Impact of projected climate change on workability, attainable yield, profitability and farm mechanization in Norwegian spring cereals

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Highlights

- Workability thresholds, based on soil water content, determined sowing dates.
- Workability was explored as number, cohesion and earliness of workable days.
- Workability can restrict early sowing of spring cereals in Norway in the future.
- In the worst-case, attainable yield will be reduced in C Norway.

Abstract

In cold-temperate climate with high soil water content in spring, the farmer often faces the choice between topsoil compaction during seedbed preparation and delayed sowing, both of which may reduce attainable cereal yield. The objective of this study was to explore whether future climate change with increasing precipitation would aggravate this dilemma. We generated weather based on historical and projected future climate in South-eastern and Central Norway. Using this weather data as input, we simulated spring workability, attainable yield, timeliness costs, and mechanization management with a workability model and a mechanization model. The projected climate changes resulted in improved workability for spring fieldwork and higher attainable yield in South-eastern Norway, and either positive or negative changes in Central Norway compared to historical conditions. We observed a general increase in variability of workability and attainable yield, and a larger risk of extremely unfavourable years in the most unfavourable scenarios in Central Norway. Changes in profitability and mechanization management were small, but followed the same pattern. The negative effects in the most unfavourable climate scenarios in Central Norway were in contrast to positive effects in earlier studies. We explained discrepancies by differences in research methods and purpose. However, simulated sowing dates of annual crops should consider workability of the soil, in terms of water content. Under worst-case conditions, in need of a certain time window to complete their spring fieldwork, farmers might adapt to impaired spring workability by working the soil at higher water content than simulated in our study. The consequence would be a larger loss of attainable yield and less profitability in the future. We anticipate that negative effects may also be expected in other northern cold-temperate regions with high soil water content in spring.

Keywords: Seedbed preparation; Topsoil compaction; Delayed sowing

1 Introduction

The timing of seedbed preparation and cereal sowing in spring is crucial for realizing yield potential, especially in northern regions with cold-temperate climate. If the cereal seedbed preparation and sowing, in this paper collectively termed spring fieldwork, is done too early, in unfavourably wet soil, the farmer risks loss of attainable yield due to topsoil compaction (Bakken et al., 1987; Hofstra et al., 1986; Håkansson, 2005; Marti, 1983; Njøs, 1978) and oxygen deficiency during germination (Wesseling and VanWijk, 1957). If it is delayed, on the other hand, the farmer risks loss of attainable yield due to a shorter crop growing season (Riley, 2016). Consequently, there is only a limited number of available days for spring fieldwork, referred to as the window of opportunity (Edwards et al., 2016; Singh et al., 2011).

Within this time window, the soil is considered workable, i.e. it can carry machinery and be tilled without any significant topsoil compaction that could hamper germination and root growth (Rounsevell, 1993). In addition to soil water content, the degree of compaction depends on machinery related factors, like number of passes, wheel track area, wheel load, wheel equipment, inflation pressure, operating speed, traction and wheel slip (Etana and Håkansson, 1996; Ljungars, 1977), all of which are assumed to be constant or negligible in this paper. According to discussions in Rounsevell (1993) and Edwards et al. (2016), with small to moderate ground contact stress, we can assume that the soil is trafficable when it is workable. Therefore, in this paper we use the term workable to represent both. Rounsevell and Jones (1993) showed sensitivity of workability to historical climate variability in the UK. Similarly, Maton et al. (2007) simulated number of available sowing days, based on frost, temperature and soil water content in France. Accordingly, the window of opportunity for spring fieldwork is especially narrow in northern regions (Edwards et al., 2016; Reeve and Fausey, 1974).

Due to feasibility, northern farmers rarely restrict their spring fieldwork to the ideal conditions of the window of opportunity. The daily decision on whether to do fieldwork or not is based on the farmer’s individual and rather subjective perception of urgency, which is depending on soil type, current soil water content, weather forecast, and number of working days required to complete spring work. The latter is commonly about 10 days in Norway and largely depending on farm size, and working capacity of machinery and men, here collectively termed working capacity. This individual perception of urgency leads the farmer to decide for fieldwork at a certain soil water content, here referred to as the workability threshold. Thus, each farmer may have an individual workability threshold, and the daily decision may have individual economic consequences.

Whether the fieldwork is done too early or too late, the farmer experiences loss of attainable yield, in economic terms here called timeliness costs. By balancing the farm specific risk of the two different types of timeliness costs, farmers have long been adapting to year-to-year climate variability to maximize short-term profit (Bryant et al., 2000; Cerf et al., 1998; Choi et al., 2016; Maton et al., 2007; Maxwell et al., 1997; Peltonen-Sainio et al., 2009b; Riley, 2016; Smit et al., 1996; Urban et al., 2015; Witney and Oskoui, 1982; Reeve and Fausey, 1974). In order to maximize long-term profitability, farm management balances those potential timeliness costs with machinery costs. A large working capacity increases the chance to complete spring work within the window of opportunity, but is also associated with high machinery costs (de Toro, 2005; Elliot et al., 1977; Søgaard and Sørensen, 2004; Witney and Oskoui, 1982). Similar to the balance between the two different timeliness costs, the balance between timeliness costs and machinery costs is depending on year-to-year climate variability. Hence, long-term machinery management and profitability may be influenced by future climate change, due to potential changes to the window of opportunity.

Climate change may aggravate the already difficult timing of spring work. Many climate impact studies predict a longer thermal growing season in Northern Europe (Bindi and Olesen, 2011; Carter, 1998; Carter et al., 1991; Harding et al., 2015; Olesen and Bindi, 2002; Parry et al., 2007; Peltonen-Sainio et al., 2009b; Persson and Kværnø, 2017). However, a longer thermal growing season does not necessarily facilitate earlier sowing of spring cereals (Maton et al., 2007; Menzel et al., 2006; van Oort et al., 2012a, b). During coming decades, more precipitation during winter and spring, and increased precipitation variability are expected in northern regions like Scandinavia, Canada, northern Europe and Midwestern US (Bedard-Haughn, 2009; Coumou and Rahmstorf, 2012; Urban et al., 2015; Groisman et al., 2005; Hov et al., 2013; Trnka et al., 2011). This could mean a higher soil water content in spring, and a narrower and more variable window of opportunity for spring fieldwork. Thus, as discussed by van Oort et al. (2012a, b), the earlier sowing projected by climate impact studies may not be realizable.

Projected future yield increases may be too optimistic, if they are based on preponed sowing dates that do not consider soil water content in spring (Choi et al., 2016; van Oort et al., 2012). Many studies of climate change impact on crop production have used dynamic crop simulation models. In general, these models consider soil water content. However, the potential impact of soil water content on the window of opportunity for spring fieldwork, and on soil structure and timeliness costs have often not been fully considered, sometimes even neglected (Bergez et al., 2006). Consequently, simulated yield potentials do neither capture loss of attainable yield due to delayed sowing, awaiting optimal soil water content, nor loss due to topsoil compaction, if the crop is sown under unfavourably wet soil conditions. Furthermore, the formation of crop yield is strongly dependent on the weather conditions during different growth stages, and the timing of the phenological development depends on the interaction of preponed sowing date and weather (Dobor et al., 2016; Kirby, 1969;

Peltonen-Sainio and Jauhiainen, 2014; White et al., 2011). In order to adapt to future climate change and to avoid additional loss of attainable yield, simulations should resemble realistic management practices (Bergez et al., 2006) and consider soil workability in spring and potential timeliness costs.

Some studies on climate change impact in crop production considered workability thresholds. Rounsevell and Brignall (1994) found that overall soil workability in autumn might not be improved by future climate change in the UK, because the positive effect of an increase in temperature may be offset by the negative effect of an increase in precipitation. Cooper et al. (1997) simulated unchanged or increased number of workable days in early spring in Scotland. Eitzinger et al. (2013) simulated future increases in spring precipitation and reductions in number of workable days in spring in some regions in Central/South-eastern Europe. Tomasek et al. (2017) simulated earlier but fewer workable days in future Midwestern US. Regions like Scandinavia, which under current climate conditions normally has a narrower window of opportunity for spring fieldwork than the regions in the studies above, could expect even greater future challenges in spring, which may alter attainable yield, farmers' machinery management and profitability.

The few available studies concerning future workability in Scandinavia are in contrast to these expectations. In simulations by Rötter et al. (2011), soil water content did not affect future spring sowing dates in Finland considerably, and Trnka et al. (2011) and Rötter et al. (2013, 2012) simulated increase in number of workable days in spring in the future, in Scandinavia and Finland, respectively. However, one of these studies did not include the projected increase in winter and spring precipitation (Rötter et al., 2011), two considered early spring fieldwork to be limited by temperature only (Rötter et al., 2013, 2012), and three of them used a workability threshold of relatively high soil water content for late spring fieldwork (Rötter et al., 2013, 2012; Trnka et al., 2011). A further problem of many studies is that workability thresholds often are not specified detailed enough to allow straightforward comparison. In addition, the process-based modelling approach, used in most studies, does not capture within-farm variation in workability, sowing dates, and its consequences on attainable yield. Lastly, no attempt has been made to simulate possible impact of climate change on timeliness costs and farm mechanization management.

The objective of this study was to explore how projected future climate change affects workability, fieldwork throughout the spring period, and farm profitability under Norwegian conditions. We simulated historical and future climate, workability, attainable yield and timeliness costs for spring work on autumn-ploughed soils in two important cereal-growing regions with contrasting climate in Norway. We based sowing dates on a representative workability threshold (0-20 cm) and calculated the loss of attainable yield by combining effects of topsoil compaction (due to soil-specific high soil water content) and delayed sowing (if later than predefined optimum sowing day). Thus, in this paper, we use the term “attainable yield” to express timeliness-limited yield potential for a given soil, where crop growth is only limited by spring fieldwork timeliness, i.e. topsoil compaction or delayed sowing or both. Finally, we exemplify the use of timeliness costs in the adaptation of long-term farm mechanization management to climate change.

2 Material and methods

In order to determine spring workability, attainable yield and timeliness costs for spring cereals under historical and projected future climate conditions for South-eastern (SE) Norway and Central (C) Norway, two important cereal-growing regions in the country, the following steps were taken.

First, generated daily historical and future weather data were used as input to the workability model described by Riley (2016), for a test case of representative Norwegian farming conditions in a range of future greenhouse gas (GHG) emissions scenarios and global climate models (GCMs) in each region (Figure 1). Based on the simulated future spring workability and attainable yield, we calculated indices of workability and of attainable yield for the different GCMs, and selected two of them for further analyses (iteration in Figure 1).

Next, the selected combinations of GCMs and GHG emissions scenarios, here collectively called climate scenarios, were used to determine workability and attainable yield for a wider range of farming conditions. In addition, workability and attainable yield were determined for historical climate conditions.

Finally, the workability model output for the different climate scenarios and baseline climate was expressed in regression equations, which were used to determine timeliness costs and total costs with the mechanization model described by Mangerud et al. (2017), together with farm management input (Figure 1).

Details about the workability and mechanization models, their input data and simulation settings are presented below.

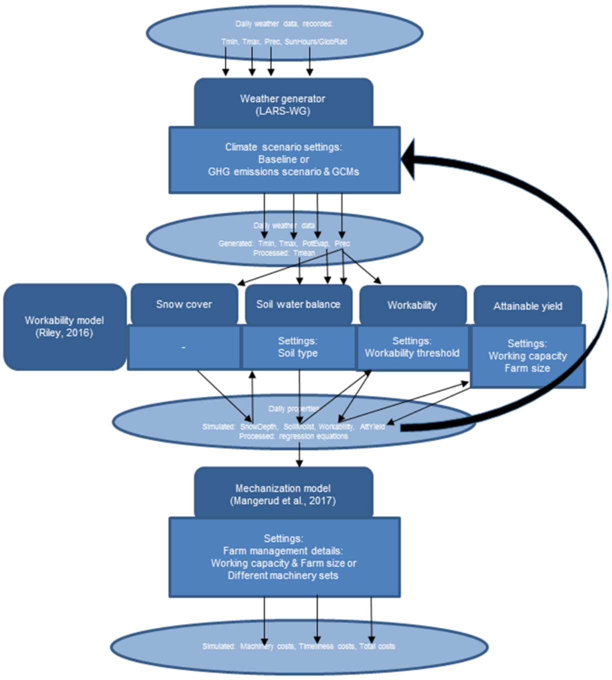

Figure 1: Overview over working steps (Rounded rectangles) and their associated data in- and output (Ellipses), and settings (Rectangles), for simulations of attainable yield, timeliness

costs and total costs under Baseline and future (2046-2065) climate scenarios in South-eastern and Central Norway.

2.1 Cereal-growing regions

South-eastern (SE) Norway is characterized as nemoral (NEM3)/ boreal (BOR8) by Metzger et al. (2005), and covers Østfold, Akershus, Oslo, Vestfold, Telemark and parts of Buskerud counties. This region includes 53 % of the total cereal area in Norway (Statistics Norway, 2018).

Central (C) Norway is classified as alpine north (ALN3/ ALN2) by Metzger et al. (2005) and covers Trøndelag and Møre/Romsdal counties. This region includes 17 % of the total cereal area in the country and is the northern-most important cereal region in Norway (Statistics Norway, 2018).

Even though Norwegian cereal production may seem negligible in a global context, e.g. considering winter wheat production (Trnka et al., 2014), it constitutes an important contribution to agricultural production on a national scale (Forbord and Vik, 2017). The majority of cereals in Norway are spring-sown, oats, barley and wheat in SE Norway and barley in C Norway (Statistics Norway, 2018).

In our study, climate conditions in SE Norway and C Norway are represented by data from weather stations at Ås (59° 40′ N, 10° 46′ E; 94 m above sea level) and Værnes (63° 27′ N, 10° 56′ E; 12 m above sea level), respectively.

2.2 Description of the workability model

The empirical workability model presented by Riley (2016) combines four modules (Figure 1), one for snow cover (Riley and Bonesmo, 2005), one for soil water balance (Kristensen and Jensen, 1975), one for workability and one for attainable yield. Based on weather data input, the module for snow cover calculates snow depth. Based on snow depth, weather data and selected soil type, the module for soil water balance calculates soil water content in a depth of 0-20 cm. Soil type is selected from four groupings (Table 1) which are representative for Norwegian cereal land. The module for workability assumes drained soil (Riley, 2016), and defines a given day as workable if (1) the amount of precipitation during the day in question does not exceed a maximum, which is depending on the soil type and the number of previous rainy days (Table A1), (2) the number of previous rainy days (precipitation > 1.5 mm) does not exceed three, and (3) the soil water content is below the selected workability threshold expressed in volume % of field capacity (FC, pF2, -10 kPa), independent from soil type. In this approach, the workability threshold expresses the farmer's individual willingness to incure topsoil compaction in favour of earlier sowing. Norwegian farmers' individual workability threshold commonly lies between 85 and 95% FC (Riley, 2016).

Based on the calculated soil water content at sowing time, the module for attainable yield simulates loss of attainable yield in spring cereals (average of barley, oats and wheat) as combined effects of (1) topsoil compaction and (2) delayed sowing. These effects on attainable cereal yield are based on functions derived from a range of field trials on topsoil compaction and sowing dates in Norway. The function for topsoil compaction (Figure A1a) calculates loss of attainable yield as $y = 43.85 - 1.495x + 0.0126\, x^2$, where x is soil water content in % FC (Riley, 2016). This function assumes zero topsoil compaction at water content below 66% FC. Related to common workability thresholds mentioned above, this means that farmers commonly experience some reduction in attainable yield due to soil compaction. The function for delayed sowing (Figure A1b) calculates loss of attainable yield as $y = -0.025x + 0.025x^2$, where x is the number of days after optimum sowing date (Ekeberg, 1987). This function assumes April 20 and June 21 to be optimum and latest sowing dates for spring cereals, respectively. For each spring season, the module for attainable yield simulates fieldwork on each workable day until the entire farm is sown. Based on working capacity, for seedbed preparation, sowing and rolling, and farm size, defined by the operator, it simulates sown area up to that day and mean attainable yield for the area worked up to that day. The attainable yield is solely based on spring work timeliness and assumes optimum growing conditions throughout the rest of the crop growing season.

Table 1: Soil type grouping in Riley (2016) and approximate corresponding classification

Soil type	FC [a] (mm)	FC - 85% FC [b] (mm)	Clay (%)	Silt (%)	USDA texture class [c]
1: coarse sand	30	4.5	<10	<50	Medium and coarse sand
2: loamy sand *	50	7.5	<10	>50	Silt loam, sandy loam
3: loam	70	10.5	10-25	-	Silt loam, sandy loam, loamy sand, loam
4: clay/ silt *	90	13.5	>25	-	Clay loam, silty clay loam, sandy clay loam, silt

[a] FC = water held at field capacity (pF2, -10 kPa).
[b] FC - 85% FC = water held between FC and 85% of FC, the latter used as workability threshold in this study.
[c] Corresponding USDA texture class (Brady and Weil, 2010; USDA, n.d.).
* Soil types selected for simulation of timeliness costs and total costs in this study.

2.2.1 Weather input data

As input for the workability model and the weather generator described later (Figure 1), we obtained historical weather data from the Norwegian Meteorological Institute (http://www.met.no). The data for SE Norway (Ås, Skogsdammen) contained daily minimum temperature, maximum temperature, precipitation and sun hours for the years 1957-1988, while the data for C Norway (Værnes airport) comprised the years 1961-1990, with global radiation replacing sun hours. For further use of the data, daily mean temperature was calculated as mean of daily minimum and maximum temperature.

Based on the historical weather data, baseline and future weather data for the period 2046-2065, were generated and downscaled using the Long Ashton Research Station Weather Generator (LARS-WG), version 5 (Semenov and Stratonovitch, 2010). In LARS-WG, the future weather represents socio-economic scenarios with high (SRA2), medium (SRA1B) and low (SRB1) greenhouse gas emissions, based on projected development of population, economy and technology as described in the Intergovernmental Panel on Climate Change

(IPCC) 4th Assessment Report (Nakicenovic and Swart, 2000). We generated 300 years each of Baseline climate and combinations of GHG emissions scenarios and GCMs, which were available in all three GHG emissions scenarios, namely IPCM4, MPEH5, INCM3, HADCM3, GFCM21, NCCCSM (Semenov and Stratonovitch, 2010; Solomon et al., 2007). The generated output comprised minimum temperature, maximum temperature, precipitation, global radiation and potential evaporation. Mean temperature was calculated as above.

Table 2: Settings, tools and farming contexts used in simulations of workability, yield potential, timeliness costs and total costs under Baseline and future (2046-2065) climate conditions in South-eastern (SE) and Central (C) Norway.

Response	Workability & loss of yield potential		Loss of yield potential		Timeliness & total costs
Farming context	Test case	Wider range	Examples	Examples	Example (worst case)
Tool	Workability model	Workability model	Regression equations	Regression equations	Mechanization model
GHG emissions scenario [a]	SRA2, SRA1B, SRB1	(Baseline), SRA2, SRB1	(Baseline), SRA2, SRB1	(Baseline), SRA2	(Baseline), SRA2
GCM [b]	IPCM4, MPEH5, INCM3, HADCM3, GFCM21, NCCCSM	(Baseline), NCCCSM, IPCM4	(Baseline), NCCCSM, IPCM4	(Baseline), NCCCSM	(Baseline), NCCCSM
Soil type [c]	4	1, 2, 3, 4	2, 4	2,4	2, 4
Working capacity (ha day^{-1})	4.5	2.5, 5, 7.5, 10, 12.5, 15	5, 10, 20	5, 10, 20	Calculated by the model
Farm size (ha)	45	15,30,45,60,75,90,105,120,135,150,165,180	60, 120, 180	40-180	40-180
Results	Table 5	Figures 2 and 3	Figure 4	Figure 5	Figures 6 and 7 (SE Norway not shown)

[a] GHG emissions scenario = greenhouse gas emissions scenario.
[b] GCM = global climate model.
[c] Description of soil type grouping in Table 1.

2.2.2 Simulation settings - test case future

As a foundation for selecting two contrasting GCMs, we simulated future workability and attainable yield in a test case in SE and C Norway in all three GHG emissions scenarios combined with the available six GCMs. For this test case, we selected a workability threshold of 85 vol % FC, described as realistic by Riley (2016). Furthermore, we selected the most widespread soil group in the regions in question (Greve et al., 2000), which was also the least workable soil group (Riley, 2016), a common farm size (NIBIO, 2018) and working capacity common for a farm of this size (Table 2).

2.2.3 Selection of GHG emissions scenarios and GCMs

In order to find two GCMs with contrasting impact on future spring workability (March – June), we defined and calculated several indices for workability and attainable yield (Table 3) for each of the 18 climate scenarios (Table 2) and compared them, as averages of each 300 years simulation. Because workability of a given soil is largely depending on soil water content and changing day-to day weather conditions (Earl, 1997), our indices not only describe the number of workable days in spring, but also their earliness and cohesion, and multiple combinations of these. As indices for attainable yield in our test case, we obtained number of years with incomplete spring work and average attainable yield per simulation. The latter includes relative attainable yield of the completed part of the farm in years with incomplete spring work.

Table 3: Definition of indices for workability and attainable yield used for selection of global climate models.

Index	Definition	Impact on window of opportunity	n
Length	Mean duration of workable spells per growing season = mean number of successive workable days	Smaller = less cohesive	300
Within10	Number of workable days within 10 days after 1st workable day	Smaller = later and less cohesive	300
FirstDay	Julian day of 1st workable day	Larger = later	300
First3Days	Mean Julian day of 1st three successive workable days	Smaller = later and less cohesive	300 – years with <3 days
ΔFirst-10thDay	Julian day difference between 10th and 1st workable day	Larger = less cohesive	300 - NoDay10
NoDay10	Number of years with less than 10 workable days by the end of June	Larger = higher risk of few days	-
NoDays	Number of years with no workable days within March to June	Larger = higher risk of no days	-
Incomplete	Number of years with incomplete spring work in the selected test case *	Larger = higher risk of too few days	-
AttYield	Relative attainable yield in the selected test case *	-	300

* Selected test case: farm size of 45 ha, working capacity of 4.5 ha d^{-1}

Based on the described indices (Table 3), we ranked the GCMs in each GHG emissions scenario according to their impact on the number, earliness and cohesion of workable days. The larger the number of indices with most favourable impact, compared to other GCMs in the same GHG emissions scenario, the higher the rank of a given GCM. The larger the number of indices with least favourable impact, the lower the rank. In order to represent a wide range of uncertainty within available climate projections, as recommended by Knutti (2010), we selected the GCMs most frequently ranked as the GCMs with best or worst impact on workability within the 3 GHG emissions scenarios and 2 regions. For further simulations of workability, attainable yield, timeliness costs and total costs, under a wider range of farming conditions, these GCMs (IPCM4 best and NCCCSM worst) were combined with GHG emissions scenarios SRA2 and SRB1 as two extremes in ICCP4, with contrasting global GHG emissions (Nakicenovic and Swart, 2000).

2.2.4 Simulation settings - wider range historical & future

For simulation of workability and attainable yield under a wider range of farming conditions, we extended the number of simulations, including all soil groups, and a range of combinations of selected farm sizes with their integer multiples of working capacities, as listed in Table 2.

2.3 Description of the mechanization model

We simulated timeliness costs, machinery costs and total costs, in Norwegian kroner per hectare (NOK ha^{-1}), with the mechanization model described by Mangerud et al. (2017). The model calculates total costs as the sum of timeliness costs and machinery costs, based on farm management details and loss of attainable yield obtained from the output of the workability model (Figure 1). By comparing total costs of different mechanization, the model can be used as a decision tool to select least-cost mechanization and optimize profitability. In the mechanization model, working capacity (ha d^{-1}) is calculated, depending on daily available working hours for operation, implement width, operation speed, suitable tractor size and field shape. Working capacity, the net working capacity of machinery in the field, is based on the Danish model Drift 2004 (DJF, 2004) with an adjustment for less favourable Norwegian conditions in terms of topography, i.e. field shapes and sizes (Mangerud et al., 2017). Calculation of timeliness costs is based on farm size, soil type and the calculated working capacity. Total costs are calculated depending on depreciation, interest, fuel costs, manpower costs, cereal price, farm size and timeliness costs. The mechanization model, which is available at https://www.nibio.no/tjenester/maskinkostnader-og-laglighetskostnader-i-varonna, can also be used for simulations with farm-specific settings.

2.3.1 Regression equation input

For use in the mechanization model, we conducted region-wise regression analyses of attainable yield output from the workability model. We obtained one regression equation for each region and climate scenario, equivalent to regression equations in Riley (2016, table 4.9, page 44), each based on 137-197 simulations (Table A2). For each regression analysis, we included simulation combinations of working capacity and farm size with up to 10 % years with incomplete spring work, due to low working capacity at a given farm size. In cases of incomplete spring work, the attainable yield of the completed part of the farm was used. The predefined maximum limit of 10 % of years with incomplete spring fieldwork led to differences in numbers of simulations included per region and climate scenario (Table A2).

2.3.2 Simulation settings - farm management

In order to assess the economic consequences of loss of attainable yield, we simulated timeliness costs for three different combinations of working capacity and farm size on the two

Table 4: Description of machinery sets and purchase prices used in simulations of machinery costs and total costs.

	Operating speed (m s^{-1})	Size [a]			Price (NOK)		
		Small	Medium	Large	Small	Medium	Large
Tractor	-	60	119	179	457 297	934 273	1 411 249
Seedbed harrow	2.4	4.5	7	9	117 876	214 426	291 666
Seed drill	1.7	3	6	9	382 465	887 845	1 393 225
Roller	1.7	5	9	10.5	89 652	189 860	227 438
Machinery set – 1 tractor	-	3.4-3.5	5.1-5.3	5.5-5.8	1 047 290	2 226 404	3 323 578
Machinery set – 2 tractors	-	6.8-7.0	10.2-10.6	11.0-11.6	1 504 587	3 160 377	4 734 827

[a] Size in terms of tractor effect in kW (Tractor), implement width in m (Seedbed harrow, seed drill, roller) or working capacity of machinery set in ha d^{-1} (Machinery sets), the latter is increasing with increasing farm size (40-180 ha), due to adjustment for increasing effectiveness in the calculation by the mechanization model.

most abundant soil types (Table 1) in these regions, for Baseline climate and four climate scenarios in SE and C Norway (Table 2). The choice of farm sizes combined with working capacities was based on the maximum farm size simulated on clay/silt in C Norway resulting from the predefined limit of maximum 10% of years with incomplete spring fieldwork. Furthermore, as an example of how simulated attainable yield may influence long-term farm mechanization management in the future, we simulated machinery costs and total costs for Baseline and worst-case future climate scenario, both regions, the same soil types, a similar range of working capacities (Table 2) and the following farm management assumptions.

- Maximum attainable yield: 7000 kg ha^{-1} (SE Norway), 5950 kg ha^{-1} (C Norway) (Riley, 2016)
- Cereal price: 2.54 NOK (Mangerud et al., 2017)
- Working hours per day: 8 (Mangerud et al., 2017)
- Interest rate: 4 % (Mangerud et al., 2017)
- Fuel price: 10 NOK l^{-1} (Mangerud et al., 2017)
- Opportunity costs of labour: 260 NOK h^{-1} (Mangerud et al., 2017)
- Use of tractor beyond cereal production: 50 h $year^{-1}$ (Mangerud et al., 2017)

- Six different machinery sets: 1 or 2 of either small, medium or large tractors with corresponding implement (Table 4) (Mangerud et al., 2017)

Based on parameters and prices of the different machinery sets, the mechanization model also calculates machinery costs (Figure A2). The machinery costs are increasing with machinery size (small-medium-large, one-two tractors) and decreasing with farm size.

2.4 Statistical analyses of model outputs, and graphics

Statistical analyses were conducted with linear models in stats package in R (R Core Team, 2015), unless otherwise specified.

In order to express the output from the workability model, loss of attainable yield, in regression equations and use them as input to the mechanization model, we built mixed models with the following model terms. Separately for each region and climate scenario, loss of attainable yield was explained by soil type (as integer, because required by mechanization model), farm size, working capacity, their interactions and their second order terms. Stepwise model selection (forward, backward, both) based on Akaike's information criterion (AIC) (Akaike, 1973) resulted in the same best model structure as in Riley (2016) (Table A2).

In order to assess the relative importance of region, GCM and GHG emissions scenario, we also conducted an ANOVA analysis for the collective future attainable yield (transformed to $\mathrm{sqrt}(y)^{-1}$) and its inter-annual standard deviation (SD) (transformed to $\ln(y)$). Stepwise model selection (forward, backward, both) based on AIC resulted in almost the same model structure as in Riley (2016), minus interaction soiltype:capacity:farmsize in loss of attainable yield, plus region, GHG emissions scenario and GCM and their interactions in both responses. Post hoc tests (Tukey's HSD) were conducted with lsmeans package (Lenth, 2016). Afterwards, lsmeans values were back-transformed for graphical presentation.

In order to compare future attainable yield to Baseline attainable yield, we conducted ANOVA analysis on Baseline loss of attainable yield (transformed to $\mathrm{sqrt}(y)^{-1}$) and its inter-annual SD with soil type as factor, followed by stepwise model selection and post hoc test as previously described.

Plots were created in ggplot2 (Wickham, 2009), grid and gridExtra (Auguie and Antonov, 2016) packages.

3 Results

3.1 Climate change

In general, with the selected climate scenarios, we project a higher temperature, more precipitation and a larger variability in temperature and precipitation in early spring compared to Baseline climate (Table A3). A higher temperature is projected in all future climate scenarios and both regions. Temperature variability is projected to increase in March in SE Norway, whilst it is consistent in C Norway. The output from the weather generator also shows more precipitation in March in the future, except in climate scenario IPCM4/SRA2 in SE Norway. We found larger future variability in precipitation in C Norway, but inconsistent changes in SE Norway (4 larger and 4 smaller out of 8 climate scenarios). In all future climate scenarios and both regions, we found less snow in early spring and less global radiation in March. Potential evaporation in March was smaller in NCCCSM compared to Baseline in both regions.

3.2 Workability

Based on the projected climate changes, we simulated improved workability for spring fieldwork in early spring in SE Norway and either positive or negative changes in C Norway

Table 5: Indices for soil workability and yield potential based on historical climate (Baseline), and selected combinations of future (2046-2065) greenhouse gas emissions scenarios (SRB1, SRA2) and global climate models (IPCM4, NCCCSM) on clay/silt in South-eastern (SE) and Central (C) Norway, with workability threshold of 85% field capacity (pF2, -10 kPa), mean and standard deviation (SD) of 300 years. Fonts indicate workability change compared to baseline (at level of presented digits): *italic* = positive, **bold** = negative.

	SE Norway					C Norway				
	Baseline	SRB1		SRA2		Baseline	SRB1		SRA2	
		IPCM4	NCCCSM	IPCM4	NCCCSM		IPCM4	NCCCSM	IPCM4	NCCCSM
	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
Number of workable days per year										
March - June	43 (12)	*51* (12)	43 (**14**)	*51* (**13**)	*45* (**13**)	35 (13)	*43* (*12*)	**30** (**14**)	*40* (*12*)	**34** (13)
March	0.0 (0.0)	*0.1* (**0.6**)	0.0 (0.0)	*0.1* (**0.6**)	0.0 (**0.2**)	0.0 (0.0)	0.0 (**0.2**)	0.0 (**0.1**)	0.0 (**0.3**)	0.0 (**0.1**)
April	5 (5)	*10* (*7*)	*8* (**7**)	*11* (**8**)	*7* (**7**)	2 (4)	*4* (**6**)	2 (4)	*4* (**5**)	2 (4)
May	18 (8)	*20* (*7*)	**17** (8)	*19* (*7*)	**17** (*7*)	15 (8)	*19* (*7*)	**13** (8)	*17* (*7*)	**14** (8)
June	21 (5)	21 (5)	**18** (**6**)	**20** (5)	21 (5)	18 (7)	*20* (*6*)	**14** (**8**)	*20* (*6*)	18 (7)
Length [*]	6 (3)	*7* (3)	6 (3)	6 (3)	6 (3)	6 (3)	6 (*2*)	**5** (3)	6 (*2*)	**5** (*2*)
Within10 [*]	7 (3)	*8* (3)	7 (3)	7 (3)	7 (3)	7 (3)	7 (3)	**6** (3)	7 (3)	**6** (3)
Julian day number										
FirstDay [*]	117 (9)	*106* (**11**)	*110* (**10**)	*104* (**11**)	*112* (**12**)	123 (13)	*117* (*12*)	123 (**15**)	*118* (13)	**124** (**14**)
First3Days [*]	122 (13)	*110* (*12*)	*116* (13)	*109* (*12*)	*118* (**15**)	130 (16)	*122* (*14*)	**131** (**21**)	*124* (*15*)	**131** (**17**)
ΔFirst-10thDay	17 (10)	*16* (*9*)	17 (**11**)	*16* (*9*)	17 (**11**)	19 (13)	*16* (*9*)	**20** (**14**)	*18* (*11*)	19 (*11*)
Number of years out of 300 simulated years										
NoDay10 [*]	1 (-)	*0* (-)	1 (-)	*0* (-)	*0* (-)	7 (-)	*1* (-)	**21** (-)	*1* (-)	**10** (-)
NoDays [*]	0 (-)	0 (-)	0 (-)	0 (-)	0 (-)	0 (-)	0 (-)	**2** (-)	0 (-)	0 (-)
Incomplete [*]	4 (-)	*0* (-)	*1* (-)	*0* (-)	*2* (-)	6 (-)	*0* (-)	**16** (-)	*1* (-)	**7** (-)
Relative attainable yield (%)										
AttYield [*]	84 (12)	*91* (*6*)	*89* (*8*)	*91* (*6*)	*86* (*11*)	81 (13)	*86* (*9*)	**78** (**19**)	*84* (*11*)	**78** (**16**)

[*] Explanations in Table 3.

compared to historical conditions (Table 5). The number of workable days in the entire spring fieldwork period (March-June) was larger and more variable in the future scenarios in SE Norway. In C Norway, the number of workable days was larger and less variable in IPCM4, but smaller and more variable in NCCCSM, compared to Baseline. In the same manner, the variability in number of workable days in March and for IPCM4 in April was larger in C Norway.

The duration of workable spells was shorter in all future climate scenarios compared to Baseline, except in the SRB1/IPCM4 climate scenario. On average, the first workable day was earlier and more variable in the future in SE Norway. In C Norway, it was earlier (IPCM4) or later (NCCCSM) and more variable, except in the SRB1/IPCM4 climate scenario. Combined measures of earliness and cohesion (Within10, First3Days, ΔFirst-10thDay) improved in SE Norway, except more variability in SRA2. In C Norway, they improved in IPCM4, but worsened in NCCCSM. Fewer years were extremely negative for workability (NoDay10, NoDays, Incomplete) in all climate scenarios in SE Norway and in IPCM4 in C Norway, whilst there was an increase in extremely negative years in NCCCSM in C Norway.

3.3 Attainable yield

In general, the analysis of the combined data of all future loss of attainable yield revealed importance of factors in increasing order: GHG emissions scenario, GCM, region (Figure 2). This ranking was based on back transformed lsmeans-values and contrast p-values. There was no significant difference between losses of attainable yield in different GHG emissions scenarios in IPCM4 in SE Norway, neither in NCCCSM in C Norway. Furthermore, there was a larger difference between losses in different GCMs in SRA2 than in SRB1 in SE Norway, and a larger difference between losses in different GCMs in SRB1 than in SRA2 in

C Norway. For all interactions, losses were smaller in SE than in C Norway, smaller in SRB1 than in SRA2 (except in IPCM4 in SE Norway), and smaller in IPCM4 than in NCCCSM.

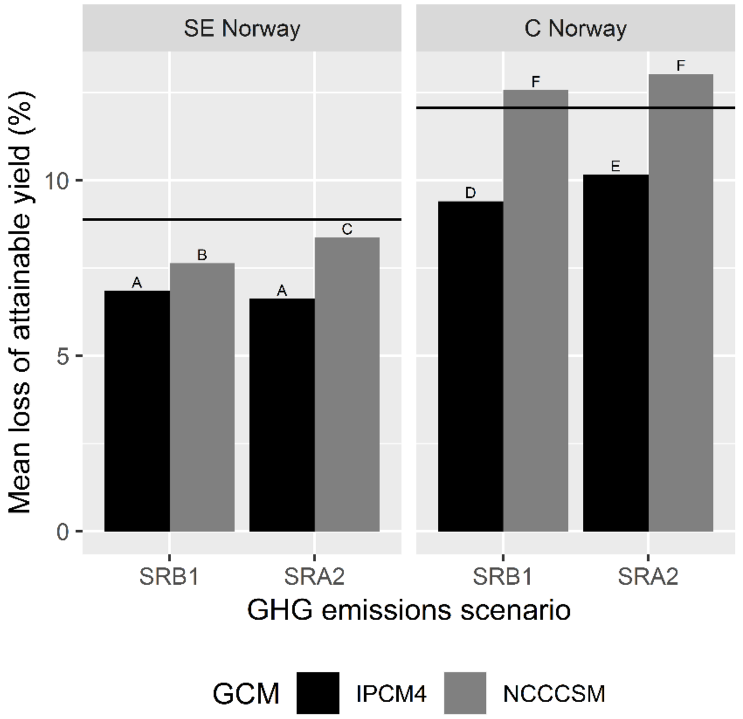

Figure 2: Interaction effect of region (SE, C Norway), greenhouse gas emissions scenario (SRB1, SRA2) and global climate model (IPCM4, NCCCSM) on loss of attainable yield (%) in South-eastern (SE) and Central (C) Norway; represents mean of 300 simulated years for the period of 2046-2065, averaged over soil types, farm sizes and working capacities (Table 2); back-transformed lsmeans values; horizontal lines indicating Baseline loss of attainable yield; different letters indicating significant difference in Tukey comparison.

As for loss of attainable yield, analysis of its inter-annual variability (SD) led to a ranking of factors with importance increasing with order: GHG emissions scenarios, GCMs, regions (Figure 3). Under the assumed conditions, we found a larger difference between SD of losses in different GCMs in C than in SE Norway, and a larger difference between SD of losses in different GCMs in SRA2 than in SRB1 in SE Norway, whilst we found a smaller difference in C Norway. For all interactions, SD was smaller in SE than in C Norway, there was no difference in SD between SRB1 and SRA2 in C Norway, and there was a smaller SD in IPCM4 than in NCCCSM.

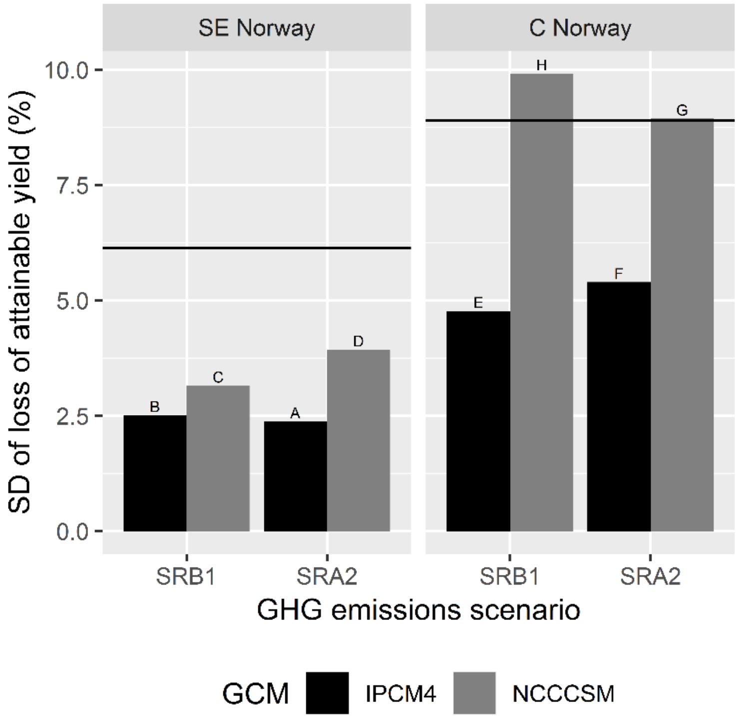

Figure 3: Interaction effect of region (SE, C Norway), greenhouse gas emissions scenario (SRB1, SRA2) and global climate model (IPCM4, NCCCSM) on standard deviation (SD) of loss of attainable yield (%) in South-eastern (SE) and Central (C) Norway; represents variability within 300 simulated years for the period of 2046-2065, averaged over soil types, farm sizes and working capacities (Table 2); back-transformed lsmeans values; horizontal lines indicating Baseline SD of loss of attainable yield; different letters indicating significant difference in Tukey comparison.

When balanced combinations of working capacity and farm size were selected, there were relatively small differences in loss of attainable yield between those combinations of working capacity and farm size than between GCMs, regions or soil types, except on clay/silt in C Norway (Figure 4).

In SE Norway, loss of attainable yield in worst-case future climate scenario was smaller than in Baseline climate conditions, whilst the opposite was the case for C Norway (Figure 5). Loss of attainable yield is increasing with increasing farm size for capacities of 5 and 10 ha per day, whilst they are decreasing for a working capacity of 20 ha.

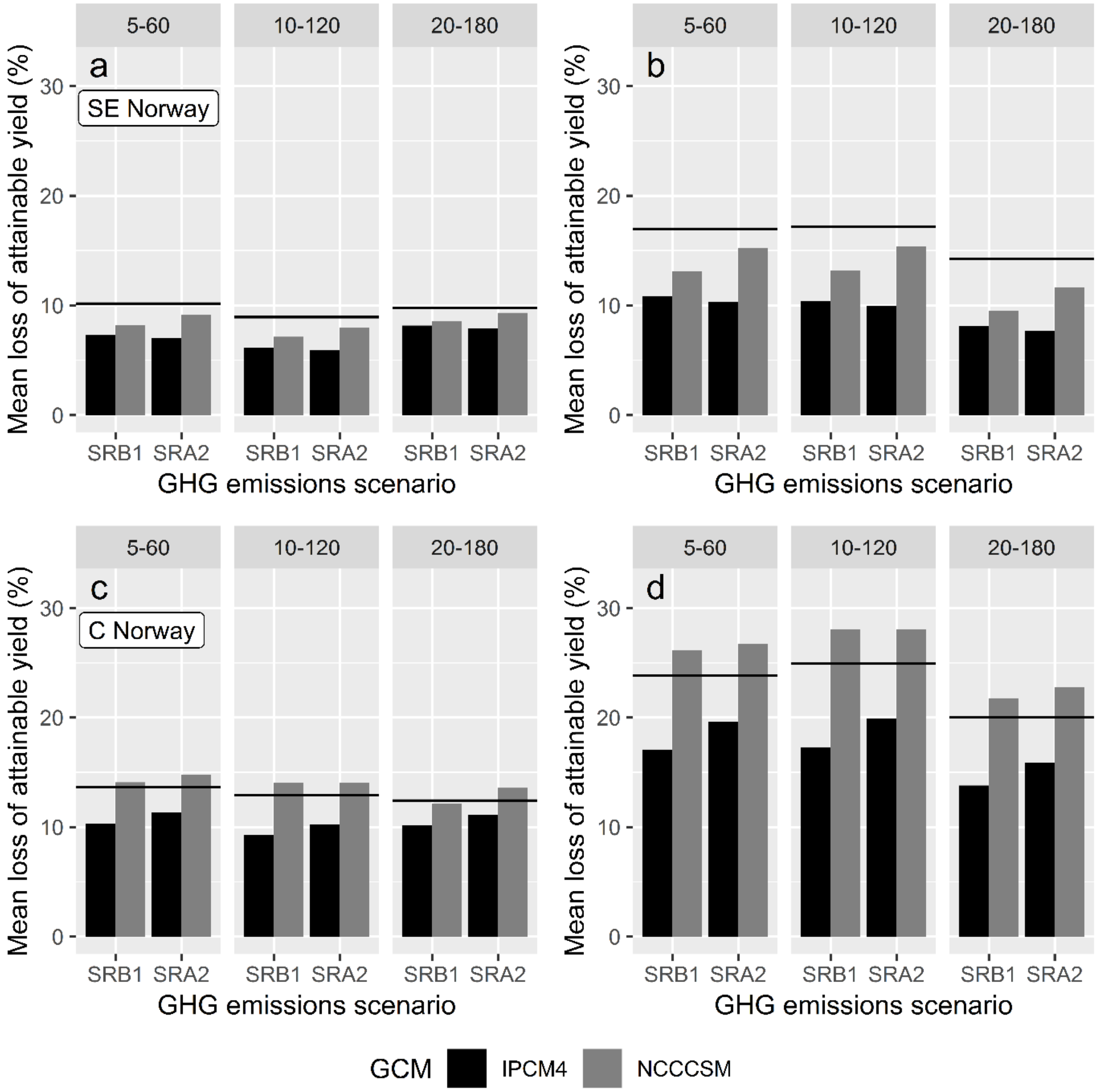

Figure 4: Predicted loss of attainable yield for three different examples of working capacity & farm size (5 ha d^{-1} & 60 ha, 10 ha d^{-1} & 120 ha, 20 ha d^{-1} & 180 ha) on loamy sand (a, c) and clay/silt (b, d) in different greenhouse gas emissions scenarios (SRB1, SRA2) and global climate models (IPCM4, NCCCSM) for the period of 2046-2065 in South-eastern (SE) and Central (C) Norway, horizontal lines indicating Baseline predictions.

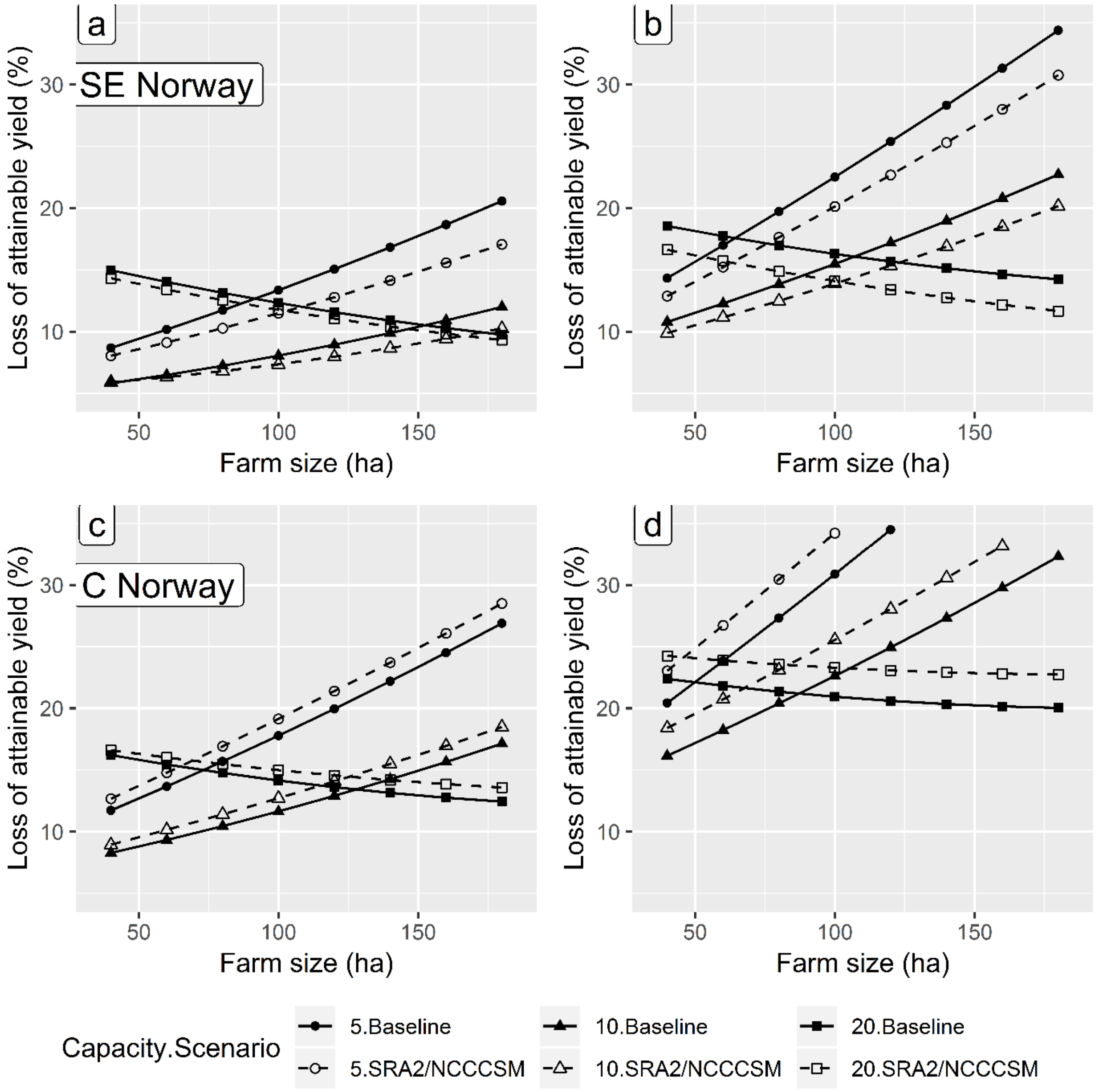

Figure 5: Predicted loss of attainable yield for different working capacities (5, 10, and 20 ha d^{-1}) with increasing farm size for historical (Baseline) and worst-case future (2046-2065) climate (greenhouse gas emissions scenario SRA2/ global climate model NCCCSM) on loamy sand (a, c) and clay/silt (b, d) in South-eastern (SE) and Central (C) Norway.

3.4 Farm mechanization management

With the predefined maximum limit of 10 % years with incomplete spring fieldwork in simulations of attainable yield, we observed varying maximum farm size that could be included in simulations of a given working capacity. In SE Norway, the maximum simulated farm size increased under future climate scenarios compared to Baseline for all soil types and

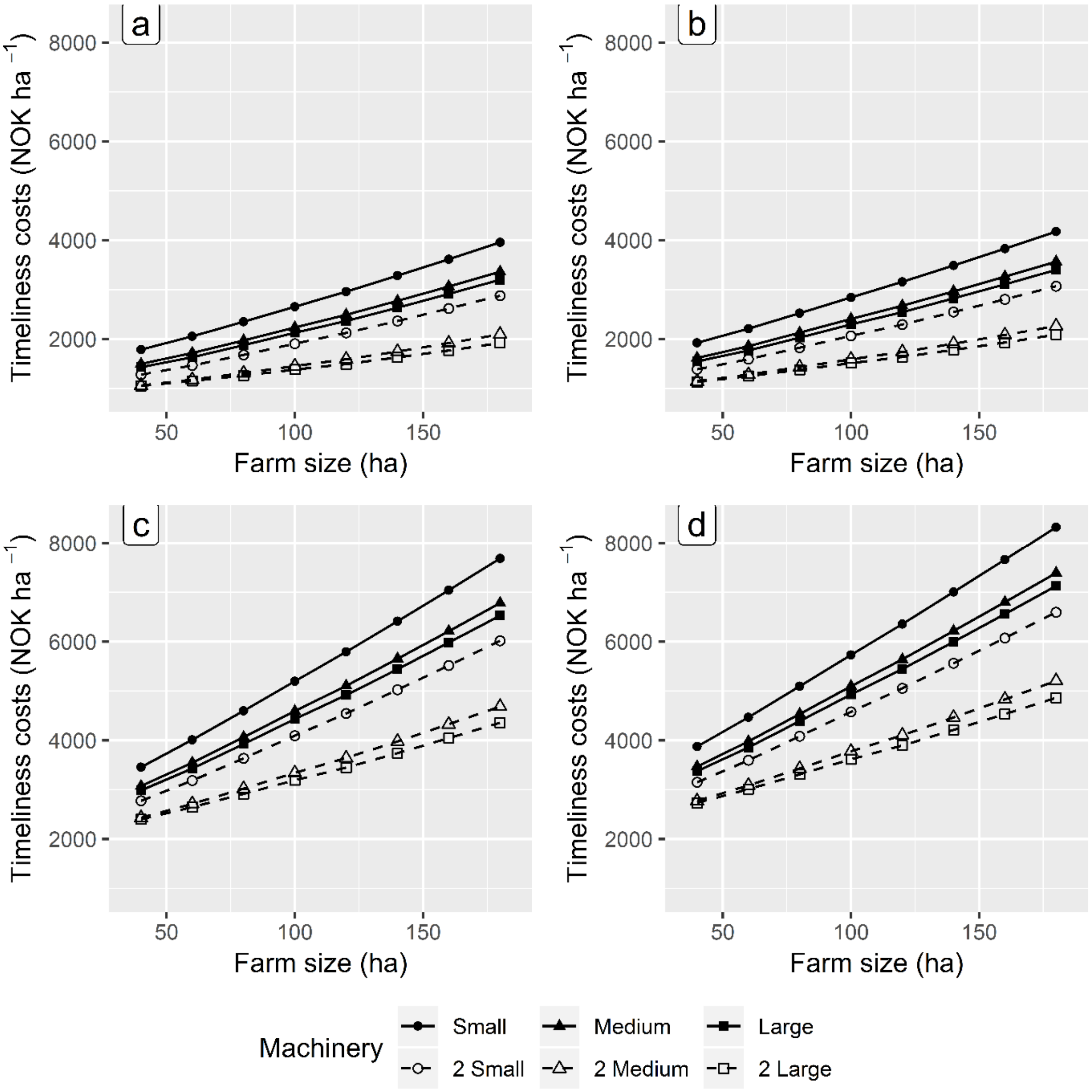

Figure 6: Simulated timeliness costs depending on farm size and machinery sets of 1 or 2 small, medium or large tractors and corresponding implement for Baseline (a, c) and worst-case future (2046-2065) climate SRA2/NCCCSM (b, d) on loamy sand (a, b) and clay/silt (c, d) in Central Norway.

all working capacities. In C Norway, it increased under IPCM, but decreased under NCCCSM, the latter more strongly and up to larger capacities under SRB1 GHG emissions scenario than under SRB2 GHG emissions scenario (data not shown). The varying maximum simulated farm size caused a varying number of simulations included (Table A2).

3.4.1 Timeliness costs

In addition to region, timeliness costs were strongly influenced by climate scenario, soil type, farm size and working capacities (Figure 6). They increased with increasing farm size and decreased with increasing machinery size. On lighter soils, timeliness costs were smaller than on heavier soils. In C Norway, they were larger than in SE Norway. In SE Norway, timeliness costs were smaller for worst-case future climate scenario (SRA2/NCCCSM) than for Baseline (data not shown). In C Norway, they were larger for the worst-case scenario than for Baseline (Figure 6).

3.4.2 Total costs

Generally, total costs increased with increasing farm size for smaller machinery sets, whilst the opposite was the case for larger machinery sets (Figure 7).

Furthermore, total costs were smaller for lighter soil than for heavier soil, and smaller for SE than for C Norway. In SE Norway, total costs were slightly smaller for worst-case future climate scenario (SRA2/NCCCSM) than for Baseline (data not shown). Machinery set “Small” was the optimum machinery set (least total costs) from 40 ha up to slightly larger farm size in worst-case future climate than for Baseline. Machinery set “2 Medium” was optimum for larger farm size up to 180 ha. In C Norway, total costs were larger in worst-case future climate scenario than in Baseline (Figure 7). Machinery set “Small” was optimum from 40 ha up to slightly smaller farm size in worst-case future climate than for Baseline. Machinery set “2 Medium” was optimum for larger farm size up to 180 ha.

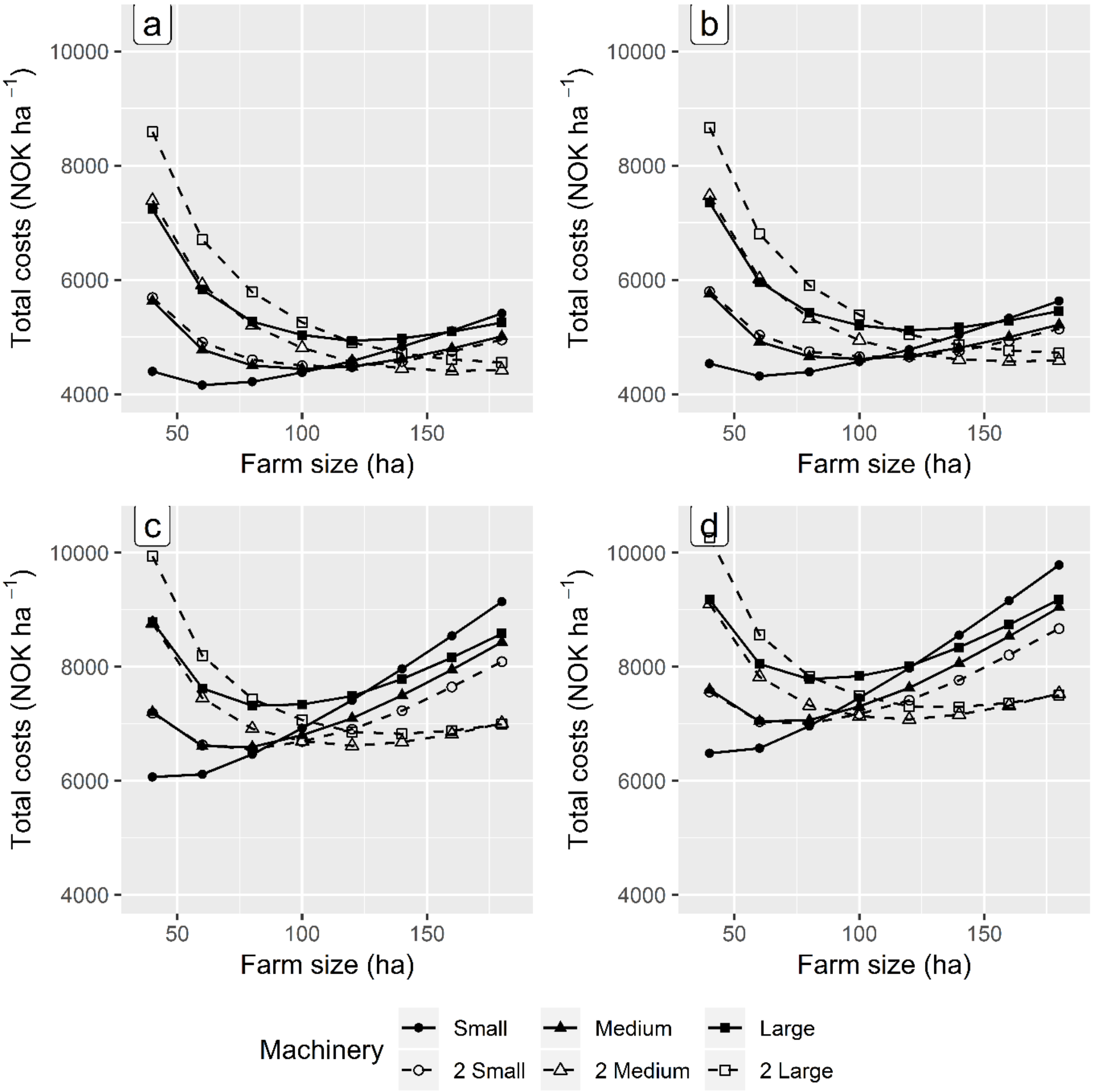

Figure 7: Simulated total costs depending on farm size and machinery sets of 1 or 2 small, medium or large tractors and corresponding implement for Baseline (a, c) and worst-case future (2046-2065) climate SRA2/NCCCSM (b, d) on loamy sand (a, b) and clay/silt (c, d) in C Norway.

4 Discussion

4.1. Climate change

Our simulated climate change in the near future in Norway (Table A3) fits in very well with what has been used in previous studies of climate change impact on cereal production. The increase in temperature and precipitation is in line with Trnka et al. (2011), Persson and

Kværnø (2017), Persson et al. (2015), Persson and Höglind (2014), and Finnish studies (Rötter et al., 2013, 2012, 2011).

Warmer conditions in spring would mean an earlier onset of the thermal growing season (Peltonen-Sainio et al., 2009b), but an increase in precipitation in early spring, or interaction between precipitation and other climate factors, may prohibit earlier spring fieldwork and sowing, due to workability restrictions (van Oort et al., 2012a, b). Therefore, we need to distinguish between the thermal growing season, as the growing period for wild and perennial plants, only limited by temperature (Carter, 1998; Walther and Linderholm, 2006), and the crop growing season, during which annual crops can be cultivated. That means also to differentiate between the phenological adaptation of wild plants to climate change, in terms of earlier onset of spring growth, and changes in management practices for annual crops by farmers (Menzel et al., 2006). Feasibility of management practices may vary strongly between and within regions due to variability in present and future climate and soil type.

4.2. Workability

The improved future workability in SE Norway, and in some climate scenarios also for C Norway, is in line with Trnka et al. (2011), who simulated an increase in number of suitable days for sowing in March and April for the same climatic region (NEM was represented by Ås/ Norway, and Ultuna/ Sweden).

Our impaired workability in the worst-case climate scenarios in C Norway is in line with the discussion by Falloon and Betts (2010) and with a simulated decrease in workable days in Eitzinger et al. (2013) in some parts of C/ SE Europe. The decrease in the number of workable days in scenario SRB1/NCCCSM is similar to what was found by Tomasek et al. (2017) for Illinois, USA, under A2 GHG emissions scenario.

A possible explanation for the discrepancy between fewer workable days found in our study and the increase in number of workable days found by Trnka et al. (2011) for C Norway may have been the workability threshold of 70 % available water capacity (AWC) or the depth of 0-10 cm in the latter study. A given percentage of AWC corresponds to a higher volumetric water content than the same percentage of FC, but the difference is highly dependent on soil type, i.e. the amount of non-available water in the soil, making a direct comparison of the workability thresholds in the two studies difficult. In the same manner, applying the workability threshold to a smaller depth corresponds to a higher water content, but cannot be compared directly to our workability threshold at a depth of 0-20 cm.

Even though the most common reference to express workability is FC (Rounsevell, 1993), the matric potential for laboratory measurements that is associated with FC differs between countries (Nemes et al., 2011), and is often not specified. The lacking specifications of FC further complicate comparisons between studies, like comparisons with Rounsevell (1993) and Cooper et al. (1997) in Trnka et al. (2011) and Eitzinger et al. (2013).

In addition, Trnka et al. (2011) selected GCMs to represent the full range of a larger ensemble of GCMs based on their projected temperature and precipitation. Nevertheless, a selection of GCMs to represent the full range of projected temperature, precipitation or yield potential does not necessarily represent the full range of workability, or any given (agro-climatic) index. In our study, we recognized that GCMs with low precipitation and high temperature not necessarily were those that were most favourable in terms of workability (Data not shown) out of the climate scenarios explored in our test case (Table 2). In general, we observed a tendency of more precipitation to be unfavourable for workability and vice versa, in line with Eitzinger et al. (2013) in C/SE Europe. However, this tendency was not consistent, probably because temperature, global radiation and potential evaporation do interfere with precipitation. In C Norway, the most favourable conditions for future workability was represented by climate scenario SRB1/IPCM4, which gave neither the lowest precipitation in March nor the highest temperature compared to other combinations of GCMs within the same GHG emissions scenario. Thus, one needs to consider that a given index may be influenced by interactions between different weather variables or between weather and agricultural management. Thus, ideally, individual selections should be made for individual indices.

The larger inter-annual variability in number and earliness of workable days in early spring in most of our future climate scenarios, and the large increase in frequency of extremely unfavourable years, in terms of workability, in the worst-case climate scenarios are in contrast to Trnka et al. (2011), who reported no future change in inter-annual variability in number of sowing days in spring in Norway. However, our results are in line with the generally reported increase in future climate variability (Field et al., 2012).

4.3. Attainable yield

4.3.1. Mean attainable yield

Our attainable yield results should not be directly compared with results from process-based models, which include a wide range of factors contributing to yield formation throughout the crop growing season, but often simplify or neglect impact of spring fieldwork conditions. Riley’s (2016) empirical-statistical model, used here, considers loss of (timeliness-limited) attainable yield, whilst other potential yield loss factors are ignored (additional factors we did not consider are listed in Table A4).

It has been discussed that empirical-statistical models cannot reliably predict future conditions outside their calibration range (Rötter et al., 2011). However, Riley’s (2016) approach is based on controlled field experiments on different soil types, including those considered in this study, under a wide range of soil water conditions during seedbed preparation in spring.

Nonetheless, presented loss of attainable yield cannot be used to predict future loss of attainable yield in Norwegian cereal production. The results presented here are averages of equal distributions of different farm sizes and mechanization for the two most relevant soil types and regions, and, thus, do not represent regional or national distribution of these factors on Norwegian cereal land.

Our decreasing loss of attainable yield with increasing working capacity is in line with Smith (1972). In addition, our results show that with very large working capacity, in relation to farm size, spring fieldwork will be completed before optimum sowing date, and a large percentage of the land will be worked before the soil water content reaches optimum (66 vol % FC in Riley, 2016). With increasing farm size, a larger percentage of the land will be closer to optimum during spring fieldwork.

Presented loss of attainable yield is based on a balanced relationship between working capacity and farm size. This balance is also revealed by relatively small differences in loss of attainable yield between the selected combinations of working capacity and farm size, in contrast to large differences between GCMs, regions and soil types in Figure 4. It can be discussed whether maximum 10 % years with incomplete spring fieldwork is a good balance, but the important point is that this balance is equal in historical and future simulations. If we used the same number of combinations of farm size and working capacity, for all climate scenarios, simulated future loss of attainable yield would have been even larger than presented, in unfavourable scenarios in C Norway; and SRB1/NCCCSM would probably have generated a larger loss of attainable yield than SRA2/NCCCSM in C Norway.

Similarly, a different choice of workability threshold would have generated higher loss of attainable yield in our study. Our choice of workability threshold of 85 vol % FC is in the conservative end of the realistic range (Riley, 2016). Workability threshold at higher soil water content, would lead to earlier sowing and a larger negative effect on loss of attainable yield (Riley, 2016), depending on working capacity.

4.3.2. Variability in attainable yield

Earlier papers have discussed that climate variability is closely related to variability in yield potential (Brown and Castellazzi, 2015; Katz and Brown, 1992; Peltonen-Sainio et al., 2010; Porter and Semenov 2005; Semenov and Porter, 1995; Sexton and Harris 2015) and may be even more important in assessments of future yield potential than averages. However, our larger inter-annual variability in loss of attainable yield in SRB1/NCCCSM than in SRA2/NCCCSM in C Norway is unexpected. As SRA2 represents the upper extreme of global GHG emissions in ICCP4 (Nakicenovic and Swart, 2000) and thus the largest climate change, we expected also more variation in attainable yield from SRA2 than from SRB1, in line with the increase in loss of attainable yield. However, the reported changes in variability in loss of attainable yield resembled the pattern of the maximum farm size included in simulations, which resulted from the predefined limit of 10 % of years with incomplete spring fieldwork.

4.4. Farm mechanization management

Timeliness costs are decreasing with increasing mechanization, in line with de Toro and Hansson (2004), van Wijk and Buitendijk (1988), and Witney (1983). De Toro and Hansson (2004) also found that total costs are increasing with increasing mechanization, in contrast to our results, which reveal a more complex interaction with farm size.

Our results indicate that in SE Norway and under favourable scenarios in C Norway, the farmer could do with slightly smaller working capacity, while slightly larger working capacity would be needed under unfavourable scenarios in C Norway. In the same way, changed maximum farm size simulated can also be interpreted as a change in maximum manageable farm size with a given working capacity and a given attitude towards risk.

Only based on attainable yield, the impact of climate change on farm mechanization management would be small, in the studied conditions and regions. However, there are several reasons why this effect should be recognized. With slightly lower total costs in SE Norway and potentially slightly larger total costs in C Norway, the relationship between total costs in SE and C Norway will change. If the difference is large enough or if it continues to develop, one may expect changes in land use, i.e. regional distribution of spring cereal production, in Norway in the future. Agricultural land in C Norway may be regarded as unsuitable for spring cereals in the future.

Furthermore, as discussed for workability, the negative effect of climate change on farm management in the worst-case scenarios in C Norway would be more distinct with a less strict workability threshold, which probably is common among farmers and will be even more so in the future.

4.5. Uncertainties

Many authors have discussed different sources of uncertainty in climate impact studies (Asseng et al., 2013; Olesen et al., 2007). In our study, uncertainty originates from GHG emissions scenarios, GCMs and different factors in workability and mechanization models. The observed uncertainty in workability is in line with descriptions in Nakicenovic and Swart (2000). Uncertainty in attainable yield in different regions and GCMs is in line with our selection of GCMs based on our test case. These uncertainties are due to different locations' different sensitivity to precipitation and temperature changes, as described in Asseng et al.

(2013) and Olesen et al. (2007). In addition, uncertainty varies with soil and management (Asseng et al., 2013).

The relative uncertainty in different variables of our study is mostly in line with earlier literature. The least uncertainty seems to originate from GHG emissions scenarios, more from GCMs, even more from regions and the most from soil types. This is in line with uncertainty in simulated workability in Cooper et al. (1997) and uncertainty in simulated cereal yields in Asseng et al. (2013), Olesen et al. (2007), Hoffmann et al. (2016), and Rötter et al. (2012), but in contrast to Skjelvåg (1998), who concluded that there is larger variation in yield potential between climatic regions than between soil types. However, in all of the mentioned cereal yield studies, yield potential refers to yield formation throughout the whole crop growing season.

In any case, the purpose of climate impact studies is not to present accurate predictions of future yield outcome, but show potential influence of climate change on different aspects of crop production, in our case the attainable yield.

4.6. Implications and applications

4.6.1 Workability threshold

Our study shows that workability is a potential future constraint to spring fieldwork, sowing date and attainable yield in regions with high soil water content in spring. Whether and how this constraint should be considered in assessment of climate change impact on annual crops, is depending on the purpose of the research.

If the focus is on the spring fieldwork period and the purpose is to represent farmers' behaviour, as well as within-farm variation in workability, sowing dates, and its consequences on attainable yield, the workability threshold should be set at relatively high soil water content. The threshold then represents the start, i.e. the wet end, of a realistic sowing period, because, in practice, the farmer does not manage to complete spring fieldwork within one day. In this approach, if one assumes profitability, one accepts some loss of attainable yield due to topsoil compaction during early fieldwork in order to avoid larger losses due to delayed sowing towards the end of the fieldwork period, as summarized in Riley (2016).

If the focus is on growing conditions throughout the season and the purpose is to predict mean yield potential based on simplified assumptions about management practices, the workability threshold should be set at relatively low soil water content, but not as low as would be optimum. The threshold then represents the mean sowing date, or economically optimum sowing day, of a realistic sowing period, as if the farmer completed spring fieldwork within one day. In this approach, one still does not totally avoid topsoil compaction, because that would not be feasible in practice and should not be assumed. The consequential loss in attainable yield must be considered in such calculations.

4.6.2 Assessments of climate impact on future attainable yield

The two approaches serve different purposes, but neither of them represent the whole picture, therefore they should complement each other. That is why our results should be related to the optimum sowing day approach. In a combination of the two approaches, the outcome of projected future attainable yield may be different. In regions with high soil water content in spring, due to unfavourable climatic or soil type characteristics, sowing dates may be delayed, in spite of a longer thermal growing season. Delayed sowing leads to higher temperatures during early cereal growth stages and may increase the rate of phenological development (Eitzinger et al., 2013). A cascade of shifts throughout the rest of the crop growing season may increase the risk of extremely high temperatures or drought at more critical growth stages, which have been projected or discussed by many studies (Eitzinger et al., 2013; Hakala et al., 2012; Ludwig and Asseng, 2010; Rötter et al., 2013, 2012, 2011; Semenov and

Shewry, 2011). That means that in addition to the loss of (timeliness-limited) attainable yield presented in this study, further losses of yield potential may be expected, due to climatic constraints to yield formation throughout the crop growing season and a potentially shorter crop growing season terminated by drought.

4.6.3 Further research

For further research, it would be interesting to explore the relative importance of different climate indices for workability, and the relative importance of different workability indices for attainable yield, equivalent to multiple regression analysis of indices in Rötter et al. (2013).

It would also be interesting to relate the window of opportunity, as we define it, to the range of soil water content for tillage (Obour et al., 2018), and explore whether results from a water content window can be directly applied to a time window.

In order to cover potential adaptation of mechanization to future climate change and its iterative effect on soil compaction, further research may include subsoil compaction and machinery related factors like traffic intensity, wheel track area, wheel load, wheel equipment, tyre inflation pressure, operating speed, traction, slippage, similar to calculations in Lorenz et al. (2016).

Even though a combination of the two approaches of (timeliness-limited) attainable yield and (growing season) yield potential may seem unachievable at this point, it might improve future research. A combined approach should consider climate change impact on spring workability, crop growth during the season, and harvest conditions. Considering all of these may result in different future changes in yield potential and profitability than our approach and allow better assessment of the effect of climate change on profitability and adaptations in farm mechanization management. If a combined approach modifies cereal-growing conditions during the crop growing season differently in C and SE Norway, loss of timeliness costs may be modified and either erase or enlarge the discussed regional differences in future distribution of spring cereal production in Norway.

4.7. Conclusions

Climate change may have positive or negative effects on spring workability, fieldwork and profitability of spring cereals in Norway, depending on region and climate scenario. We anticipate that negative effects may also be expected in other northern cold-temperate regions with high soil water content in spring, if (timeliness-limited) attainable yield is studied. Furthermore, the partially negative effects on attainable yield in this study indicate that simulations of phenological development during the whole crop growing season need to consider workability and potential timeliness costs, especially in regions that expect an increase in spring precipitation. This would also allow a more realistic assessment of adaptation possibilities to climate change, in order to avoid further loss of attainable yield.

Our results also show that workability comprises the number of workable days within a certain time window, as well as the earliness and cohesion of those workable days. With increasing climate variability in the future, the distribution of the workable days will become more important.

In need of a certain time window to complete their spring fieldwork, farmers might adapt to impaired spring workability by relaxing their subjective workability threshold and work the soil at higher water content under worst-case conditions. The consequence would be a larger loss of attainable yield and less profitability in the future.

Acknowledgements

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Appendix

Table A1: Maximum amount of precipitation on a given day to be defined workable, depending on soil type group [a] and number of previous rainy days (precipitation > 1.5 mm).

	Number of previous rainy days			
Soil type [a]	0	1	2	3
1	6	5	4	3
2	5	4	3	2
3	4	3	2	1
4	3	2	1	0

[a] Description of soil type grouping in Table 1.

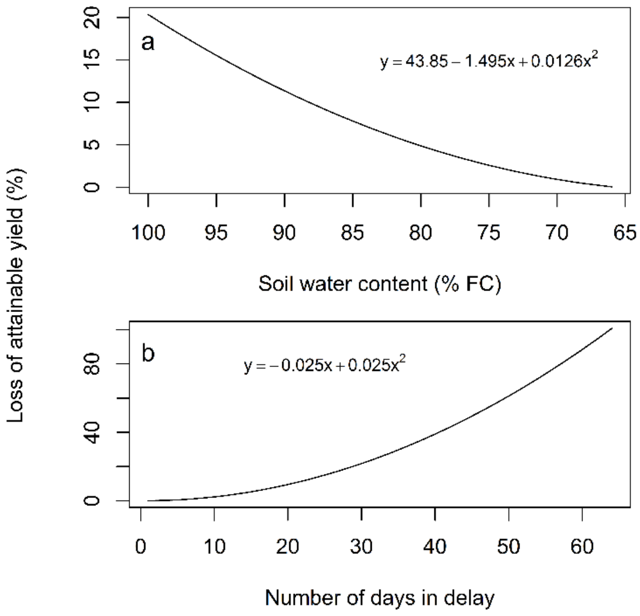

Figure A1: Functions for calculation of loss of attainable yield affected by soil water content in % of field capacity (FC, pF2, -10 kPa) in 0-20 cm soil depth during spring fieldwork (a), and number of days after optimum sowing date April 20 (b), used in the workability model (Riley, 2016).

Table A2: Regression coefficients of model terms used in the mechanization model to describe attainable yield in Baseline, and selected combinations of future (2046-2065) greenhouse gas emissions scenarios (SRB1, SRA2) and global climate models (IPCM4, NCCCSM), in South-eastern (SE) and Central (C) Norway.

	SE Norway					C Norway				
	Baseline	SRB1		SRA2		Baseline	SRB1		SRA2	
		IPCM4	NCCCSM	IPCM4	NCCCSM		IPCM4	NCCCSM	IPCM4	NCCCSM
Intercept	9.12E+01	9.13E+01	9.11E+01	9.16E+01	9.12E+01	9.12E+01	9.15E+01	9.39E+01	9.12E+01	9.16E+01
Soiltype	-1.66E+00	-3.94E-01	-6.24E-01	-3.57E-01	-1.15E+00	-2.89E+00	-1.70E+00	-3.77E+00	-2.14E+00	-3.61E+00
Capacity	1.73E+00	1.14E+00	1.23E+00	9.89E-01	1.43E+00	1.81E+00	1.45E+00	1.30E+00	1.71E+00	1.90E+00
Farmsize	-3.11E-02	1.33E-02	2.01E-02	2.03E-02	5.54E-03	-3.91E-02	-1.37E-02	-2.43E-02	-1.85E-02	-4.19E-02
(Capacity)^2	-9.92E-02	-7.27E-02	-7.50E-02	-6.43E-02	-8.47E-02	-9.87E-02	-8.28E-02	-7.04E-02	-9.51E-02	-1.01E-01
(Farmsize)^2	-8.58E-05	-9.21E-05	-1.06E-04	-9.10E-05	-8.63E-05	-9.21E-05	-7.05E-05	-8.68E-05	-6.46E-05	-6.61E-05
Soiltype:Farmsize	-3.78E-02	-3.12E-02	-4.09E-02	-3.00E-02	-4.22E-02	-4.71E-02	-3.74E-02	-4.83E-02	-4.39E-02	-5.08E-02
Capacity:Farmsize	4.69E-03	2.07E-03	1.86E-03	1.53E-03	2.47E-03	4.82E-03	3.03E-03	3.57E-03	3.28E-03	4.44E-03
SoilT:Cap:FarmS	1.73E-03	1.67E-03	2.08E-03	1.63E-03	2.10E-03	2.10E-03	1.84E-03	2.12E-03	2.13E-03	2.27E-03
R^2_{adj} *	0.92	0.81	0.88	0.80	0.91	0.96	0.95	0.96	0.94	0.96
ResStError *	1.33	1.35	1.25	1.27	1.33	1.18	1.09	1.00	1.28	1.20
sd *	4.86	3.08	3.59	2.82	4.30	5.86	4.62	5.26	5.34	6.34
DF *	174	188	179	188	179	159	176	128	173	153
n *	183	197	188	197	188	168	185	137	182	162

* R^2_{adj} = adjusted R-squared; ResStError = residual standard error; sd = standard deviation; DF = degrees of freedom; n = number of simulations à 300 years

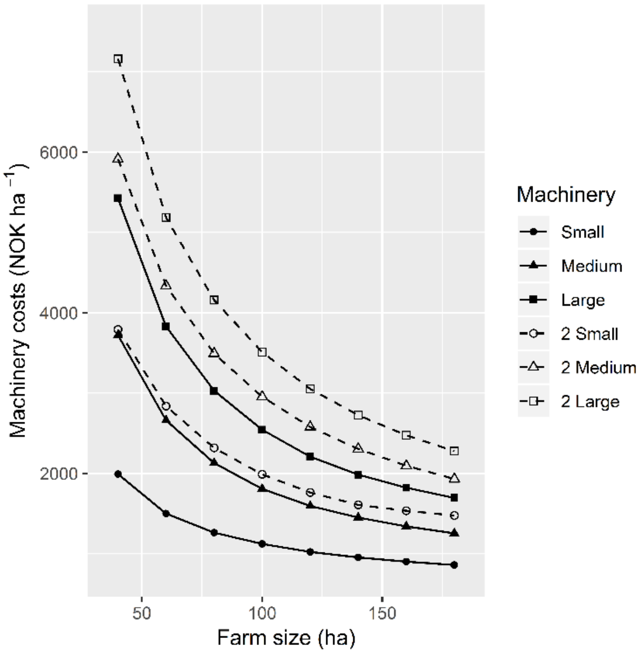

Figure A2: Simulated machinery costs depending on farm size and machinery sets of 1 or 2 small, medium or large tractors and corresponding implement, independent from climate scenario and region.

Table A3: Climate indices based on historical climate (Baseline), and selected combinations of future (2046-2065) greenhouse gas emissions scenarios (SRB1, SRA2) and global climate models (IPCM4, NCCCSM) on clay/silt in South-eastern (SE) and Central (C) Norway, with workability threshold of 85% FC, mean and standard deviation (SD) of 300 years. Fonts indicate favourability of climate change for workability, compared to baseline (at level of presented digits): *italic* = positive, **bold** = negative.

	SE Norway					C Norway				
	Baseline	SRB1		SRA2		Baseline	SRB1		SRA2	
		IPCM4	NCCCSM	IPCM4	NCCCSM		IPCM4	NCCCSM	IPCM4	NCCCSM
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Mean temperature (°C)										
March	**-**1.0 (0.7)	*2.2* (**0.8**)	*1.2* (**0.8**)	*2.4* (**0.8**)	*1.9* (0.7)	0.7 (0.7)	*3.8* (0.7)	*3.3* (0.7)	*3.9* (0.7)	*4.1* (0.7)
April	4.0 (0.5)	*7.6* (0.5)	*5.9* (0.5)	*7.7* (0.5)	*6.5* (0.5)	4.3 (0.6)	*7.7* (0.6)	*6.6* (0.6)	*7.9* (0.6)	*7.2* (0.6)
May	10.2 (0.5)	*13.7* (0.5)	*11.8* (0.5)	*14.1* (0.5)	*12.6* (0.5)	9.4 (0.7)	*13.3* (0.7)	*11.2* (0.7)	*13.7* (*0.6*)	*11.8* (0.7)
June	14.5 (0.6)	*17.7* (0.6)	*15.9* (0.6)	*18.3* (0.6)	*17.0* (0.6)	12.8 (0.7)	*16.5* (0.7)	*14.3* (0.7)	*17.2* (0.7)	*15.3* (0.7)
Precipitation sum (mm)										
March	43.1 (25.6)	**44.4** (**25.7**)	**43.5** (**26.3**)	*40.0* (*24.7*)	**48.0** (**29.4**)	54.5 (26.6)	**59.6** (**27.0**)	**57.3** (**27.8**)	**58.7** (**29.0**)	**60.7** (**29.8**)
April	37.9 (22.5)	**42.4** (**23.7**)	*35.7* (*20.2*)	*37.5* (*20.4*)	**39.1** (*21.9*)	49.9 (21.8)	**50.7** (**25.6**)	**50.9** (**22.9**)	**53.5** (**24.2**)	**54.1** (**24.7**)
May	56.1 (28.7)	**57.7** (**29.6**)	**61.3** (**34.2**)	**61.8** (**31.0**)	**59.3** (*28.6*)	56.8 (29.1)	*51.3* (*23.8*)	**59.8** (**29.7**)	**58.3** (*28.2*)	**58.7** (*28.3*)
June	67.0 (34.3)	**71.4** (**36.8**)	**80.9** (**41.6**)	**77.3** (**38.5**)	**68.4** (**34.7**)	63.8 (29.0)	**66.7** (*28.6*)	**75.4** (**31.0**)	**68.9** (**30.5**)	**64.5** (*27.0*)
Mean snow depth (cm)										
1 March	40.5 (17.2)	*6.0* (*9.6*)	*8.4* (*11.2*)	*3.2* (*6.3*)	*6.6* (*10.4*)	18.7 (17.1)	*0.8* (*3.0*)	*1.4* (*5.0*)	*0.7* (*2.3*)	*1.0* (*3.9*)
15 March	37.4 (17.9)	*0.8* (*3.5*)	*2.8* (*7.1*)	*0.4* (*2.3*)	*1.0* (*4.3*)	9.5 (13.6)	*0.2* (*1.0*)	*0.2* (*1.1*)	*0.1* (*0.6*)	*0.1* (*0.7*)
1 April	16.4 (15.5)	*0.0* (*0.0*)	*0.1* (*1.2*)	*0.0* (*0.0*)	*0.0* (*0.0*)	1.0 (3.4)	*0.0* (*0.1*)	*0.0* (*0.2*)	*0.0* (*0.0*)	*0.0* (*0.2*)
15 April	0.5 (3.8)	*0.0* (*0.0*)	*0.0* (*0.0*)	*0.0* (*0.0*)	*0.0* (*0.0*)	0.1 (0.3)	*0.0* (*0.1*)	*0.0* (*0.2*)	*0.0* (*0.0*)	*0.0* (*0.2*)
Global radiation sum (MJ m^{-2})										
March	202 (29)	**190** (*26*)	**172** (*25*)	**192** (*27*)	**159** (*21*)	185 (16)	**166** (*15*)	**152** (*14*)	**165** (**17**)	**140** (*14*)
April	343 (37)	*346* (*36*)	**315** (*35*)	*347* (**38**)	**295** (*32*)	291 (22)	**285** (22)	**255** (*19*)	**279** (22)	**242** (*19*)
May	494 (47)	*536* (**53**)	**477** (47)	*525* (**49**)	**479** (*43*)	441 (33)	*480* (**34**)	**402** (*30*)	*459* (*31*)	**420** (*29*)
June	613 (49)	*663* (**51**)	**583** (*47*)	*650* (*48*)	*623* (49)	459 (31)	*504* (**33**)	**422** (*29*)	*504* (**34**)	*469* (31)
Potential evaporation sum (mm)										
March	26 (4)	*28* (4)	**24** (4)	*29* (4)	**23** (*3*)	26 (3)	26 (3)	**23** (*2*)	**25** (3)	**21** (*2*)
April	56 (6)	*63* (**7**)	**54** (6)	*63* (**7**)	**51** (6)	47 (4)	*52* (4)	**44** (4)	*51* (4)	**43** (4)
May	97 (10)	*115* (**12**)	97 (10)	*113* (**11**)	*100* (*9*)	84 (7)	*101* (**8**)	**80** (7)	*98* (7)	*85* (7)
June	134 (11)	*154* (**13**)	**131** (11)	*153* (**12**)	*143* (**12**)	96 (7)	*114* (**8**)	**91** (7)	*115* (**9**)	*103* (**8**)

Table A4: Factors we did not consider

Climate change	The latest (5th) IPCC assessment contains a wider range of climate projections than the 4th.
Soil type	Differences in soil type beyond the four groupings (Table 1) or variability in soil types within a farm (Persson and Kværnø, 2017).
Bulk density	Impact of bulk density on workability (Dexter and Bird, 2001; Obour et al., 2018; Rotz and Harrigan, 2005).
Workability thresholds	Other workability thresholds or changing farmers' decisions on workability thresholds during the spring work period (Aurbacher et al., 2013; Leenhardt and Lemaire, 2002; Maton et al., 2007; Tomasek et al., 2017; van Oort et al., 2012).
Soil organic matter content	Variability or future change in SOM/SOC (Falloon and Betts, 2010; Rounsevell, 1993) and soil fertility. Future changes in organic matter content may influence soil water content, aggregate stability, water-holding capacity, permeability, bulk density, friability, compactability (Singh et al., 2011). SOM content influences number of available workdays: more SOM = fewer workable days (Rotz and Harrigan, 2005). Dexter and Bird (2001) and Obour et al. (2018) found a larger moisture range for tillage and at higher moisture content with increasing SOM content. However, the latter study showed an increased gravimetric water content at FC at the same time. They also recommend the use of the consistency approach, related to the soil's lower plastic (Atterberg) limit, instead of a water retention approach, when comparing soils with uniform texture and varying SOM content.
Drainage	Suboptimal, variable or changing drainage: In less than well-drained soil, loss of yield potential would be larger (van Wijk and Buitendijk, 1988).
Impact of soil water content	Impact of soil water content on albedo and by that evapotranspiration (Falloon and Betts, 2010). Impact of changes in soil water content changes on SOM and water retention (Rounsevell and Loveland, 1992 in Rounsevell and Jones 1993). Direct relationship between soil water content/soil strength and demand for energy and traction (van Wijk and Buitendijk, 1988; Witney, 1983).
Mechanization	Impact of machinery size and type on workability (Rounsevell and Jones, 1993) and compaction (Lorenz et al., 2016) Potential changes in sowing techniques in the future. Direct impact of tractor size on timeliness costs: Ploughing timeliness costs for tractors above 65 kW strongly depend on workability threshold (Witney and Oskoui, 1982).
Sub soil compaction	(Birkás et al., 2009; Håkansson, 2005; Jones et al., 2003; Håkansson and Reeder, 1994)
Crop type	Impact of crop type on workability (Rounsevell and Jones, 1993)
Optimum seeding day	Regional differences in optimum seeding day or future change due to climate change.
Yield potential reduction	Other yield potential reducing factors like weeds, pests, diseases, nutritional deficiencies or tillage other than seedbed harrowing, crop rotation or effects of straw or other crops.
Genetic improvements	Future genetic improvements: varieties adapted to longer growing season, larger yield potential.
Climate effects on crop growth	Other effects of climate change on yield potential: effects of rainfall and temperature during the crop growing season, CO2 on growth, phenological growth patterns and yield formation.
Working hours	Different number of working hours per day (Mangerud et al., 2017).
Economy	Future changes in relationship between input prices and cereal prices, interest rates of machinery, or labour costs (Mangerud et al., 2017).

References

Akaike, H., 1973. Information theory and an extension of the maximum likelihood principle, in: Petrov, B.N., Caski, F. (Eds.), Proceeding of the Second International Symposium on Information Theory. Akademiai Kiado, Budapest, Hungary, pp. 267-281.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P.J., Rotter, R.P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P.K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A.J., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L.A., Ingwersen, J., Izaurralde, R.C., Kersebaum, K.C., Muller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stockle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J.W., Williams, J.R., Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 3, 827–832.

Auguie, B., Antonov, A., 2016. gridExtra: Miscellaneous Functions for "Grid" Graphics. R package version 2.2.1. https://CRAN.R-project.org/package=gridExtra (retrieved 19.06.18).

Aurbacher, J., Parker, P.S., Sánchez, G.A.C., Steinbach, J., Reinmuth, E., Ingwersen, J., Dabbert, S., 2013. Influence of climate change on short term management of field crops: A modelling approach. Agric. Syst. 119, 44-57.

Bakken, L.R., Børresen, T., Njøs, A., 1987. Effect of soil compaction by tractor traffic on soil structure, denitrification, and yield of wheat (*Triticum aestivum* L.). J. Soil Sci. 38, 541-552.

Bedard-Haughn, A., 2009. Managing excess water in Canadian prairie soils: A review. Can. J. Soil Sci. 89, 157-168.

Bergez, J.-E., Garcia, F., Wallach, D., 2006. Representing and optimizing management decisions with crop models, in: Wallach, D., Makowski, D., Jones, J.W. (Eds.), Working with

Dynamic Crop Models: Evaluating, Analyzing, Parameterizing and Using Them. Elsevier, Amsterdam, Netherlands, pp. 175–210.

Bindi, M., Olesen, J., 2011. The responses of agriculture in Europe to climate change. Reg. Environ. Change 11 (Suppl. 1), 151–158.

Birkás, M., Kisi, I., Bottlik, L., Jolánkai, M., Mesi, M., Kalmár, T., 2009. Subsoil compaction as a climate damage indicator. Agric. Conspec. Sci. 74, 91–97.

Brady, N.C., Weil, R.R., 2010. Elements of the Nature and properties of soils, third ed. Pearson: Boston.

Brown, I., Castellazzi, M., 2015. Changes in climate variability with reference to land quality and agriculture in Scotland. Int. J. Biometeorol. 59, 717–732.

Bryant, R.C., Smit, B., Brklacich, M., Johnston, T.R., Smithers, J., Chiotti, Q., Singh, B., 2000. Adaptation in Canadian agriculture to climatic variability and change. Clim. Change, 45, 181-201.

Carter, T.R., Parry, M.L., Porter, J.R., 1991. Climatic change and future agroclimatic potential in Europe. Int. J. Climatol. 11, 251-269.

Carter, T.R., 1998. Changes in the thermal growing season in Nordic countries during the past century and prospects for the future. Agric. Food Sci. 7, 161-179.

Cerf, M., Papy, F., Angevin, F., 1998. Are farmers expert at identifying workable days for tillage? Agronomy 18, 45-59.

Choi, Y.-S., Gim H.-J., Ho C.-H., Jeong S.-J., Park S.K., Hayes M.J., 2016. Climatic influence on corn sowing date in the Midwestern United States. Int. J. Clim. 37, 1595–1602.

Cooper, G., McGechan, M.B., Vinten, A.J.A., 1997. The influence of a changed climate on soil workability and available workdays in Scotland. J. Agric. Eng. Res. 68, 253-269.

Coumou D., Rahmstorf, S., 2012. A decade of weather extremes. Nat. Clim. Change 2, 491–496.

De Toro, A., Hansson, P.-A., 2004. Analysis of field machinery performance based on daily soil workability status using discrete event simulation or on average workday probability. Agric. Syst. 79, 109-129.

De Toro, A., 2005. Influences on timeliness costs and their variability on arable farms. Biosyst. Eng. 92, 1–13.

Dexter, A.R., Bird, N.R.A., 2001. Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. Soil Tillage Res. 57, 203-212.

DJF, 2004. Beregn arbejdsbehovet ved markarbejde med regnearket DRIFT 2004. https://www.landbrugsinfo.dk/Itvaerktoejer/Maskiner-og-arbejde/Sider/Beregn_arbejdsbehovet_ved_markarbejde_me.aspx (retrieved 19.06.18).

Dobor, L., Barcza, Z., Hlásny, T., Árendás, T., Spitkó, T., Fodor, N., 2016. Crop planting date matters: Estimation methods and effect on future yields. Agric. For. Meteorol. 223, 103-115.

Earl, R., 1997. Prediction of trafficability and workability from soil moisture deficit. Soil Tillage Res. 40, 155-168.

Edwards, G., White, D.R., Munkholm, L.J., Sørensen, C.G., Lamandé, M., 2016. Modelling the readiness of soil for different methods of tillage. Soil Tillage Res. 155, 339-350.

Eitzinger, J., Trnka, M., Semerádova, D., Thaler, S., Svobodova, E., Hlavinka, P., Šiska, B., Takác, J., Malatinská, L., Nováková, M., Dubrovský, M., Žalud, Z., 2013. Regional climate change impacts on agricultural crop production in Central and Eastern Europe – hotspots, regional differences and common trends. J. Agric. Sci. 151, 787–812.

Ekeberg, E., 1987. Hva taper vi ved å utsette våronna [What do we lose by delaying spring fieldwork]? Aktuelt fra Statens fagtjeneste for landbruket 3, 121-126.

Elliot, T.R., Lembke, W.D., Hunt, D.R., 1977. A simulation model for predicting available days for soil tillage. Trans. ASAE 20, 4-8.

Etana, A., Håkansson, I., 1996. Effects of traffic with a tractor and a wheel loader on two ploughed moist soils. Swedish J. Agric. Res. 26, 61-68.

Falloon, P., Betts, R., 2010. Climate impacts on European agriculture and water management in the context of adaptation and mitigation - The importance of an integrated approach. Sci. Total Environ. 408, 5667–5687.

Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, P.M. Midgley (Eds.), 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA. https://www.ipcc.ch/pdf/special-reports/srex/SREX_Full_Report.pdf (retrieved 19.06.18).

Forbord, M., Vik, J., 2017. Food, farmers, and the future: Investigating prospects of increased food production within a national context. Land Use Policy 67, 546-557.

Greve, M.H., Yli-Halla, M., Nyborg, A.A., Oborn, I., 2000. Appraisal of world reference base for soil resources - from a nordic point of view. Dan. J. Geogr. 100, 15-26.

Groisman, P.Y., Knight, R.W., Easterling, D.R., Karl, T.R., Hegerl, G.C., Razuvaev, V.N., 2005. Trends in intense precipitation in the climate record. J. Clim. 18, 1326–1350.

Hakala, K., Jauhiainen, L., Himanen, S.J., Rötter, R.P., Salo, T., Kahiluoto, H., 2012. Sensitivity of barley varieties to weather in Finland. J. Agric. Sci. 150, 145–160.

Håkansson, I., 2005. Machinery-induced compaction of arable soils: Incidence, consequences, counter-measures. Div. Soil Manag., Swed. Univ. Agric. Sci. Rep. 109.

Harding, A.E., Rivington, M., Mineter, M.J., Tettet, S.F.B., 2015. Agro-meteorological indices and climate model uncertainty over the UK. Clim. Change, 128, 113–126.

Hoffmann, H., Zhao, G., Asseng, S., Bindi, M., Biernath, C., Constantin, J., Coucheney, E., Dechow, R., Doro, L., Eckersten, H., Gaiser, T., Grosz, B., Heinlein, F., Kassie, B.T., Kersebaum, K.-C., Klein, C., Kuhnert, M., Lewan, E., Moriondo, M., Nendel, C., Priesack, E., Raynal, H., Roggero, P.P., Rötter, R.P., Siebert, S., Specka, X., Tao, F., Teixeira, E., Trombi, G., Wallach, D., Weihermüller, L., Yeluripati, J., Ewert, F., 2016. Impact of spatial soil and climate input data aggregation on regional yield simulations. PLoS ONE 11, e0151782. doi:10.1371/journal.pone.0151782.

Hofstra, S., Marti, M., Børresen, T., Njøs, A., 1986. Effects of tractor traffic and liming on yields and soil physical properties in three field experiments in S.E.-Norway. Sci. Rep. Agric. Univ. Nor. 65, 1-23.

Hov, Ø., Cubasch, U., Fischer, E., Höppe, P., Iversen, T., Kvamstø, N.G., Kundzewicz, Z.W., Rezacova, D., Rios, D., Santos, F.D., Schädler, B., Veisz, O., Zerefos, C., Benestad, R., Murlis, J., Donat, M., Leckebusch, G.C., Ulbrich, U., 2013. Extreme Weather Events in Europe: Preparing for Climate Change Adaptation. Norwegian Meteorological Institute, Oslo. http://www.easac.eu/fileadmin/PDF_s/reports_statements/Extreme_Weather/Extreme_Weather_full_version_EASAC-EWWG_final_low_resolution_Oct_2013f.pdf (retrieved 19.06.2018).

Jones, R.J.A., Spoor, G., Thomasson, A.J., 2003. Vulnerability of subsoils in Europe to compaction: A preliminary analysis. Soil Tillage Res. 73, 131–143.

Katz, R.W., Brown, B.G., 1992. Extreme events in a changing climate: variability is more important than averages. Clim. Change 21, 289–302.

Kirby, E.J.M., 1969. The effect of sowing date and plant density on barley. Ann. Appl. Biol. 63, 513–521.

Knutti, R., 2010. The end of model democracy? Clim. Change, 102, 395-404.

Kristensen, K.J., Jensen, S.E., 1975. A model for estimating actual evapotranspiration from potential evapotranspiration. Nord. Hydrol. 6, 170-188.

Leenhardt, D., Lemaire, P., 2002. Estimating the spatial and temporal distribution of sowing dates for regional water management. Agric. W. Manag. 55, 37–52.

Lenth, R.V., 2016. Least-Squares Means: The R Package lsmeans. J. Stat. Softw. 69, 1-33.

Ljungars, A., 1977. Importance of different factors on soil compaction by tractors - measurements in 1974-1976. SLU, Uppsala, Rep. Div. Soil Manag. 52.

Ludwig, F., Asseng, S., 2010. Potential benefits of early vigor and changes in phenology in wheat to adapt to warmer and drier climates. Agric. Syst. 103, 127-136.

Mangerud, K., Riley, H., Kolberg, D., 2017. Maskinkostnader og laglighetskostnader i våronna: Hvor stor redskapspark er det lønnsomt å ha i forhold til kornareal? [Machinery and timeliness costs of spring tillage: What level of mechanisation is most profitable in relation to cereal area?]. NIBIO Rep. 3(158). https://brage.bibsys.no/xmlui/bitstream/handle/11250/2479779/NIBIO_RAPPORT_2017_3_158.pdf?sequence=2&isAllowed=y (retrieved 19.06.2018).

Marti, M., 1983. Effects of soil compaction and lime on yield and soil parameters on three silty clay soils in South Eastern Norway. Sci. Rep. Agric. Univ. Nor. 62, 1-28.

Maton, L., Bergez, J.-E., Leenhardt, D., 2007. Modelling the days which are agronomically suitable for sowing maize. Eur. J. Agron. 27, 123–129.

Maxwell, B., Mayer, N., Street, R., 1997. The Canada Country study: climate impacts and adaptation, Natl. Summ. For. Policy Mak. Environ. Can. http://publications.gc.ca/collections/Collection/En56-119-7-1998E.pdf (retrieved 19.06.2018).

Menzel, A., von Vopelius, J., Estrella, N., Schleip, C., Dose, V., 2006. Farmers' annual activities are not tracking the speed of climate change. Clim. Res. 32, 201–207.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher, C.A., Watkins, J.W., 2005. A climatic stratification of Europe. Glob. Ecol. Biogeogr. 14, 549–563.

Nakicenovic, N., Swart, R. (Eds.), 2000. Emissions scenarios. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://www.ipcc.ch/pdf/special-reports/emissions_scenarios.pdf (retrieved 19.06.2018).

Nemes, A., Pachepsky, Y.A., Timlin, D.J., 2011. Towards improving global estimates of field soil water capacity. Soil Sci. Soc. Am. J. 75, 807-812.

NIBIO, 2018. Main Table 17d, Part 1. Summary of Accounts for Cereal Production. Eastern Norway and Trøndelag. http://nilf.no/english/Driftsgranskinger/account_statistics_in_agriculture_and_farm_forestry_2016 (retrieved 22.06.2018).

Njøs, A., 1978. Effects of tractor traffic and liming on yields and soil physical properties of a silty clay loam soil. Sci. Rep. Agric. Univ. Nor. 57, 1-26.

Obour, P.B., Jensen, J.L., Lamandé, M., Watts, C.W., Munkholm, L.J., 2018. Soil organic matter widens the range of water contents for tillage. Soil Tillage Res. 182, 57-65.

Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. Eur. J. Agron. 16, 239–262.

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.

Parry, M.L., Canziani, O.F., de Alba, A.E., Allali, A., Kajfež-Bogataj, L., Love, G., Stone, J., van Ypersele, J.P., Palutikof, J.P. (Eds.), 2007. Climate change 2007: Working Group II: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University

Press, Cambridge, UK. https://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4_wg2_full_report.pdf (retrieved 19.06.2018).

Peltonen-Sainio, P., Rajala, A., Känkänen, H., Hakala, K., 2009a. Improving farming systems in northern European conditions, in Sadras, V.O., Calderini, D. (Eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. Elsevier, Amsterdam, Netherlands, pp. 71–97.

Peltonen-Sainio, P., Jauhiainen, L., Hakala, K., 2009b. Climate change and prolongation of growing season: Changes in regional potential for field crop production in Finland. Agric. Food Sci. 18, 171-190.

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., Dalla Marta, A., Micale, F., Schaap, B., Seguin, B., Skjelvåg, A.O., Orlandini, S., 2010. Coincidence of variation in yield and climate in Europe. Agric. Ecosyst. Environ. 139, 483-489.

Peltonen-Sainio, P., Jauhiainen, L., 2014. Lessons from the past in weather variability: Sowing to ripening dynamics and yield penalties for northern agriculture in 1970-2012. Reg. Environ. Change 14, 1505-1516.

Persson, T., Höglind, M., 2014. Impact of climate change on harvest security and biomass yield of two timothy ley harvesting systems in Norway. J. Agric. Sci. 152, 205–216.

Persson, T., Kværnø, S., Höglind, M., 2015. Impact of soil type extrapolation on timothy grass yield under baseline and future climate conditions in southeastern Norway. Clim. Res. 65, 71-86.

Persson, T., Kværnø, S., 2017. Impact of projected mid-21st century climate and soil extrapolation on simulated spring wheat grain yield in south-eastern Norway. J. Agric. Sci. 155, 361–377.

Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. B 360, 2021–2035.

R Core Team, 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/ (retrieved 19.06.2018).

Reeve, R.C., Fausey, N.R., 1974. Drainage and timeliness of farming operations, in: van Schilfgaarde, J. (Ed.), Drainage for Agriculture. Agronomy, 17, 55-66.

Riley, H., Bonesmo, H., 2005. Modelling of snow and freeze-thaw cycles in the EU-rotate_N decision support system. Planteforsk Grønn Kunnskap, 9(112).

Riley, H., 2016. Tillage timeliness for spring cereals in Norway: Yield losses due to soil compaction and sowing delay and their consequences for optimal mechanisation in relation to crop area. NIBIO Rep. 2(112).

Rötter, R.P., Palosuo, T., Pirttioja, N.K., Dubrovsky, M., Salo, T., Fronzek, S., Aikasalo, R., Ristolainen, A., Carter, T.R., 2011. What would happen to barley production in Finland if global warming exceeded 4 C? A model-based assessment. Eur. J. Agron. 35, 205-214.

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.

Rötter, R.P., Höhn, J., Trnka, M., Fronzek, S., Salo, T., Carter, T. R., Kahiluoto, H., 2013. Modelling shifts in agroclimate and crop cultivar response under climate change. Ecol. Evol. 3, 4197–4214.

Rotz, C.A., Harrigan, T.M., 2005. Predicting suitable days for field machinery operations in a whole farm simulation. Appl. Eng. Agric. 21, 563–571.

Rounsevell, M.D.A., 1993. A review of soil workability models and their limitations in temperate regions. Soil Use Manag. 9, 15-21.

Rounsevell, M.D.A., Jones, R.J.A., 1993. A soil and agroclimatic model for estimating machinery work-days: The basic model and climatic sensitivity. Soil Tillage Res. 26, 179–191.

Rounsevell, M.D.A., Loveland, P.J., 1992. An overview of hydrologically-controlled soil responses to climate change in temperate regions. SEESOIL 8, 69-78.

Rounsevell, M.D.A., Brignall, A.P., 1994. The potential effects of climate change on autumn soil tillage opportunities in England and Wales. Soil Tillage Res. 32, 275–289.

Semenov, M.A., Porter, J.R., 1995. Climatic variability and the modelling of crop yields. Agric. For. Meteorol. 73, 265–283.

Semenov, M.A., Stratonovitch, P., 2010. The use of multi-model ensembles from global climate models for impact assessments of climate change. Clim. Res., 41, 1-14.

Semenov, M.A., Shewry, P.R., 2011. Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. Sci. Rep. 1(66).

Sexton, D.M.H., Harris, G.R., 2015. The importance of including variability in climate change projections used for adaptation. Nat. Clim. Change 5, 931–936. http://dx.doi.org/10.1038/nclimate2705 (retrieved 16.08.2018).

Singh, B.P, Cowie, A., Chan, K.Y. (Eds.), 2011. Soil Health and Climate Change. Springer, Berlin, Germany.

Skjelvåg, A.O., 1998. Climatic conditions for crop production in Nordic countries. Agric. Food Sci. 7, 149-160.

Smit, B., McNabb, D., Smithers, J., 1996. Agricultural adaptation to climatic variation. Clim. Change 33, 7-29.

Smith, L.P., 1972. The effect of weather, drainage efficiency and duration of spring cultivations on barley yields in England. Outlook Agric. 7, 79-83.

Søgaard, H.T., Sørensen, C.G., 2004. A model for optimal selection of machinery sizes within the farm machinery system. Biosyst. Eng. 89, 13–28.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor M., Miller, H.L. (Eds.), 2007. Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm (retrieved 19.06.2018).

Statistics Norway (2018). Table 1: Holdings with area of grain and oil seeds. Area used for grain and oil seeds. County. https://www.ssb.no/en/jord-skog-jakt-og-fiskeri/statistikker/korn (retrieved 22.06.2018).

Tomasek, B.J., Williams, M.M., II, Davis, A.S., 2017. Changes in field workability and drought risk from projected climate change drive spatially variable risks in Illinois cropping systems. PLoS ONE 12, e0172301. doi:10.1371/journal. pone.0172301

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovský, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vučetić, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V., Semerádová, D., Žalud, Z., 2011. Agroclimatic conditions in Europe under climate change. Glob. Change Biol. 17, 2298-2318.

Trnka, M., Rötter, R.P., Ruiz-Ramos, M., Kersebaum, K.C., Olesen, J.E., Zalud, Z., Semenov, M.A., 2014. Adverse weather conditions for European wheat production will become more frequent with climate change. Nat. Clim. Change 4, 637–643.

Urban, D.W., Roberts, M.J., Schlenker, W., Lobell, D.B., 2015. The effects of extremely wet planting conditions on maize and soybean yields. Clim. Change 130, 247-260.

USDA (n.d.). Soil texture calculator. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167 (retrieved 19.06.2018).

Van Oort, P.A.J., Timmermans, B.G.H., van Swaaij, A.C.P.M., 2012. Why farmers' sowing dates hardly change when temperature rises. Eur. J. Agron. 40, 102-111.

Van Oort, P.A.J., Timmermans, B.G.H., Meinke, H., van Ittersum, M.K., 2012b. Key weather extremes affecting potato production in the Netherlands. Eur. J. Agron. 37, 11–22.

Van Wijk, A.L.M., Buitendijk, J., 1988. A method to predict workability of arable soils and its influence on crop yield, in: Drescher, J., Horn, R., De Boodt, M. (Eds.), Impact of water and external forces on soil structure. Catena Supplement, 11, 129 – 140. Catena: Cremlingen, pp. 129-140.

Walther, A., Linderholm, H.W., 2006. A comparison of growing season indices for the Greater Baltic Area. Int. J. Biometeorol. 51, 107–118.

Wesseling, J., van Wijk, W.R., 1957. Soil physical conditions in relation to drain depth, in Luthin, J.N. (Ed.), Drainage of agricultural lands. Agronomy 7, 461-504.

White, J.W., Kimball, B.A., Wall, G.W., Ottman, M.J., Hunt, L.A., 2011. Responses of time of anthesis and maturity to sowing dates and infrared warming in spring wheat. Field Crops Res. 124, 213–222

Wickham, H., 2009. ggplot2: Elegant Graphics for Data Analysis. Springer, New York.

Witney, B.D., Oskoui, K.E., 1982. The basis of tractor power selection on arable farms. J. Agric. Eng. Res. 27, 513–527.

Witney, B.D. 1983. Power Demand Prediction from Climate variable. Paper No. 83-1057. ASAE, St. Joseph, MI.