easily made or where these negative outcomes are not even known. The great number of climate change and impact scenarios as well as perspectives on plausible adaptation strategies under a future climate signifies that it is not entirely obvious whether climate change will present mainly challenges or opportunities, meaning that the required and recommended adaptation measures are diverse and may even counteract one another. The adaptation actions identified in this review were often found in discussion sections of impact studies, as potential solutions to the anticipated impacts. This paper further identifies a scientific knowledge gap regarding climate adaptation priorities, barriers and experiences in Nordic agricultural contexts.

Further, this systematic review shows that adaptation actions mentioned in the literature are mostly farm-based measures. Decisions on farm-based adaptation have to be based on very local conditions with the cropping system in focus. However, the identified challenges and lacking understanding of trade-offs indicate that it is not obvious how to adapt and what to prioritize, both in terms of farm-based and policy-driven adaptation. This review suggests that policies and guidelines for drainage systems, non-toxic environments, and zero eutrophication are in conflict, i.e., involving trade-offs between agricultural production and environmental considerations. Such policies should preferably be assessed with focus on how to adapt and what to prioritize, to prevent conflicting policies and measures as far as possible.

This paper concludes that more research should focus on evaluation of trade-offs between different agricultural climate adaptation policies and measures but also in relation to other agricultural policies and measures. Such negative impacts require communication between researchers, policy-makers and individual farmers in order to make better-informed recommendations and decisions. The variety of climate challenges, opportunities and potential adaptation actions identified in this first systematic review for Nordic agriculture shows that the sector expect certain benefits in the light of climate change. Nevertheless, there are essential challenges related both directly to climate change as well as in relation to adaptation-induced trade-offs, which require an increased understanding of these interlinkages. Failing to address these challenges might impede Nordic agriculture's possibility to capitalise on climate change in a long-term perspective. Therefore, these challenges should be recognised in a larger regional context if, or when, Nordic agriculture is described as a "winner" in terms of climate change.

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Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., Soussana, J.-F., Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., Soussana, J.-F., 2014. Europe, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1267–1326.

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Lehtonen, H., 2015. Evaluating adaptation and the production development of Finnish agriculture in climate and global change. Agric. Food Sci. 24, 219–234.

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Marttila, V., Granholm, H., Laanikari, J., Yrjölä, T., Aalto, A., Heikinheimo, P., Honkatuki, J., Järvinen, H., Liski, J., Merivirta, R., Paunio, M., 2005. Nationell strategi för anpassning till klimatförändringen, 1b/2005. ed. Jord- och skogsbruksministeriet.

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Olesen, J.E., Børgesen, C.D., Elsgaard, L., Palosuo, T., Rötter, R.P., Skjelvåg, A.O., Peltonen-Sainio, P., Börjesson, T., Trnka, M., Ewert, F., Siebert, S., Brisson, N., Eitzinger, J., van Asselt, E.D., Oberforster, M., van der Fels-Klerx, H.J., 2012. Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. Food Addit. Contam. Part A. Chem. Anal. Control. Expo. Risk Assess. 29, 1527–42.

Olesen, J.E., Carter, T.R., Díaz-Ambrona, C.H., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Minguez, M.I., Morales, P., Palutikof, J.P., Quemada, M., Ruiz-Ramos, M., Rubæk, G.H., Sau, F., Smith, B., Sykes, M.T., 2007. Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Clim. Change 81, 123–143. https://doi.org/10.1007/s10584-006-9216-1

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

Olesen, Jør.E., 2005. Climate Change and CO 2 Effects on Productivity of Danish Agricultural Systems. J. Crop Improv. 13, 257–274.

Ozturk, I., Sharif, B., Baby, S., Jabloun, M., Olesen, J.E., 2017. The long-term effect of climate change on productivity of winter wheat in Denmark: a scenario analysis using three crop models. J. Agric. Sci. 155, 733–750. https://doi.org/10.1017/S0021859616001040

Patil, R.H., Laegdsmand, M., Olesen, J.E., Porter, J.R., 2010. Growth and yield response of winter wheat to soil warming and rainfall patterns. J. Agric. Sci. 148, 553–566.

Peltonen-Sainio, P., Jauhiainen, L., Trnka, M., Olesen, J.E., Calanca, P., Eckersten, H., Eitzinger, J., Gobin, A., Kersebaum, K.C., Kozyra, J., Kumar, S., Marta, A.D., Micale, F., Schaap, B., Seguin, B., Skjelvåg, A.O., Orlandini, S., 2010a. Coincidence of variation in yield and climate in Europe. Agric. Ecosyst. Environ. 139, 483–489. https://doi.org/http://dx.doi.org/10.1016/j.agee.2010.09.006

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Pulatov, B., Linderson, M.L., Hall, K., J??nsson, A.M., 2015. Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe. Agric. For. Meteorol. 214–215, 281–292. https://doi.org/10.1016/j.agrformet.2015.08.266

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Reinfeldt, F., Erlandsson, E., 2012. Regeringens skrivelse 2011/12:124 - Miljö-, klimat- och energiinsatser inom jordbruket.

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

Rötter, R.P., Höhn, J.G., Fronzek, S., 2012. Projections of climate change impacts on crop production: A global and a Nordic perspective. Acta Agric. Scand. Sect. A - Anim. Sci. 62, 166–180. https://doi.org/10.1080/09064702.2013.793735

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

Sharif, B., Makowski, D., Plauborg, F., Olesen, J.E., 2017. Comparison of regression techniques to predict response of oilseed rape yield to variation in climatic conditions in Denmark. Eur. J. Agron. 82, 11–20. https://doi.org/10.1016/j.eja.2016.09.015

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H.H., Rice, C.. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014. Agriculture, Forestry and Other Land Use (AFOLU), in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, J.C. Minx (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, United Kingdom and New York, NY, USA.

Smith, P., Olesen, J.E., 2010. Synergies between the mitigation of, and adaptation to, climate change in agriculture. J. Agric. Sci. 148, 543–552.

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Thorsen, S.M., Höglind, M., 2010. Assessing winter survival of forage grasses in Norway under future climate scenarios by simulating potential frost tolerance in combination with simple agroclimatic indices. Agric. For. Meteorol. 150, 1272–1282.

Tol, R.S.J., 2005. Adaptation and mitigation: trade-offs in substance and methods. Environ. Sci. Policy 8, 572–578. https://doi.org/10.1016/j.envsci.2005.06.011

Torvanger, A., Twena, M., Romstad, B., 2004. Climate Change Impacts on Agricultural Productivity in Norway (No. 10), CICERO Working Paper, 04.

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., et al. 2011. Agroclimatic conditions in Europe under climate change. Glob. Chang. Biol. 17, 2298–2318.

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

Wivstad, M., 2010. Klimatförändringarna - en utmaning för jordbruket och giftfri miljö PM 2/10.

Woods, B., Nielsen, H., Pedersen, A.B., Kristofersson, D., 2017. Farmers' perceptions of climate change and their likely responses in Danish agriculture. Land use policy 65, 109–120. https://doi.org/10.1016/j.landusepol.2017.04.007

Appendix

The 60 publications included in the systematic literature review. The references are listed together with the type of analysis (IA – Impact Assessment; AA – Adaptation Assessment; Contextual vulnerability assessment (VA); Other) and the addressed system dimension (Biophysical; Socio-economical; Integrated; Policy).

Reference	Study type	System dimension
Peer-reviwed scientific papers		
Asplund, T., M. Hjerpe, and V. Wibeck. 2013. Framings and coverage of climate change in Swedish specialized farming magazines. *Climatic Change 117: 197-209*	Other	Social
Bizikova, L., E. Crawford, M. Nijnik, and R. Swart. 2014. Climate change adaptation planning in agriculture: processes, experiences and lessons learned from early adapters. *MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE* 19: 411–430. doi:10.1007/s11027-012-9440-0.	AA	Social
Eckersten, H., A. Herrmann, A. Kornher, M. Halling, E. Sindhøj, and E. Lewan. 2012. Predicting silage maize yield and quality in Sweden as influenced by climate change and variability. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science* 62. Taylor & Francis: 151–165. doi:10.1080/09064710.2011.585176.	IA	Biophysical
Eckersten, H., K. Blombäck, T. Kätterer, and P. Nyman. 2001. Modelling C, N, water and heat dynamics in winter wheat under climate change in southern Sweden. *Agriculture, Ecosystems & Environment* 86: 221–235.	IA	Biophysical

Elsgaard, L., C. D. Børgesen, J. E. Olesen, S. Siebert, F. Ewert, P. Peltonen-Sainio, R. P. Rötter, and A. O. Skjelvåg. 2012. Shifts in comparative advantages for maize, oat and wheat cropping under climate change in Europe. *Food additives & contaminants. Part A, Chemistry, analysis, control, exposure & risk assessment* 29. Taylor & Francis: 1514–26.	IA	Biophysical
Hakala, K., L. Jauhiainen, S. J. Himanen, R. Rotter, T. Salo, and H. Kahiluoto. 2012. Sensitivity of barley varieties to weather in Finland. *JOURNAL OF AGRICULTURAL SCIENCE* 150: 145–160. doi:10.1017/S0021859611000694.	IA	Biophysical
Himanen, S. J., K. Hakala, and H. Kahiluoto. 2013. Crop responses to climate and socioeconomic change in northern regions. *REGIONAL ENVIRONMENTAL CHANGE* 13: 17–32. doi:10.1007/s10113-012-0308-3.	IA	Integrated
Himanen, S., H. Mäkinen, K. Rimhanen, and R. Savikko. 2016. Engaging Farmers in Climate Change Adaptation Planning: Assessing Intercropping as a Means to Support Farm Adaptive Capacity. *Agriculture* 6:34	AA	Integrated
Huttunen, I., H. Lehtonen, M. Huttunen, V. Piirainen, M. Korppoo, N. Veijalainen, M. Viitasalo, and B. Vehviläinen. 2015. Effects of climate change and agricultural adaptation on nutrient loading from Finnish catchments to the Baltic Sea. *Science of the Total Environment* 529:168-181	IA	Biophysical
Höglind, M., S. M. Thorsen, and M. A. Semenov. 2013. Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models. *Agricultural and Forest Meteorology* 170: 103–113 Höglind, M., S. M. Thorsen, and M. A. Semenov. 2013. Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models. *Agricultural and Forest Meteorology* 170: 103–113	IA	Biophysical
Jeppesen, E., B. Kronvang, J. E. Olesen, J. Audet, M. Søndergaard, C. C. Hoffmann, H. E. Andersen, T. L. Lauridsen, et al. 2010. Climate change effects on nitrogen loading from cultivated catchments in Europe: implications for nitrogen retention, ecological state of lakes and adaptation. *Hydrobiologia* 663: 1–21.	IA	Biophysical
Juhola, S.N. Klein, J. Käyhkö, T-S. Schmid Neset. 2017. Climate change transformations in Nordic agriculture? *Journal of Rural Studies* 51:28-36	VA; AA	Integrated
Kaukoranta, T., and K. Hakala. 2008. Impact of spring warming on sowing times of cereal , potato and sugar beet in Finland. *AGRICULTURAL AND FOOD SCIENCE* 17: 165–176.	IA	Biophysical
Kleemola, J., E. Pehu, P. Peltonen-Sainio, and T. Karvonen. 1995. Modelling the impact of climatic change on growth of spring barley in Finland. *Journal of Biogeography* 22: 581–590.	IA	Biophysical

Kristensen, K., K. Schelde, and J. E. Olesen. 2010. Winter wheat yield response to climate variability in Denmark. *The Journal of Agricultural Science* 149. Cambridge University Press: 33–47.	IA	Biophysical
Kvalvik, I., S. Dalmannsdottir, H. Dannevig, G. Hovelsrud, L. Rønning, and E. Uleberg. 2011. Climate change vulnerability and adaptive capacity in the agricultural sector in Northern Norway. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science* 61: 27–37. doi:10.1080/09064710.2011.627376.	VA; AA	Integrated
Laurila, H. 1995. Modelling the effects of elevated CO2 and temperature on Swedish and German spring wheat varieties with CERES-wheat and AFRC-wheat crop models. *Journal of Biogeography* 22: 591–595.	IA	Biophysical
Lethonen. 2015. Evaluating adaptation and the production development of Finnish agriculture in climate and global change. *AGRICULTURAL AND FOOD SCIENCE 24: 219-234*	IA; AA	Integrated
Olesen, J. E., C. D. Børgesen, L. Elsgaard, T. Palosuo, R. P. Rötter, A. O. Skjelvåg, P. Peltonen-Sainio, T. Börjesson, et al. 2012. Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. *Food additives & contaminants. Part A, Chemistry, analysis, control, exposure & risk assessment* 29. Taylor & Francis: 1527–42.	IA; AA	Biophysical
Olesen, Jør. E. 2005. Climate Change and CO 2 Effects on Productivity of Danish Agricultural Systems. *Journal of Crop Improvement* 13. Taylor & Francis: 257–274.	IA	Biophysical
Ozturk, I., B. Sharif, S. Baby, M. Jabloun, and J.E. Olesen. 2017. The long-term effect of climate change on productivity of winter wheat in Denmark: a scenario analysis using three crop models. *The Journal of Agricultural Science* 155: 733–750	IA	Biophysical
Palosuo, T., R. Rötter, T. Salo, P. Peltonen-Sainio, F. Tao, and H. Lehtonen. 2015. Effects of climate and historical adaptation measures on barley yield trends in Finland. *Climate Research.* 65: 221-236	IA; AA	Biophysical
Patil, R. H., M. Laegdsmand, J. E. Olesen, and J. R. Porter. 2010. Growth and yield response of winter wheat to soil warming and rainfall patterns. *The Journal of Agricultural Science* 148. Cambridge University Press: 553–566.	IA	Biophysical
Peltonen-Sainio, P., L. Jauhiainen, M. Trnka, J. E. Olesen, P. Calanca, H. Eckersten, J. Eitzinger, A. Gobin, et al. 2010a. Coincidence of variation in yield and climate in Europe. *Agriculture, Ecosystems & Environment* 139: 483–489. doi:http://dx.doi.org/10.1016/j.agee.2010.09.006.	IA	Biophysical
Peltonen-Sainio, P., P. Pirinen, H. Mäkelä, O. Hyvärinen, E. Huusela-Veistola, H. Ojanen, and A. Venäläinen. 2016. Spatial and temporal variation in weather events critical for boreal agriculture: I Elevated temperatures. *AGRICULTURAL AND FOOD SCIENCE* 25: 44-56	IA	Biophysical

Pulatov, B., M-L. Linderson, K. Hall, and A.M. Jönsson. 2015. Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe. *Agricultural and Forest Meteorology* 214-215: 281-292	IA	Biophysical
Rötter, R. P., J. G. Höhn, and S. Fronzek. 2012. Projections of climate change impacts on crop production: A global and a Nordic perspective. *Acta Agriculturae Scandinavica, Section A - Animal Science* 62: 166–180. doi:10.1080/09064702.2013.793735.	IA	Biophysical
Rötter, R. P., J. Hohn, M. Trnka, S. Fronzek, T. R. Carter, and H. Kahiluoto. 2013. Modelling shifts in agroclimate and crop cultivar response under climate change. *ECOLOGY AND EVOLUTION* 3: 4197–4214. doi:10.1002/ece3.782.	IA	Biophysical
Rötter, R. P., T. Palosuo, N. K. Pirttioja, M. Dubrovsky, T. Salo, S. Fronzek, R. Aikasalo, M. Trnka, et al. 2011. What would happen to barley production in Finland if global warming exceeded 4 degrees C? A model-based assessment. *EUROPEAN JOURNAL OF AGRONOMY* 35: 205–214. doi:10.1016/j.eja.2011.06.003.	IA; AA	Biophysical
Sharif, B., D. Makowski, F. Plauborg, and J.E. Olesen. 2017. Comparison of regression techniques to predict response of oilseed rape yield to variation in climatic conditions in Denmark. *European Journal of Agronomy* 82: 11-20	IA	Biophysical
Thorsen, S. M., and M. Höglind. 2010. Assessing winter survival of forage grasses in Norway under future climate scenarios by simulating potential frost tolerance in combination with simple agroclimatic indices. *Agricultural and Forest Meteorology* 150: 1272–1282.	IA	Biophysical
Trnka, M., J. E. Olesen, K. C. Kersebaum, A. O. Skjelvåg, J. Eitzinger, B. Seguin, et al. 2011. Agroclimatic conditions in Europe under climate change. *Global Change Biology* 17: 2298–2318.	IA	Biophysical
Uleberg, E., I. Hanssen-Bauer, B. van Oort, and S. Dalmannsdottir. 2014. Impact of climate change on agriculture in Northern Norway and potential strategies for adaptation. *CLIMATIC CHANGE* 122: 27–39. doi:10.1007/s10584-013-0983-1.	IA; AA	Integrated
Woods, B., H. Nielsen, A.B. Pedersen, and D. Kristofersson. 2017. Farmers' perceptions of climate change and their likely responses in Danish agriculture. *Land Use Policy* 65: 109-120	AA	Social
Grey literature		
Andersson, L., A. Bohman, L. Van Well, A. Jonsson, G. Persson, and J. Farelius. 2015. *Underlag till kontrollstation 2015 för anpassning till ett förändrat klimat. KLIMATOLOGI Nr*. Vol. 12.	AA	Social; Policy

Bastviken, S., A. Bratt, H. Ek Henning, and P. Lindmark. 2015. *Jordbruk och vattenmiljöer i ett förändrat klimat (JoVaK)*. County administrative board Östergötland, Report 2015:22. ISBN: 978-91-7488-394-7	IA	Biophysical
Blombäck K., C.D. Børgesen, H. Eckersten, M. Giełczewski, M. Piniewski, S. Sundin, S. Tattari, and S. Väisänen. 2012. *Productive agriculture adapted to reduced nutrient losses in future climate - Model and stakeholder based scenarios of Baltic Sea catchments*. Baltic COMPASS –report.	IA	Integrated
de Toro, A., H. Eckersten, L. Nkurunziza, and D. von Rosen. 2015. *Effects of extreme weather on yield of major arable crops in Sweden*. Swedish University of Agricultural Sciences. Report no. 086	IA	Biophysical
Eckersten, H., L. Andersson, F. Holstein, B. Mannerstedt, H. Fogelfors, E. Lewan, Roland, and B. Torssell. 2007. *Bedömningar av klimatförändringars effekter på växtproduktion inom jordbruket i Sverige*.	IA; AA	Biophysical
Fogelfors, H., M. Wivstad, H. Eckersten, F. Holstein, S. Johansson, and T. Verwijst. 2009. *Strategic Analysis of Swedish Agriculture in a time of change*.	IA; AA	Integrated
Gaasland, I. 2004. *Can a warmer climate save northern agriculture?* 16. 04. Bergen: SNF Project No.2365.	IA	Economic
Hildén, M., H. Lehtonen, I. Bärlund, K. Hakala, T. Kaukoranta, S. Tattari. 2005. *The practice and process of adaptation in Finnish agriculture. FINADAPT. Finnish environmental institute.*	IA; AA	Integrated
Jordbruksverket. 2013. *Jordbrukets markavvattningsanläggningar i ett nytt klimat.* Report 2013:14	AA	Integrated
Jordbruksverket. 2014. *Drainage of agricultural land 2013, final statistics.* JO Statistiska Meddelanden: JO 41 SM 1402	other	Other
Jordbruksverket. 2016a. *Översvämning! Samhällets krisberedskap och förebyggande arbete när det gäller översvämningar som drabbar jordbrukssektorn.* Report 2016:01	AA	Integrated
Jordbruksverket. 2016b. *Jordbruket och väderrelaterade störningar Konsekvenser av översvämningar för växtodling och djurhållning*	IA	Integrated
Jordbruksverket. 2016c. *Kartläggning av åtgärder för att klara avvattningen av jordbruks- mark i ett förändrat klimat.* Delredovisning	AA	Integrated
Jordbruksverket. 2017. *Handlingsplan för klimatanpassning - Jordbruksverkets arbete med klimatanpassning inom jordbruks- och trädgårdssektorn*. Report 2017:7	AA	Policy

Kommunal. 2010. *Klimatet och Jordbruket – En skrift om klimatförändringarna*	Other	Other
Maracchi, G., O. Sirotenko, and M. Bindi. 2005. Impacts of Present and Future Climate Variability on Agriculture and Forestry in the Temperate Regions: Europe. In *Increasing Climate Variability and Change*, ed. J. Salinger, M. V. K. Sivakumar, and R. P. Motha, 117–135. Berlin/Heidelberg: Springer-Verlag. doi:10.1007/1-4020-4166-7.	IA	Biophysical
Marttila, V., H. Granholm, J. Laanikari, T. Yrjölä, A. Aalto, P. Heikinheimo, J. Honkatuki, H. Järvinen, et al. 2005. *Nationell strategi för anpassning till klimatförändringen*. 1b/2005. Jord- och skogsbruksministeriet.	AA	Integrated
MMM. 2009. *Evaluation of the Implementation of Finland's National Strategy for Adaptation to Climate Change 2009*. Ministry of Agriculture and Forestry - Finland.	AA	Other
MMM. 2014. *Climate Programme for Finnish Agriculture - steps towards climate friendly food.* Ministry of Agriculture and Forestry - Finland, 2014:8	Other	Integrated
NOU. 2010. *Tilpassing til eit klima i endring*. Oslo: Servicesenteret for departementa Informasjonsforvaltning.	AA	Integrated
Peltonen-Sainio, P., K. Hakala, and L. Jauhiainen. 2010b. Klimatförändringen innebär en ny era för växtproduktioenen i Finland. In *Finlands lantbruk och landsbygdsnäringar 2010*, ed. J. Niemi and J. Ahlstedt. MTT Ekonomisk forskning.	AA	Integrated
Reinfeldt, F., and E. Erlandsson. 2012. *Regeringens skrivelse 2011/12:124 - Miljö-, klimat- och energiinsatser inom jordbruket*.	Other	Other
SOU. 2007. *Sweden facing climate change: threats and opportunities*. *Swedish Government Official Reports 2007:60*. Stockholm, Sweden.	IA; AA	Integrated
Torvanger, A., M. Twena, and B. Romstad. 2004. *Climate Change Impacts on Agricultural Productivity in Norway*. 10. *CICERO Working Paper*. 04.	IA	Biophysical
West J. and G.K. Hovelsrud. 2008. *Climate change in Northern Norway: Toward an understanding of socio-economic vulnerability of natural resource-dependent sectors and communities*. CICERO Report 2008:04	VA	Integrated
Wivstad, M. 2010. *Klimatförändringarna - en utmaning för jordbruket och giftfri miljö PM 2/10*.	IA; AA	Integrated