Norwegian University of Life Sciences
Faculty of Environmental Sciences
and Natural Resource Management

Philosophiae Doctor (PhD)
Thesis 2019:13

Timeliness in seedbed preparation for spring cereals: Studies to prepare for climate change in Norway

Tidsrammen for klargjøring av såbed til vårkorn: Laglighet og klimaendringer i Norge

Dorothee Kolberg

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PhD Supervisors

Prof. Trond Børresen (Main supervisor)
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences
P.O. Box 5003, NO-1432 Ås, Norway
trond.borresen@nmbu.no

Hans Christian Endrerud, PhD (Co-supervisor)
Department of Agricultural Sciences
Inland Norway University of Applied Sciences
P.O. Box 400, NO-2418 Elverum, Norway
hans.endrerud@inn.no

Hugh Riley, PhD (Co-supervisor)
Norwegian Institute of Bioeconomy Research – NIBIO Apelsvoll
Nylinna 226, NO-2849 Kapp, Norway
hugh.riley@nibio.no

Thesis Evaluation Committee

Prof. Laura Alakukku (Opponent 1)
Department of Agricultural Sciences
University of Helsinki
P.O. Box 28, FI-00014 Helsinki, Finland
laura.alakukku@helsinki.fi

Prof. Thomas Keller (Opponent 2)
Department of Soil and Environment
Swedish University of Agricultural Sciences
P.O. Box 7014, SE-75007 Uppsala, Sweden
thomas.keller@slu.se

Agroscope
Reckenholzstrasse 191
CH-8046 Zürich, Switzerland
thomas.keller@agroscope.admin.ch

Marina A. Bleken, PhD (Coordinator and secretary)
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences
P.O. Box 5003, NO-1432 Ås, Norway
marina.bleken@nmbu.no

Preface

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Ås, 10th March 2019
Dorothee Kolberg

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Contents

PAPERS I-IV (Individual page numbers)

Abstract

Future increases in winter and spring precipitation in Norway may exacerbate the dilemma of spring fieldwork that farmers have, concerning topsoil compaction versus delayed sowing on autumn-ploughed soil. Both topsoil compaction and delayed sowing increase the loss of yield potential. The overall aim of this PhD project was to explore how seedbed preparation for spring cereals can be adapted to future climate change and how further loss of cereal yield potential can be avoided, on different soil types under contrasting climatic conditions in Norway. To pursue this aim, the thesis starts with presenting the overall agronomical context of northern growing conditions and the theoretical background to seedbed preparation physics. After that, it presents and discusses results from two field experiments and a simulation study.

One field experiment focused on timing and traffic intensity in spring tillage operations that minimise soil physical degradation under unfavourably wet conditions. This experiment compared spring fieldwork conducted on different dates (early, medium, late) with different traffic intensity (no wheeling, one, two or three wheelings), with regard to soil physical properties and crop performance. The results show that early spring fieldwork in excessively wet soil gave rise to larger and stronger aggregates, higher penetration resistance and slightly changed pore characteristics, with resulting reduced yields. The increased penetration resistance persisted until autumn. The effect of traffic intensity was less pronounced, probably due to location, soil type and the small range of intensities involved. The proportion of 2-6 mm aggregates and penetration resistance were the most important soil physical factors for both soil quality and cereal yield. This experiment shows that soil physical degradation can be minimised by conducting spring fieldwork at a time when the soil has dried up sufficiently, and that moderate traffic intensity does not interfere with this strategy. The most important aspect of such timing is to avoid unfavourable aggregate size distributions and increases in penetration resistance.

The second field experiment explored possibilities, under unfavourably wet conditions, to create a seedbed that can cope with more precipitation by maximising moisture loss after sowing. This experiment compared different implements for seedbed preparation (light, heavy, extra heavy) with regard to the soil physical properties they create, as well as moisture content in the seedbed and crop

performance. The results show that, under excess moisture conditions, lighter mechanisation resulted in more favourable seedbed properties, lower moisture content and more uniform crop emergence. In contrast to established seedbed theory, larger aggregates did not reduce the moisture content in the seedbed. From this experiment, it was inferred that heavy modern seed drills with press wheels may cause compaction in the seedbed and limit moisture loss. Larger aggregates did not increase moisture loss after sowing, because the seedbed had become compacted at the same time.

The simulation study addressed the question whether projected future climate change, in regions with high soil water content in spring, would aggravate the dilemma that farmers have concerning topsoil compaction versus delayed sowing. Further, it explores how farmers may adjust their long-term farm mechanisation management accordingly. Based on historical and projected future climate for two contrasting cereal-growing regions in Norway, weather data were generated. These data were used in a workability model and a mechanization model for simulations of spring workability, timeliness-limited yield potential, timeliness costs, and mechanization management. Simulations of the two most abundant soil types and different farm mechanisation parameters were included. The results showed that future workability and yield potential in Norway might be either improved or impaired, depending on the region and the soil type. In the future, there will be a general increase in the variability of workability and yield potential, and Central Norway will experience a larger risk of extremely unfavourable years in the least favourable climate scenarios. The study highlighted the importance of soil moisture content in spring as a criterion for sowing dates in simulation studies in general and in impact studies of future climate change in particular.

The common thread running through this thesis is that avoidance of compaction seems to be the most important adaptation to climate change in seedbed preparation. Minimum compaction can be realised if spring fieldwork is performed under sufficiently dry conditions and by careful selection of implements, regarding their weight and mode of function. In Norwegian cereal production, seedbed preparation is a bottleneck, which is going to gain even more importance in the future, as we expect an increasing incidence of extremely unfavourable spring conditions. The transferability of the agronomical consequences to other countries with northern growing conditions may be possible but remains to be explored.

Sammendrag

Klimaendringer med mer nedbør om vinteren og våren kan vanskeliggjøre gjennomføringen av våronna i Skandinavia i fremtiden. Gårdbrukeren kan komme til å stå foran valget mellom jordpakking og utsatt såtid. Uansett hva som velges, vil det kunne føre til avlingstap. Formålet med PhD-prosjektet var å studere hvordan klargjøring av såbed til vårkorn kan tilpasses klimaendringene og hvordan man best kan unngå avlingstap på forskjellige jordarter og i kornregioner med ulikt klima. Avhandlingen starter med å presentere den klimatiske, pedologiske og agronomiske konteksten, og den teoretiske bakgrunnen for fysisk såbedskvalitet. Deretter blir resultater fra to feltforsøk og en modelleringsstudie presentert og diskutert.

Det ene feltforsøket handlet om hvordan man med valg av såtid og kjøreintensitet under klargjøring av såbedet kan minimere pakkeskader i våt jord. Dette forsøket sammenliknet våronn på forskjellige datoer (tidlig, middels, sein) og med forskjellig kjøreintensitet (ingen, en, to eller tre overkjøringer) med tanke på jordfysiske egenskaper i såbedet og effekten på kornplantene. Resultatene viste at tidlig våronn i for våt jord ga større og sterkere aggregater, høyere penetrasjonsmotstand, delvis endrete egenskaper av porene i jorda og reduserte avlinger. Høyere penetrasjonsmotstand ble også påvist om høsten i samme vekstsesong. Effekten av kjøreintensitet var ikke like tydelig, mest sannsynlig på grunn av lokalisering, jordart og relativt liten forskjell mellom nivåene av denne forsøksfaktoren. Andelen av 2-6 mm store aggregater og penetrasjonsmotstand var de to viktigste jordfysiske egenskapene for jordkvalitet og kornavling. Dette forsøket viser at jordpakking kan minimeres ved å utsette såingen til jorda har tørket opp tilstrekkelig og at moderat kjøreintensitet ikke har så mye å si. Det er spesielt viktig å unngå en uheldig aggregatstørrelsessammensetning og økt penetrasjonsmotstand i såbedet.

Det andre feltforsøket undersøkte muligheten for a klargjøre såbedet under for fuktige forhold på en slik måte at det kan tåle vedvarende høy jordfuktighet etter såing ved hjelp av et økt vanntap. Dette forsøket sammenliknet forskjellig mekanisering (lett, tung, ekstra tung) med tanke på jordfysiske egenskaper, vanninnhold i såbedet og effekten på kornplantene. Under for fuktige forhold var det den lette mekaniseringen som resulterte i et bedre såbed med lavere jordfuktighet og jevnere spiring. I motsetning til allment anerkjent såbedsteori, førte ikke større aggregater til lavere jordfuktighet. Ut

fra dette forsøket kan man anta at moderne kombisåmaskiner med pakkehjul fører til jordpakking og ikke øker vanntapet, slik det hadde vært ønskelig ved mye nedbør etter såing. Større aggregater økte ikke vanntapet, fordi såbedet samtidig var pakket.

Modelleringsstudien undersøkte om klimaendringer vil gjøre våronna vanskeligere i fremtiden på grunn av et høyt vanninnhold i jorda. Dessuten ble det vurdert hvordan gårdbrukere bør tilpasse mekaniseringen til dette. Basert på historisk klima og flere fremtidsscenarier ble det generert værdata. Disse værdata ble brukt i en laglighetsmodell og en mekaniseringsmodell for å simulere jordas laglighet om våren, avlingspotensial, laglighetskostnader og optimal mekanisering. Simuleringene ble gjennomført for de to vanligste jordartene og med forskjellig mekanisering. Resultatene viser at lagligheten og avlingspotensialet enten kan bli forbedret eller forringet i fremtiden i Norge, avhengig av region og jordart. Variabiliteten i laglighet og avlingspotensial kommer generelt til å øke i fremtiden, og Midt-Norge kommer til å oppleve en kraftig økt hyppighet av ekstremt vanskelige år i følge de mest pessimistiske scenariene. Denne studien tydeliggjør viktigheten av vanninnhold i jorda som kriterie for valg av sådato i modelleringsstudier generelt og i studier av effekten av klimaendringer spesielt.

Den røde tråden i denne avhandlingen viser at det å unngå pakkeskader er det aller viktigste når våronna skal tilpasses klimaendringer. Man kan minimere pakkeskader ved å utføre våronna i tørr nok jord og ved å velge redskap nøye, med tanke på vekt og arbeidsmåte. Våronna er en flaskehals i kornproduksjonen og kommer til å bli enda mer utfordrende i fremtiden når vi forventer hyppigere år med ekstremt vanskelige forhold. Hvorvidt de agronomiske konsekvensene av dette er overførbare til andre land med liknende agroklimatiske forhold gjenstår å bli undersøkt.

List of papers

Paper I

Obour, P.B., Kolberg, D., Lamandé, M., Børresen, T., Edwards, G., Sørensen, C., Munkholm, L.J. (2018). Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil. *Soil and Tillage Research, 184*, 153-163.

Paper II

Kolberg, D., Riley, H., Børresen, T. Timeliness and traffic intensity in seedbed preparation for spring cereals in Norway: Importance of soil physical properties, persistence of soil degradation, and consequences for yield. Manuscript.

Paper III

Kolberg, D., Endrerud, H.C., Børresen, T. Adaptation of seedbed preparation to unfavourably high soil moisture conditions. Under review.

Paper IV

Kolberg, D., Persson, T., Mangerud, K., Riley, H. (2019). Impact of projected climate change on workability, attainable yield, profitability and farm mechanization in Norwegian spring cereals. *Soil and Tillage Research, 185*, 122-138.

1. Introduction

A seedbed is here "defined as a loose and usually shallow surface layer, tilled by harrowing prior to sowing. The basal layer underneath, untilled during seedbed preparation, is usually firm" (Håkansson et al. 2002). The seedbed consists of assemblies of mineral and organic soil particles, called aggregates.

In this thesis, an aggregate may be any secondary soil structure unit, i.e. an assembly of "soil particles that cohere to each other more than to other surrounding particles", irrespective of its origin (Dexter 1988; Diaz-Zorita et al. 2002), including sizes which elsewhere might be defined as domains, clusters, micro aggregates, peds, crumbs, fragments or clods.

The term spring fieldwork comprises here all secondary tillage that is performed on autumn-ploughed soil in spring to prepare physically favourable conditions for the cereals to germinate, emerge and grow. Thus, seedbed preparation may include levelling (where applicable), harrowing, sowing, rolling (where applicable), and stone picking (on morainic soils). The term spring fieldwork is here used equivalent to the term seedbed preparation.

1.1. Rationale: The dilemma of spring fieldwork timeliness today and in the future

The timing of spring fieldwork in cereal production is crucial for realizing yield potential in northern regions with cold-temperate climate. In cold-temperate regions, farmers have traditionally adapted to a short growing season by ploughing their soil in autumn and starting seedbed preparation as early as possible in the following spring (Peltonen-Sainio et al., 2009a). The decision on when to start spring fieldwork presents farmers with a dilemma of timeliness. If the cereal seedbed preparation and sowing is done too early, in unfavourably wet soil, the farmer risks loss of yield potential (Figure 1) due to topsoil compaction (Njøs, 1978; Hofstra et al., 1986; Bakken et al., 1987; Håkansson, 2005; Marti, 1983) and oxygen deficiency during germination (Wesseling and VanWijk, 1957). If, on the other hand, the farmer has to wait too long for the soil to become ready for seedbed preparation, the delayed sowing entails loss of yield potential (Figure 1) due to a shorter crop growing season (Riley, 2016).

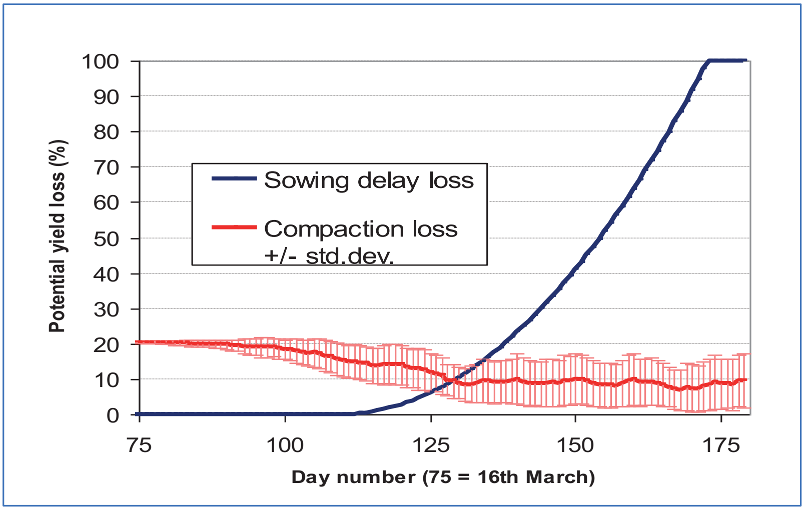

Figure 1: Average potential yield losses due to delayed sowing and topsoil compaction on loam soil using 1973-2012 weather data for the northern part of southeastern Norway, adopted from Riley (2016).

Consequently, for minimizing loss of yield potential, the number of available days for spring fieldwork is limited. The number of available days depends on the farmer's individual and subjective willingness to incur the resulting compaction loss in favour of earlier sowing, which again depends on soil type, current soil water content, weather forecast, and the number of working days required to complete spring work.

On a given farm, the factors that most influence the number of available days for spring fieldwork are day-to-day and year-to-year weather variations. Farmers have long been adapting to variable weather (Reeve and Fausey, 1974; Witney and Oskoui, 1982; Smit et al., 1996; Maxwell et al., 1997; Cerf et al., 1998; Bryant et al., 2000; Maton et al., 2007; Peltonen-Sainio et al., 2009a; Urban et al., 2015; Choi et al., 2016; Riley, 2016). However, during the coming decades, climate change may aggravate the already difficult timing of spring work. In northern regions with cold-temperate climate we expect more precipitation during winter and spring, and increased variability (Groisman et al., 2005; Bedard-Haughn, 2009; Trnka et al., 2011; Coumou and Rahmstorf, 2012; Hov et al., 2013; Urban et al., 2015). This could mean a higher soil water content in spring (Figure 2), and even fewer days available for spring fieldwork. In addition, high water supply after sowing (Figure 3) may hamper germination and early growth of the crop.

In order to find possibilities to adapt seedbed preparation to a changing climate and avoid further loss of yield potential, the concept of seedbed preparation needs to be explored in a wider context, as well as delimited within this thesis.


Figure 2: Cereal field saturated after snowmelt and precipitation prior to sowing in spring (Unni Abrahamsen, 2013).


Figure 3: Saturated soil after precipitation during early spring cereal growth (Unni Abrahamsen, 2006).

1.2. Wider agronomical context: Norwegian and Northern growing conditions for spring cereals

The focus of this thesis is on seedbed preparation for spring cereals under Norwegian conditions. However, the topic may be relevant for other countries with similar agronomical conditions. It is therefore sensible to relate Norway to other countries with similar climatic conditions, termed «northern growing conditions» by Peltonen-Sainio (2012). According to that definition, northern growing conditions are found in "the northernmost high latitude European countries (also referred to as the northern Baltic Sea region, Fennoscandia and Boreal regions) characterized mainly as the Boreal Environmental Zone (Metzger et al., 2005). Using this classification, Finland, Sweden, Norway and Estonia are well covered."

1.2.1 Climate today and in the future

Most of the cereal production in Norway is concentrated in a few regions with contrasting climate. The most important cereal growing regions in Norway are the southern part of southeastern Norway (SE), the northern part of southeastern Norway, and central Norway (C) (Figure 4), which represent 53, 28 and 17 % of the country's

Table 1: Mean and standard deviation (sd) of climatic parameters in northernmost (Central) and southernmost (Southeastern) Norwegian cereal growing regions and the country as a whole, during standard normal period, recent climate change (from standard normal to 1979-2008) and projected climate change (from standard normal to 2021-2050), in winter (December, January, February), spring (March, April, May) and the year as a whole.

	Climate	Climate change	
	Standard normal [a]	From standard normal to 1979-2008 [b]	From standard normal to 2021-2050 [c]
Temperature mean (°C ± sd, change in °C)			
Norway			
Year	1.0 ± 0.8	+0.6	+1.9 (1.2-2.5)
Winter	-6.8 ± 2.3	+1.0	+2.3 (1.5-3.3)
Spring	-0.5 ± 0.9	+0.5	+1.9 (1.2-2.6)
Southeastern Norway [d]			
Year	5.3 ± 0.9	+0.6	+1.9 (1.2-2.6)
Winter	-4.7 ± 2.6	+1.3	+2.4 (1.5-3.5)
Spring	4.5 ± 1.1	+0.6	+1.7 (1.1-2.5)
Central Norway [e]			
Year	5.5 ± 0.9	+0.6	+1.7 (1.2-2.4)
Winter	-2.5 ± 2.7	+1.1	+2.2 (1.4-3.2)
Spring	4.7 ± 1.0	+0.4	+1.8 (1.1-2.5)
Precipitation sum (mm ± sd, change in %)			
Norway			
Year	1486	+5	+9.6 (2.4-14.0)
Winter	-	+17	+11.1 (3.8-18.4)
Spring	-	+10	+10.0 (3.7-20.0)
Southeastern Norway [d]			
Year	795 ± 156	+4	+6.7 (3.1-10.3)
Winter	136 ± 54	+8	+15.8 (7.0-26.6)
Spring	144 ± 53	+9	+7.6 (2.9-15.5)
Central Norway [e]			
Year	892 ± 175	+4	+12.3 (0.6-28.3)
Winter	197 ± 88	+15	+10.1 (-6.3-19.9)
Spring	156 ± 46	+8	+12.3 (3.1-31.3)

[a] Source: Norwegian Meteorological Institute, http://www.met.no (Southeastern and Central Norway), https://www.yr.no/place/Norway/climate.html (Norway); Precipitation sum for Norway as a whole from Hanssen-Bauer et al. (2009)

[b] Source: Hanssen-Bauer et al. (2009)

[c] Average value with range of 10-percentile to 90-percentile of three different greenhouse gas emissions scenarios (B1, A1B and A2 from the 4th assessment report of the International Panel on Climate Change, IPCC, 2007) coupled with 72 different climate models (22 in a dynamic and 50 in a statistical ensemble, see appendices in Hanssen-Bauer et al., 2009) in parentheses

[d] Southeastern Norway is represented by Ås (59° 40′ N, 10° 46′ E; 94 m above sea level) with standard normal period 1957-1988 and temperature region 1 and precipitation region 2 in Hanssen-Bauer et al. (2009)

[e] Central Norway is represented by Værnes (63° 27′ N, 10° 56′ E; 12 m above sea level) with standard normal period 1961-1990 and temperature region 3 and precipitation region 10 in Hanssen-Bauer et al. (2009)

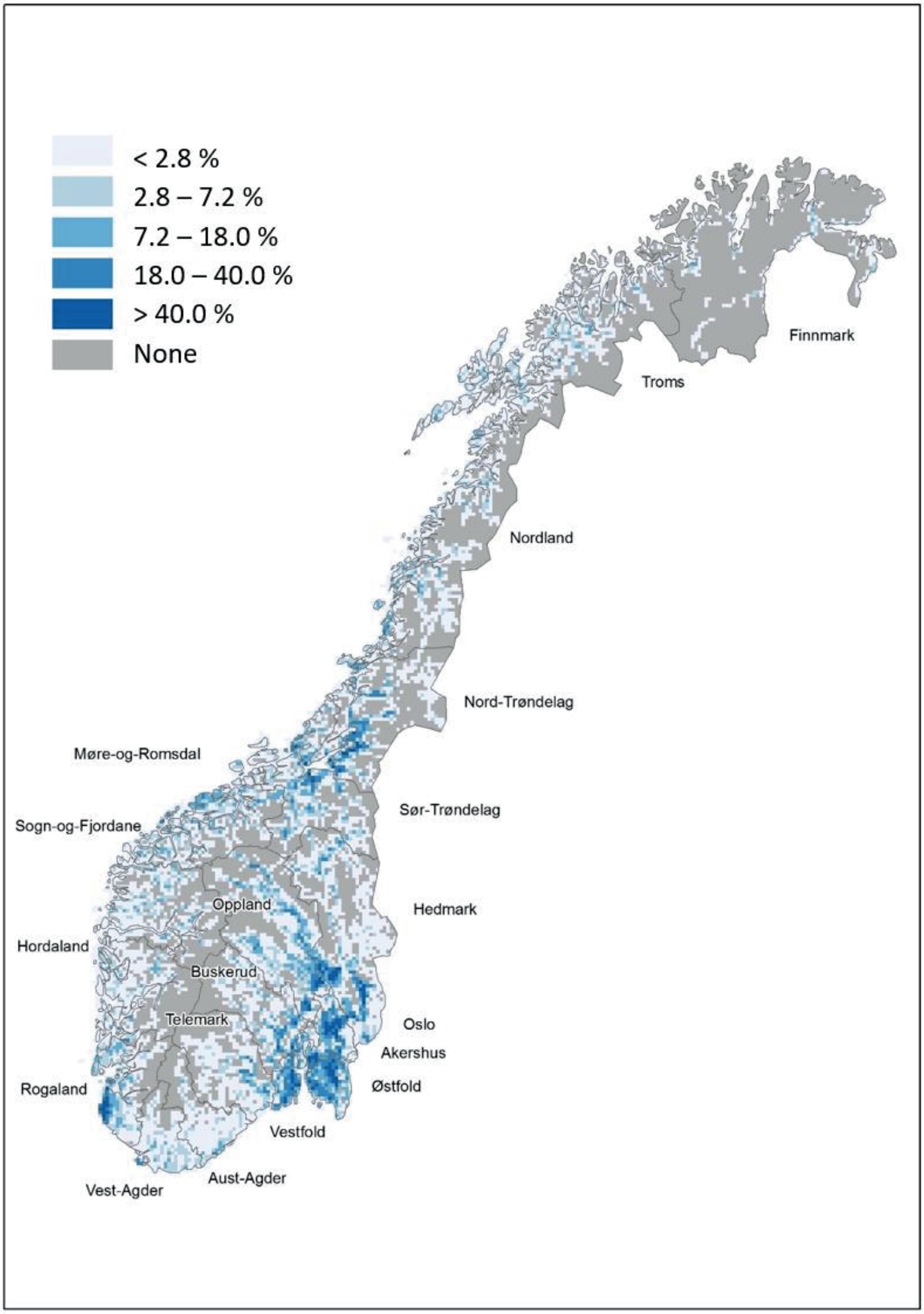

Figure 4: Arable land in Norway in percentage of a 5x5 km grid cell, adopted from Krøgli and Stokstad (2015).

total cereal area, respectively (Statistics Norway, 2019a). In addition to the Boreal zone in the northern part of southeastern Norway, an important share of the cereal growing land is classified as Alpine North in C Norway and as Nemoral zone in SE Norway (Metzger et al., 2005; Statistics Norway, 2019a).

This means that most of the cereal growing land in Norway is climatically comparable to the cereal growing land in the nemoral zone of southern Sweden, southernmost parts of Finland, and most of Estonia (Ahlenius, 2005; Metzger et al., 2005). In the northern part of southeastern Norway, climatic conditions are comparable to most of Finland, Central Sweden and Eastern Estonia, while climatic conditions in C Norway seem to be unique for cereal growing.

Average climatic conditions for C Norway, SE Norway and the country as a whole during standard normal period are shown in Table 1, together with recorded recent climate change and projected future climate change. In addition to higher temperatures, in the future, we also expect increased precipitation during winter and spring, with largest increases in Central Norway by up to 31 % in spring (Hanssen-Bauer et al., 2009). Increased precipitation during winter and spring increases the probability of high soil moisture content in spring and high water supply during plant establishment. Similar increases in temperature and precipitation are projected for the other countries with northern growing conditions (Trnka et al., 2011). Due to largest projected temperature increases in the Boreal zone, which covers major parts of Finland, the latter may expect the overall largest temperature increases in the region.

1.2.2. Land use and limitations

Among the countries with northern growing conditions, Norway is the least attractive for cereal production. Norway is the country with the least percentages of agricultural land, arable land and cereal land compared to the other countries (Table 2). Only 3 % of Norwegian land is in agricultural use, because soils that are unattractive for agricultural use cover most of the country. The two most abundant soil classification groups in Norway are Podsols and Leptosols (Table 2). Podsols are mostly vegetated by coniferous forests, because they are poor in nutrients, have little available moisture, low pH, and thus problems with Al-toxicity (FAO, 2015). Leptosols are shallow soils in mountainous areas, some of which are used for extensive grazing during summer time.

Most of the agricultural land in Norway is not suitable for cereal growing, due to limiting soil conditions. On 46 % of the agricultural land, production is limited by unfavourable topography (slope, field shape and size) or content of coarse material (stoniness), on 54 % it is limited by poor drainage and on 7 % it is limited by negative consequences of land levelling (Lågbu et al., 2018). This can be linked to the characteristics of the most abundant WRB soil classification groups on agricultural land (Table 2). Stagnosols and Gleysols typically have drainage problems, due to high content of marine clay or compacted layers (e.g. plough pan, fragipan, frost or ground moraines) (Sperstad and Nyborg, 2008; Lågbu et al., 2018).

On these soils, there can be high risk for erosion and nutrient leaching, depending on local conditions of precipitation, slope and drainage. On morainic Cambisols, coarse materials can limit cereal production. On Histosols and Umbrisols a high content of organic matter may limit use of machinery and low pH may restrict plant growth.

Table 2: Land use and soil types in countries with northern growing conditions.

	Norway	Sweden	Finland	Estonia
Land area (1000 ha) [a]	30,428.2	41,033.5	30,381.5	4,238.8
Agricultural land [b] (% of land area, 2016)	3.2	7.4	7.5	23.5
Arable land [b] (% of land area, 2010-2016)	2.7	6.3	6.5	14.3
Cereal land [b] (% of arable land, 2010-2016)	35.6	38.6	57.1	52.0
Spring-sown cereal land [b] (% of cereal land, 2010-2016)	92.5	60.2	95.0	71.0
Most abundant soil types [c]	PZ, LP	PZ, LP	PZ, HS	GL, ST, HS
Most abundant soil types on agricultural land (%) [d]	**ST** (28), **CM** (21), HS (8), UM (8), Gl (8)	**CM**, HS, RG, AR	**CM**, **Gl**, **HS**	**CM**, **LV**, Gl, ST, HS, RG

[a] Source: https://www.worldatlas.com/

[b] Sources: Statistics Norway (2019a), Swedish Board of Agriculture (2018), Natural Resources Institute Finland (2018), Statistics Estonia (2018)

[c] Source: Jones et al. (2009)

[d] Sources: Jones et al. (2009), Lågbu et al. (2018), Figure 5 (Ahlenius, 2005), Kasparinskis and Nikodemus (2017); Abbreviations for WRB soil classification groups: Stagnosol (ST), Cambisol (CM), Histosol (HS), Umbrisol (UM), Gleysol (Gl), Regosol (RG), Arenosol (AR), Luvisol (LV); bold means most abundant on arable land

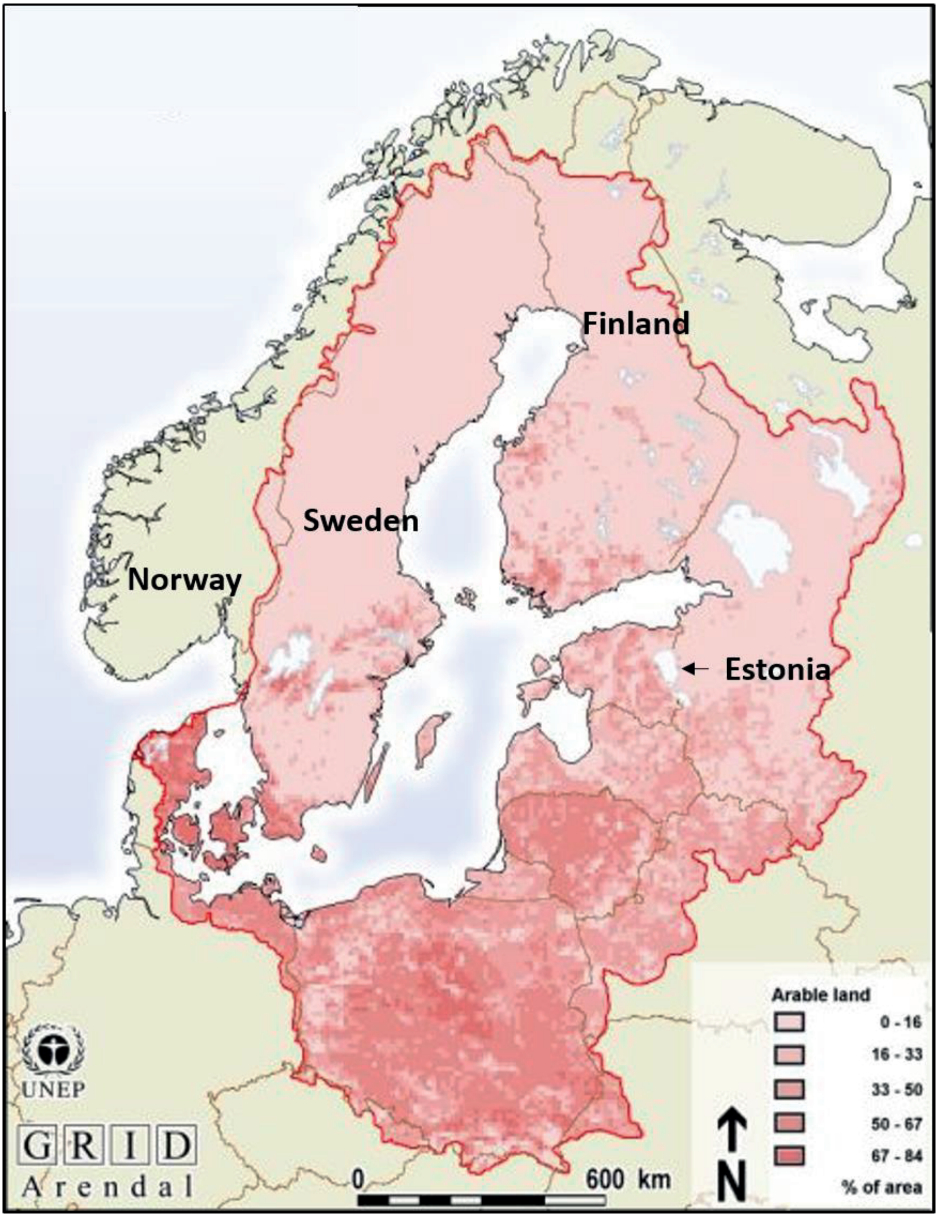

Figure 5: Arable land in Sweden, Finland and Estonia, in percentage of land area, adopted from Ahlenius (2005).

In the future, the described drainage limitations of Norwegian soils to cereal production are likely to persist or increase. Apart from potential limitations, the most important soil types for cereal growing in Norway are Stagnosols and Cambisols, with their typically clay/silt and loam textured topsoils, respectively (Lågbu et al., 2018).

Therefore, the studies in this thesis focus on mineral soils with textures dominated by loam and clay/silt. With an increased probability of high soil moisture content in spring in the future, the spring fieldwork dilemma may be aggravated, especially on Stagnosols of SE and C Norway. The agricultural soils of the other countries with northern growing conditions seem to experience less drainage problems, but this may change with changing climate in the future.

According to Arnoldussen et al. (2014), cereal production on land suitable for cereals is to a small degree also limited by agricultural policies in counties favoured for milk production. Due to the natural growing conditions described above, cereal production is the critical part in Norwegian self-sufficiency and food security (Norwegian Government, 2015) and thus highly prioritised by agricultural policies. Regionally differentiated subsidies and "farm-specific milk quotas, which are tradable only at the county level," are incentives to save the best agricultural land in eastern and central Norway for cereal cropping (Bjørkhaug and Wiborg, 2010; Mittenzwei and Britz, 2018). At the same time, these policies favour milk production in remoter regions irrespective of the soil quality. If remote agricultural land which, based on favourable climate and low erosion risk, is suitable for cereals were to be used for cereal production then the total cereal area could be increased by 3% (Arnoldussen et al., 2014). This calculation assumes good agronomical practice with rotations including oilseed crops and legumes in cereal production all over the country. However, the possible increase may change with a changing climate in the future.

1.2.3. Production systems for cereals in Norway

The majority of cereals in Norway are spring-sown barley, oats and wheat, ordered in decreasing share of land (Statistics Norway, 2019b). The traditional production system for cereals in Norway is autumn ploughing combined with spring sowing (Bechmann et al., 2011). The advantages of autumn ploughing are an improved seedbed quality through the physical influence of freezing-thawing cycles on clay soil (Håkansson et al., 2002) and an improved working capacity and timeliness through the spread of fieldwork over the year. Improved seedbed quality and improved timeliness of fieldwork increases yield potential.

Today, one can find different types of tillage, like autumn harrowing, autumn ploughing, spring harrowing, spring ploughing or direct drilling (Bechmann et al., 2011).

Approximately half of the cereal area is ploughed in autumn, with a slightly decreasing trend, in favour for spring tillage (Tørresen et al., 2012). Autumn harrowing is performed on less than 10 % of the area, while the percentage of direct drilling is negligible (Statistics Norway, 2019c).

Most of the cereal area in Norway is still spring-sown (Table 2), which is similar to the situation in Finland, but a higher percentage than in Sweden and Estonia. There are several reasons for the high percentage of spring-sown cereals in Norway. One of them is that until recently only spring-sown varieties of barley, oats and oilseeds have been available in Norway. A second reason is that Norwegian farmers, like Estonian farmers (Koppel and Ingver, 2008), experience more stable yield quality with spring-sown wheat than with autumn-sown wheat. In practice, this means that a Norwegian wheat flour mixture cannot contain more than 50% winter wheat to obtain baking quality, which limits the demand for winter wheat. Yield quality, especially protein content, is an important governmental consideration because of cereals' critical role in food security, which is reflected in Norwegian agricultural policies and grain prices. Other reasons to favour spring sowing are risks of soil erosion and nutrient leaching from autumn-ploughed sloping land and risk of reduced winter survival on flat areas (Grønlund, 2013).

Winter cereal cropping is usually based on autumn-ploughing (Grønlund, 2013), because ploughing increases drainage of autumn and winter precipitation, reduces infection of fungal plant pathogens from straw residues, reduces perennial weeds and reduces machinery size (Tørresen et al., 2012; Hofgaard et al., 2016). In addition, and probably as a result from the previous factors, under relatively wet conditions farmers often experience better plant establishment and larger yields and higher protein content on ploughed soil compared to direct sowing or reduced tillage (Riley et al., 2009).

However, autumn ploughing, especially when followed directly by seedbed harrowing, increases the risk of soil erosion and nutrient leaching on sloping land, which leads to pollution of watercourses, lakes and seas (Øygarden et al., 2006). Therefore, international agreements on the protection of the sea have been made, with the goal of reducing the inputs of nutrients to the sea (OSPAR Commission, 2019; HELCOM, 2019). These agreements have resulted in national action plans and policies on protection of water. In Norway, one of the priorities to reduce erosion and nutrient leaching from agriculture to watercourses is the reduction of the autumn-ploughed area on land susceptible to erosion (Arnoldussen, 2005). Problems with and measures against erosion and nutrient leaching are similar in other countries with northern growing conditions (Tattari and Rekolainen, 2006; Ulén, 2006; Marine Committee of Estonia, 2008). Together with Sweden, Norway is involved in the "North Sea Declaration", while Sweden, Finland and Estonia are involved in the "Baltic Sea Action Plan".

Norway's water protection policies (Øygarden et al., 2006) resulted in reduction of autumn-ploughed land from 82 % in 1990 to 43 % in 2002, with large annual variation (Bye et al., 2017). In 2010, 54 % of the cropped area in Norway was ploughed or harrowed in autumn (Statistics Norway, 2019c), while 37 % of cereal land was without any plant cover during that winter (Bye et al., 2017).

Concerning erosion and winter survival, which depend on drainage and slope, one third of the land in the best regions in Norway is suitable for winter cereal cropping (Grønlund, 2013). On a national scale, under historical climatic conditions, this would mean that in theory the winter cereal area could be increased to approximately 21 % of the cereal area (Statistics Norway, 2019a and d). However, with the expected increases in winter and spring precipitation and increases in climate variability, erosion risk may also increase in the future and give larger limitations for winter cereal cropping on sloping areas, as well as winter survival may be reduced in flat areas.

Due to steep slopes in general and earlier levelling of silty clay soils on some arable land, there is possibly a higher erosion risk on agricultural land in Norway compared to the other countries (Bechmann et al., 2011). In Sweden, erosion problems are mainly found in southern and central plain areas (Ulén, 2006), and in Finland on coastal plains (Tattari and Rekolainen, 2006). In Estonia, one can find sloping land in end-morainic hills in southeastern areas (of which some were levelled in the 1970´s), on the other hand, land use changes (decrease in arable land) have reduced their importance for erosion (Kask et al., 2006). In the future, with increasing climate variability and generally increasing off-season precipitation, erosion risk from agricultural land may increase also in the other countries with northern growing conditions (Ministry of Agriculture and Forestry of Finland, 2005; Swedish Commission on Climate and Vulnerability, 2007; Ministry of the Environment, 2017).

Resulting from the above, the percentage of autumn-ploughed land will probably decrease also in the future, but most of the Norwegian cereal land will be spring-sown. Reduced tillage methods may increase further on well-drained soil (Øygarden et al., 2006), but use of direct drilling may increase only if plant protection methods can be improved and yields be kept more stable. Therefore, the studies included in this thesis are based on spring-sown cereals with seedbed preparation in spring. This assumption resembles the farming conditions on the majority of Norwegian cereal farms. The ploughing in the studies is assumed to be in autumn in order to facilitate comparison between seedbed preparations at different soil moisture content without confounding effects from the ploughing. However, the effects of seedbed preparation on seedbed quality may be transferred to a farming context with spring ploughing. Compared to Norway, the other countries with northern growing conditions may have better possibilities to adapt their cereal production systems to a changing climate, because of their relatively smaller drainage problems and erosion risk.

1.3. Seedbed preparation for spring cereals

1.3.1. Physical requirements for early plant development

For the farmer, good germination, emergence and establishment of the cereal stand are crucial, because they form the basis for yield potential and economical outcome. Under the assumption that soil temperature is sufficiently high, good establishment of cereal stands requires a good soil structure that balances the interrelated parameters **water supply**, **aeration** and **soil strength** (Currie, 1962; Grable, 1966; Whitmore and Whalley, 2009).

Water supply is an important requirement for imbibition and normal development in seed germination (Bewley et al., 2013), as well as for plant physiological function in general. Plants need water for transport, photosynthesis and other metabolic processes, structure/rigidity, growth (cell division, cell expansion), transpiration, the latter being the most important process of water loss from land plants, as an inevitable result of photosynthesis (Hillel, 2004; Taiz and Zeiger, 2010). Too little water supply in the elongating root leads to reduced cell turgor and difficulties in overcoming soil strength (Bengough et al., 2011) and maintaining nutrient uptake. Too low or too high water supply can lower the speed and degree of germination of spring-sown crops (Alakukku, 2006). Too high water supply is not a restriction for plant growth per se, but leads to reduced aeration. In Norway, the latter is found particularly on silty soils.

Soil aeration is defined as "the exchange of gases between the soil's air phase and the external atmosphere, supplying oxygen to growing roots and microorganisms and removing carbon dioxide (the product of aerobic respiration) " (Hillel, 2004). Oxygen demand in the soil depends on temperature, soil texture, microbial activity and plant growth stage. The germinating seed requires oxygen for respiration and removal of carbon dioxide and other gases (Bewley et al., 2013), as well as plant roots in general require oxygen for respiration and plant metabolism (Taiz and Zeiger, 2010). If the soil is near saturation, oxygen demand easily can exceed oxygen supply, because diffusion of oxygen through water is up to 10,000 times slower than through air (Whitmore and Whalley, 2009). Therefore, in waterlogged conditions, germination and respiration are restricted, emergence is delayed, root growth is restricted, roots are weakened and more prone to drought damage in later growth stages (Dasberg and Mendel, 1971; Whitmore and Whalley, 2009).

Soil strength is defined as "the capacity of a soil body to withstand forces without experiencing failure, whether by rupture, fragmentation, or flow" (Hillel, 2004). Soil strength, or mechanical resistance, can be either positive, by providing anchorage for the plant root system, or negative by constituting mechanical resistance to the growing plant (Bengough and Mullins, 1990), depending on its degree. Transferred to the seedbed, soil strength may be positive by providing contact between seed and soil and thus ensuring water supply. Too high soil strength on the other hand, may mechanically restrict germination, root elongation, coleoptile elongation and emergence of cereals (Collis-George and Yoganathan, 1985; Bengough et al., 2011). Among these processes, restriction of root elongation is the most studied, probably because it applies to plant growth in all developmental stages of most species.

If we disregard expansion into the soil pore system, an elongating root has to weaken its cell wall and overcome the soil's strength at the same time (Hillel, 2004). This is possible because of a physiological mechanism called relaxation of the cell wall and because of the cell turgor in the root cells (Clark et al., 2003; Whitmore and Whalley, 2009). If the soil strength is unfavourably high for the root to deform the soil, root elongation rate decreases, root diameter increases and other morphological changes occur in the root (Bengough and Mullins, 1990; Atwell, 1993; Whalley et al. 1995;

Bingham and Bengough, 2003; Parent et al., 2008; Lipiec et al., 2012; Chen et al., 2014; Hernandez-Ramirez et al., 2014; Pfeifer et al., 2014; Colombi and Walter, 2016; Szatanic-Kloc et al., 2018). As a result, emergence is decreased or delayed (Nasr and Selles, 1995), and the plant develops a shallower root system with potentially less access to water and nutrients (Shah et al., 2017; Colombi et al., 2018). There have also been reported decreases in leaf elongation rates in cereal seedlings because of high soil strength (Bingham and Bengough, 2003; Jin et al., 2015).

Interrelation between water supply, aeration and soil strength

As implied above, the described plant growth restricting parameters are interrelated, with respect to cause, effect and time. For example, a feedback has been described between high soil strength and water uptake/accessibility of water, because root growth is impaired (Colombi et al., 2018) and soil hydraulic conductivity is reduced (Shah et al., 2017). Similarly, too much aeration or inadequate soil strength (too loose seedbed) does not restrict plant growth per se, but can lead to critically low water supply in light and heavy soils, due to poor capillarity and high evaporation (Johnson and Buchele, 1961; Håkansson et al., 2002).

Water supply affects soil strength (Wang et al., 2016). High soil strength can limit root growth under dry conditions, when the plants cannot built up sufficient cell turgor, whilst in saturated soils low aeration can limit root growth under wet conditions, because oxygen supply is reduced which further reduces cell turgor (Håkansson, 2005; Whitmore and Whalley, 2009; Bengough et al., 2011). Both high soil strength and low aeration can be indicators of the same soil compaction process, and yet restrict plant growth during different weather periods of the same growing season.

Water supply, aeration and soil strength, together with temperature, are partially taken into account in models that predict emergence (Guerif et al. 2001; Atkinson et al., 2007) or plant growth in agro-ecosystem dynamics (Maharjan et al., 2018). However, no model exists that considers all of these parameters at the same time.

Due to the interdependency between water supply, aeration and soil strength as restrictions for plant establishment, all of these parameters are dependent upon the interaction between the soil conditions and the weather. Traditionally, in Scandinavian seedbeds for spring cereals, water supply has been the most acknowledged restriction for early plant development, due to its effects on soil strength and aeration, and due to the risk of early summer drought. The importance of water supply restriction is reflected in the existing literature's focus on how to minimise water loss from the seedbed (Henriksson, 1974; Håkansson and von Polgar, 1984; Håkansson et al., 2002; Arvidsson et al., 2012). In order to be able to manipulate water loss from the seedbed, one needs to be aware of the process of soil drying.

The process of soil drying can be divided into three stages with different evaporation rates as described by Lemon (1956) and Qiu and Ben-Asher (2010) amongst others. In the first stage, drainage and evaporation are equally important. In this stage, evaporation proceeds at a constantly high rate, mainly as diffusion of water from filled soil pores, until field capacity is reached (Lemon, 1956). Evaporation is not water-limited in this stage, its rate depending on radiation and atmospheric conditions (available energy at the surface) (Qiu and Ben-Asher 2010). In the second stage, evaporation continues with a falling-rate as a combination of liquid flow (diffusion), vapour flow and capillary condensation, from pores that are incompletely filled with water until the soil surface is dry. Capillary condensation reaches its maximum at approximately -150 kPa (Lemon, 1956). In this second stage, the evaporation rate is dependent upon both the soil water supply, radiation and atmospheric conditions (Qiu and Ben-Asher 2010). In the third stage, evaporation continues at a low-rate, mostly as vapor diffusion through the dry surface layer (Lemon, 1956). Its rate is solely dependent upon soil physical conditions (Qiu and Ben-Asher 2010).

According to Lemon (1956), the farmer has the possibility to counteract soil drying in the first and second stages. In the context of early summer drought, especially in the second stage of drying, this was the intention of the model of the ideal seedbed (Figure 6), described by Heinonen (1985). This ideal seedbed ensures enough water supply for germination by minimising evaporation and maximising capillary water transfer from the subsoil to the seed zone. Evaporation is minimised by creating a relatively large percentage (> 50 %) of small aggregates (~0.6-6 mm) (Figure 7) in the loose layer of the seedbed (usually 4-7 cm deep). Water uptake is maximised by placing the seed on a firm seedbed bottom, also called the basal layer.

With the help of the model of the ideal seedbed, farmers have managed to protect the germinating seed against drought under northern growing conditions. Due to projected future increases in weather variability and in winter and spring precipitation, the concern of traditional early summer drought may be replaced, at least in a certain percentage of years, by a concern for unfavourably high water supply and related oxygen deficiency, during seed germination and early plant growth. At present, in seedbed research for northern growing conditions, there is a lack of literature on how to protect the seed by maximising evaporation from the seedbed.

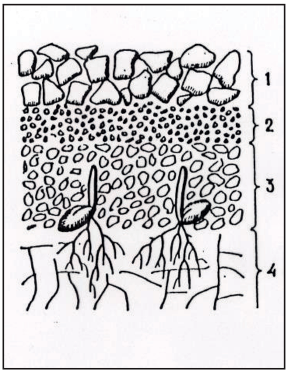

Figure 6: The ideal seedbed with loose layer (1-3) and a firm seedbed bottom (4), adopted from Heinonen (1985).

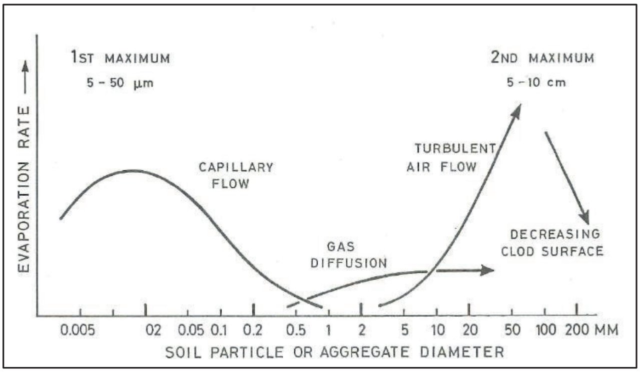

Figure 7: Relative evaporation loss from the seedbed in relation to aggregate size, adopted from Heinonen (1985).

At the same time, the ideal aggregate size distribution, also containing larger aggregates in the loose layer, counteracts surface layer hardening during soil drying, also called crusting. Crusting may restrict seedling emergence because of exessively high soil strength in the surface layer. In the context of early summer drought, crusting is an acknowledged problem in Sweden, especially on soil with high silt content (Håkansson et al., 2002). In Norway, crusting is often a problem on silty clay soils that have been levelled to improve mechanisation, because of their low organic matter content in the topsoil. On clay soil crusting is less pronounced and less frequent (Straume, 1995). However, in the context of high water supply, resulting from future increase in precipitation, crusting is assumed unproblematic in this thesis.

1.3.2. Seedbed preparation

Following from the above intention to provide good seedbed quality with favourable water supply, aeration and soil strength, the next step is the practical execution of seedbed preparation. After autumn ploughing, the purpose of seedbed preparation in spring is to level and fragment the soil in order to provide uniformly favourable conditions for the cereal seedling to germinate and grow.

A suitable moisture content at the start of seedbed preparation is the basic requirement for obtaining a good seedbed quality. The tillage effect of seedbed preparation manipulates the physical conditions of the soil in different ways depending on the soil moisture content at the start of seedbed preparation (Braunack and Dexter, 1989b). Moisture content at the start of seedbed preparation affects workability, and by that friability, fragmentation and compaction risk during seedbed preparation (Figure 8). The resulting seedbed quality can be optimised with the right timing of seedbed preparation with regard to soil moisture content. Thus, seedbed preparation can be regarded as an iterative relationship between machinery and soil conditions, as indicated in Figure 12, which is introduced in section 1.6. The soil conditions determine the timing of seedbed preparation, which in turn determines the soil conditions.

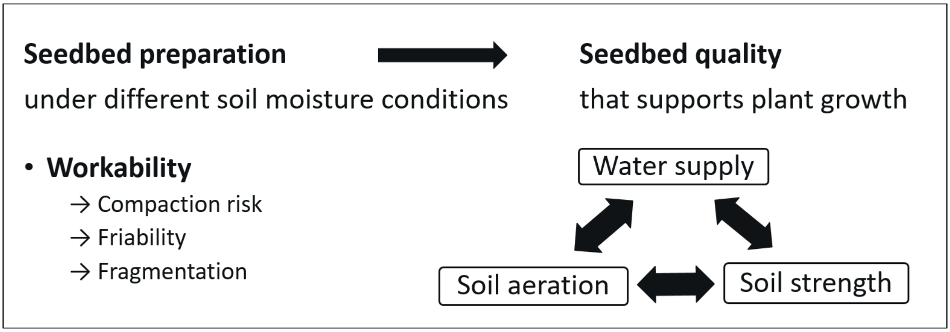

Figure 8: The timing of seedbed preparation with regard to soil moisture content affects the resulting seedbed quality.

The soil's moisture content, or the field water balance, prior to seedbed preparation in spring, is dependent upon precipitation during winter and spring, and upon the duration of snow and soil frost. In addition, it depends upon soil texture, organic matter content, profile characteristics, water holding capacity, hydraulic conductivity, evaporation, infiltration, redistribution, drainage and capillary transfer (Hillel, 2004). In the second stage of soil drying, the most important process of moisture loss is evaporation, which is governed by temperature, humidity, global radiation and wind speed. Numerous methods are used to estimate evaporation and soil moisture content (Monteith, 1965; Ripple et al., 1970; Priestley and Taylor, 1972; Ehlers and Van Der Ploeg, 1976; Yasuda and Toya, 1981; Mwendera and Feyen, 1997; Riley and

Berentsen, 2009). Gravimetric determination of soil moisture content (sampling and drying) is a direct method, but subject to error due to soil variability. Time domain reflectometry (TDR) is an indirect method, but reduces the variability problem as the same soil volume can be measured repeatedly. The most commonly applied method used by farmers to assess soil moisture content prior to seedbed preparation is manual kneading to assess the crumbling of the soil.

The crumbling of the soil tells the farmer whether the soil is workable. Workability describes the soil's readiness for seedbed preparation, depending on soil properties (texture, structure) and moisture content (Dexter, 1988). A soil is considered workable when it is in a state where it easily crumbles and can be tilled without any significant physical soil degradation that could hamper plant development (Rounsevell and Jones, 1993). In this thesis, the term workable also includes that the soil is trafficable, i.e. the soil can support and withstand traffic (Rounsevell and Jones, 1993), based on the assumption of small to moderate ground contact stresses during traffic, as discussed by Rounsevell (1993) and Edwards et al. (2016). The term workability sometimes includes a time element (Thomasson, 1982). A soil that is in a workable state for long periods has a high workability. In practice, such soil is workable in a large range of moisture contents suited for tillage.

If the seedbed preparation is performed within the range of moisture content for tillage, the soil fragments into aggregates that are neither too large nor too small (Dexter and Bird, 2001). In the range of moisture content for tillage, the soil is in a consistency state where it easily crumbles into smaller aggregates (Figure 9) in a favourable manner. This favourable manner is tensile failure, i.e. large aggregates crumble into smaller ones with their microstructure remaining intact (Munkholm and Kay, 2002), i.e. the soil does not fragment further into dust size particles.

The consistency state determines whether a soil is able to crumble, i.e. it is in a friable state (Figure 9). However, the quality of the crumbling depends on the soils friability. A friable soil consists of large aggregates with low tensile strength and small aggregates with high tensile strength (Munkholm, 2013). The larger the difference in tensile strength between large and small aggregates, the larger will be the soil's friability (Utomo and Dexter, 1981). The condition of high friability is in line with the conception of a good soil structure (Koolen and Kuipers, 1989). In addition to their dependency on moisture content, a soil's friability and structure are also effected by texture (Figure 9),

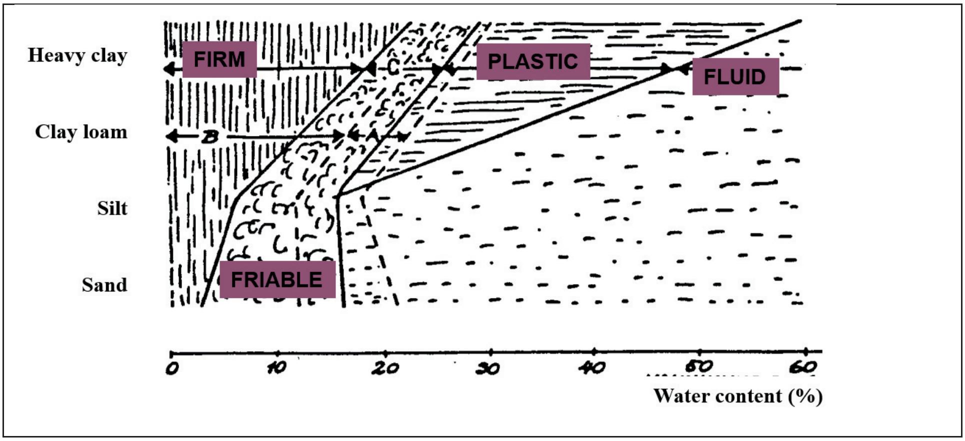

Figure 9: Soil consistency in relation to texture and water content. Recommendations A: small load traffic, autumn ploughing; B: heavy load traffic, PTO-driven harrowing, rolling; C: harrowing, spring ploughing, adopted from Arnor Njøs (unpublished).

organic matter content (Obour et al., 2018), and by earlier traffic and tillage. Therefore, a soil's friability is at its maximum within the range of moisture content for tillage, but it is not necessarily high, depending on the soil's texture and earlier management.

In addition, good soil structure, or a soil with high friability, is often the result of soil drying-wetting, shrinking-swelling and freezing-thawing processes throughout the year (Aluko and Koolen, 2000). Norwegian soils are commonly ploughed in autumn to expose them to such processes during wintertime. These processes are especially important for soil structure and friability in fine-textured soils (Håkansson et al., 2002), such as the Stagnosols dominating in southern parts of Southeastern Norway and Central Norway (Lågbu, 2018).

If the seedbed preparation is performed in soil that is still too wet, the risk of soil compaction arises. Soil compaction is here the process of physical degradation of the topsoil during seedbed preparation, caused by traffic from light tractor and implement with small to moderate ground contact stresses, and by tillage effects from implements in soil which is not workable yet (too high soil moisture content). Here, the term collectively describes a number of physically degrading processes, such as smearing, shearing, kneading, remoulding and compaction, which may occur in the soil under such conditions. This is a simplification to express the general compacting effect of small to medium contact stress on topsoil under conditions with unfavourably high soil moisture to a soil depth of 20 cm.

In addition to soil moisture 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 (Ljungars, 1977; Etana and Håkansson, 1996), all of which are assumed to be constant or negligible in the included studies. Another reason for assuming light implements with small to moderate ground stresses is to separate the effect of compaction on the topsoil from that on the subsoil, as the latter is related to high axle load (Håkansson, 2005; Hamaza and Anderson, 2005).

In addition to soil moisture content during tillage, a given soil's susceptibility to compaction is dependent upon its clay content (Schjønning and Lamandé, 2018). With moisture contents above field capacity, the susceptibility to compaction increases with increasing clay content. This means that the Stagnosols with the highest clay content, found in SE and C Norway, are the most susceptible in this context of early spring fieldwork.

In general, the result of soil compaction during seedbed preparation in excessively wet soil is poor seedbed quality, namely higher soil strength, and consequently lower aeration and unfavourable water supply. Unfavourable water supply could be either waterlogging or reduced water accessibility (Hamza and Anderson 2005; Batey and McKenzie, 2006; Colombi et al., 2018), depending on the precipitation pattern after seedbed preparation. Furthermore, compaction and increased soil strength potentially affect workability, friability and soil structure at the next tillage occasion in autumn (Dexter and Bird, 2001; Munkholm and Schjønning, 2004).

In theory, the soil can also be too dry to obtain an optimum result from seedbed preparation. Depending on the soil type (Figure 9) and earlier management, the result may be large and strong aggregates or large energy use to fragment them. With high energy input, too dry soil is easily pulverised and eroded or turned into a soil crust after the next precipitation event (Braunack and Dexter, 1989a). In these cases, the strength of single aggregates or the crust may be unfavourably high for plant establishment. Such unfavourable soil strength may also affect aeration and water supply (Figure 8).

In general, reduced seedbed quality in Norway is more commonly caused by too wet than by too dry conditions during seedbed preparation. Because of the short growing season, farmers rarely restrict their spring fieldwork to workable conditions.

In practice, farmers sow rather early. They commonly accept some loss of yield potential due to soil compaction in order to avoid larger losses due to delayed sowing. The reason for this is that under average spring conditions, the economic consequences of delayed sowing increase faster as the spring progresses than those of soil compaction decrease as the soil becomes drier (Figure 1). If the moisture content in spring increases in the future, the farmer may be forced to start seedbed preparation under even wetter conditions. Therefore, the studies in this thesis focus on the effects of seedbed preparation under too wet conditions.

The exact starting day of seedbed preparation at a given farm depends on the farmer's individual workability threshold. The workability threshold is the soil moisture content at which the farmer is willing to incur compaction and resulting loss of yield potential in favour of earlier sowing. This individual and rather subjective workability threshold is dependent upon the weather forecast, the soil type's susceptibility to compaction, and the farm-specific number of working days required to complete spring work.

In Norway, seedbed preparation in spring starts as soon as the farmer perceives the soil to be dry enough, i.e. it reaches the workability threshold, in order to exploit as much as possible of the short growing season. Fine-textured soils are ready, i.e. workable and friable, at higher soil moisture content then coarser soils (Figure 9). Occasionally, the topsoil may be workable while the subsoil still is frozen. However, this situation is less common in Norway than on the clay soils of Finland described by the Ministry of the Environment and Statistics Finland (2009). With future increases in winter and spring precipitation, this situation will occur even more seldomly.

The traditional methods for seedbed preparation on autumn-ploughed soil in spring in Norway are similar to those described by Håkansson et al. (2002) in Sweden. Traditionally, seedbed preparation includes furrow levelling, harrowing, sowing and rolling (Morken et al., 2003). The first operation is the fragmentation and levelling of the soil with a land leveller, which has the side effect of slowing down evaporation. Except on morainic and clay soil, this operation is most often omitted today, because the design and functionality of modern harrows and ploughs makes it superfluous, and because seedbed preparation as a whole is done in a shorter time now.

After that, the soil is harrowed with 1-2 passes to a depth representing the target seeding depth (4-7 cm), but also depending on soil type, current soil moisture content and weather forecast. The most common harrow for cereal seedbed preparation is the tine harrow, but more seldomly disc or PTO-driven harrows are used. Traditionally, seeding has been performed with simple and relatively light drag-coulter seed drills at a narrow row spacing (12.5 cm). In recent years, many of the simple seed drills have been replaced by modern disc-coulter seed drills, which are very heavy, especially with maximum loaded hopper. They commonley have press wheels attached at the rear.

The final operation is rolling. The most common rollers in Norway are rollers of the Cambridge type. The objective of rolling is to re-compact the loose layer to ensure seed-soil contact, and to prevent stones from complicating combine harvesting in the following autumn. This is mostly important on morainic soil where it is often practiced even following the use of modern seed drills with press wheels which have the same purpose. In contrast to press wheels, rolling can be postponed or omitted if sowing is done under unfavourably wet conditions.

1.3.3. Assessment of seedbed quality

After the seedbed is prepared, its quality can be assessed in terms of different physical parameters. The quality of these physical parameters determine how well the seedbed covers the requirements for germination and plant establishment, namely water supply, aeration and favourable soil strength.

Soil aeration can be assessed by measurements of oxygen content, oxygen diffusion, or indirectly by measurements of pore size distribution, air-filled porosity, air permeability, pore characteristics or aggregate size distribution.

Soil porosity is the volume of pores relative to the total bulk volume of soil (Kutílek, 2014). Soil pores can, depending on their size, be classified as submicroscopic, capillary or macropores (> 1000 μm, Luxmoore, 1981), with the latter two being important for water flow. Capillary pores are often devided further into mesopores (10-1000 μm) and micropores (< 10 μm). If the pore frequency in general is considered as a smooth function of the pore sizes, it is called the pore size distribution. This function usually is bimodal with one peak for textural pores and one for strucutural pores. The pore size distribution function is the derivative of the soil water retention curve which describes the soil's volumetric water content relative to the matric potential. For aeration, macropores are the most important. Macropore volume can be expressed as air-filled pore volume at field capacity (-10 kPa matric potential most often used in Norway), also called air-filled porosity. Air-filled porosity is an important factor for soil crumbling, soil structure and workability at the next tillage occasion (Obour et al., 2019).

Air permeability is the soil's permeability for air that is forced through it at a certain pressure (Stępniewski, 2014) and at a certain matric potential, e.g. at field capacity (-10 kPa). Due to the close relationship between compaction and aeration (Lipiec and Hatano, 2003), air-filled porosity and air permeability serve as indicators for soil compaction (Nawaz et al., 2013). A compacted seedbed has lower air permeability (Sanchez-Giron et al., 1998) and less air-filled porosity (Braunack et al., 1979).

The soil pore characteristics are descriptions of the pores' continuity, tortuosity, or organisation. For example, pore organization indices relate air-permeability to air-filled porosity (Ball, 1981; Groenevelt et al., 1984) at a certain matric potential (e.g. -10 kPa).

Aggregate size in the seedbed affects aeration (Braunack and Dexter, 1989a, 1989b), air-filled porosity (Voorhees et al., 1966) and air permeability at constant level of compactness (Lipiec, 1992, cited in Lipiec and Hatano, 2003). If one assumes a more or less direct linear relationship between pore size and aggregate size, also aggregate size distribution can be considered as an expression of aeration conditions. Aggregate size distribution is the frequency of aggregates relative in pre-defined aggregate size fractions, which can be expressed by different parameters, e.g. percentage of specific aggregate size fractions, the mean weight diameter (MWD) or the geometric mean diameter (GMD), as described by Diaz-Zorita et al. (2000).

Soil strength can be assessed by measurements of penetration resistance, bulk density, aggregate tensile strength, shear strength, modulus of rupture, or more indirectly by aggregate size distribution. In such soil strength assessment it is important to compare soils with equal moisture content, texture and organic matter content, because these factors affect soil strength (Bathke et al., 1992).

Penetration resistance is the soil's resistance to penetration a measuring device called penetrometer. This is considered to reflect the root's ability to penetrate the soil, and is called penetrability (Arriaga et al., 2014). The bulk density of a soil is the ratio of total mass of solids to sample volume, and hence related to texture and porosity of the soil. High soil strength, specifically penetration resistance or bulk density are used as indicators for soil compaction (Bachmann et al., 2006; Arriaga et al., 2014; Shah et al., 2017).

Aggregate tensile strength is the maximum load an aggregate is able to withstand without cracking (Dexter and Kroesbergen, 1985). This parameter is important for root elongation and morphology. If the elongating root is not able to overcome the particular aggregate's tensile strength, it has to grow around the aggregate. As described earlier, the relationship between tensile strength of different aggregate sizes in a given soil volume can be expressed as the soil's friability. In addition to being a requirement for seedbed preparation, friability can be regarded as a result from it, and assessment of how well this requirement is fit on the next tillage occasion, as reviewed by Obour et al. (2017).

In seedbeds with larger aggregates, there has been measured larger penetration resistance (Misra et al., 1988). Therefore, aggregate size distribution, as described above, may indirectly be used to get an impression of changes in soil strength.

Water supply in the seedbed is affected by tillage in general (Minhas et al., 1986; Sillon et al., 2003; Schwartz et al., 2010) and seedbed preparation in particular (Mwendera and Feyen, 1994). Evaporation, infiltration, internal drainage and capillary supply are affected by aeration and soil strength (Johnson and Buchele, 1961; Benoit, 1973; Currie, 1984). This means that water supply in the seedbed can, in addition to direct measurements of soil moisture content, and saturated or unsaturated hydraulic conductivity, be related to the parameters mentioned under soil aeration and soil strength.

Soil moisture content should be measured at seeding depth or as a mean of the loose layer of the seedbed, because the moisture content can vary a lot within the seedbed during the second stage of soil drying. With regard to measuring time, soil moisture content during germination and emergence of the cereals are the most relevant in this seedbed context.

Due to the interrelation between the plant growth requirements, many seedbed quality parameters can be used to assess several or all of them, at least indirectly. For example, aggregate size affects evaporation, infiltration, internal drainage and capillary supply. Evaporation increases with increasing aggregate size (Figure 7) (Heinonen, 1985; Braunack and Dexter, 1989b; Håkansson et al., 2011). Infiltration and internal drainage are controlled by the soil's saturated hydraulic conductivity (Hillel, 2004), which increases with increasing aggregate size and increasing air-filled porosity (Benoit, 1973; Kuncoro et al., 2014). Capillary supply, on the other hand, decreases with increasing aggregate size. Hubbell (1947) and Holmes et al. (1960) showed that larger aggregates result in slower capillary rise.

Another example is the effect of compaction on evaporation, infiltration, internal drainage and capillary supply. Compaction leads to less aeration, less gas diffusion and less vapour convection (Currie, 1984) and consequently less evaporation (Johnson and Buchele, 1961). A compacted layer reduces infiltration and internal drainage, because the profile's layer of least conductivity controls these processes (Hillel, 2004). Therefore, compaction at the seedbed bottom or below can reduce the profile's porosity, air permeability (Berisso et al., 2012; Chen et al., 2014) and saturated hydraulic conductivity (Horn et al., 1995), and hence its infiltration and internal drainage. In like manner, Stenberg (2000) observed higher moisture content in a compacted seedbed compared to a seedbed with a loose bottom. From compacted soil, in terms of soil with less porosity and permeability, one expects greater capillarity (Stenberg, 2000).

Critical limits

In practice, there are no universal critical limits of those physical parameters affecting plant growth in soil, because such limits depend on soil type (texture, SOM), oxygen demand (temperature, microbial activity), cultivation system and growth stage (Collis-George and Yoganathan, 1985; da Silva and Kay, 1997; Bartholomeus et al., 2008; Reichert et al., 2009). Despite these dependencies, researchers often assume critical limits of physical soil properties for feasibility's sake.

For plant growth in general, the two most commonly accepted critical limits are a penetration resistance of > 2MPa and an air-filled porosity of < 10 % measured at -10 kPa matric potential, for example used within the concept of the least limiting water range (Reichert et al., 2009; Chen et al., 2014; Safadoust et al., 2014; Keller et al., 2015). The latter was proposed by da Silva et al. (1994) to describe a soil's physical quality for crop growth by combining soil strength, aeration and water supply (Figure 10). The least limiting water range is "the range in soil water content in which limitations for

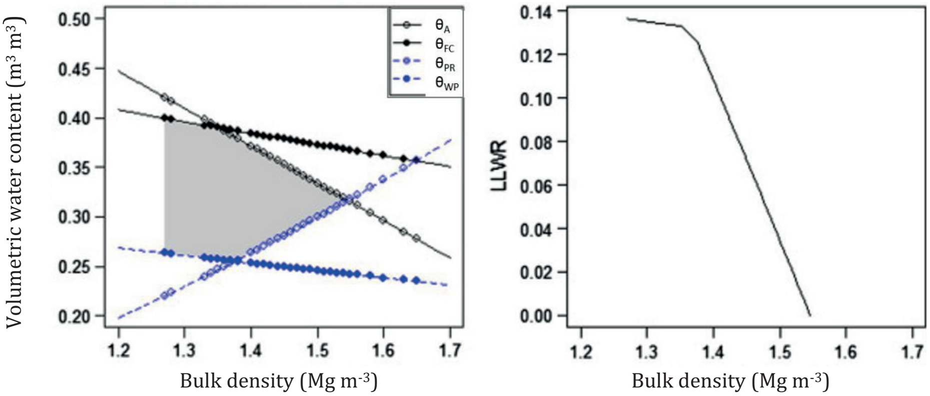

Figure 10: The least limiting water range (LLWR) describes a soil's physical quality, dependent on bulk density, within the boundaries of field capacity (θ_{FC}), wilting point (θ_{WP}), penetration resistance (θ_{PR}) and air-filled porosity (θ_{A}). The shaded area represents the water content at which plant growth is restricted neither by soil moisture content nor by aeration når by soil strength. Adopted from de Lima et al. (2016).

plant growth associated with matric pressure, aeration, and mechanical resistance are minimal" (da Silva et al., 1994).

Compared to plant development in general, critical physical limits during the earliest stages of plant development may differ markedly. For example, Collis-George and Yoganathan (1985) found critical soil strength limits of > 3.0, 2.3, 1.7 and 0.8 MPa during germination, root elongation, coleoptile elongation and emergence early of cereals, respectively.

In addition to penetration resistance and air-filled porosity, critical limits have also been proposed for bulk density, macro porosity, saturated and unsaturated hydraulic conductivity and air permeability (McQueen and Shepherd, 2002), all of which are used as indicators for one or several of the soil physical parameters soil moisture, aeration and soil strength. For example, Riley (1988) found that the critical limit of 10 % air-filled porosity agrees quite well with an air permeability of 3 μm^2. Due to the consensus about critical limits not being universally applicable, measurements of the physical parameters should be interpreted as relative to earlier measurements, reference treatments or similar and supplemented with assessments of plant development. For, at least partially, improved comparability to other studies, such measurements should always be accompanied by descriptions of soil type, sampling time, cultivation system, and plant growth stage.

1.3.4. Consequences of seedbed quality

The first non-destructive possibility to assess the effect of seedbed quality on plant establishment is at the time of emergence. There are several aspects of emergence that may be affected differently by seedbed quality. Thus, for the farmer it is important that the cereal stand is established as rapidly, uniformly and completely as possible. These aspects can be assessed by an emergence time course of the plant stand, which can usually be described by a sigmoid curve, similarly as practiced for germination in Bewley et al. (2013). Different equations may be used to fit such emergence time courses, for example, the logistic, the Richards, the Weibull, or the Gompertz growth curve. The latter describes the cumulative percentage of emerged seedlings as

$$y = \alpha e^{-e^{(\beta-\gamma x)}}$$

, where x is the time in number of days after sowing, and α, β and γ are parameters that need to be estimated for the given data. Those parameters determine the shape and placement of the curve (Figure 11). From the fitted curve one can extract the speed of emergence as the x-value at inflection point (β/γ), the uniformity of emergence as the slope at inflection point ((α*γ)/e), and the degree of emergence as the maximum y-value (α).

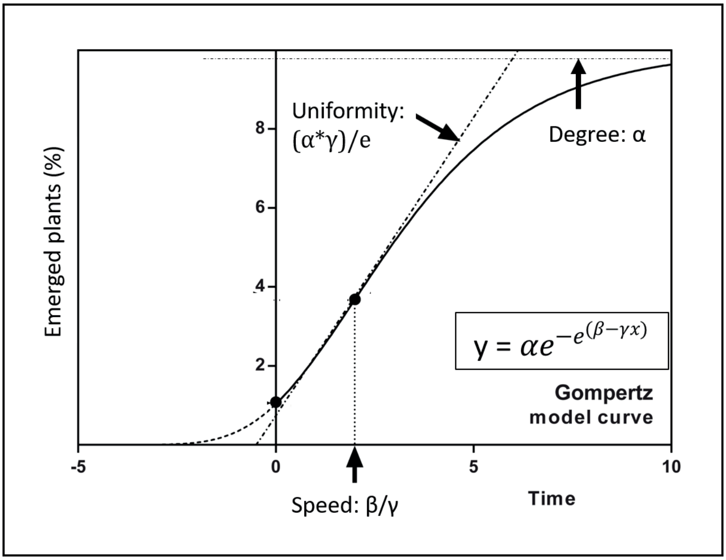

Figure 11: Example of a Gompertz growth curve, which can be fitted to cumulative emergence (%) of a cereal stand in relation to time, adopted from Tjørve and Tjørve (2017).

Another possibility for assessment of plant response to seedbed quality is to record the cereal yield in autumn, but recorded yield may or may not resemble the physical conditions during plant establishment in spring. Cereals have a great capability to compensate for limitations during establishment by a number of yield-forming components, especially those that contribute to the number of grains per square meter (Peltonen-Sainio et al., 2007), i.e. number of tillers, spikes per plant, spikelets per spike and grains per spikelet. Thus, the recorded yield depends on the combination of specific weather and management conditions in all growth stages throughout the season.

Resulting from the inconsistent relationship between physical seedbed conditions in spring and the recorded yield in autumn, a special type of theoretical yield potential has been used in several of the studies included in this thesis (termed “risk of yield loss” in Paper II and “attainable yield” in Paper IV). The yield potential here differs from the use of the term elsewhere by representing just this part of the yield potential that is provided by seedbed preparation, as reflected by Figure 13 (introduced in section 1.6.). That means that the yield potential in this thesis is solely depending on the timeliness of the seedbed preparation, while disregarding other factors (climate or management) which elsewhere are involved in formation of yield potential throughout the crop growing season.

Timeliness is “the quality of happening at exactly the right time” (OALD). In the context of this thesis, timeliness expresses whether the seedbed preparation is done when the soil is workable, i.e. no soil physical degradation from tillage or traffic on still too wet soil occurs, and there is enough time left for crop development, i.e. no delayed sowing which shortens the growing season (Riley, 2016).

In this context, delayed sowing means sowing after a predefined optimum sowing date after which there is a loss of yield potential. With this theoretical approach, adopted from Riley (2016), losses due to delayed sowing will reach 100 % at some point. However, in practice, there will always be some kind of yield potential left, because the farmer will probably adapt to extreme conditions by short-term changes in crop or cultivation system.

Resulting from the timeliness of the seedbed preparation, the theoretical yield potential would give the farmer a certain economic income. Expressed in economic terms, seedbed preparation in too wet soil would produce timeliness costs (NOK), because of the risk of yield loss due to soil compaction. Similarly, seedbed preparation that is delayed further than a given theoretically optimum sowing date would produce timeliness costs because of the risk of yield loss due to a shorter growing season.

If the farmer were able to complete seedbed preparation in one day, namely at the optimum sowing date, timeliness costs would be minimal. In Norway, farmers need commonly about 10 workdays to complete the seedbed preparation in spring. Except for farm size, the most important factor that determines the number of days needed is the working capacity of machinery and men (Mangerud et al., 2017). This working capacity expresses the daily area where the whole seedbed preparation (levelling, harrowing, sowing, rolling) can be completed, for a given farm mechanisation and work force. This is a theoretical capacity since the farmer rarely completes all seedbed preparation operations on that area in one day. The different operations may be prioritised differently and different fields on a farm may be ready for tillage at different times. Thus, the working capacity rather expresses an average for the entire spring fieldwork period. Working capacity of machinery is depending on implement width, operation speed, field size and field shape (Riley, 2016).

The working capacity of machinery can be increased by increasing tractor and implement size or by increasing the number of tractors and drivers at work. A large working capacity increases the chance to complete spring work with minimum timeliness costs, but is also associated with high machinery costs (Elliot et al., 1977; Witney and Oskoui, 1982; Søgaard and Sørensen, 2004; de Toro, 2005). Thus, the reduction in timeliness costs needs to be balanced with the increase in machinery costs that are related to spring fieldwork.

Mechanisation management describes here the choices of machinery and implement purchase and their use in spring fieldwork. With the aim of profitability, these choices ought to minimise the total costs involved in spring fieldwork. Mechanisation management includes considerations on how working capacity relates to farm size, average climatic availability of workable days in spring, timeliness and yield potential. Thus, mechanisation management is an iterative process that affects and is affected by spring fieldwork timeliness, as reflected in Figure 12 (introduced in section 1.6).

Total costs are the sum of machinery costs and timeliness costs related to spring fieldwork, adopted from Mangerud et al. (2017). The total costs are dependent upon depreciation, interest, fuel costs, labour costs, cereal price, farm size and timeliness costs. As timeliness and timeliness costs depend on soil type and climate, also total costs and mechanisation management are dependent upon soil and climatic conditions. In the future, the farm-specific total costs and mechanisation management may therefore be influenced differently by climate change under local soil conditions.

1.4. Possible adaptations of seedbed preparation to climate change

Within the context of seedbed preparation for spring cereals in Norway, the projected climate change may more frequently increase the farmers' willingness to incure soil compaction and by that reduce their yield potential. In order to avoid further yield loss in those years, farmers may adapt to wetter conditions, as discussed in the following three chapters, by:

(1) Adjusting time and traffic intensity of spring fieldwork operations in order to **minimise soil physical degradation** under unfavourably wet conditions (Paper I, Paper II).
(2) Creating a seedbed that can cope with more precipitation by **maximising moisture loss** after sowing (Paper III).
(3) Adjusting **long-term farm mechanization** management (Paper IV).

1.4.1 Minimum soil physical degradation

As summarised by Riley (2016), some international and Norwegian research exists on the relationship between timing of spring fieldwork and yield potential. Riley (2016) attributed the yield reducing effect of early tillage in unfavourably wet soil to topsoil compaction. All of these processes included in topsoil compaction impair the soil's structure and agronomic value, by changing a number of soil physical properties.

The most extensively studied physical property in the seedbed is the aggregate size distribution. After seedbed harrowing under unfavourably wet conditions in early spring, Tisdall and Adem (1986) and de Toro and Arvidsson (2003) reported larger aggregate sizes compared to later tillage under drier conditions. Apart from aggregate size, our knowledge is sparse about effects of unfavourably wet seedbed preparation in spring on other physical properties. For primary tillage, Watts et al. (1996) measured increasing tensile strength and content of dispersed clay (particles < 0.7 µm) in large aggregates (13-19 mm diameter), with increasing soil water content above plastic limit during primary tillage in autumn. Similarly, Munkholm and Schjønning (2004) studied high traffic intensity and high tillage intensity in wet soil (around field capacity, -100 hPa) in early spring, followed by secondary tillage later in spring. They reported increases in aggregate size, and larger aggregate density, aggregate tensile strength and penetration resistance, compared to soil on plots that only received conventional seedbed preparation.

In the latter study, as in most previous experiments on traffic intensity or soil compaction in wet soil in early spring, the seedbed harrowing and sowing operations were conducted later in spring and at the same time for all treatments. A reason for this may be that researchers have been apprehensive of differences in other soil properties caused by increasing temperature later in spring, or, if the yield response was measured, of confounding the early traffic treatment with the advantage of a lengthened growing season.

In addition, the persistence and implications of structural soil degradation during wet spring fieldwork remain unclear. In some studies, topsoil compaction in general has been shown to persist for several years (Håkansson et al., 1988). In the case of intensive tillage (Munkholm and Schjønning, 2004), the effect on aggregate tensile strength has been reported to last until the following autumn, but we do not know whether, for instance, structural degradation of soil during wet spring fieldwork may affect workability of the soil in the following autumn (Obour et al., 2017).

1.4.2 Maximum moisture loss after sowing

In contrast to the traditional approach to seedbed preparation, we need to explore how to increase moisture loss from the seedbed, in order to adapt to wetter soil moisture conditions in the future. This may possibly be achieved by creating seedbed characteristics that are opposite to those of the ideal seedbed, namely larger aggregates and a less compact seedbed. According to studies with narrow ranges of aggregate sizes reviewed by Heinonen (1985), larger aggregates in the seedbed would in theory increase evaporation by increasing turbulent airflow (Figure 7). In field trials by Stenberg (2000), a loose seedbed bottom resulted in a lower moisture content in the seedbed.

Furthermore, we need to explore which kinds of implement can create these seedbed characteristics and thus give good germination at high soil moisture contents.

In recent years, many farmers have replaced their traditionally light mechanisation with disc harrows and large and heavy seed drills with press wheels. Since press wheels are used to maximise water supply to the seed, the suitability of such modern seed drills under excessively high moisture conditions is questionable.

1.4.3 Long-term farm mechanization management

Many studies on the impact of climate change project positive effects on Northern European agriculture in general and sowing time specifically (Carter et al., 1991; Olesen and Bindi, 2002; Parry et al., 2007; Peltonen-Sainio et al., 2009b; Bindi and Olesen, 2011; Harding et al., 2015; Persson and Kværnø, 2017). However, a longer thermal growing season does not necessarily facilitate earlier sowing of spring cereals (Menzel et al., 2006; Maton et al., 2007; Van Oort et al., 2012). In general, the dynamic crop simulation models used in most of these studies, consider soil water content, but not as a limitation for workability and sowing in spring, or its effects on soil structure and profitability. As a result, the simulated yield potentials do not capture potential losses due to delayed sowing or topsoil compaction.

In addition, if the simulated yield potential for the growing season is based on unrealistically optimistic sowing dates, it may be overestimated. Yield potential is strongly dependent on weather conditions throughout the different phases of the crops phenological development and on the interaction between sowing date and weather (Kirby, 1969; White et al., 2011; Peltonen-Sainio and Jauhiainen, 2014; Dobor et al., 2016). In order to assess possibilities to adapt to future climate change and avoid loss of yield potential, simulations should resemble realistic management practices (Bergez et al., 2006) and consider soil workability in spring and potential timeliness costs.

Based on studies on the impact of climate change in other parts of Europe (Rounsevell and Brignall, 1994; Cooper et al., 1997; Eitzinger et al., 2013) and Midwestern US (Tomasek et al., 2017), one would expect fewer available workable days for spring fieldwork in Scandinavia in the future. In contrast to this expectation, the few available Scandinavian studies project improved future workability (Trnka et al., 2011; Rötter et al., 2011, 2012, 2013). However, none of these studies fully considered increased soil moisture in spring.

If the projected increase in precipitation results in an increase in soil moisture content in spring, thus impairing the soil's workability for seedbed preparation, farmers may have to re-evaluate their machinery's working capacity and costs, and consider changes in farm mechanization management. With a constant working capacity, fewer workable days result in an increase in loss of yield potential, either due to topsoil compaction or delayed sowing, or both. In any case, this loss of yield potential, in economic terms called timeliness costs, will affect the farm profitability. Changes in profitability may influence farmers' decisions regarding long-term mechanization management. This can be regarded as an adaptation to climate change, where it is important to balance between soil protection and profitability. Until now, no study has related future climate change and its associated workability to farm mechanization management.

1.5. Research objectives and hypotheses

Resulting from the above outlined knowledge gaps, the overall objective of this thesis is to reassess the traditional approach to seedbed preparation for spring cereals in Norway in the light of future climate change, and to explore whether climate change would aggravate the dilemma that farmers have concerning topsoil compaction versus delayed sowing.

As derived above, we need more detailed knowledge on how seedbed preparation under unfavourably wet conditions impairs the physical properties of the seedbed in spring. In addition, there is a need for knowledge on the persistence and practical implications of such degrading effects. Therefore, the objective of Paper I was to quantify the effect of sowing date (soil moisture) and traffic intensity on different soil physical properties, yield and autumn workability. It was hypothesised that early seedbed preparation and high traffic intensity would impair the physical seedbed quality, in terms of larger and stronger aggregates, increased penetration resistance, and impaired pore characteristics.

The objective of Paper II was to study the effect of timeliness and traffic intensity on soil physical properties in spring and the following autumn, and on yield potential. In this paper, it was hypothesised that early seedbed preparation and high traffic intensity would impair the physical seedbed quality, in terms of unfavourable aggregate size distribution in spring, unfavourable pore size distribution and larger penetration resistance in autumn, and reduced cereal yields. In addition, it was hypothesised that delayed sowing would reduce cereal yield. The relationship of aggregate size distribution to other soil physical properties was explored.

Further, there is a need to explore whether we can increase moisture loss from the seedbed after sowing by creating larger aggregates and a less compact seedbed, and to find with which kind of implement we can achieve this. Thus, the objective of Paper III was to compare contrasting mechanization alternatives for seedbed preparation in Norway in a field experiment under excessively high moisture conditions, with regard to their applicability, the obtained seedbed moisture content and plant responses. Within this paper, it was hypothesised that unfavourably wet conditions during seedbed preparation and heavy machinery would create seedbeds with larger aggregate size, larger penetration resistance, impaired aeration indicators, and impaired cereal emergence. It was expected that heavy mechanisation, representing modern seed drills, would be less suitable. However, it was also expected that larger aggregates in general would result in lower soil water content in the seedbed during emergence and early growth.

As outlined earlier, studies on the impact of climate change on workability and cereal yield have not fully considered increased soil moisture content in spring. In addition, changes in workability need to be related to profitability and farm mechanisation management. Therefore, the objective of Paper IV was to simulate the impact of projected climate change on workability, yield potential, timeliness costs and long-term farm mechanization management in the future in two contrasting cereal-growing regions in Norway. It was hypothesised that the projected climate change would aggravate the timing of spring fieldwork, in terms of reduced soil workability for spring fieldwork, reduced yield potential, increased timeliness costs, increased total costs and a demand for increased working capacity, i.e. larger number or size of tractors and implement and labour input.

1.6. Thesis structure and delimitations

In Norway, cereal seedbed preparation is adapted to climatic conditions, natural soil conditions and political considerations (Figure 12), as described in earlier parts of this introduction. Within these boundaries, the farmer manages agronomical activities to obtain good soil physical quality that supports plant growth. Based on the projected climate change, this thesis focuses on the influence of wet conditions on the physical quality of the seedbed, the consequences for plant establishment and yield potential, and possibilities for limiting such consequences by adjusting timing and traffic intensity of seedbed preparation and farm mechanisation management.

In this context, farm mechanisation management considers factors that are important for spring fieldwork timeliness, plant establishment and its resulting yield potential. Thus, the work of this thesis is delimited within the spring period (Figure 13), with the exception of the recorded cereal yield in one of the field experiments. All of the included papers consider the effects of seedbed preparation on soil physical quality and plant establishment (Figure 12).

The four papers complement each other in several ways. Paper I, Paper II and Paper IV concern the effect of high soil moisture content during seedbed preparation on the physical seedbed quality, while Paper III further relates these effects to water supply after seedbed preparation. Paper II and IV proceed from plant establishment to the theoretical concept of yield potential. Paper IV encompasses everything marked as relevant in Figure 12, by also including economic consequences and mechanisation management. In addition, the studies complement each other through their differences in climate, soil conditions and aspects of machinery use, as described in the following section.

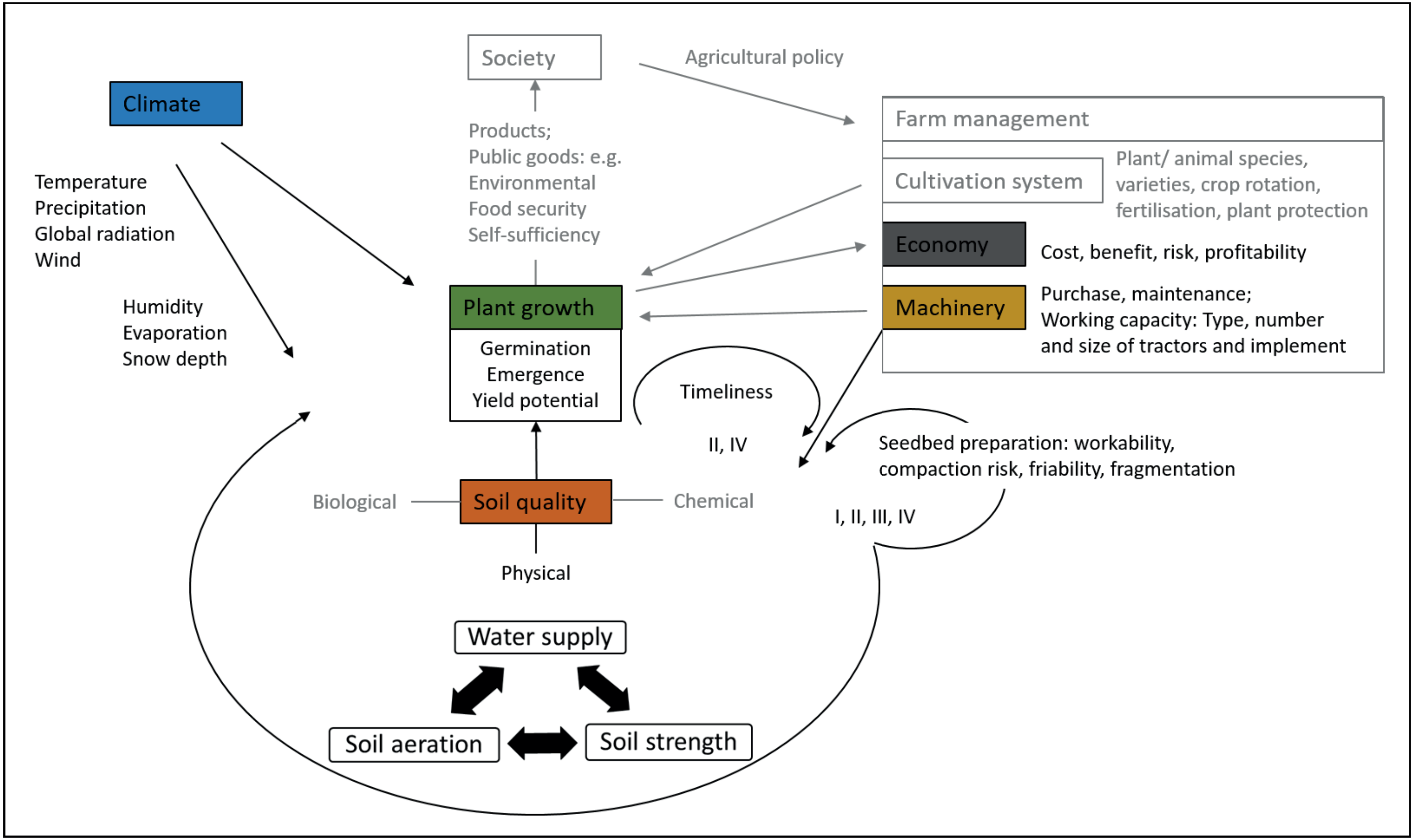

Figure 12: Delimitation of this thesis in a wider agronomical context of factors related to soil, plant, climate, society, and farm management. Relevant topics are marked black. The topical placement of the included papers is indicated with roman numerals.

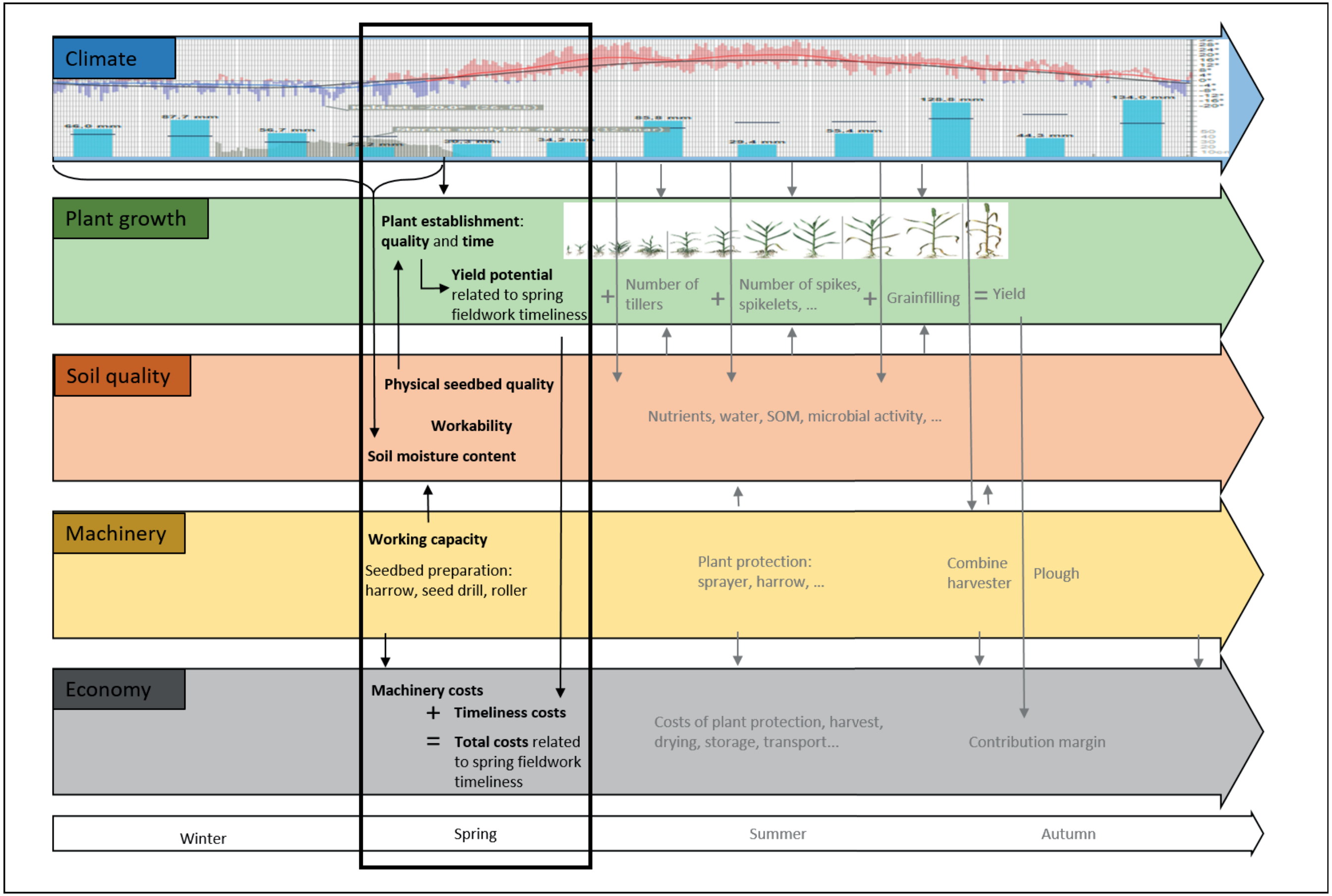

Figure 13: Timewise delimitation of this thesis' work within the cereal production year, with relevant factors marked black. Illustrations adopted from www.yr.no and www.plantekultur.no.

2. Material and methods

Table 3: Main features of the studies included in this thesis.

	Field experiments		Simulation study
Year	2014-2017	2016	Baseline and 2046–2065
Site	Ås	Blæstad (B1, B2), Solør (S)	Ås, Værnes
Region	SE Norway	NE Norway	SE, C Norway
Soil type [a]	3	2, 3	(1), 2, (3), 4
Dimension	Full size implement, 4.5 Mg tractor, 150 kPa tyre inflation, 24 plots à 3.75 x 12 m	Test implement, at each site 18 plots à 1.25 x 12 m, in between tractor and implement wheels	Empirical-statistical models at farm level: **Workability model**, assuming 2.5-3.5 Mg tractor with 80-120 kPa tyre inflation; 38 + 1787 simulations **Mechanisation model**, 564 simulations
Design	Split plot	Complete block	**Test case:** selected farm scenario, complete climate screening **Examples**: range of farm scenarios, selected climate scenarios
Reps [b]	2 (main), 6 (split)	3	300 years per simulation
Rando-misation	Main plots, split plots within main plots	B2: completely; B1&S: partially (treatments)	Years within one simulation
Factors and levels [c]	**Sowing date** (Main): early (60-104 %FC), medium (56-74 %FC), late (52-78 %FC) **Traffic intensity** (Split): 1-3 wheelings	**Sowing date**: early (B1&B2: 96 %FC; S: 103 %FC), medium (B1&S: 83 %FC; B2: 74 %FC) **Mechanization**: light (0.27 Mg m^{-1}), heavy (1.1 Mg m^{-1}), Xheavy (2.0 Mg m^{-1} rolling)	**GHG emissions scenario**: SRA2, (SRA1B), SRB1 **GCM**: IPCM4, (MPEH5), (INCM3), (HADCM3), (GFCM21), NCCCSM **Working capacity**: 2.5 -20 ha day^{-1} **Farm size**: 15-180 ha
Responses	**Soil physical properties**: Aggregate size distribution, aggregate tensile strength, friability, penetration resistance, bulk density, air permeability, pore size distribution, pore organization, water content for tillage **Cereal yield**: Actual yield, yield potential	**Soil physical properties**: Aggregate size distribution, penetration resistance, bulk density, pore size distribution, air permeability, moisture at emergence **Barley emergence**: Speed, uniformity, degree	**Soil physical property**: Workability **Cereal yield**: Risk of loss of yield potential **Economic properties**: Timeliness costs, total costs
Paper	**Paper I** and **Paper II**	**Paper III**	**Paper IV**

[a] Description of soil type groupings in Table 4.

[b] Replications

[c] Abbreviations: Soil moisture content at sowing presented as percentage of field capacity (FC). Greenhouse gas (GHG) emissions scenarios. Global climate models (GCMs).
GHG emissions scenarios and GCMs in parentheses were additionally included in preliminary screening with test case farm conditions.

2.1. Localisation of the studies – climate and soil type

The experimental work represented in this thesis consists of two different types of field experiment and a simulation study (Table 3). The study sites in both the field experiments and the simulation study (Figure 14) represent important cereal-growing regions and the location choices in the studies attempted to cover the large diversity in climate and soil types in these regions.

In field experiment 1 and the simulation study, Ås represents the most favourable climatic conditions (Paper I, Paper II, Paper IV) in the southern part of southeastern Norway (SE, Figure 14), which is classified as nemoral/boreal by Metzger et al. (2005). In the same studies, Værnes represents the least favourable climatic

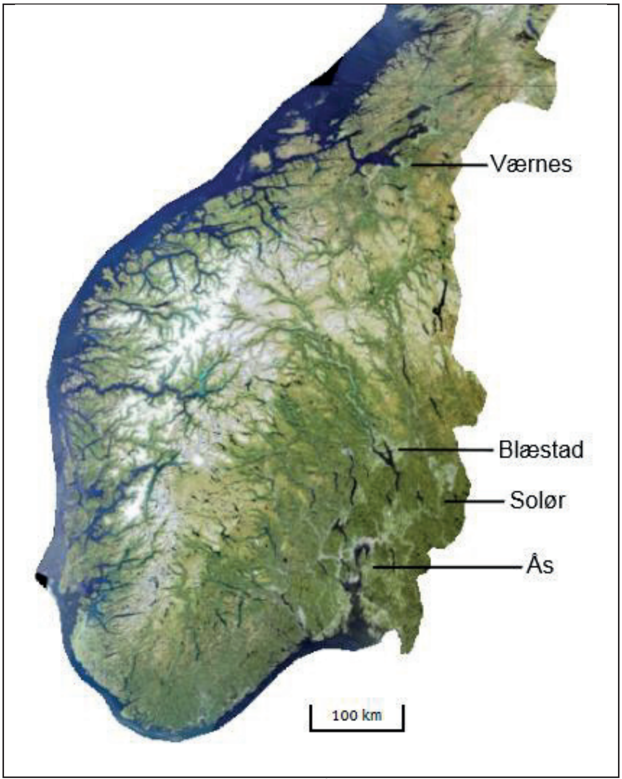

Figure 14: Location of study sites Ås (field experiment 1 in **Paper I** and **Paper II**, representing the southern part of southeastern Norway in simulations in **Paper IV**), Blæstad (field experiment 2 in **Paper III**), Solør (field experiment 2 in **Paper III**) and Værnes (representing central Norway in simulations in **Paper IV**). Created at http://www.norgeskart.no.

conditions (Paper IV) in central Norway (C), which are classified as alpine north by Metzger et al. (2005). In field experiment 2, Blæstad and Solør (Paper III) represent the northeastern part of southeastern Norway, which lies climatically between the abovecontrasts. In order to cover variability in weather, the field experiments were conducted for several years (Paper I, Paper II), or at sites with differing local climate and at different time within the growing season (Paper III), or with a large number of simulated years for regions with contrasting climate (Paper IV).

For the specific years 2014-2017 of experiment 1, selected weather variables at Ås are presented in Paper I (Figure 1 and Figure 2) and Paper II (Table 3). For 2016 in experiment 2, precipitation between sowing and complete emergence at Blæstad and in Solør is reported in Paper III (Figure 1). For the simulation study, synthetic weather data were generated, based on observations at Ås and Værnes during a historical reference period and projected future climate scenarios for 2046–2065, as described in Paper IV.

In general, soil types on Norwegian cereal land can be grouped as shown in Table 4, with respect to their workability characteristics, in terms of water holding capacity (Riley, 2016). In order to cover the most prevalent of these soil types (Greve et al., 2000), soil type groupings 2 and 3 were represented in field experiments (Paper I, Paper II, Paper III), whilst soil type groupings 2 and 4 received special attention in the simulation study (Paper IV) (Table 3).

Table 4: Soil type groupings representing Norwegian cereal land in Riley (2016), and their 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 (-100 hPa matric potential) in 0-20 cm depth.

[b] FC - 85% FC = water held between FC and 85% of FC, the latter used as workability threshold in Paper IV.

[c] Corresponding USDA texture class (Brady and Weil, 2010).

2.2. Experimental design and concepts

The included studies had differing experimental design (Table 3). Experiment 1 at Ås had a randomized split-plot design with two replications (Figure 3 in Paper I), including main plot treatment “timing of spring fieldwork” (early, medium or late) and split-plot treatment “traffic intensity during spring fieldwork” (no, one, two or three wheelings). The low number of replications had, prior to the PhD project, been regarded as appropriate for demonstration at farmers’ days. The split-plot design had been chosen based on feasibility considerations. Field experiment 2 had a two-factor randomized complete block design with three replications, including experimental factors workability (no or yes) and mechanization (light, heavy, extra heavy). The experiment was conducted at three sites, two at Blæstad (Blæstad 1 and Blæstad 2) and one at Solør. However, in Blæstad 1 and Solør, the available (non-liftable) equipment did not allow full randomization of the plots. In order to explore the implement effect on the seedbed in non-trafficked soil, a customised test implement was used on small-scale plots.

All studies included unfavourable moisture conditions, the field experiments in terms of early sowing date, and the simulation study in terms of a workability threshold that represented a higher moisture content than optimum. In the field experiments, the different sowing dates were determined based on perception of soil moisture and friability during manual kneading as practiced by farmers. In field experiment 1, the intention was to select an early sowing date with soil that was considered unfavourably wet, a medium date with soil that was considered favourably moist for tillage, and a late date with soil that was at least as dry as on the medium date. In field experiment 2, only unfavourably wet and favourably moist conditions were included. In both experiments, actual volumetric water content during the fieldwork was determined (Table 2 in Paper II, Table 1 in Paper III) and expressed in % of FC in order to evaluate the sowing date decisions related to the concept of ‘workability threshold’. The simulation study assumed a constant workability threshold of 85 % FC as the criterion for commencing spring fieldwork. That means that spring fieldwork was simulated as soon as the soil had dried up 15 volume % in addition to assumed drainage to field capacity, independently from consequential risk of yield loss.

All studies, explored spring fieldwork under excessively wet conditions, but they focused on different aspects of machinery use. On one hand side, soil degradation in such conditions can be caused by traffic by tractor and implement wheels, depending on surface coverage and the number of wheelings (Håkansson, 2005). This aspect of machinery use is considered in the experimental factor “traffic intensity” in experiment 1. On the other hand, soil degradation under wet conditions can be caused by tillage implement, as well as by rolling or press wheels attached to seed drills, depending on the type of implement, in particular its weight and mode of functioning, as discussed in Appendix A in Paper III. This aspect of machinery use is considered in the experimental factor “mechanisation” in experiment 2, where different harrowing and sowing implements were used between the tractor and implement tracks. In the simulation study, the physical degradation includes all of the above. The approach is adopted from Riley (2016) who used the term topsoil compaction to collectively describe a number of processes, like smearing, shearing, kneading, remoulding and compaction, which may occur in the soil during seedbed preparation under wet conditions.

Riley’s (2016) approach was based on a number of field experiments with small to moderate ground contact stress, negligible slippage and surface coverage representative of common field situations in Norway. These experiments compared cereal and grass yields obtained with and without compaction of soil with varying moisture content during seedbed preparation. The experiments included a wide range of soils (clay loam, loam, silt, sand) that were drained as necessary, and varying weather conditions as they are experienced in different regions in Norway at the time of seedbed preparation. Based on this large variation in soil and climatic conditions in different regions in Norway and between years, Riley’s (2016) model should be applicable also under projected future climate change. However, simulations during late spring in future climate scenarios may be considered extrapolations of the model.

2.3. Responses

In the different studies, the effects of timeliness and use of machinery are expressed in terms of a range of different soil physical, plant and economic responses (Table 3), either measured or simulated.

2.3.1. Measured responses

In the field experiments, a number of soil physical parameters were measured to assess soil strength, aeration and water supply for plant growth, and workability for subsequent tillage operations. Soil strength was assessed by aggregate tensile strength, penetration resistance and bulk density. Aeration was assessed by air-filled porosity, total porosity, air permeability, pore organisation indices, and indirectly by aggregate size distribution. Water supply was assessed by direct measurement of soil moisture content and related to the other parameters.

Tensile strength of 8–16 mm aggregates was obtained by an indirect tension test, where an aggregate is crushed between two parallel plates of a mechanical press and maximum force at failure is measured (Rogowski, 1964). Prior to the test, the aggregates were air-dried, some were rewetted and adjusted to different moisture contents by tension tables, vacuum pots and pressure plates (Dane and Hopmans, 2002). Aggregate tensile strength was calculated from the measured maximum force, and the aggregate's diameter and mass (Dexter and Kroesbergen, 1985) (Paper I).

Penetration resistance was measured in the field with a hand-held cone penetrometer, either at emergence (Paper III), in summer (Paper I, Paper II) or after harvest in autumn (Paper II).

Bulk density was calculated from oven-dry mass of soil cores devided by their total soil volume, sampled either at emergence (Paper III), 2-6 weeks after sowing (Paper I), or after cereal harvest (Paper II).

Volumetric water content at -100 hPa was calculated from bulk density multiplied with the soil cores' gravimetric water content at – 100 hPa (Paper I, Paper II, Paper III). Prior to weighing, the soil cores underwent saturation from below and desorption to different matric potential in a sandbox and ceramic pressure plates (Richards, 1947, 1948) (Paper II, Paper III), or tension tables, vacuum pots and pressure plates (Dane and Hopmans, 2002) (Paper I).

Air-filled porosity at -100 hPa was calculated from volumetric water content at -100 hPa subtracted from total porosity (Paper I) or measured by air pycnometer (Torstensson and Eriksson, 1936) (Paper II).

Total porosity was calculated from bulk density of soil cores and particle density from literature (Paper I) or calculated from air-filled porosity at -100 hPa plus volumetric water content at -100 hPa (Paper II, Paper III).

Air permeability was measured on soil cores that were saturated and drained to -100 hPa matric potential, either by the Forchheimer approach (Schjønning and Koppelgaard, 2017) (Paper I) or the method of Green and Fordham (1975) (Paper II, Paper III).

Pore organization indices were calculated from air-filled porosity and air permeability (Blackwell et al., 1990) (Paper I).

Aggregate size distribution was obtained from sieving of air-dried bulk soil, sampled either immediately after sowing (Paper II) or after emergence (Paper III). Aggregate size distribution was expressed as % of different size fractions and as MWD (Paper II, Paper III).

Moisture content was measured at emergence in 0-10 cm depth, and made it possible to discuss the physical properties with regard to moisture loss after sowing (Paper III).

Friability index for air-dried aggregates was obtained as the slope of the relationship between the natural logarithm of tensile strength and the natural logarithm of aggregate volume (Utomo and Dexter, 1981) (Paper I).

The degree of fragmentation was obtained from the aggregate size distribution, measured as described above, after fragmentation of soil cores in drop shatter test (Schjønning et al., 2002). Prior to the test, the soil cores were sampled 2-6 weeks after sowing, and adjusted to different moisture content using tension tables, vacuum pots and pressure plates (Dane and Hopmans, 2002). The degree of fragmentation was expressed as GMD after air-drying (Paper I).

The range of moisture content for tillage was calculated as the difference between wet and dry tillage limits, which were determined with the consistency approach described by Obour et al. (2018).

The **plants' responses** to seedbed quality were assessed by the speed, uniformity and degree of emergence, based on daily emergence counts fitted to Gompertz growth curves, as applied for germination course in Bewley et al. (2013) (Paper III). In addition, cereal yields were harvested and recorded at full maturity, expressed as absolute value (Paper I) or relative to the maximum yield obtained in a given replication (Paper II).

2.3.2. Simulated responses

In Paper II, the recorded yield of field experiment 1 was compared to the simulated yield potential attained from the timeliness of the seedbed preparation in spring. The yield potential was simulated with the yield potential module of Riley's (2016) workability model. This model expresses yield potential as risk of yield loss, i.e. timeliness related

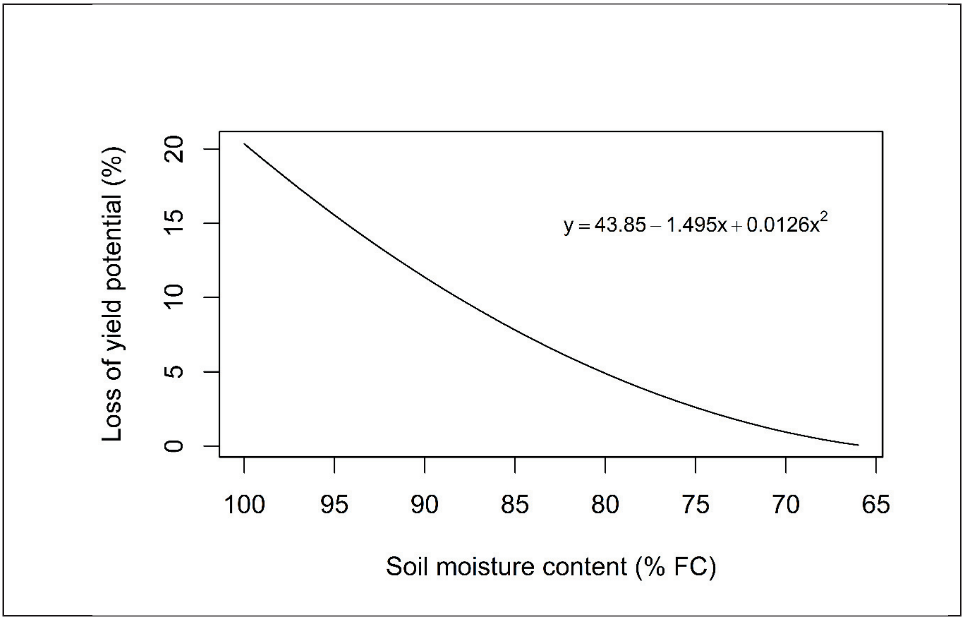

Figure 15: Function for calculation of loss of yield potential affected by soil moisture content in % of moisture content at field capacity (FC, -10 kPa) in 0-20 cm soil depth during spring fieldwork used in the workability model by Riley (2016) and in Paper II and Paper IV.

loss of yield potential (Figure A1 in Paper IV), by disregarding other yield-forming factors, as discussed in Paper II and Paper IV. The yield loss module combines two types of timeliness related loss of yield potential. The first type is expressed by the relationship between soil water content at the start of spring fieldwork and loss of yield potential due to topsoil compaction (Figure 15). This function assumes spring fieldwork to cause no compaction loss at moisture content of less than 66 % of field capacity (FC, -100 hPa). The second type is expressed by the relationship between the sowing date and loss of yield potential due to delayed seeding. This function assumes spring fieldwork before 16th April to cause no delay loss. Input data were average recorded soil moisture contents on each sowing date of the field experiment, expressed as % of field capacity for that soil type, and the Julian day of sowing dates. Both of these relationships are based on Norwegian field experiments, as described by Riley (2016).

In the simulation study (Paper IV), the yield potential was simulated by use of all four modules in Riley's (2016) spread sheet of the workability model, one for snow cover (Riley and Bonesmo, 2005), one for soil moisture balance (Kristensen and Jensen, 1975) and one for workability and one for yield potential. Input data were generated weather data for historical and projected future climate for two different cereal-growing regions in Norway (Table 3). The weather data was generated by a stochastic weather generator, which includes downscaling for the projected future climate, as described by Rötter et al. (2012).

Based on the daily weather input data, the snow module simulated daily snow depth. Based on the weather input data, the simulated snow depth and the selected soil type grouping (Table 1), the soil moisture balance module simulated daily soil moisture balance, expressed in % FC. Based on the simulated soil moisture balance and the selected workability threshold, the workability module simulated whether seedbed preparation was performed on a given day or not. If seedbed preparation was simulated on a given day, the yield potential module determined the yield potential for that day, as described by the above relationships to soil moisture content and Julian day of sowing date. In addition, this module consecutively accumulated the daily area of completed seedbed preparation for the spring fieldwork period March-June, as well as the accumulated yield potential, based on selected working capacities and farm sizes.

From the daily workability output, the number of workable days in the spring fieldwork period for a given year couls be determined, as well as their earliness and cohesion, and multiple combinations of these, described as workability indices in Paper IV. From the final accumulated yield potential for a given year, soil type, working capacity and farm size, the average yield potential for a whole simulation of 300 years of a given climate scenario and region could be determined.

These averages were expressed either as yield potential or as timeliness costs. Expressed as yield potential, these averages were used to test for statistically significant differences in yield potential between different regions, GHG emissions scenarios, GCMs (Figure 3 in Paper IV), as well as to illustrate differences between selected soil types, working capacities and farm sizes in the different regions, GHG emissions scenarios and GCMs (Figure 4 and Figure 5 in Paper IV). Based on the timeliness cost averages, regression analysis was used to describe the relationship between yield potential (y) and soil type (x_1), working capacity (x_2) and farm size (x_3), for a given region and climate scenario, with a model of the form [1], as described in the appendix in section 6. The equations with fitted regression coefficients (Table A1, in appendix) were used as input to a mechanisation model (Mangerud, 2017), which was used to calculate total costs for different sets of machinery for the mentioned regions, climate scenarios and soil types, depending on farm size (Figure 6 and Figure 7 in Paper IV).

2.4. Data analyses and statistics

In all studies, the main statistical method was ANOVA F-test, followed by Tukey HSD test when applicable, as described in detail in the individual papers. Statistical analyses were done in R (R Core Team, 2015, 2018), with rejection level $\alpha = 0.05$ for hypothesis testing. Despite the similarities, for analyses of experiment 1, different approaches to pre-processing (arithmetic mean vs geometric mean) and statistical analysis (split-plot vs completely randomised) were used in Paper II, compared to Paper I, as described and discussed in Paper II. In addition, corrections in raw data of yield in 2014 and 2016 were made prior to their use in that paper.

In Paper II, the relationships between different soil physical responses and between these and cereal yield were explored. For this purpose, correlation coefficients were preferred over regression analyses, because a regression analyses should not ignore an existing experimental design.

The regression models, which were used to describe yield potential in the simulation study (Paper IV), as well as their selection and sensitivity analysis, are described in detail in the appendix.

3. Discussion of main results

3.1. Minimum soil physical degradation (Paper I, Paper II)

In experiment 1, minimum soil physical degradation of the topsoil was obtained when spring fieldwork was done under sufficiently dry conditions. In contrast, early fieldwork in soil that was too wet impaired the physical seedbed quality in terms of larger and stronger aggregates, increased penetration resistance, changed pore characteristics and reduced cereal yields (Table 5). The percentage change in soil physical and plant parameters are similar to what has been reported from the most comparable field experiments in the literature.

Higher penetration resistance indicates compaction (Bachmann et al., 2006) in the topsoil of the plots with wet seedbed preparation. Due to the close relationship between compaction and aeration (Lipiec and Hatano, 2003), impaired pore characteristics (Nawaz et al., 2013) also indicate that the soil has been compacted, though even larger effects were expected.

Table 5: Changes in soil physical parameters (at specified depth) and cereal yield after seedbed preparation in wet soil (103-104% FC at 5-10 cm depth) related to workable conditions (69% FC), obtained 2016 and 2017 from experiment 1 on loam in Ås with 0-3 wheelings (4.5 Mg tractor, 150 kPa tyre inflation), compared to similar changes reported in the literature.

This thesis	Literature (soil moisture content max/min in % dry matter (measured in cm depth))	
Aggregate size		
- 61-79%, aggregates <0.6mm **+ 419-767%**, aggregates >20mm **+ 98-218%**, MWD (0-5 cm depth) **+ 47-64%**, drop shatter test (matric potential -10 to -100 kPa), GMD (5-15 cm depth) (Table 4 in Paper I, Figure 1 and 3 in Paper II)	+ **73%** MWD, moisture 21%/ 13% (5-10 cm), loam	Adam and Erbach, 1992
	- 80%, aggregates <0.5mm, **+ 980%** aggregates >20mm, moisture 24%/ 11% (10-15 cm), clay loam	Tisdall and Adem, 1986
	+ **289%**, aggregates >20mm, moisture 29-32%/ 22-27% (0-10cm), loam	Bakken et al., 1987
	+ 35%, aggregates >15mm, **-17%** aggregates 1-5 mm, moisture 21%/ 11% (0-10cm), clay	Braunack and McPhee, 1991
	+ **2700%**, aggregates >5mm, - **51%** aggregates <2mm, moisture 35%(88%FC)/ 29%(73%FC) (10-15 cm), clay	De Toro and Arvidsson, 2003
	+ 14-59%, aggregates >20mm, **- 25-57%** aggregates <0.6mm, moisture 32-46%/ 21-34%, silty clay loam, 1-4 wheelings (2.4 Mg)	Marti, 1983
	+ **164%**, aggregates >20mm, - **43%** aggregates <0.6mm, moisture 35-41%/ 22-31% (0-10 cm depth), silty clay loam, 1-6 wheelings (2.2 Mg/ 90 kPa)	Njøs, 1978
Aggregate strength		
+ 5-139%, aggregates 8-16 mm, matric potential -10 kPa to air-dry (0-10 cm depth) (Table 3 in Paper I, Table 4 in Paper II)	**+ 11-57%**, air-dry aggregates 1-16mm, after spring rotary cultivation, moisture 22%(103%FC)/ 19%(88%FC), sandy loam	Munkholm and Schjønning, 2004
	+ **195%**, air-dry aggregates 13.2-19mm, after autumn rotary cultivation, moisture 38%(143%FC)/ 21%(80%FC) (7.5 cm depth), clay loam	Watts et al., 1996
Penetration resistance		
+ **62-84%**, July **+ 20-111%**, September (0-15 cm depth) (Table 4 in Paper II)	**Slight increase**, after spring rotary cultivation, moisture 22%(103%FC)/ 19%(88%FC), sandy loam	Munkholm and Schjønning, 2004
	+ 15-38%, shear strength, moisture 35-41%/ 22-31% (0-10 cm depth), silty clay loam, 0-6 wheelings (2.2 Mg/ 90 kPa)	Njøs, 1978; Hofstra et al., 1986
Air-filled porosity at -10 kPa		
- **0-29 %** (0-5 cm depth) (Table 2 in Paper I; Table 3 in Paper II)	**- 56-80%**, moisture 35-41%/ 22-31% (0-10 cm depth), silty clay loam, 0-6 wheelings (2.2 Mg/ 90 kPa)	Njøs, 1978; Hofstra et al., 1986
Cereal yield		
- 15-22 % (Table 6 in Paper II)	**- 18-21%**, moisture 32-46%/ 21-34%, silty clay loam, 0-4 wheelings (2.4 Mg)	Marti, 1983
	- 24%, moisture 35-41%/ 22-31% (0-10 cm depth), silty clay loam, 0-6 wheelings (2.2 Mg/ 90 kPa)	Njøs, 1978; Hofstra et al., 1986

In earlier research, with more severe physical impedance and reduced diffusion, larger and stronger aggregates or higher penetration resistance have been shown to be negative for plant growth and nutrient uptake under normal conditions after sowing (Barley et al., 1965; Taylor et al., 1966; Taylor and Ratliff, 1969; Misra et al., 1988; Braunack and Dexter, 1989b; Bengough and Mullins, 1991; Martino and Shaykewich, 1994; Nasr and Selles, 1995; Arvidsson, 1999; Håkansson et al., 2002; Dexter, 2004; Dexter and Czyz, 2007).

Penetration resistance measurements in July did not exceed the common critical limit of 2 MPa in any case (Table 4, Paper II), but according to Collis-George and Yoganathan (1985), it would have restricted coleoptile elongation and emergence in September in those plots that had been tilled in wet soil with 2 and 3 additional wheelings the previous spring. Even though measurements of penetration resistance increased during the growing season, there may have been (non-measured) soil strength restrictions for emergence in spring in the most unfavourable treatments.

In May, air-filled porosity at -100 hPa did not drop below the common critical limit of 10%, but in September, a growing plant would have been restricted following wet spring tillage (Table 3, Paper II). Similarly, in September air permeability was below Riley's (1988) critical limit of 3 µm2 in plots that received wet spring tillage.

The final consequence of the treatments in this experiment can be seen in the yield reductions recorded in 2016. The year 2016 was that year with the most significant changes in soil physical properties and the only year with significant differences in cereal yield. The most important reason for this is probably the weather during the experimental period, as discussed later. From this experiment, one cannot conclude anything about the maximum soil moisture content at which spring fieldwork will not degrade soil physical quality. However, when comparing recorded to simulated yield (Table 6 in Paper II), the compaction loss after performing fieldwork when the soil was too wet seems to agree quite well with Riley's (2016) model, which assumes 66 % FC to be the maximum soil moisture content at which no yield loss occurs due to soil physical degradation.

High traffic intensity had similar, but weaker effects on soil physical quality than did early fieldwork. The reason for this is probably that only moderate traffic intensities were included in the experiment. If a larger range of traffic intensity had been included, as in Reintam et al. (2009), Njøs (1978) and Hofstra et al. (1986), larger effects on soil physical properties and crop performance would have been expected.

In addition to effects on the well-known aggregate size distribution, the most distinct and important changes in soil physical quality were increases in penetration resistance (Table 5, Table 7 in Paper II). The specific importance of penetration resistance has been highlighted by Bölenius et al. (2017). They discuss that penetration resistance is influenced by a number of other soil physical properties, and thus it indicates no specific aspects of physical degradation. Nevertheless, they argue that penetration resistance can be considered a good indicator of overall soil physical quality and yield potential.

To sum up, this experiment shows that soil physical degradation can be minimised by conducting spring fieldwork at a time when the soil has dried sufficiently, and that moderate traffic intensity does not interfere with this strategy. The most important aspect of such timing is to avoid creating unfavourable aggregate size distributions and topsoil compaction. The right timing supports favourable soil strength, aeration and water supply for plant growth.

3.2. Maximum moisture loss after sowing (Paper III)

In experiment 2, maximum moisture loss was found from the least compacted seedbed, which was prepared using light mechanisation. In contrast, early seedbed preparation with heavier mechanisation under unfavourably wet conditions, created less favourable seedbed characteristics, in terms of larger aggregate size, larger penetration resistance, reduced aeration and higher soil moisture content at emergence (Table 6).

According to generally accepted seedbed theory, larger aggregates should increase moisture loss from the seedbed, in terms of increased evaporation, reduced capillary transfer, increased infiltration and increased internal drainage, as shown in Table 6 and discussed in Paper III. Based only on the larger aggregates, the heavier mechanisation should therefore be better suited to maximise moisture loss from the seedbed after sowing. However, based on higher penetration resistance and reduced aeration, the heavier mechanisation caused compaction, which has the opposite impact on moisture loss (Johnson and Buchele 1961; Currie 1984; Stenberg 2000). In our study, larger aggregates did not increase moisture loss from the seedbed, as they were compacted at the same time. This can be seen in a higher soil moisture content.

Table 6: Increases in aggregate size and compaction indicators at emergence after seedbed preparation in wet (96%FC) compared to workable soil (74%FC), resulting in **+18%** moisture content at emergence (A); and after seedbed preparation with extra heavy (2.00 Mg m^{-1}) compared to light mechanisation (0.27 Mg m^{-1}), resulting in **+ 57%** moisture content at emergence (B); obtained from 0-5 cm depth in field experiment 2 on sandy loam at Blæstad 2 in 2015, compared to moisture loss reported in the literature.

This thesis	Soil moisture loss in the literature	
Aggregate size		
A: wet seedbed preparation **- 5%** aggregates 0.6-2mm **+ 40%** aggregates 6-20mm **+ 21%** MWD (not shown) **B: extra heavy mechanisation** **- 15%** aggregates 0.6-2mm **+ 58%** aggregates 6-20mm **+ 35%** MWD (Figure 2 in **Paper III**)	**+ 100%** aggregate size (from 2.5 to 5, from 5 to 10 mm) -> **+ 50-200%** evaporation rate or relative vapor flux	Heinonen, 1985; Scotter and Raats, 1969
	+ 150% aggregate size (from 2 to 5 mm) -> **+ 25%** cumulative evaporation after 5 days, 20 mm day^{-1} potential evaporation, sandy loam	Hillel and Hadas, 1972
	+ 900% aggregate size (from 1 to 10 mm) -> **+ 100%** drying rate coefficient or **+ 19-50%** moisture (from 16 to 19-24%), non-compacted silty clay loam	Johnson and Henry, 1964
	+ 68% aggregate size (from 1.2 to 2 mm) -> **- 50/29%** capillary rise and **+ 35/86%** internal drainage, sandy loam/ clay	Hubbel, 1947
	+ 60% aggregate size (from 1.0 to 1.6 mm) -> **+ 130%** hydraulic conductivity, silt loam	Benoit, 1973
Compaction indicators		
A: wet seedbed preparation **+ 65-67%** penetration resistance **- 7%** air-filled porosity **- 21%** air permeability (not shown) **B: extra heavy mechanisation** **+ 92-98%** penetration resistance **- 10%** air-filled porosity **- 18%** air permeability (Figure 3 and Figure 4 in **Paper III**)	**+ 100%** compaction (from150 to 300 kPa) -> **- 70%** air permeability, **- 43%** gas diffusivity, **- 32%** air-filled porosity, **- 63%** hydraulic conductivity	Kuncoro et al., 2014
	+ 22% porosity (from 51 to 62%) -> **+ 20-68%** evaporation at 0-6 km h^{-1} wind speed in 1-4 cm mulch of sandy loam	Acharya and Prihar, 1969

According to common critical limits, there was no aeration restriction at emergence in field experiment 2 (Figure 3 in Paper III). However, according to Collis-George and Yoganathan (1985), emergence was restricted by penetration resistance in plots that received seedbed preparation by heavy and extra heavy mechanisation in wet soil. This is in line with the less uniform cereal emergence recorded after those treatments (Figure 5c in Paper III).

Parts of the design of this field experiment may be subject to question. Even so, the focus of Paper III has been on the completely randomised trial at Blæstad 2. The results of Blæstad 1 and Solør trials show the same tendency as Blæstad 2 (Table 4 in Paper III) and thus support the statistically significant findings in the latter. Although this experiment was only performed in one year, it was considered that, as only emergence is recorded, rather than yield, it was of larger interest to include different soil types and different times of season, in order to obtain the necessary variation in experimental conditions.

The results of this field experiment are similar to those of field experiment 1. Compared to experiment 1, this experiment did not include the effect of traffic. The effect of traffic on soil physical properties and crop performance would have to be added to the implement effects reported in this study. However, the larger aggregates, the higher penetration resistance and the reduced aeration found in this experiment are similar to the results in field experiment 1. When compared to the latter field experiment, the approach used in field experiment 2 may seem to be contradictory. The background for the different approaches are assumptions of normal dry conditions after sowing (experiment 1) vs. persisting high soil moisture content (experiment 2). Therefore, in theory, in field experiment 1 we regard large aggregates to be negative for seedbed quality and crop growth, while in field experiment 2 we regard large aggregates to be positive for maximum moisture loss. With regard to aeration (air permeability, pore size distribution) and penetration resistance, the two approaches are therefore not contradictory.

To sum up field experiment 2, heavy mechanisation caused compaction in the seedbed and limited moisture loss. Larger aggregates did not increase moisture loss after sowing, because the seedbed became compacted at the same time. Therefore, the avoidance of compaction seems to be the most important consideration to support favourable soil strength, aeration and water supply for the emerging cereal seedling.

3.3. Long-term farm mechanization management (Paper IV)

Despite general increases in future precipitation (Table A3 in Paper IV) in the simulation study, there were substantial differences in results between the included cereal growing regions, climate scenarios and soil types.

In SE Norway, despite some increase in the variability of soil workability, projected climate change relieved the spring fieldwork dilemma in terms of mostly improved workability, reduced loss of yield potential and reduced annual variability in yield potential (Table 7).

In C Norway, the most favourable climate scenarios relieved the spring fieldwork dilemma similarly to SE Norway, while the worst-case scenarios aggravated the timing of spring fieldwork in terms of reduced workability and increased number of extremely unfavourable years, increased loss of yield potential and increased annual variability in yield potential (Table 7).

Consequently, in SE Norway and in the best case in C Norway timeliness costs (Figure 6 in Paper IV) and total costs decreased (Figure 7 in Paper IV) in the future and there was a slightly smaller demand for working capacity (Figure 7 in Paper IV). In contrast to this, in the worst case scenario in C Norway, timeliness costs (Figure 6 in Paper IV) and total costs increased (Figure 7 in Paper IV) in the future and there was a slightly increased demand for working capacity (Figure 7 in Paper IV). Changes in demand for working capacity may influence mechanisation management at the farm level.

The results from this study are partially in line with, and partially in contrast to earlier research. The improved workability and increased yield potential in SE Norway and in the most favourable scenarios in C Norway are in line with earlier research, which simulated improved workability (Trnka et al., 2011; Rötter et al., 2012, 2013), a longer growing season and improved yields in Northern Europe (Carter et al., 1991; Carter, 1998; Olesen and Bindi, 2002; Parry et al., 2007; Peltonen-Sainio et al., 2009b; Bindi and Olesen, 2011; Harding et al., 2015; Persson and Kværnø, 2017). However, the reduced workability and increased risk of yield loss in C Norway are in contrast to earlier research. This contrast may be explained by methodological differences, as discussed in

Table 7: Selected changes in workability and yield potential on clay/silt from baseline (standard normal) to future (2046-2065) climate (greenhouse gas (GHG) emissions scenarios SRB1 and SRA2, global climate models (GCM) IPCM4 and NCCCSM) for southern part of southeastern (SE) and central (C) Norway, compared to similar studies in the literature, based on a workability threshold of 85% field capacity (FC) in 0-20 cm depth. Devided in changes that are positive (A) and negative (B) for spring fieldwork timeliness.

This thesis	Literature (study area, GHG emissions scenario/GCM, baseline period/future period, workability threshold, soil)	
Workability		
A: SE and best case C Norway: **+ 0-23%** workable days March-June **B: Worst case C Norway**: **- 14%** workable days March-June **+ 17-167%** extremely unfavourable years (Table 5 in Paper IV)	**+ 9-12%** workable days March/April (Norway, SRA2/(ECHAM5, HadCM, NCAR-PCM), 1971-2000/2030-2050, <70 % available water capacity in 0-10 cm depth, water-holding capacity of 0.27m in 0-10 cm depth)	Trnka et al., 2011
	- 10% workable days April/May (Illinois, USA, (SRB1/SRA2)/CCSM3, 1960-2000/2040–2065, 0.7-1 PL (based on recorded workdays), range of soil types	Tomasek et al., 2017
	+ 12-47 days growing season (as above, threshold temperature-based)	Trnka et al., 2011
	15 days earlier sowing date (Finland, (SRA2/SRB1)/(CSIRO-MK3.5/GISS-ER/IPSL-CM4), 1971-2000/2041-1070, temperature-based, clay loam/ silty sand, 0.18 and 0.22 cm^3 cm^{-3} plant available water) **- 4-44%** workable days in late spring (as above, threshold <70 % available water capacity in 0-10 cm depth)	Rötter et al., 2012, 2013
	sowing dates affected in only a few cases (Finland, (SRA1FI/SRB1)/HadCM3, 1971-2000/2071-2100, 75%FC, heavy clay) increase in climate variability not considered	Rötter et al., 2011
	two weeks earlier sowing (Finland, (B1/A2)/19 GCMs, 1979-2000/2010-2100, spring workability not considered	Peltonen-Sainio et al., 2009b
Cereal yield potential		
A: SE + best case C Norway: **+ 4-46%** yield potential **- 36-61%** annual variability in yield potential, depending on region, GHG emissions scenario, GCM **B: Worst case C Norway**: **- 3-14%** yield potential **+ 0-11%** annual variability in yield potential, depending on GHG emissions scenario (Figure 2, Figure 3 and Figure 4 in Paper IV)	**- 21-35%** yield **+ 47-173%** annual variability (as above)	Rötter et al., 2011
	+ 17-21%/ 21-68% yield (Sweden/Finland, SRA2/HadCM3, 1961-2000/2050)	Audsley et al., 2006
	+ 33% wheat production reviewed (Nordic countries, 1995–1999/2050)	Olesen and Bindi, 2002
	+ 7-21% yield **+ 8%/16%** min/max yield (SE Norway, A1B/(BCM2.0, CSIRO-M. k3.0, GISS-AOM, HadCM3), standard normal/2046-2065, spring workability not considered, range of soil types)	Persson and Kværnø, 2017
	+ 35–54% net primary productivity (Northern Europe, (SRA2/SRB2)/(range of GCMs/RCMs), standard normal/2071-2100, spring workability not considered)	Olesen et al., 2007
	+ 40% wheat yield (SE Norway, SRA1FI/HadCM3, 2000/2080)	Ewert et al., 2005

detail in Paper IV. The most important differences between the simulation study and previous research on the impact of climate change are the nature of the models involved and the applied criteria for the timing of sowing.

In studies of climate change impact, the most common models are process-based. The commonly simulated yield potential of such models cannot be compared directly to the loss of yield potential from Riley's (2016) empirical-statistical workability model. The loss of yield potential in the latter is exclusively based on compaction loss and delay loss due to spring fieldwork timeliness and disregards other yield-forming factors. Other consequences of climate change, such as drought or excessive heat, are excluded and the overall loss of yield potential may thus be underestimated.

The commonly applied criteria for sowing is the spring temperature. However, a higher temperature in spring in the future does not necessarily facilitate earlier sowing, if the soil is still too wet for fieldwork. To account for that, one would either have to include the soil moisture content as a criterion for sowing to occur or consider the resulting loss of yield potential when the soil is worked when still too wet. Highlighting these aspects of spring fieldwork is an important contribution to the research field of climate change impact.

The relevance of the effects of climate change on economic parameters related to spring fieldwork may be larger than is obvious from the simulation results. Final differences in demand for working capacity may seem small, but should be recognized for several reasons. A demand for slightly smaller number or size of machinery in SE Norway, combined with a demand for slightly larger number or size of machinery in C Norway may change the relationship between these regions with regard to profitability, and thus affect future land use in Norway. Agricultural land in C Norway may come to be regarded as unsuitable for spring cereals in the future. In addition, larger differences are possible if one additionally considers:

(1) subsoil compaction which is an important threat to soil physical quality in modern agriculture compared to the empirical foundations of the workability model,

(2) the iterative effect of working capacity on surface coverage of field traffic, consequential loss of yield potential, and farm mechanization management,

(3) a less strict workability threshold, which probably is common among farmers and will be even more so in the future,

(4) other effects of climate change on crop performance, such as the effects of drought or excessive heat during the crop growing season on growth, phenological growth patterns and formation of yield.

To sum up, this simulation study showed that climate change may have a negative impact on soil workability for spring fieldwork and spring cereal production in regions where winter and spring precipitation increases in the future. The study highlights the importance of soil moisture content in spring as a criterion for defining sowing dates in simulation studies in general and particularly in impact studies of future climate change.

3.4. Common discussion

The combination of field experiments and a simulation study in this thesis shows how yield potential is related to soil physical quality. Through the workability model, future increases in loss of yield potential are in the worst case in C Norway clearly related to reductions in workability and soil physical degradation at the selected workability threshold (85 %FC), when soil moisture content is still unfavourably high (Paper IV). Important reasons for risk of yield loss in soil tilled when still too wet (>66%FC) may be larger and stronger aggregates and higher penetration resistance, as found in the field experiments (Paper I, Paper II, Paper III).

Compared to the simulated risk of yield loss in Paper IV, the field experiments (Paper I, Paper II, Paper III) resulted in relatively small effects of timing of spring fieldwork on crop performance. There may be several explanations for this, but the most important is probably the localisation of the field experiments. Considering the large differences between cereal growing regions and soil types in the simulation study, the spread in localisation of field experiments with regard to climate and soil type could have been better. The selected localisations represent well the average or most important climate and soil conditions with regard to regional distribution of cereal production. However, they resulted in less relevant conditions with regard to the research context of soil degradation induced by climate change. The soil types in the field experiments were mainly well-structured and commonly non-problematic. Initially, another field experiment, including clay soil at Ås and Øsaker, was meant to be part of the PhD project. Clay soils are more susceptible to soil compaction in wet conditions, but this experiment could unfortunately not be included in the thesis, due to flood-water damage caused during the experimental period.

The location choices may also be discussed with regard to the relevance of the experienced weather conditions in the specific experimental years of the field experiments. In experiment 1 (Paper I, Paper II), in two of the experimental years the weather did not provide sufficiently relevant experimental conditions. In 2014, March was unusually warm and dry at Ås, while April was unusually warm (Table 1 in Paper II). In 2015, March was unusually warm, April was unusually warm and extremely dry. On the other hand, in that year, May was extremely wet, which is the reason for why the above-mentioned experiment at Ås and Øsaker could not be included in this thesis. In experiment 2 (Paper III), the weather conditions were not as determinant and the timing of fieldwork could be adjusted to the weather, in accordance with the experimental design. If other locations were chosen, more relevant experimental conditions and larger treatment effects might have been obtained.

Furthermore, the results from these studies resemble only part of the effects of seedbed preparation in practical agriculture. In modern agriculture, machinery effect, size and weight are steadily increasing. This means that the presented studies, which either do not consider field traffic (Paper III) or are based on moderate mechanisation (Paper I, Paper II, Paper IV), underestimate the effects of spring fieldwork in too wet soil on soil physical quality and crop performance. In the practical context of crop production, more intense topsoil compaction and additional subsoil compaction would potentially add to the effects reported here.

Uncertainty in the climate impact study (Paper IV) consists of uncertainty from emission scenarios, climate models, generation of synthetic weather data and the impact models (workability model, mechanisation model), as discussed by Rötter et al. (2012). In addition, uncertainty varies with soil and management (Asseng et al., 2013). Being aware of these uncertainties, a range of different combinations of GHG emissions scenarios and GCMs was tested in the study and contrasting ones were selected for further simulations. For the same reason cereal growing regions with contrasting climate, and contrasting soil types were chosen. The uncertainties that were reflected in the results were in line with those reported in the literature, as discussed in Paper IV.

To sum up, the weaknesses of this thesis were the lack of (1) field experiments on soil with higher clay content, (2) PCA of soil physical parameters in field experiment

1, (3) importance analysis of different climatic factors affecting workability and different workability factors affecting yield potential, (4) dynamic field measurements. The strengths of the thesis are that it (1) relates soil moisture content at sowing to soil physical properties and crop establishment, (2) combines a simulation study with field experiments, (3) relates workability to climate change, (4) relates the theoretical approach of workability to mechanisation descisions at farm level, by (5) considering working capacity and timeliness costs under changing climatic conditions. The latter is of particular interest as rapid structural changes are taking place nowadays in Norwegian agriculture, as a response to current political incentives.

4. Conclusions and recommendations

Based on the presented studies, avoidance of compaction seems to be the most important adaptation to climate change in seedbed preparation. The importance of avoiding compaction, as it is defined here, must also be taken into consideration in relation to implement choice when optimising the working capacity for spring sowing at the farm level. To increase working capacity, farmers should consider increasing the number of machines and operators rather than increasing machinery size. Considering future climate projections and general mechanisation trends in agriculture, focus on the avoidance of soil compaction during spring fieldwork will become even more important in the future than in the past.

Farmers can achieve both minimum soil physical degradation and maximum moisture loss from the seedbed after sowing by minimising soil compaction. Minimum compaction can be realised by careful timing of spring fieldwork and selection of the implements used, depending on their weight and mode of function. However, when dealing with the question of optimum sowing date, it is important to recognise the practical demand of a certain number workdays and farmers' need to balance soil protection (agronomical optimum) and profitability (economical optimum) in practical farming, as shown and discussed in Paper IV.

In the future, there is a need for a new approach to implement management in seedbed preparation. Due to the experimental designs, from the presented studies we cannot conclude about the suitability of specific implements under unfavourably wet conditions. Thus, studies are needed that separately test different types of harrows and seed drills under wet conditions. Nevertheless, the presented results indicate that heavy modern seed drills with press wheels are not as well-suited under unfavourably wet conditions as they are under normal dry conditions. Due to their design, modern seed drills cannot function without press wheels. Therefore, new designs or a return of older implements should be considered. On the other hand, an individual farmer cannot invest in several types of machinery for different weather situations. Therefore, there is a need for developing new designs and adjustable implements.

Another solution could be more diversified offers from large contractors. This would allow differentiated implement use, i.e. the use of lighter implements when necessary. Furthermore, future mechanisation management for seedbed preparation may as well focus on differentiated implement use, such as skipping or delaying rolling in years with unfavourably high soil moisture conditions in spring. This strategy may allow an advantage from larger aggregates if the soil is tilled under unfavourably wet conditions, so long as it is not compacted at the same time.

The assumption of autumn ploughing in the presented studies must not be regarded as a limitation. The requirement for spring workability also applies for ploughing. Thus, the presented concepts and results are transferable to production systems with spring ploughing. However, further effort should be put into research on cereal establishment in production systems with reduced or no tillage. In addition, the effect of subsoil compaction on long-term soil qualitity needs to be considered.

Future research should explore a larger range of traffic intensities. Furthermore, it should be studied whether the relative importance of different soil physical properties changes if the experimental range of traffic intensity or soil moisture content is widened or if high soil moisture conditions continue after sowing.

The lacking advantage from larger aggregates when the seedbed is compacted at the same time, shows that the traditional approach to seedbed preparation for spring cereals in Scandinavia under normal dry conditions is not necessarily fully applicable in the light of future climate change. Existing methods within the traditional approach need to be re-evaluated for wet conditions. The relationship between size and compaction of aggregates with other structural soil properties, directly affecting the movement of water and air in soils, is likely to be different in dry and wet soil. Therefore, established seedbed knowledge should be tested specifically under wet conditions, during and after seedbed preparation, including direct measurements of evaporation, infiltration and internal drainage.

In addition to modifying aggregate size, porosity, permeability and compaction, there are other potential methods of increasing moisture loss that need to be explored. For example, a smaller seeding depth could increase moisture loss from the seed zone. Another example is to modify the depth of the loose layer. A deeper loose layer may decrease capillarity and increase infiltration.

Another area of interest is aggregate stability, which is an important physical property for seedbed quality, because it is closely related to crusting. Heavy or prevailing precipitation can modify the surface roughness and porosity of recently tilled soil and lead to structural collapse. Therefore, in relation to seedbed preparation and increasing moisture, agronomical practices that increase aggregate stability should receive more experimental attention.

In cereal production, seedbed preparation is a bottleneck, which is going to gain importance in the future, as we expect an increasing incidence of extremely unfavourable spring conditions. In the future, Norwegian farmers may experience the familiar spring fieldwork dilemma either less or more frequently and severely. Climate change may have positive or negative effects on spring workability, fieldwork and the profitability of spring cereals in Norway, depending on region, climate scenario and soil type.

Even though other regions with northern growing conditions expect similar climate change as Norway in the future, the results from this thesis are not directly transferable. Country-specific differences in soil types, traditional tillage practices, adaptation possibilities, and the role of cereals in national agricultural production, self-sufficiency and food security may give different results in similar studies.

Despite the focus of this thesis on wet conditions, increases in future climate variability will also more frequently result in years with unusually dry spring conditions. In the future, it may be even less feasible to prepare a seedbed that fits the whole range of subsequent weather that a given farmer must expect. However, from the presented work one can conclude that there is one requirement that is common for all situations: Soil compaction must be avoided.

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6. Appendix

The workability model was used to simulated relative yield potential with differing soil types, working capacities and farm sizes, for the southern part of southeastern Norway (SE) and Central Norway(C), for Baseline climate and selected combinations of future (2046-2065), greenhouse gas emmissions scenario (SRB1 or SRA2) and global climate model (IPCM4 or NCCCSM). Based on the output from these simulations, for each combination of region, greenhouse gas emissions scenario and global climate model, regression analysis was used to fit regression coefficients and compare the goodness of fit (AIC = Akaike's information criterion, Akaike, 1973) for different linear mixed models. The full models included soil type, working capacity and farm size, their interactions and second order terms. In most cases, stepwise model selection (forward, backward, both) based on AIC resulted in the same best model structure as in Riley (2016):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 {x_2}^2 + \beta_5 {x_3}^2 + \beta_6 x_1 x_3 + \beta_7 x_2 x_3 + \beta_8 x_1 x_2 x_3 + \epsilon$$

$$, \epsilon \sim N(0,\sigma^2) \qquad [1]$$

, where relative yield potential (y) is described as a response to soil type (x_1), working capacity (x_2), and farm size (x_3). This model structure was therefore used for all combinations of region, GHG emissions scenario and GCM. The values of the fitted regression coefficients β_0-β_8 are shown in Table A1. Soil type was considered integer (1= coarse sand, 2= loamy sand, 3= loam, 4= clay/silt), as described in Table 4, because this was required for later use as input into the mechanisation model. Due to the predefined maximum limit of 10 % of years with incomplete spring fieldwork, the regression equations for the different combinations of region, greenhouse gas emissions scenario and global climate model were based on different numbers of simulations with the workability model (Table A1).

A sensitivity analysis was conducted in order to describe the sensitivity of the relative yield potential (y) to small changes in the model terms (x_1, x_2, x_3, x_2^2, x_3^2, x_1x_3, x_2x_3, $x_1x_2x_3$). The sensitivity analysis applied standardised regression coefficients (Saltelli et al., 1993), based on unit normal scaling (Montgomery et al., 2006), which is useful for linear models with $R_{adj}^2 > 0.7$ (Saltelli et al., 2008), as for the models here (Table A1). In most cases, the sensitivity analysis revealed the following ranking of the most to the least influential model terms: soil type > working capacity > farm size > interaction capacity:farmsize > capacity^2 > interaction soiltype:farmsize > farmsize^2 > interaction soiltype:capacity:farmsize (Table A2). Slightly deviating rankings were observed in SRA2/IPCM4 at Ås and NCCCSM at Værnes.

Table A1: Fitted regression coefficients of models, in the form of [1], that describe relative yield potential (y) as a response to soil type (x_1), working capacity (x_2), and farm size (x_3) in Baseline climate, 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
β_0	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
β_1	-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
β_2	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
β_3	-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
β_4	-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
β_5	-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
β_6	-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
β_7	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
β_8	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
RSE *	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; RSE = residual standard error; sd = standard deviation; DF = degrees of freedom; n = number of simulations (means of 300 years) included

Table A2: Standardised correlation coefficients of models, in the form of [1], that describe relative yield potential (y) as a response to soil type (x_1), working capacity (x_2), and farm size (x_3) in Baseline climate, 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, used in sensitivity analysis.

	SE Norway					C Norway				
	Baseline	SRB1		SRA2		Baseline	SRB1		SRA2	
		IPCM4	NCCCSM	IPCM4	NCCCSM		IPCM4	NCCCSM	IPCM4	NCCCSM
β_0	2.62E-01	3.76E-01	2.82E-01	3.66E-01	2.57E-01	1.65E-01	2.27E-01	9.49E-02	2.08E-01	1.40E-01
β_1	-7.98E-01	-6.74E-01	-7.76E-01	-6.94E-01	-8.07E-01	-9.33E-01	-8.35E-01	-1.09E+00	-8.62E-01	-9.82E-01
β_2	6.18E-01	5.88E-01	5.63E-01	5.46E-01	5.64E-01	5.44E-01	5.57E-01	4.05E-01	5.53E-01	5.01E-01
β_3	-5.62E-01	-4.03E-01	-4.64E-01	-3.60E-01	-4.83E-01	-5.80E-01	-5.13E-01	-5.06E-01	-5.22E-01	-5.57E-01
β_4	-3.30E-01	-3.89E-01	-3.15E-01	-3.71E-01	-3.03E-01	-2.56E-01	-2.83E-01	-1.91E-01	-2.76E-01	-2.38E-01
β_5	-2.84E-02	-7.08E-02	-6.17E-02	-7.67E-02	-3.93E-02	-1.12E-02	-2.71E-02	-1.42E-02	-1.62E-02	2.16E-03
β_6	-2.01E-01	-2.49E-01	-2.73E-01	-2.59E-01	-2.41E-01	-1.82E-01	-2.03E-01	-1.73E-01	-1.97E-01	-1.66E-01
β_7	3.51E-01	3.99E-01	3.58E-01	3.87E-01	3.32E-01	2.91E-01	3.11E-01	2.27E-01	2.92E-01	2.53E-01
β_8	-1.78E-02	3.78E-02	2.42E-02	4.32E-02	1.27E-02	-1.49E-02	5.95E-03	-3.45E-02	-5.22E-03	-2.18E-02
R^2_{adj} *	0.9019	0.7463	0.8157	0.7271	0.8595	0.9416	0.9143	0.9537	0.9149	0.9491
RSE *	0.3133	0.5037	0.4293	0.5224	0.3748	0.2416	0.2927	0.2152	0.2917	0.2255
sd *	1	1	1	1	1	1	1	1	1	1
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; RSE = residual standard error; sd = standard deviation; DF = degrees of freedom; n = number of simulations (means of 300 years) included

Paper I

Photographer: Stig T. Rasmussen (2016)

Photographer: Peter B. Obour (2016)

Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil

Peter Bilson Obour[1], Dorothee Kolberg[2,3], Mathieu Lamandé[1,2], Trond Børresen[2], Gareth Edwards[4], Claus G. Sørensen[5], Lars J. Munkholm[1]

[1] *Department of Agroecology, Aarhus University, Research Centre Foulum, Blichers Allé 20, P.O. Box 50, DK-8830 Tjele, Denmark*

[2] *Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003 NO-1432 Ås, Norway*

[3] *Faculty of Applied Ecology and Agricultural Sciences, Inland Norway University of Applied Sciences, P.O. Box 400, NO-2418 Elverum, Norway*

[4] *Agro Intelligence ApS, Agro Food Park 13, Skejby, DK-8200 Aarhus N, Denmark*

[5] *Department of Engineering, Aarhus University, Inge Lehmansgade 10, DK-8000 Aarhus, Denmark*

*Corresponding author:

Email address: peter.bilson.obour@agro.au.dk (P. B. Obour)

Abstract

Timing of tillage operations is of utmost importance in arable farming because tillage performed under inappropriate soil water conditions results in soil structural damage and creation of undesirable seedbeds for crop establishment and growth. In a field experiment on a loamy soil in Ås, Norway, we investigated the effect of compaction and sowing dates on (i) seedbed physical properties, (ii) crop yield, and (iii) the range of water contents for tillage. The experiment was established in 2014 and the same experimental treatments were repeated in 2015, 2016 and 2017. The sowing dates included early (A1), normal/timely (A2) and late (A3) sowing dates. The compaction treatments applied each year were done wheel-by-wheel by a MF 4225 tractor weighing 4.5 Mg with a single pass (B1) and compared with a control treatment (B0). This study reported soil physical properties for only 2016 and small grain cereal yield for the four years. The soil pore characteristics measured were soil bulk density (ρb), volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a) and pore organization indices ($PO_1 = k_a/\varepsilon_a$ *and* $PO_2 = k_a/\varepsilon_a^2$); strength properties measured were tensile strength (Y), soil penetration resistance (PR), degree of soil fragmentation by drop-shatter test, and water contents for tillage by calculating the range of water content for tillage ($\Delta\theta_{\mathrm{RANGE}}$). The interaction of compaction with sowing date, generally affected soil pore characteristics, particularly at 1–5 cm depth. The A1 treatment significantly affected the strength characteristics of seedbed by decreasing soil friability and increasing Y at 1–10 cm depth, and PR down to 27 cm depth. The A3 treatment decreased yield of spring-sown small grain cereal crops, but this may be ascribed to a shorter growing season rather than an influence of soil physical properties. The A1 and A3 decreased the range of water contents for tillage compared to the A2, although the difference was not significant at any of the depths studied. Findings of the study have practical implications for cropping regimes in colder climates where farmers can be faced with a short growing period by showing that cultivation in wet soil conditions such as early spring can adversely affect seedbed physical properties and soil workability for subsequent tillage operations.

Keywords: Pore characteristics; soil fragmentation; soil workability

1. Introduction

Tillage is an integral part of arable farming practices— it induces changes in soil structure that may be beneficial or detrimental to soil physical properties and crop growth. In a conventional cultivation, secondary tillage means harrowing after primary tillage with the aim of preparing the soil for seeding, also called seedbed preparation, by creating optimum physical conditions for crop establishment and growth (Arvidsson et al., 2000). In this paper, the term "tillage" without an adjective refers to secondary tillage for seedbed preparation. One important aim of tillage is to fragment soil in order to minimize the proportion of large aggregates (Ojeniyi and Dexter, 1979). It is, generally accepted that soil aggregate size range of 1–5 mm is required for good seedbed that favors seed emergence and growth (Russell, 1961). This is because such seedbed has good aeration, water holding capacity, and improve soil-seed-contact area (Braunack and Dexter, 1989b).

Soil workability is a key condition in tillage. In seedbed preparation, soil workability is the ease with which a well-drained soil can be tilled to produce an optimum seedbed for crop establishment (Dexter, 1988). Moisture content at tillage is a major factor affecting soil workability. Soil is workable over a range of water content ($\Delta\theta_{\mathrm{RANGE}}$) between an upper (wet tillage limit, θ_{WTL}) and a lower (dry tillage limit, θ_{DTL}). $\Delta\theta_{\mathrm{RANGE}}$ decreases with decreasing soil organic matter content and with increasing clay content and soil bulk density (Dexter and Bird, 2001). This suggests that farmers can be faced with cultivation problems in regions with hard-setting soils (Mullins et al., 1988) and in colder climates with a short period for spring or autumn cultivation.

Improved tires and power of modern field machinery mean that farmers are able to till in less-than-ideal soil conditions such as early spring tillage in temperate regions like Northern Europe. Therefore, modern agricultural machinery might improve trafficability, that is, the ability of soil to support and withstand field traffic without irreversible soil degradation (Rounsevell, 1993), at the expense of increased risk of detrimental effects from tillage, and the farmers' decisions on tillage and sowing date become crucial.

When performed in less-than-ideal soil conditions, tillage can produce short- and long-term detrimental effects on soil. The described tillage effects on germination, emergence and growth of the current crop can be considered short-term effects. On the other hand, changes induced by tillage which persist over cropping seasons or years can be considered long-term effects. Structural degradation in the topsoil due to tillage in too wet conditions has been shown to persist until the following autumn (Munkholm and Schjønning, 2004), which can affect the water contents for tillage and seedbed preparation for a subsequent winter crop. Therefore, tillage-induced soil structural degradation in spring might reduce soil workability for autumn tillage and complicate scheduling of these operations. It must be emphasized that there is a lack of quantitative information on this effect as reviewed by Obour et al. (2017).

In addition to the short- and long-term effects, in too wet soil condition, tillage can create a seedbed composed of large and strong soil fragments because of kneading. According to Dexter and Birkas (2004), large soil fragments have less agronomic value because they do not favor good soil-seed-contact area. Further, large soil fragments can impede crop emergence and root growth (Nasr and Selles, 1995), which adversely affect crop yield. In too dry soil condition, soil becomes strong and high specific energy is required for soil crumbling. Also, tillage can produce undesirably finer fragments, which are susceptible to surface crusting, and wind and water erosion (Braunack and Dexter, 1989a). Therefore, knowledge of the effects of sowing date on seedbed physical properties is a pre-requisite for decision support for scheduling and planning tillage operations to create optimal seedbeds for crop establishment.

The objectives of the study were to quantify the effect of compaction and sowing dates on (i) seedbed physical properties, (ii) crop yield, and (iii) the range of water contents for tillage. Tillage is most often conducted in either spring or autumn, but in this study, only spring tillage is considered. Three sowing dates, namely early, timely/normal and late, were chosen as being representative of real farming practice of carrying out early, normal and delayed spring tillage. We focused on soil strength characteristics, namely tensile strength, friability, penetration resistance and soil fragmentation to assess soil workability. We hypothesized that the strength of soil aggregates and soil fragmentation will differ for different compaction treatments and sowing dates. The hypothesis was tested by comparing the strength properties of soil after early, normal and late sowing in spring.

2. Materials and methods

2.1. The experimental site

Soil samples were collected from a compaction experiment in Ås, Norway (59° 39′ 47″ N 10° 45′ 49″ E). Mean annual precipitation and temperature in the area are 785 mm and 5.3 ºC, respectively (Wolff et al., 2017). The monthly precipitation and temperature data covering the period September 2015 and September 2016 (Fig. 1) were obtained from a meteorological station located about 1 km from the experimental site. The period covers autumn plowing of the field in 2015, cultivation in the spring and harvest in autumn 2016. Daily precipitation and air temperature cycles prior to the specific field operations and sampling are also shown (Fig. 2a–d).

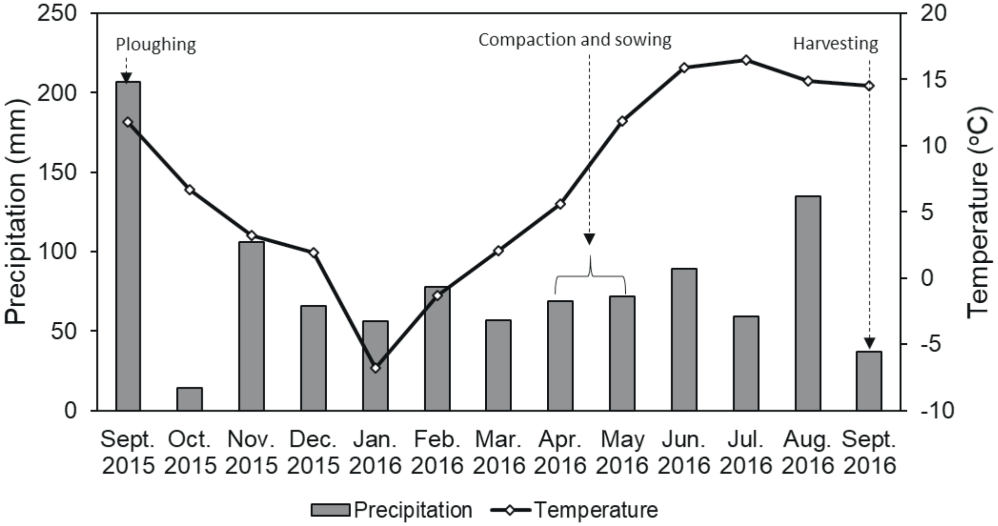

Fig. 1. Mean monthly precipitation and air temperature of the experimental site from September 2015 to September 2016. Source: Data from Wolff et al. (2017)

Soils at the site are characterized as loam over silt loam and silty clay loam and are classified as Luvic Stagnosol (Siltic) in the World Reference Base (WRB) classification system (WRB, 2006). Soil textural characteristics for the upper layer (0–15 cm depth) are: 22% clay (<2 µm), 29% silt (2–20 µm), 29% fine sand (20–200 µm), 15% coarse sand (200–2000 µm) and 4.5% soil organic matter.

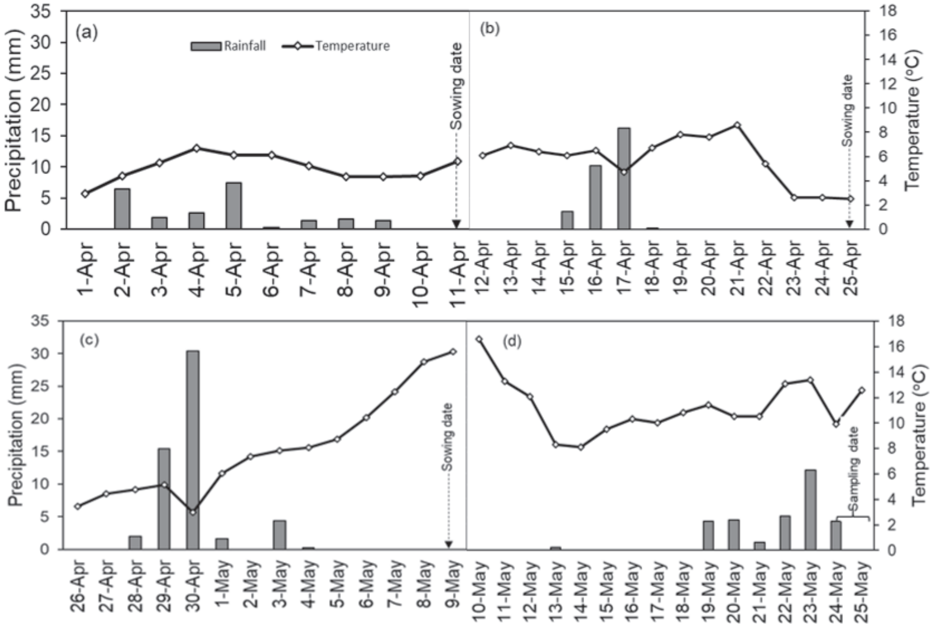

Fig. 2. Daily precipitation and air temperature before (a) early sowing date, (b) normal sowing date, (c) late sowing date and (d) sampling. No data for March 28–30, 2015. Source: Data from Wolff et al. (2017)

2.2. Experimental design and treatments

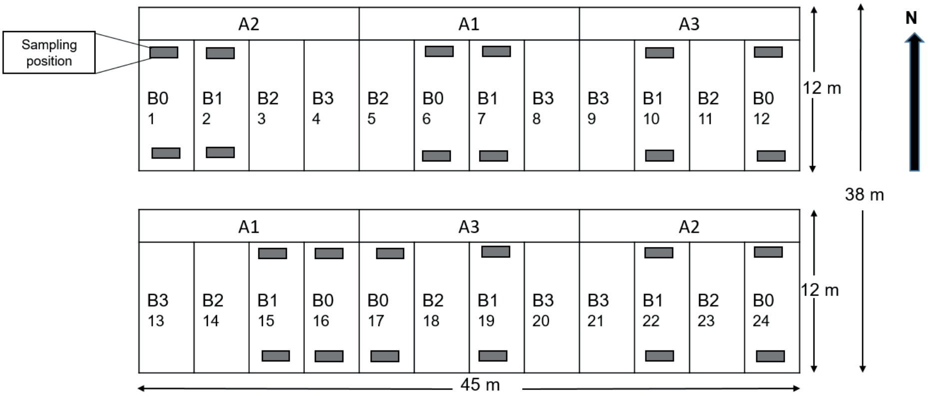

Fig. 3. Outline of experimental design used in this study. The figure also shows the sampling positions where soil samples were collected from each plot.

The experiment was established in 2014 and the same experimental treatments were repeated in 2015, 2016 and 2017. This study investigated results for soil physical properties for only 2016. The design was a randomized split-plot in two replications comprising two factors. The main plot treatment was sowing date and the split-plot treatment was compaction. The sowing dates included early (A1), normal/timely (A2) and late (A3) sowing dates (Fig. 3). The compaction treatments applied each year included no compaction (B0) and compaction by a MF 4225 tractor weighing 4.5 Mg with one pass (B1). Compaction was done wheel-by-wheel. The front and rear tires of the tractors were adjusted to an inflation pressure of 1.5 bars.

Prior to the experiment in 2016, the field was plowed to ~20 cm depth the previous autumn with a reversible plow with two moldboards. In A1, plots were either compacted or not compacted, and harrowed and seeded on the same day in the second week of April 2016 when the soil was wet to represent the worst-case scenario when farmers will sow early in spring. In the same manner, A2 plots were treated in the fourth week of April, i.e., two weeks after the A1 treatment, when the soil was expected to be in semi-moist condition. Finally, in A3, treatment was carried out in the second week of May 2016 when the soil was expected to be dry. Water content at sowing time (Table 1) was determined volumetrically in the field using a hand-held time-domain reflectometer (TDR, HH2-ML3, Delta-T Devices, Cambridge, England).

The six treatment combinations were labelled A1+B1, A1+B0, A2+B1, A2+B0, A3+B1 and A3+B0. Secondary tillage was done to a depth of ~5 cm using a Ferraboli rotary power harrow (rotorharv). A small grain cereal crop was established on each of the experimental plots: Wheat (*Triticum aestivum* L.*)* in 2014, barley (*Hordeum vulgare* L.) in 2015, oats (*Avena sativa* L.*)* in 2016 and barley in 2017. For each year, the crop was harvested at full maturity using a plot harvester. The harvested area was 9 m^2 (1.5 m × 6 m) for each plot. The grain yield for each experimental plot was recorded.

Table 1. Sowing dates and soil water content during treatment in 2016.

Depth (cm)	Early sowing (April 11)	Normal/timely sowing (April 25)	Late sowing (May 9)
	Water content (m^3 m^{-3})		
0–5	0.35	0.19	0.19
5–10	0.36	0.24	0.27

2.3. Sampling

Sampling was carried out in spring of 2016 from May 24–25, two weeks after the late sowing date. Undisturbed soil cores (9.6 cm diameter, 8 cm high, 580 cm^3, hereafter called 'large soil cores') and (6.1 cm diameter, 3.4 cm high, 100 cm^3, hereafter called 'small soil cores') were sampled. The large soil cores were sampled at only one depth (~5–15 cm), i.e., below the harrowed layer. The small soil cores were sampled from two depths: ~1–5 cm and at ~5–10 cm. Bulk soil was taken from each sampling position and depth using a spade and were placed in plastic boxes. All soil samples were covered with plastic lids and stored in a 2 ºC room until laboratory analyses.

2.4. Penetration resistance

To determine soil strength in the seedbed layer and the layer below, soil penetration resistance (PR) was measured in the field on July 4, 2016 down to 27 cm depth with a hand-held cone penetrometer (Eijkelkamp Penetrologger 06.15.SA, Eijkelkamp Soil and Water, Giesbeek, The Netherlands). It has a cone angle of 60° and a penetration speed of 2 cm s^{-1}. Average soil water content at penetration was 0.28 m^3 m^{-3}. Fifteen replicate penetration measurements were taken in each experimental plot. The geometric mean of PR was computed at the following soil depths per plot: 1–5, 7–15, 15–20 and 20–27 cm. The depths represent the seedbed layer, seedbed bottom, lower part of the tilled layer and the bottom of the plow layer, respectively. The depths were chosen on the basis that given the small size of the machinery used in this experiment, we did not expect a remarkable effect of compaction in the subsoil, below the plow layer.

2.5. Laboratory measurements

The bulk soil samples were gently fractured by hands along planes of natural weakness, and left to air-dry in a ventilated room at a temperature of ~20 °C. Portions of the air-dry soil samples were crushed and passed through a 2 mm sieve to determine soil texture. The rest of the air-dry samples were crushed using the roller method (Hartge, 1971) before sieving through a nest of sieves to obtain 8–16, 4–8, 2–4 and 1–2 mm soil aggregate size fractions. Some of the 8–16 mm aggregates were capillary-adjusted to -100, -300 and -1000 hPa matric potentials using tension tables, vacuum pots and pressure plates, respectively (Dane and Hopmans, 2002). A batch of 15 aggregates were randomly selected from each plot and size fraction to test their tensile strength (Y) using the indirect tension test (Rogowski, 1964). In brief, each of the aggregates was weighed and thereafter subjected to indirect tensile testing by crushing the aggregates between two parallel plates (Rogowski, 1964) using a mechanical press (Instron Model 5969, Instron, MA,USA) at a constant rate of displacement of 1 mm min^{-1}. The point of failure for each aggregate was automatically detected when there was a continuous crack in the aggregate. The maximum force at failure was automatically recorded.

The small soil cores were saturated and drained to -10, -30, -100, -300, and -1000 hPa matric potentials to obtain water retention data. Water content at -15000 hPa was determined on oven-dried soil sieved to 2 mm at 105° C for 24 h. Briefly, soil was crushed and sieved to 2 mm. Subsamples (~10 g) were placed in PVC rings on ceramic pressure plates (Richards, 1948), water-saturated and drained to -15000 hPa. After 10 days, the subsamples were weighed before and after oven-drying. Water content was then calculated.

The large soil cores were drained to -100, -300 and -1000 hPa and thereafter subjected to a drop-shatter test (Schjønning et al., 2002) in the laboratory to determine how the soil fragmented upon energy application. The soil was removed from the metal ring using a special plastic flange so that it dropped from a height of 200 cm onto a concrete floor covered with a plastic sheet to avoid losing the soil fragments. The dropped samples were collected and left to air-dry before sieving through a nest of sieves with apertures of 16, 8, 4 and 2 mm to determine fragment size distribution. The degree of soil fragmentation from the drop-shatter test was expressed as geometric mean diameter (GMD). Following equilibrium at each water potential the small soil cores and soil fragments obtained from dropped large soil cores were oven dried at 105° C for 24 h.

2.6. Calculations

Soil bulk density (ρb) was calculated from the oven-dried mass of each soil core (both large and small soil cores) divided by the total soil volume. Total porosity (Φ) was calculated from ρb and particle density (ρd) as $\Phi = 1- \rho b/\rho d$. A particle density of 2.54 Mg m^{-3} reported for the experimental site by Hofstra et al. (1986) was used. In addition, the volumetric water content (θ, m^3 m^{-3}) at -100 hPa was calculated by multiplying ρb and gravimetric water content at -100 hPa. Air-filled porosity (ε_a) at -100 hPa was calculated by subtracting θ at -100 hPa from Φ.

Air permeability (k_a) was measured on the small soil cores using the Forchheimer approach for soil air permeability measurement recently developed by Schjønning and Koppelgaard (2017). Individual soil samples were attached to the measuring chamber by a polyurethane tube. The sample was kept airtight by means of an inflatable rubber O-ring. The apparatus measures air flow through the sample at a range of pressure differences across the sample. A polynomial regression of flow-pressure data was then used to determine the true Darcian flow based on the coefficient to the linear part of the relation (Schjønning and Koppelgaard, 2017). Two indices of pore characteristics were derived from the relation between k_a and ε_a (Groenevelt et al., 1984), which relate to the term pore organization (*PO*) (Blackwell et al., 1990): $PO_1 = k_a/\varepsilon_a$ *and* $PO_2 = k_a/\varepsilon_a^2$. The indices are explained in detail in section 4.1.

Tensile strength (*Y*) was calculated according to Dexter and Kroesbergen (1985):

$$Y=0.567F/d^2 \tag{1}$$

where *F* is the maximum force (N) required to fracture the aggregate and *d* is the effective diameter of the spherical aggregate (m) obtained by adjusting the aggregate diameter according to the individual masses (Dexter and Kroesbergen, 1985):

$$d=d_1(m_0/m_1)^{1/3} \tag{2}$$

where d_1= is the diameter of aggregates defined by the average sieve sizes, m_0 is the mass (g) of the individual aggregate and m_1 is the mean mass of a batch of aggregates of the same size class.

The friability index (k_Y) for the air-dry aggregates was taken as the slope of the plot of the natural logarithm of *Y* (kPa) for all size fractions and the natural logarithm of aggregate volume (Utomo and Dexter, 1981):

$$\mathrm{Ln}\,(Y) = -k\,\mathrm{Ln}\,(V) + A \tag{3}$$

where Ln is the natural logarithm, *k* is an estimate of friability (large value of *k* indicates that large aggregates are much weaker than smaller aggregates and are easily fragmented into small and stronger aggregates, whereas a small value of *k* shows that the strength of the large aggregates does not differ from that of smaller aggregates (Utomo and Dexter, 1981). *A* is the intercept of the regression and denotes the predicted Ln tensile strength (kPa) of 1 m^3 of bulk soil, and *V* (m^3) is the estimated aggregate volume. Friability of the treatments was classified according to Imhoff et al. (2002) where F<0.1 = not friable, 0.1–0.2 = slightly friable, 0.2–0.5 = friable, 0.5–0.8 = very friable and >0.8 = mechanically unstable.

The water contents for tillage (dry tillage limit, θ_{DTL}; optimum water contents for tillage, θ_{OPT}; and wet tillage limit, θ_{WTL}) were determined using the consistency approach described by Obour et al. (2018). The range of water contents for tillage was calculated as the difference between θ_{WTL} and θ_{DTL}.

2.7. Statistical analysis

Data analyses were done in the R software package version 3.4.1 (R Core Team, 2017). Tensile strength, air permeability and pore organization indices (PO_1 and PO_2) data were log-transformed to yield normality. The data were analyzed using a generalized linear model. The family, gaussian and link, identity functions implemented in R were used. The ANOVA F-test was used to determine the statistical significance of compaction, sowing dates and their interaction effect. When interaction between the treatments was significant, we carried out further analyses to identify differences between treatment combinations using the Tukey method. When interaction between treatments was not significant, further analyses with interaction term excluded from the model were also carried out to identify which of the main effects was significantly different. We applied $p<0.05$ as a criterion for statistical significance. A parallel lines test was conducted to determine if the regression slopes indicating friability index were significantly different from each other.

3. Results

3.1. Soil pore characteristics

At 1–5 cm depth, sowing date significantly affected soil soil bulk density (ρb) ($p<0.001$). The early (A1) and late (A3) sowing treatments had higher ρb values compared to the normal/timely sowing (A2) treatment (Table 2). Neither the compaction × sowing date interaction nor compaction on its own significantly affected ρb ($p>0.05$). The parameters volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a), and pore organization indices (PO_1 and PO_2) at -100 hPa were significantly affected by the compaction × sowing date interaction ($p<0.05$). The θ and ε_a at -100 hPa are taken to represent the volume of pores below and above the 30 µm tube-equivalent pore diameter, respectively (Hillel, 1982). Overall, the results for the interaction effect at 1–5 cm depth were inconsistent (Table 2).

At 5–10 cm depth, ρb was higher for the A1+B1 treatment than for A1+B0, A2+B0 and A2+B1. Further, the A1+B1 treatment had the highest volume of pores < 30 µm. For A1+B1, ε_a was significantly reduced compared to the other treatments, except A3+B1 (Table 2). Compaction significantly reduced k_a, PO_1 and PO_2 ($p<0.001$), and the A1 treatment had a lower k_a than A2 ($p=0.04$).

3.2. Tensile strength

At -100 hPa, sowing date significantly affected Y ($p=0.03$), but only at 1–5 cm depth. Tensile strength was lower for A2 than for the A1 treatment (Table 3). At both 1–5 and 5–10 cm depths, the interaction effect of compaction × sowing date was significant ($p<0.05$) when Y was tested at -300 and -1000 hPa and in the air-dry state. At 1–5 cm depth, Y was consistently lower for A2+B0 than for A1+B1, A1+B0 and A2+B1 when tested at -300 and -1000 hPa. At 5–10 cm depth, A1+B1 consistently yielded a higher Y than the other treatments at -1000 hPa and in the air-dry state (Table 3).

Table 2. Arithmetic mean of bulk density (ρ_b), volumetric water content (θ), air-filled porosity (ε_a), and geometric means of air permeability (k_a) and pore organization indices ($PO_1 = k_a/\varepsilon_a$ and $PO_2 = k_a/\varepsilon_a^2$) at -100 hPa matric potential (data from small soil cores).

Depth (cm)	**Treatment**	**ρ_b (Mg m^{-3})**	**$\theta_{,-100\ hPa}$ (m^3 m^{-3})**	**$\varepsilon_{a,-100\ hPa}$ (m^3 m^{-3})**	**$k_{a,\ -100\ hPa}$ (µm^2)**	**$PO_{1,\ -100\ hPa}$ (µm^2)**	**$PO_{2,\ -100\ hPa}$ (µm^2)**
1–5	A1+B1	1.09	0.31ab	0.26b	539bc	2140ab	8503ab
	A1+B0	1.10	0.32ab	0.25ab	337ac	1389ab	5721ab
	A2+B1	1.05	0.30a	0.28b	327ab	1187a	4310a
	A2+B0	1.05	0.31ab	0.28b	735c	2674b	9732b
	A3+B1	1.17	0.33b	0.21a	215a	1082a	5452ab
	A3+B0	1.11	0.30a	0.27b	415ac	1562ab	5873ab
	Average compaction						
	B1	1.10	0.32	0.25	336	1401	5846
	B0	1.09	0.31	0.27	469	1797	6889
	Average sowing date						
	A1	1.10b	0.31	0.25	426	1724	6975
	A2	1.05a	0.31	0.28	490	1782	6476
	A3	1.14b	0.31	0.24	299	1300	5658
5–10	A1+B1	1.28d	0.38c	0.12a	32	310	3004
	A1+B0	1.20ac	0.35ab	0.18bc	206	1254	7626
	A2+B1	1.12a	0.34ab	0.21c	174	830	3972
	A2+B0	1.14ab	0.35ab	0.20c	231	1162	5835
	A3+B1	1.27cd	0.36b	0.14ab	48	350	2529
	A3+B0	1.21bcd	0.33a	0.19c	155	830	4434
	Average compaction						
	B1	1.23	0.36	0.16	64a	448a	3113b
	B0	1.19	0.34	0.19	196b	1071b	5856a
	Average sowing date						
	A1	1.24	0.36	0.15	81a	623	4787
	A2	1.13	0.35	0.21	200b	982	4814
	A3	1.24	0.34	0.17	85ab	531	3318

Values with different letters are significantly different at $p<0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg.

Table 3. Geometric means of tensile strength (*Y*) of 8–16 mm soil aggregates.

Depth (cm)	**Treatment**	***Y* (kPa)**			
		-100 hPa	-300 hPa	-1000 hPa	Air-dry
1–5	A1+B1	6.9	11.4bc	24.2b	135b
	A1+B0	5.8	12.9c	22.8b	96ab
	A2+B1	4.3	11.4bc	19.6b	76a
	A2+B0	4.4	6.7a	10.9a	93ab
	A3+B1	5.3	7.4ab	19.3b	112b
	A3+B0	4.9	9.4ac	18.3b	69a
	Average compaction				
	B1	5.4	9.9	20.9	105
	B0	5.0	9.3	16.6	85
	Average sowing date				
	A1	6.3b	12.1	23.5	114
	A2	4.4a	8.7	14.6	84
	A3	5.1ab	8.4	18.8	88
5–10	A1+B1	7.6	18.2b	41.9c	175c
	A1+B0	5.8	13.5b	23.3b	110b
	A2+B1	5.5	6.9a	14.1a	98ab
	A2+B0	4.7	11.2ab	12.1a	71a
	A3+B1	5.8	12.9b	22.8b	87ab
	A3+B0	6.7	11.3ab	20.8b	94ab
	Average compaction				
	B1	6.3	11.8	23.8	114
	B0	5.7	12.0	18.0	90
	Average sowing date				
	A1	6.6	15.6	31.3	138
	A2	5.1	8.8	13.1	84
	A3	6.3	12.1	21.8	91

Values with different letters are significantly different at $p<0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg.

3.3. Friability indices and soil fragmentation

At 1–5 cm depth, higher friability (k_Y), indicated by the steepest slope, was found for the A2 treatment, and for the A2 and A3 treatments at 5–10 cm depth (Fig. 4a and c). Regardless of depth, there was a significant difference of k_Y between the compacted and control soil (Fig. 4b and d).

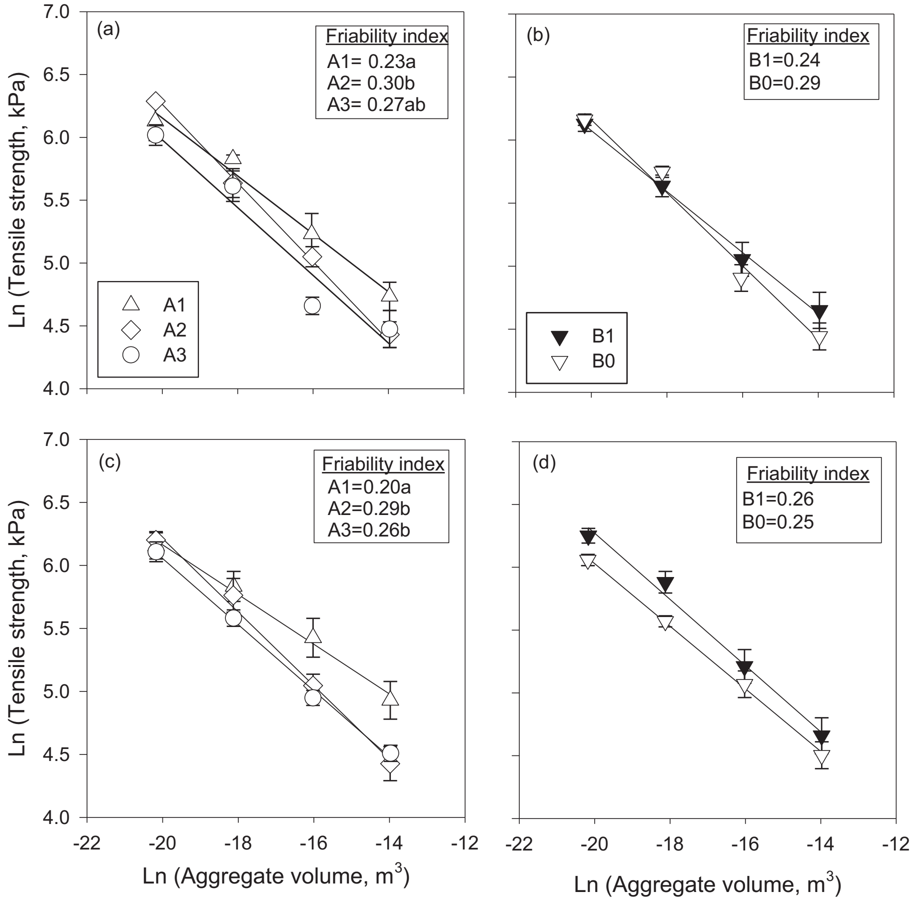

Fig. 4. Natural logarithm (Ln) of tensile strength, Y (kPa), as a function of Ln aggregate volume, V (m3), for air-dry aggregates. Soil friability index (kY), determined as the slope of the regression equation, is shown for each treatment: Averages of kY for sowing dates (a and c) and for compaction (b and d). A1, early sowing date; A2, normal sowing date; and A3, late sowing date. B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg. Values with different letters are significantly different at p<0.05. Error bars indicate the standard errors of the mean.

Table 4. Fragmentation of soil cores dropped at -100, -300 and -1000 hPa matric potentials (data from large soil cores). Geometric mean diameter (GMD) and the fraction of soil fragments <5 and >32 mm in diameter after the drop-shatter test are shown.

	-100 hPa			-300 hPa			-1000 hPa		
		Soil fragments			Soil fragments			Soil fragments	
Treatment	GMD (mm)	<5 mm	>32 mm	GMD (mm)	<5 mm	>32 mm	GMD (mm)	<5 mm	>32 mm
A1+B1	50.5b	0.03a	0.84b	52.3b	0.03a	0.86b	51.3c	0.03a	0.85b
A1+B0	29.4a	0.09ab	0.48ab	41.1ab	0.06ab	0.68ab	34.8ab	0.09ab	0.58b
A2+B1	27.8a	0.11ab	0.43a	32.4ab	0.11ab	0.55ab	-	-	-
A2+B0	25.9a	0.14ab	0.44a	24.7a	0.14ab	0.39a	-	-	-
A3+B1	25.7a	0.15b	0.38a	39.8ab	0.08ab	0.68ab	37.6bc	0.08a	0.64b
A3+B0	23.1a	0.13ab	0.34a	21.7a	0.15b	0.30a	20.7a	0.15b	0.30a
Average compaction									
B0	26.1	0.12	0.42	29.2	0.12	0.46	27.8	0.12	0.44
B1	34.6	0.09	0.55	41.5	0.07	0.70	44.4	0.05	0.75
Average sowing date									
A1	39.9	0.06	0.66	46.7	0.05	0.77	43.0	0.06	0.72
A2	26.9	0.12	0.44	28.6	0.12	0.47	-	-	-
A3	24.4	0.14	0.36	30.7	0.12	0.49	29.2	0.12	0.47

Values with different letters are significantly different at $p<0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg

There was a significant (p<0.05) compaction × sowing date interaction effect on soil fragmentation at all the matric potentials studied. At -100 hPa, the A1+B1 treatment resulted in poor fragmentation compared to the other treatments, indicated by the larger geometric mean diameter (GMD) values, i.e., soil cloddiness (Table 4). However, at -300 hPa, the GMD for the A1+B1 treatment significantly differed only from A3+B0 (Table 4). A similar trend of significantly larger GMD values was obtained at -1000 hPa for the A1+B1 compared to the A1+B0 and A3+B0 treatments. Further, the poor fragmentation of the A1+B1 treatment is illustrated by a generally smaller proportion of small soil fragments (<5 mm in diameter) and larger proportion of large soil fragments (>32 mm in diameter) for the matric potentials studied (Table 4).

3.4. Grain yield

Table 5: Yield of spring-sown small grain cereal crops (2014–2017).

Treatment	Yield (Mg ha^{-1})			
	2014 (Wheat)	2015 (Barley)	2016 (Oats)	2017 (Barley)
A1+B0	5.5	7.3	5.8	5.0
A1+B1	5.2	6.9	5.5	4.9
A2+B0	5.8	7.8	6.5	5.9
A2+B1	5.1	6.8	6.8	5.2
A3+B0	5.0	7.0	6.5	5.0
A3+B1	4.8	6.1	5.9	4.8
Average compaction				
B1	5.0a	6.6a	6.1	5.0
B0	5.5b	7.3b	6.3	5.3
Average sowing date				
A1	5.3b	7.1b	5.7	5.0
A2	5.5b	7.3b	6.6	5.5
A3	4.9a	6.5a	6.2	4.9

Values with different letters are significantly different at *p*<0.05. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg.

Compaction and late sowing significantly affected yield of wheat and barley ($p<0.05$) in 2014 and 2015, respectively (Table 5). There was a trend showing that compaction and late sowing reduced yield of oats in 2016, and barley in 2017 compared to the control and the early and normal sowing treatments, respectively, albeit not statistically significant ($p>0.05$). Yield of the small grain cereals for the A1 and A2 treatments, however, did not differ significantly for any of the years studied (Table 5).

3.5. Drop-shatter results, soil pore and aggregate characteristics vs yield

Across all treatments, the yield of oats in 2016 negatively related to the GMD of soil fragments and Y tested at -100 hPa. On the other hand, there was a positive linear relationship between yield of oats and porosity (Φ). Overall, only 27% of the variation in the yield of oats can be explained by the GMD of soil fragments produced from dropped soil cores at -100 hPa, and 37% and 51% by Φ and Y, respectively (Fig. 5a, b and c).

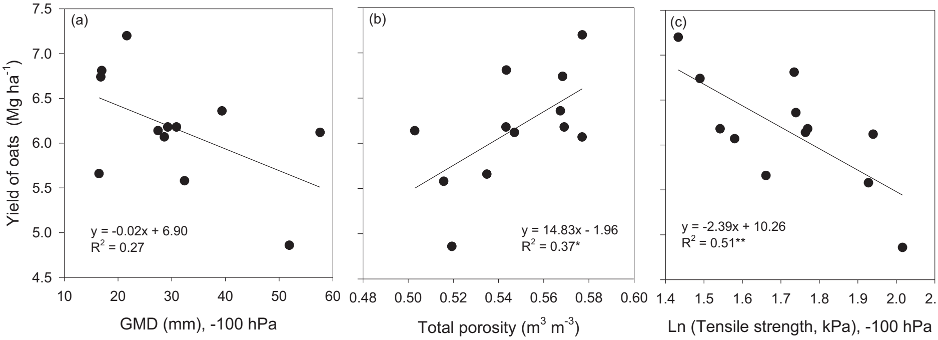

Fig. 5. Relationship between yield of oats and (a) geometric mean diameter (GMD) of soil fragments produced from drop-shatter test at -100 hPa, and (b) porosity and (c) tensile strength of aggregates from 1–10 cm depth measured at -100 hPa. ** $p<0.01$ and *$p<0.05$.

3.6. Soil penetration resistance and yield

There was a significant effect of sowing date and depth on penetration resistance (PR) (*p*=0.002) (data not shown). The early sowing date treatment consistently had a higher PR in the seedbed layer (1–5 cm depth) and below (at 5, 15, 20 and 27 cm depth). In contrast, the PR for the compacted treatment was higher than the control only at 15 cm depth (data not shown). In general, mean PR measured on July 4, 2016 in the topsoil for all experimental plots was 0.43 and 1.02 MPa for 1–5 and 7–15 cm depth, respectively.

Yield of oats was significantly and inversely related to PR at 1–5 cm (*p*=0.004) and 7–15 cm depth (*p*= 0.021). A similar – although not significant – negative relationship between yield and PR was found at 15–20, 20–27 cm as well as the overall PR at 1–27 cm depth (Fig. 6a–e).

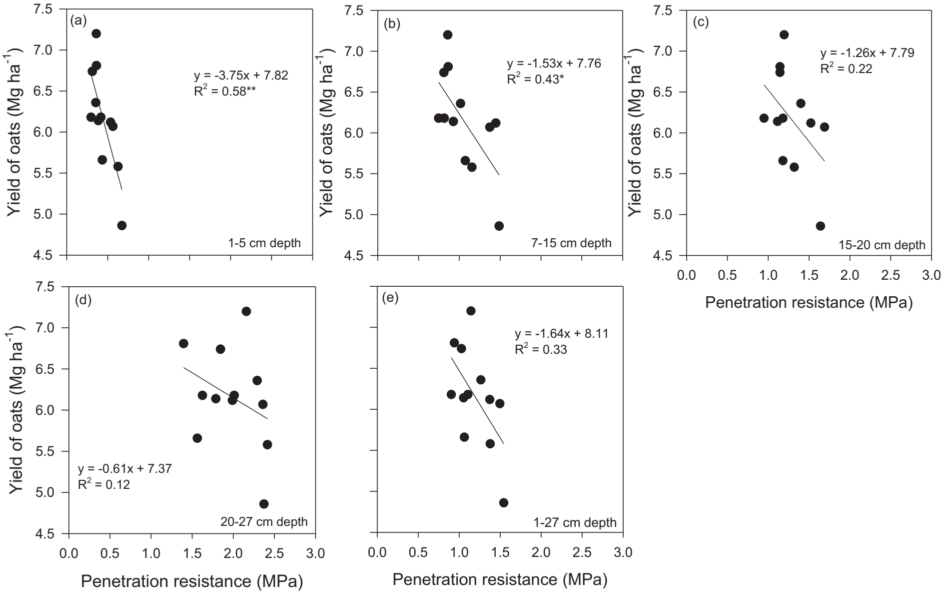

Fig. 6. Yield of oats related to penetration resistance (PR) at (a) 1–5, (b) 7–15, (c) 15–20 cm, (d) 20–27 cm depth and (e) average PR at 1–27 cm. Data points show observation for each individual experimental plot. Penetrometer measurements were done on July 4, 2016 which means 56, 70 and 84 days after the establishment of A3, late sowing date; A2, normal sowing date and A1, early sowing date, respectively. Lines indicate regression. $^{**}p<0.01$ and $^{*}p<0.05$.

3.7. Water contents for tillage

At both 1–5 and 5–10 cm depths, the range of water contents for tillage ($\Delta\theta_{\mathrm{RANGE}}$) was similar for the compacted and the control treatments. With respect to sowing date, the early and late sowing reduced $\Delta\theta_{\mathrm{RANGE}}$ compared to the normal sowing, although the difference was not significant at any of the depths studied (Fig. 7a–d). $\Delta\theta_{\mathrm{RANGE}}$ was positively related to soil porosity at both 1–5 and 5–10 cm depth, although not statistically significant (Fig. 8a and b).

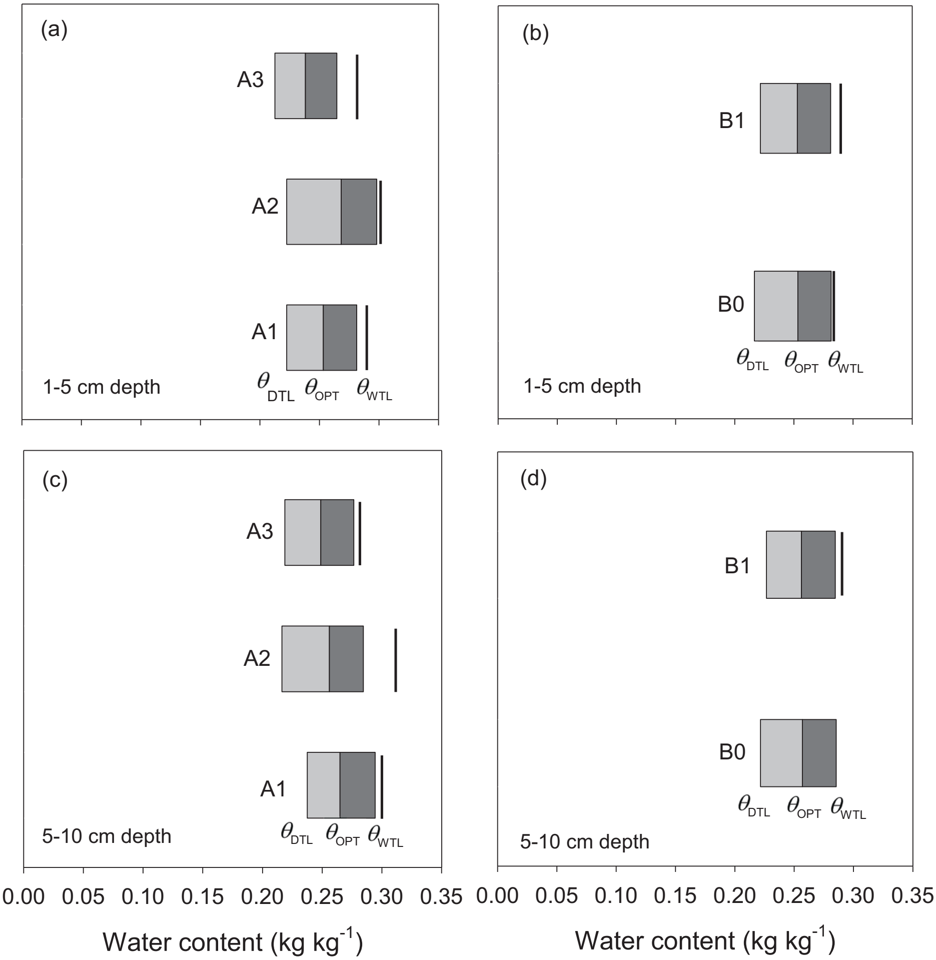

Fig. 7. Water contents for tillage. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg. θDTL: dry tillage limit, θOPT: optimum water content for tillage and θWTL: wet tillage limit. Solid short vertical lines show water contents at -100 hPa.

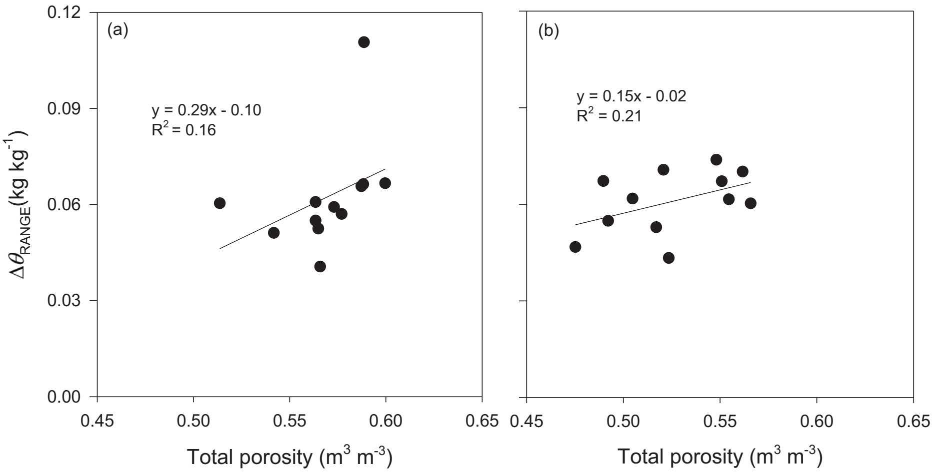

Fig. 8. Range of water contents for tillage as a function of soil porosity at (a) 1–5 cm and (b) 5–10 cm depth.

4. Discussion

4.1. Effect of compaction and sowing dates on seedbed physical properties

To assess the effect of treatment on pore structure characteristics of the seedbed, soil bulk density, water retention, aeration and pore organization indices (k_a/ε_a (PO_1) and k_a/ε_a^2 (PO_2) were determined. At 1–5 cm depth, the compaction × sowing date interaction significantly affected volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a) and pore organization indices (k_a/ε_a (PO_1) and k_a/ε_a^2 (PO_2)) although not bulk density (Table 2). The effects observed were not consistent for all the treatment combinations. A higher volume of pores <30 µm and lower volume of pores >30 µm were found for the A3+B1 compared to, for instance, the A2+B1 and A3+B0 treatments. This may be interpreted as compaction combined with late sowing (A3) reducing ε_a at -100 hPa.

The pore organization indices, PO_1 and PO_2, can be used to describe the effects of soil management on pore size distribution, tortuosity and continuity of ε_a (Groenevelt et al., 1984). These authors proposed that soils with similar PO_1 values have identical pore-size distributions and pore continuities because k_a is normalized only with respect to the volume of air-conducting pores. Soils with similar PO_2 values, on the other hand, only have identical pore size distributions. This implies that the difference between PO_1 and PO_2 mainly relates to the pore continuity, independent of the pore size distribution (Ball et al., 1988). At 5–10 cm depth, compaction reduced k_a, PO_1 and PO_2 (Table 2). Generally, a value of k_a of less than 1 μm^2 has been suggested as a critical limit, inferring soil impermeability, which restricts water and air transport necessary for many biological processes. The results showed k_a values above the critical limit in all cases (Table 2).

Effect of compaction and sowing dates on soil strength characteristics of seedbed was quantified by measuring the tensile strength (Y) of aggregates and soil penetration resistance (PR). At -100 hPa, compaction and sowing date affected Y of aggregates. For the latter, the difference was only significant between early sowing date (A1) and normal sowing date (A2) at 1–5 cm depth (Table 3). At both 1–5 cm and 5–10 cm depths, Y was lower for the A2+B0 treatment, whereas the A1+B1 treatment, in general, increased Y at -300, -1000 hPa and at air-dry state (Table 3). The higher Y for the compacted and A1 treatments can be explained by structural damage due to kneading by tillage implements in wet conditions, which consequently increased Y following the drying of soil fragments produced by tillage (Watts et al., 1996). The results are consistent with the Munkholm and Schjønning (2004) study. These authors also showed that the effect of structural damage on Y can be persistent, and further found that after six months, aggregates produced by intensive rotary tillage when soil was too wet for optimal tillage remained stronger than a reference soil, which was tilled when the soil had dried to a friable condition. Håkansson et al. (1988) found that the effects of compaction in the topsoil may persist even after mechanical loosening such as plowing and harrowing.

The results in this study showing significant effects of the compaction × early sowing interaction on Y tested at -300, -1000 hPa and in air-dry state at 1–5 cm depth are, however, surprising, because such a significant interaction effect was not observed for soil bulk density (ρ_b) at the same depth (Table 2). This can be explained by Y, unlike ρ_b, being highly affected by the particle-particle bonds participating in the particular mode of failure as well as the presence of micro-cracks serving as planes of weakness to initiate tensile failure (Chakraborty et al., 2014).

Interestingly, even though the A2 and A3 treatments had similar water contents at 1–5 cm depth at the time of compaction and/or sowing operations (Table 1), Y differed between the two treatments. For instance, Y at -1000 hPa for A2+B0 was significantly different from A3+B0 at 1–5 cm depth (Table 3). This may be ascribed to soil 'memory' of antecedent preciptiation events prior to treatments and sampling. Thus, maximum rainfall amounts of 10.2 and 16.2 mm on April 16–17, 2016 before the A2 treatment (Fig. 2b) compared to 15.4 and 30.4 mm on April 29–30, 2016 prior to the A3 treatment (Fig. 2c) may have differently influenced the spontaneous and mechanical dispersion of clay as well as wetting and drying cycles, which in turn affect the temporal variation of Y (Kay and Dexter, 1992).

Penetration resistance was significantly affected by sowing date ($p<0.05$). The A1 treatment had a higher PR in the seedbed and down to 27 cm depth compared to the A2 and A3 treatments (data not shown). As expected, compaction increased PR down to 27 cm depth, although the effect was significant ($p=0.02$) only at 7–15 cm depth (data not shown). de Toro and Arvidsson (2003) also found an increased PR down to a depth of 18 cm after harrowing operations for seedbed preparation were performed on clayey soil in Sweden at different water contents in spring. In the upper soil layers, tire inflation pressure is the major driver of stresses exerted on soil by agricultural machinery (Schjønning et al., 2012). Thus, the effect of the A1 treatment on PR measured at 1–5 cm and below the seedbed down to 27 cm depth can be due to stresses exerted by tractor wheels and tillage implement, but could also be an accumulated effect over the three years of experimental treatments (Håkansson et al., 1988) despite soil loosening by plowing each autumn as well as freezing and thawing cycles prior to the experimental treatments in spring.

In general, the soil aggregates studied can be described as friable according to the classification by Imhoff et al. (2002). Notwithstanding this, the A1 treatment reduced friability (k_Y) at both soil depths studied compared to the A2 treatment. Compaction also reduced k_Y, particularly at 1–5 cm depth, although not significantly (Fig. 4). The results illustrate that tilling soil in wet condition reduces k_Y due to soil structural degradation. Higher k_Y values for the A2 treatment imply that bulk soil or soil clods produced after primary tillage can be more easily fragmented into smaller fragments, whereas smaller aggregates are difficult to further fragment into undesirably smaller elements (Munkholm, 2011).

Measurement of soil fragmentation at 5–15 cm depth, i.e., below the seedbed, yielded information on soil compaction and fragment size distribution. Compaction × early sowing date resulted in poor soil fragmentation, evidenced by the large geometric mean diameters

(GMD) of soil fragments, the smaller proportion of small soil fragments (<5 mm in diameter) and larger proportion of soil clods (>32 mm in diameter) (Table 4). Seedbeds consisting of fragments <5 mm in size increase the number of plants and crop yield of small grain cereals by 5% compared to coarse seedbeds in silty soil in Sweden (Håkansson et al., 2002). Our results showed that, in general, the proportion of soil fragments <5 mm in diameter produced from the dropped soil cores was small (maximum of 15% at all the matric potentials studied). This implies that, in practice, larger number of successive seedbed harrowings, including their negative impact on soil physical properties, would be required to fragment the soil into a suitable seedbed for spring-sown small grain cereal crops.

4.2. Effect of compacton and sowing dates on crop yield

Compaction and late sowing reduced the yield of spring-sown small grain cereal crops, but the effect was significant only in 2014 and 2015 for wheat and barley, respectively (Table 5). This may be ascribed to a short growing season rather than the influence of soil physical properties. Riley (2016) also explained a yield loss after late sowing by a shorter growing season. Likewise Perez-Bidegain et al. (2007) found that the yield of corn in Newton, USA was not significantly affected by sowing date in the first two years, but was in the third year. However, their study did not include compaction treatment, in contrast to our study. The insignificant effect of compaction and sowing dates in 2016 and 2017 for oats and barley, respectively, can be interpreted as multiple factors affecting the final yield of crops (Perez-Bidegain et al., 2007) —not least the specific weather conditions during the growing season.

Simple regression analyses showed that when tested at -100 hPa, the yield of oats in 2016 was negatively related to the GMD of soil fragments produced from the drop-shatter test and to Y, but positively related to Φ (Fig. 5a–c). In relation to soil strength, the yield of oats was negatively related to PR (Fig. 6a–e). Overall, the relationship was significant for Φ and Y as well as for PR at 1–5 and 7–15 cm depth, explaining 37–58% of the variation in the yield of oats. The negative and significant relationship between yield and Y and PR can be explained by the effect of soil strength on root growth and penetration, which can adversely affect crop yield (Taylor et al., 1966). The negative and weak linear relation between yield and GMD is indicative of the generally negative effect of poor soil fragmentation on plant growth.

4.3. Effect of compaction and sowing dates on water contents for tillage

Compaction, and early and late sowing dates reduced the range of water contents for tillage ($\Delta\theta_{\mathrm{RANGE}}$), but the effect was not significant at any of the depths studied (Fig. 7a–d). $\Delta\theta_{\mathrm{RANGE}}$ was positively related to soil porosity (Φ) (Fig. 8a and b), which agrees with the results of Dexter and Bird (2001) who showed that the range of water contents for tillage and its upper (θ_{WTL}) and lower limits (θ_{DTL}) decrease with increasing soil bulk density (ρ_b), an indication of a reduced Φ. However, in their study, θ_{WTL} and θ_{DTL} were predicted using pedotransfer functions, in contrast to the consistency approach used in this study.

From our results it could be deduced that compaction and early sowing date reduce macroporosity. Air-filled pores and cracks elongate and coalesce under mechanical stress, resulting in soil fragmentation during tillage (Dexter and Richard, 2009). This means soil structural degradation due to disturbances by tillage implements and stresses exerted by the wheels of machinery in less-than-ideal soil moisture conditions will increase soil ρ_b and, consequently, reduce the $\Delta\theta_{\mathrm{RANGE}}$.

It should be pointed out that the presented results only provide a snap-shot of soil workability, assessed as the $\Delta\theta_{\mathrm{RANGE}}$ within which tillage can be executed satisfactorily after a secondary tillage in spring. As mentioned previously, we expect a relatively small residual effect of treatment on soil workability in the following spring after plowing and freezing and thawing cycles during the winter. Nevertheless, a narrowing of the $\Delta\theta_{\mathrm{RANGE}}$ for the early and late sowing can reduce the water contents at which soil is suitable for primary tillage in the following autumn (Munkholm and Schjønning, 2004). Findings of the study indicate that a combination of quantitative information on soil structural and strength characteristics provide useful criteria for assessing soil workability and fragmentation during tillage.

5. Conclusions and practical implications of the results

Results from this study confirmed, to some extent, the hypothesis that soil fragmentation and the strength of soil aggregates differ for different compaction treatments and sowing dates. The main conclusions were that the interaction of compaction with sowing date significantly affected soil pore characteristics, particularly at 1–5 cm depth, although the effect was not consistent for all treatment combinations. Compaction combined with early sowing increased tensile strength at both 1–5 and 5–10 cm depth, whereas the dropped soil cores, in general, fragmented poorly for all treatments and at all matric potentials studied. Early sowing significantly decreased soil friability and increased soil penetration resistance in the seedbed layer and down to 27 cm depth. Late sowing decreased yield of spring-sown small grain cereal crops, but this may mainly be ascribed to a shorter growing season rather than an influence of soil physical properties and compaction. Finally, early and late sowing decreased the range of water contents for tillage, which can reduce soil workability for subsequent tillage operations, especially autumn plowing.

The overall findings of the study have practical implications for cropping regimes in colder climates, where the growing period for cereals is short by showing that cultivation in less-than-ideal moisture conditions such as early spring when soil is still wet limits the capacity of soil to produce desirable seedbeds after tillage. It also adversely affects soil physical properties of a seedbed, which in turn affect crop yield. Present and future farm managers need to consider the implications of compaction and sowing dates on soil physical conditions even more than in the past.

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Paper II

Photographer: Trond Børresen (1995)

Timeliness and traffic intensity in seedbed preparation for spring cereals in Norway: Importance of soil physical properties, persistence of soil degradation, and consequences for yield

Kolberg, D., Riley, H., Børresen, T.

Abstract

Future increase in winter and spring precipitation in Scandinavia may exacerbate the dilemma of spring fieldwork that farmers have, concerning topsoil compaction versus delayed sowing on autumn-ploughed soil. In order to avoid loss of cereal yield potential and adapt to climate change, we need to know how optimized timing and traffic intensity of spring fieldwork can minimize soil physical degradation. To study the effects of timing (early, medium, late) and traffic intensity of spring fieldwork (no wheeling, one, two or three additional wheelings) on soil physical quality and yield, we used a split-plot experiment, performed in southeastern Norway with two replications in 2014-2017, to obtain aggregate size distribution, pore characteristics, aggregate tensile strength, penetration resistance, as well as actual and simulated yield. In the unfavourable conditions of 2016, early spring fieldwork in excessively wet soil gave rise to larger and stronger aggregates, higher penetration resistance and slightly changed pore characteristics, with resulting reduced yields. The increased penetration resistance persisted until autumn. The effect of traffic intensity was less pronounced, probably due to location, soil type and the small range of intensities involved. In this context of spring fieldwork timeliness, the proportion of 2-6 mm aggregates and penetration resistance were the most important soil physical factors for both soil quality and cereal yield.

1. Introduction

In cold-temperate regions with high soil water content in spring, timing and intensity of field traffic during seedbed preparation for spring cereals may strongly influence the physical quality of the soil and the risk of yield loss. In cold-temperate regions, farmers traditionally have adapted to a short growing season by ploughing their soil in autumn and starting seedbed preparation as early as possible in the following spring (Peltonen-Sainio et al., 2009). The decision on when to start spring fieldwork presents farmers with a dilemma of timeliness. If the fieldwork starts too early, when the soil is still wet, the farmer risks yield loss due to topsoil compaction (Bakken et al., 1987; Håkansson, 2005; Hofstra et al., 1986; Marti, 1983; Njøs, 1978) and oxygen deficiency during germination (Wesseling and VanWijk, 1957). If the farmer waits until the soil is dry enough, there is a risk of yield loss due to delayed sowing and a shorter growing season (Riley, 2016).

In the future, climate change may exacerbate this dilemma, due to projected increases in precipitation during winter and spring in Scandinavia (Hov et al., 2013; Trnka et al., 2011). Generally, after the optimum sowing date, the risk of yield loss due to delayed sowing increases even faster than the risk of yield loss due to soil compaction (Riley, 2016). This often leads farmers to accept some compaction loss in order to avoid larger loss due to delayed sowing. In the future, farmers may be forced to start their spring fieldwork at higher soil moisture content. In order to avoid further yield loss and adapt to climate change, we need to know how optimized timing and traffic intensity of spring fieldwork can minimize soil physical degradation in unfavourably wet soil.

In earlier Scandinavian seedbed research, the most common physical property used to describe a seedbed is aggregate size distribution (Håkansson et al., 2002; Håkansson et al., 2011a-c). Aggregate size usually increases with increasing soil water content at the time of seedbed preparation (Tisdall and Adem, 1986; Braunack and McPhee, 1991; Adam and Erbach, 1992; Håkansson et al., 2002; De Toro and Arvidsson, 2003; Dexter and Birkas, 2004). Traditionally, with normal dry conditions after sowing, seedbeds with larger aggregate size, i.e. <50% aggregates <5 mm, are considered less ideal for plant establishment (Håkansson et al., 2002; Nasr and Selles, 1995).

Other physical properties may be important for early plant growth, but we do not know as much about how they are affected soil moisture conditions or by traffic intensity during seedbed preparation. In a recent publication, Obour et al. (2018) presented several soil physical properties of seedbeds with and without additional wheeling on different sowing dates in spring 2016 in southeastern Norway. For example, they found that the timing of spring fieldwork affected soil pore characteristics, soil strength and friability in spring. For several of the physical properties they also found a degrading effect of traffic in early spring. This is in contrast to the advantageous effect of moderate seedbed compaction on crop growth under drier conditions, which ensures capillary transfer to the germinating seed and nutrient uptake during early growth (Arvidsson, 1999; Arvidsson and Håkansson, 2014; Håkansson et al., 2011c; Håkansson et al., 2012).

The degree of the physically degrading effect of compaction in unfavourably wet soil on the seedbed quality is considered to depend on the traffic intensity (Arvidsson and Håkansson, 1991) and the type of implement used (Kolberg et al., n.d.). During traditional seedbed preparation, traffic by tractor or implement tyres commonly reaches a surface coverage of up to more than 200 % in Sweden (Håkansson, 2005). On Norwegian agricultural land, coverage may be even larger, due to less favourable topography, field shape and size, and a greater percentage of headland.

Earlier studies on traffic intensity in Norway often represented traffic by wheeling in wet conditions in early spring, but the seedbed preparation was conducted later in spring and at the same time for all treatments (Marti, 1983; Bakken et al., 1987; Njøs, 1978; Hofstra et al., 1986). To better resemble agricultural practices, experiments that combine both wheeling and seedbed preparation in early spring are needed, such as the field experiment partially presented by Obour et al. (2018). Furthermore, soil degradation in terms of soil compaction has often been found to persist for a long time (Arvidsson and Håkansson, 1991; Håkansson and Reeder, 1994; Håkansson, 2005). This persistence of structural degradation in the seedbed may also apply to other physical properties. Thus, we need to explore whether the timing and traffic intensity of spring fieldwork also affect soil physical properties and yield in autumn.

Based on the above, the aim of this paper is to study the effects of timing and traffic intensity of spring fieldwork on soil physical quality in both spring and autumn, and their consequences for cereal yield. This paper presents results from a field experiment in southeastern Norway (partially described in Obour et al., 2018) which combined wheeling and seedbed preparation in early spring, compared to later in spring. The study relates aggregate size distribution to physical properties such as air-filled porosity, air permeability and soil strength, in spring and autumn. In addition, the relationship between the assumed risk of yield loss due to untimely spring fieldwork and the yield actually obtained is explored. It was hypothesized that spring fieldwork performed too early impairs the physical quality of the seedbed, that this effect increases with increasing traffic intensity, and that soil degrading effects and reduced yields can be found in the following autumn. It was also hypothesized that delayed spring fieldwork reduces yields. It was expected that obtained yields are correlated with the risk of yield loss, in terms of simulated yield. Further, it was explored whether aggregate size distribution is correlated with other physical properties and whether physical properties are correlated with obtained yield.

2. Material and methods

2.1. Study site

The field experiment was conducted at the Norwegian University of Life Sciences, Ås (59° 39′ 37″ N 10° 46′ 54″ E, 93.3 m above sea level) in Akershus County in southeastern Norway. Southeastern Norway is the most important cereal-growing region in Norway, with 53 % of the total cereal area. In this region, crop rotations are dominated by spring

Table 1: Selected weather variables at the experimental site during spring in climatic reference period (1973-2012) and the experimental years (2014-2017).

	1973-2012 Mean (SD)	2014	2015	2016	2017
Temperature (°C)					
March	0.1 (2.3)	3.7	2.6	1.8	1.9
April	4.7 (1.5)	6.7	6.2	5.2	4.4
May	10.6 (1.2)	10.9	8.3	11.1	10.8
Precipitation (mm)					
March	55.2 (43.2)	38.7	62.9	56.9	41.3
April	43.8 (26.6)	62.8	11.9	68.9	33.7
May	55.0 (28.9)	39.8	101.7	71.7	69.3
Potential evaporation (mm)					
March	4.3 (4.9)	7.6	3.9	0.4	3.0
April	37.3 (9.7)	41.3	53.3	34.9	41.8
May	83.8 (14.0)	76.2	71.1	84.8	70.1

cereals, mostly barley, oats and wheat (Statistics Norway, 2018). At the experimental site, spring cereals have dominated for at least 60 years. The climate in Ås is characterized as nemoral (NEM3) by Metzger et al. (2005). Selected weather variables in spring during the reference period and the experimental years are shown in Table 1, from the nearest climate station. Calculations are based on daily precipitation (mm), mean temperature (°C), relative humidity (%), global radiation (MJ day^{-1}) and wind speed (m s^{-1}), obtained from the Norwegian Institute of Bioeconomy Research (http://lmt.nibio.no/) and supplemented with data from the Norwegian Meteorological Institute (http://www.met.no) and the Norwegian University of Life Sciences (Wolff et al., 2018). Potential evaporation calculated by a method based on measured pan evaporation in Norway (Riley and Berentsen, 2009). The soil at the experimental site is classified as Luvic Stagnosol (Siltic) in the World Reference Base classification system (FAO, 2006), with a loam A horizon overlaying silt loam and silty clay loam. The topsoil (0–27 cm) consists of 21 % clay (<2 µm), 42 % silt (2–60 µm) and 37 % sand (> 60 µm) (Hofstra et al., 1986). Soil organic matter content at 0-15 cm depth is 4.5 % (Obour et al., 2018). The soil has been drained artificially in the 1980's.

2.2. Experimental design and management

Prior to each of the experimental seasons of 2014-2017, the experimental site was mouldboard ploughed in autumn to a depth of approximately 22 cm. Twenty-four plots of 3.75 x 12 m were created in a randomized split-plot design, as illustrated by Obour et al. (2018), representing two factors and two replications. The main plot treatment was timing of spring fieldwork (harrowing and sowing) and the split-plot treatment was traffic intensity during spring fieldwork. The timing was either early (A1), medium (A2) or late (A3) sowing date. Different degrees of traffic intensities were obtained by different numbers of wheelings with a tractor just before harrowing. Traffic intensity levels were no (B0), one (B1), two (B2) or three wheelings (B3).

The decision on when to start fieldwork was based on perception of soil moisture and friability by manual kneading as practiced by farmers. The intention was to select an early sowing date with soil that was considered unfavourably wet, a medium date with soil that was considered favourably moist for tillage, and a late date with soil that was at least as dry as the medium date. Actual volumetric water content in the field was determined just before sowing with a hand-held time-domain reflectometer (TDR) (HH2-ML3, Delta-T

Devices, Cambridge, England) at 5-10 cm depth. Means of 5 TDR measurements per sowing date were used, with the exception of values for early and medium fieldwork in 2014 which were determined by manual soil sampling, weighing and drying. Actual dates and soil water contents for different sowing time in the different years are presented in Table 2. Water contents are presented relative to the soil's water content at field capacity (FC, -100 hPa) of 35.0 vol % as assumed for the soil type group "loam" in the workability model by Riley (2016) for depth of 0-20 cm. This agrees quite well with earlier lab measurements of 35.6 vol % for 0-27 cm at the experimental site by Hofstra et al. (1986).

All fieldwork, i.e. wheeling, harrowing, sowing and rolling, was done on the same day. The soil was compacted wheel-by-wheel with a MF 4225 tractor loaded to 4.5 Mg with tyre inflation pressure of 1.5 bars, and harrowed to a target depth of 5 cm with a Ferraboli rotary harrow. Wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and barley were sown, in 2014, 2015, 2016 and 2017 respectively, with a Junkkari Simulta 2500 combined seed-fertilizer drill. Rolling was done with a light Cambridge roller.

Table 2: Actual dates for different sowing time and their associated mean soil water content at 5-10 cm depth, presented in % of field capacity (FC), in spring 2014-2017 at Ås.

	Sowing date		
	Early	Medium	Late
	Soil water content (% FC)		
2014	2nd April	15th April	25th April
	60	56	52
2015	8th April	13th April	23th April
	90	73	63
2016	11th April	25th April	9th May
	104	69	78
2017	3th April	11th April	5th May
	103	74	69

2.3. Soil sampling and in-situ measurements

In order to assess short term effects of timing and traffic intensity during spring fieldwork on aggregate size distribution in the seedbed, two litres of bulk soil per plot were sampled with a spade immediately after sowing, air-dried without further manipulation and stored dry until analysis. Furthermore, in May 2016 bulk soil and small soil cores were sampled from B0 and B1 treatments plots and prepared as described in Obour et al. (2018).

In order to assess long-term effects on physical properties undisturbed soil cores (5.8 cm diameter, 3.7 cm height, ≈ 100 cm^3) were sampled after cereal harvest in autumn 2015-2017 at a depth of 1-5 cm. Three (2015) or two cores per plot (2016 and 2017) were taken in both replications. In all years, the soil cores were covered with plastic lids and stored at 4 °C until analysis. In addition, penetration resistance in the field was measured after cereal harvest in spring 2016 (24th/25th May), in autumn 2016 (19th September) and in autumn 2017 (28th September). In spring 2016, non-compacted and once-compacted plots were measured 5 times each with a Eijkelkamp Penetrologger 06.15.31 (Giesbeek, NL), to a depth of 15 cm using a 60° cone with 11.28 mm base diameter and 2 cm s^{-1} penetration speed. In autumn 2017, the same was done for all plots. In autumn 2016 penetration resistance was measured to a depth of 15 cm in all plots with a Eijkelkamp hand penetrometer (Giesbeek, NL), using a 60° cone with 15.96 mm base diameter. Geometric mean values of penetration resistance were calculated for depths of 0-5, 5-10 and 10-15 cm.

2.4. Laboratory measurements and analyses

In order to obtain aggregate size distribution, the air-dried bulk soil was sieved for 3 min (240 shakes min-1, 12 mm amplitude) in a set of sieves with mesh sizes of 0.6, 2, 6 and 20 mm. The different fractions were weighed and their proportion of the total weight of bulk soil minus stones were calculated per plot. The mean weight diameter (MWD) was calculated as the sum of products of the mean diameter of the size fraction and the proportion of total sample in that fraction (Van Bavel, 1949).

In order to obtain pore size distribution, the soil cores were weighed, saturated from below and water retention was measured after desorption to different matric potentials. Desorption at -20 hPa and -50 hPa (except 2017) was measured in an Eijkelkamp sandbox (Giesbeek, NL), whilst for matric potentials of -100, -1000 and -15000 hPa ceramic pressure plates (Richards, 1947, 1948) were used. At -100 hPa, air-filled porosity was measured by air pycnometer (Torstensson and Eriksson, 1936) and air permeability was measured with the method described by Green and Fordham (1975). Finally, the cores were dried at 105 °C and bulk density was calculated. Total porosity was calculated as air-filled porosity at -100 hPa plus water volume at -100 hPa.

The plot-wise values of volumetric water content at -15000 hPa from 2017 were used for further calculations with respective plot-wise bulk density values in all years. Percentages of macropores were calculated as total porosity minus water contents at -100 hPa. Percentages of coarse medium pores were calculated as water contents at -100 hPa minus those at -1000 hPa. Percentages of fine medium pores were calculated as water contents at -1000 hPa minus those at -15000 hPa.

Soil cores sampled in May 2016 were analysed for air-filled porosity and air permeability, while bulk soil was analysed for aggregate tensile strength, as described in Obour et al. (2018).

2.5. Actual and simulated yield

The cereal crops were harvested with a plot combine at full maturity and yields were recorded on 1.5 m x 6 m of each plot. Yields were expressed relative to the maximum yield obtained in a given replication.

In order to compare actual yield with simulated yield, exclusively depending on timeliness of spring fieldwork, yield potential was simulated with the yield loss module of the workability model described by Riley (2016). The yield loss module combines two types of timeliness related loss of yield potential (Figure 1). The first type is expressed by the relationship between soil water content at the start of spring fieldwork and loss of yield potential due to topsoil compaction (Figure 1a). This function assumes spring fieldwork to cause no compaction loss at moisture content of less than 66 % of field capacity (FC, -100 hPa). The second type is expressed by the relationship between the sowing date and loss of yield potential due to delayed seeding (Figure 1b). This function assumes spring fieldwork before 16th April to cause no delay loss. As simulation setting we selected soil type 3 in Riley (2016), i.e. loam with 10-25 % clay and a water content of 70 mm at FC at 0-20 cm depth. Average recorded soil moisture contents on each sowing date were used as simulation input.

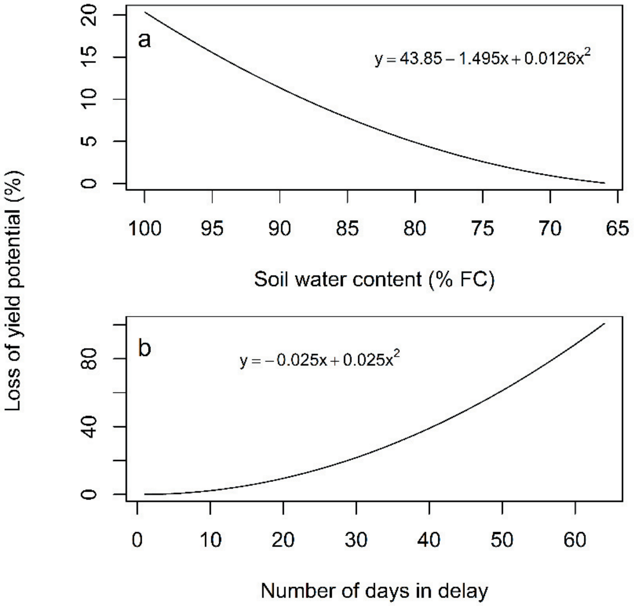

Figure 1: Functions used in the workability model (Riley, 2016) for calculation of loss of yield potential affected by (a) soil water content in % of field capacity (FC, -100 hPa) at 0-20 cm soil depth during spring fieldwork, and (b) number of days after optimum sowing date 15th April (from Kolberg et al., 2019).

2.6. Data analyses and statistics

Some of the raw data have already been used in Obour et al. (2018) (aggregate tensile strength, air-filled porosity and air permeability in May 2016; penetration resistance in July 2016; actual yield in 2014-2017). The Obour et al. (2018) study included only plots with no wheeling and with one wheeling, while the present study includes all plots. Furthermore, compared to Obour et al. (2018), the present study uses different methods of data pre-processing and statistical analyses, as specified in this section. In addition, there were made some corrections in the raw data of actual yield in 2014 and 2016 before use in the present study.

The response data were analysed separately for each year in R version 3.5.1 (R Core Team, 2018). Mixed effects models were built in lmerTest package (Kuznetsova et al., 2017), with random “Replication” and considering the split-plot design by including an interaction “Replication:Timing”. ANOVA type III was conducted with Satterthwaite’s method for degrees of freedom (DF). Least squares mean (lsmean) values were calculated and post hoc tests (Tukey HSD with Satterthwaite's method for DF) conducted by emmeans package (Lenth, 2018), the latter only in cases where ANOVA F-test p-values < 0.05. Significant differences are reported for $\alpha < 0.05$. In order to allow direct comparisons with results from May 2016, some of the data from September 2016 (penetration resistance, air-filled porosity and air permeability) was analysed twice, (1) as the whole experiment and (2) only including non-compacted and once compacted plots. Correlation coefficients were calculated by the Spearman method. Graphics were created in ggplot2 (Wickham, 2009), grid and gridExtra (Auguie and Antonov, 2016) packages.

3. Results

3.1. Effects of timing and traffic intensity of spring fieldwork on physical properties

3.1.1. Aggregate size distribution in spring

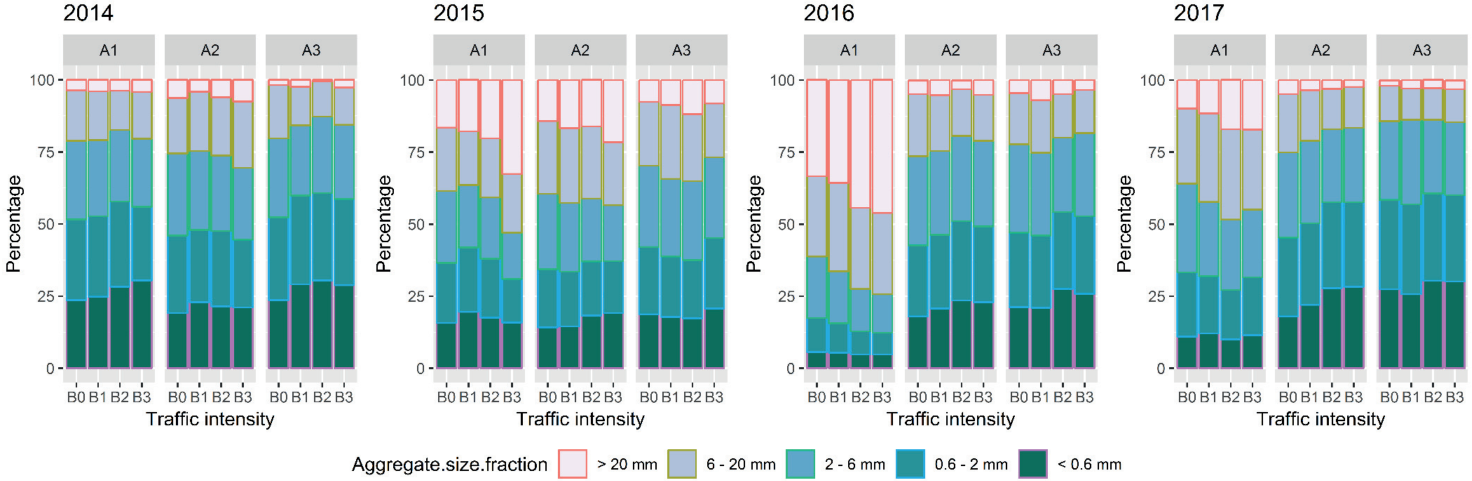

Figure 2: Percentage of different aggregate size fractions (> 20 mm, 6 – 20 mm, 2 – 6 mm, 0.6 – 2 mm, < 0.6 mm, affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late) and traffic intensity (B0 = no, B1 = one, B2 = two, B3 = three wheelings) during spring fieldwork in 2014 – 2017.

In general, we found larger aggregates after early seedbed preparation on wetter soil and larger aggregate size with increasing number of wheelings under the wettest conditions (Figure 2).

In 2014, there was a significant difference in the proportion of aggregates >20 mm between the different sowing dates, largest in A2, smaller in A1 and smallest in A3. There was a larger proportion of 6-20 mm aggregates in A2 than in A1 and A3, as well as a larger proportion of 0.6-2 mm aggregates in A2 than in A3 and a larger proportion of <0.6 mm aggregates after A2 than after A1 and A3.

In 2015, there was a significantly larger proportion of >20 mm aggregates in B3 than in B0 and B1, a larger proportion of 6-20 mm aggregates in A2 than in A1 and a larger proportion of 2-6 mm aggregates in A3 and no wheelings in A2 than three wheelings in A1 and A2.

In 2016, we found a significantly larger proportion of >20 mm, 6-20 mm and 0.6-2 mm aggregates in A1 than in A2 and A3. In addition, we found a larger proportion of 6-20 mm aggregates in B1 than in B3, a larger proportion of 2-6 mm aggregates in A2 and A3 than in compacted plots of A1, as well as a larger proportion of <0.6 in A2 and A3 than in A1, and larger in double and triple compacted of A2 and A3 than in non-compacted A2.

In 2017, we recorded a significantly larger proportion of >20 mm aggregates in A1 than in A2 and A3 (p-values?), and a larger proportion in A1B3 and A1B2 than in A1B1 and A1B0. In addition, there was a larger proportion of 6-20 mm in A1 than in A3 and twice and triple compacted of A2, as well as a larger proportion of 2-6mm in B0 and B1 than in B2 and B3, a larger proportion of 0.6-2 mm in A2 and A3 than in A1, and a arger proportion of <0.6 mm in A3 and compacted A2 than in A1.

In 2014, there was a significant difference between the mean weight diameters (MWD) of the aggregates from the different sowing dates (Figure 2), with largest MWD after medium, smaller after early and smallest after late seedbed preparation. In 2015, there were no significant differences. In 2016, there was a significantly larger MWD after early than after medium and late seedbed preparation. In 2017, there was a significantly larger MWD after A1 than after A3 and compacted A2. In addition, double and triple compacted A1 had larger MWD than non-compacted A1.

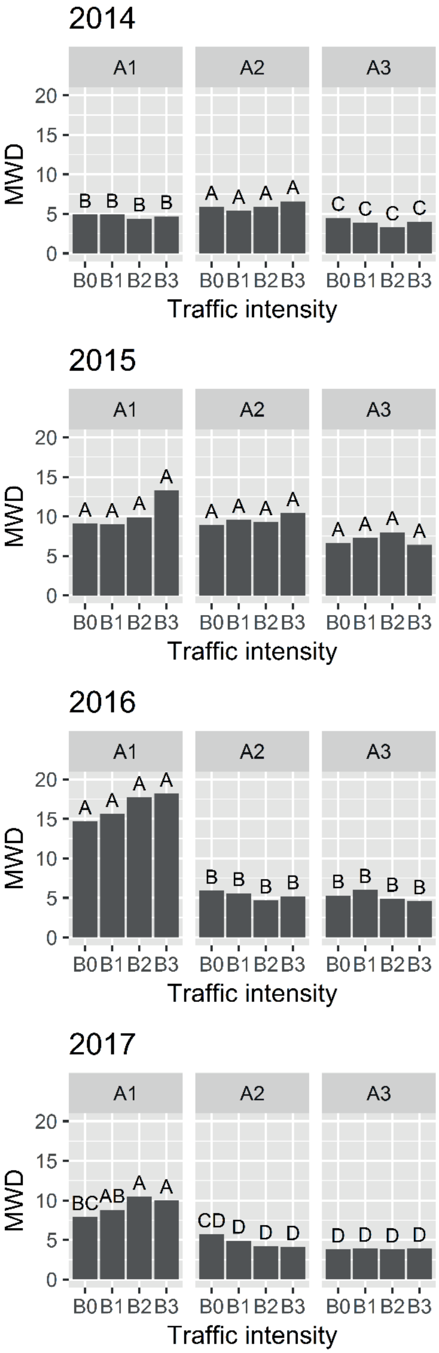

Figure 3: Mean weight diameter (MWD) of aggregates, affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late) and traffic intensity (B0 = no, B1 = one, B2 = two, B3 = three wheelings) during spring fieldwork in 2014 – 2017.

3.1.2. Soil pore characteristics

In general, largest effects of timing and traffic intensity of spring fieldwork on soil pore characteristics were found in 2016. In 2016 there was a significantly larger total porosity (not shown) in autumn after medium fieldwork (51.8 vol%) than after early (48.0 vol%) and late spring fieldwork (47.1 vol%). In that year, soil samples also had a significantly smaller volumetric water content at -100 (in pores < 30µm) and -1000 hPa (in pores < 3µm) matric potential in autumn after late than after early spring fieldwork. There was no effect on the proportion of macropores (> 30µm) in spring (Table 3), but a significant interaction effect between traffic intensity and timing on the proportion of macropores in autumn 2016. The proportion of macro pores was larger after non-compacted medium spring fieldwork than after zero, once and triple compacted early and once compacted late spring fieldwork. That year, there was no significant influence on the proportions of micro (< 0.2µm), fine medium (0.2 - 3µm) or coarse medium (3 - 30µm) pores. There was no significant effect of timing or traffic intensity of spring fieldwork on air permeability through macropores in 2016.

Table 3: Proportion of macro pores (> 30µm) and their corresponding air permeability (AirPerm), measured at -100 hPa matric potential at a depth of 0-5 cm in May and September 2016, affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late) and traffic intensity (B0 = no, B1 = one, B2 = two, B3 = three wheelings) during spring fieldwork in 2016.

		Macro pores		Air permeability	
Timing	Traffic	May (vol%)	Sept (vol%)	May (μm^2)	Sept (μm^2)
A1	B0	25	$^{\alpha}$7.1^{a}	541	2.2
A1	B1	26	$^{\alpha}$8.2^{ab}	725	1.7
A1	B2	-	11.1^{abc}	-	2.3
A1	B3	-	4.9^{a}	-	0.9
A2	B0	28	$^{\beta}$18.2^{c}	783	12.6
A2	B1	28	$^{\beta}$10.5^{abc}	386	6.9
A2	B2	-	15.7^{bc}	-	12.2
A2	B3	-	10.2^{abc}	-	4.2
A3	B0	27	$^{\alpha\beta}$7.8^{ab}	491	3.9
A3	B1	21	$^{\alpha\beta}$11.4^{abc}	254	4.5
A3	B2	-	10.2^{abc}	-	4.4
A3	B3	-	11.1^{abc}	-	4.1

Different letters indicate significant difference in Tukey comparison; with Greek letters for comparisons including non-compacted and once compacted plots, with Latin letters for comparisons including all plots.

In other years, there were some cases of significant effects on pore characteristics (not shown). In autumn 2015, volumetric water contents at -20, -50 and -100 hPa were significantly lower after late than after early spring fieldwork, though without any impact on the proportions of micro (< 0.2µm), fine medium (0.2 - 3µm), coarse medium (3 - 30µm) or macro (> 30µm) pores. In autumn 2017, we observed a significantly larger proportion of coarse medium pores (3 - 30µm) after medium and late fieldwork than after early fieldwork.

During the crop growing season of 2016, when comparing autumn to spring measurements, the proportion of macropores and their corresponding air permeability decreased from May to September (Table 3). The interaction effect on the proportion of macropores in spring did not persist consistently until autumn, and the described effect on air permeability of macropores was no longer significant in autumn.

3.1.3. Strength of aggregates and bulk soil

Table 4: Lsmean values of geometric mean tensile strength (kPa) of air-dried 8-16 mm aggregates in May and penetration resistance (MPa) measured at different depths (0-5 cm, 5-10 cm, 10-15 cm) in July (27.5 vol% water) and September 2016 (29.1 vol% water), affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late) and traffic intensity (B0 = no, B1 = one, B2 = two, B3 = three wheelings).

		Aggregate tensile strength (kPa)		Penetration resistance (MPa)					
		May		July			September		
Timing	Traffic	0-5	5-10	0-5	5-10	10-15	0-5	5-10	10-15
A1	B0	97	$^{\alpha A}$ 111	$^{\alpha}$ 0.6	$^{\alpha A}$ 1.2	$^{\alpha}$ 1.3	1.4^{a}	$^{\alpha}$ 1.5^{a}	$^{\alpha}$ 1.6^{a}
A1	B1	135	$^{\alpha B}$ 175	$^{\alpha}$ 0.6	$^{\alpha B}$ 1.3	$^{\alpha}$ 1.5	1.2^{a}	$^{\alpha}$ 1.5^{a}	$^{\alpha}$ 1.6^{a}
A1	B2	-	-	-	-	-	1.9^{a}	1.9^{a}	1.8^{a}
A1	B3	-	-	-	-	-	1.7^{a}	1.9^{a}	1.9^{a}
A2	B0	95	$^{\beta A}$ 74	$^{\beta}$ 0.4	$^{\beta A}$ 0.7	$^{\beta}$ 0.9	0.7^{b}	$^{\beta}$ 0.9^{b}	$^{\beta}$ 1.0^{b}
A2	B1	76	$^{\beta B}$ 98	$^{\beta}$ 0.4	$^{\beta B}$ 0.7	$^{\beta}$ 1.0	0.8^{b}	$^{\beta}$ 0.9^{b}	$^{\beta}$ 1.0^{b}
A2	B2	-	-	-	-	-	0.7^{b}	0.9^{b}	1.1^{b}
A2	B3	-	-	-	-	-	0.8^{b}	1.1^{b}	1.1^{b}
A3	B0	69	$^{\beta A}$ 94	$^{\beta}$ 0.3	$^{\beta A}$ 0.7	$^{\beta}$ 0.9	1.0^{ab}	$^{\alpha\beta}$ 1.3^{c}	$^{\alpha\beta}$ 1.4^{ab}
A3	B1	113	$^{\beta B}$ 88	$^{\beta}$ 0.4	$^{\beta B}$ 0.9	$^{\beta}$ 1.0	1.0^{ab}	$^{\alpha\beta}$ 1.2^{c}	$^{\alpha\beta}$ 1.1^{ab}
A3	B2	-	-	-	-	-	1.0^{ab}	1.3^{c}	1.4^{ab}
A3	B3	-	-	-	-	-	1.2^{ab}	1.2^{c}	1.3^{ab}

Different letters indicate significant differences in Tukey comparison; with Greek letters for comparisons including non-compacted and once compacted plots, with Latin letters for comparisons including all plots.

The only year with a significant effect of timing on bulk density (not shown) was 2016. We observed a significantly smaller bulk density at 0-5 cm depth in the following autumn after medium fieldwork (1.26 g cm^{-3}) than after early (1.37 g cm^{-3}) and late spring fieldwork (1.36 g cm^{-3}). This was an increase from an average bulk density of 1.1 g cm^{-3} in May (Obour et al., 2018).

In 2016, we also found significant effects of timing ($p = 0.007$) and traffic intensity ($p = 0.035$) on aggregate tensile strength at a depth of 5-10 cm (Table 4). Aggregates were significantly stronger after early than after medium and late spring fieldwork, and significantly stronger after wheeling.

In addition, soil penetration resistance was significantly affected by the experimental treatments in July and September. In July, penetration resistance at 0-5 cm depth was affected by timing ($p = 0.028$), while at 5-10 cm depth it was affected by timing ($p = 0.001$) and wheeling ($p = 0.008$). There was a significantly larger penetration resistance in July after early than after medium and late spring fieldwork at 0-5, 5-10, and 10-15 cm depth. At the same time in July, there was a significantly larger penetration resistance after compacted than in compacted than in non-compacted plots at the 5-10 cm depth.

In September, penetration resistance was affected ($p = 0.031$) by timing at 5-10 cm depth. There was a significantly larger penetration resistance after early than after medium spring fieldwork at all depths (Table 4). When comparing July and September measurements, penetration resistance generally increased during the growing season. When comparing the development of the described effects' significance (Greek letters), we observe that the effect of timing on penetration resistance decreases at 0-5 cm depth from July to September, while it increases at 5-10 and 10-15 cm depth. At 5-10 cm depth, the effect of wheeling disappears between July and September.

3.1.4. Correlations between aggregate size distribution and other physical properties

In order to get an impression of the importance of a number of other soil physical properties for soil quality, correlation coefficients between these and the well-known properties of aggregate size distribution are presented in Table 5. The strongest relationship was observed between the proportion of 2-6 mm aggregates and penetration resistance at 5-10 cm depth.

Table 5: Correlation coefficients for relationship between different expressions of aggregate size distribution in spring and physical properties * in autumn 2016. Increasing shading illustrates increasing strength of relationship between respective soil properties. Ranked from strong to weak correlation with 2-6 mm aggregate size fraction.

	>20 mm	>6 mm	6-20 mm	2-6 mm	0.6-6 mm	0.6-2 mm	<0.6 mm	MWD
Pen5cm	0.64	0.52	0.42	-0.75	-0.68	-0.51	-0.48	0.55
Pen10cm	0.68	0.55	0.48	-0.76	-0.73	-0.57	-0.50	0.57
Pen15cm	0.66	0.53	0.49	-0.75	-0.70	-0.56	-0.50	0.55
AirPerm (> 30µm)	-0.34	-0.38	-0.48	0.67	0.58	0.39	0.37	-0.37
Pores > 30µm	-0.35	-0.34	-0.41	0.47	0.44	0.33	0.34	-0.32
Total porosity	-0.19	-0.22	-0.29	0.42	0.39	0.28	0.17	-0.18
Bulk density	0.17	0.19	0.25	-0.41	-0.37	-0.24	-0.15	0.16
Pores < 3µm	0.48	0.42	0.47	-0.40	-0.39	-0.32	-0.46	0.41
Pores 3 - 30µm	-0.23	-0.27	-0.36	0.38	0.38	0.35	0.21	-0.22
Pores < 30µm	0.37	0.26	0.29	-0.28	-0.22	-0.13	-0.35	0.27
Pores < 60µm	0.32	0.21	0.20	-0.25	-0.18	-0.08	-0.28	0.23
Pores < 0.2µm	0.31	0.27	0.21	-0.17	-0.11	-0.20	-0.34	0.30
Pores 0.2 - 3µm	0.04	0.09	0.19	-0.11	-0.16	-0.11	-0.09	0.06
Pores < 150µm	0.10	0.00	-0.03	0.01	0.07	0.12	-0.06	0.02
Pores 0.2 - 30µm	-0.04	-0.03	0.06	-0.01	-0.06	0.03	0.03	-0.05

* - Pen5cm = penetration resistance at 0-5 cm depth
- Pen10cm = penetration resistance at 5-10 cm depth
- Pen15cm = penetration resistance at 10-15 cm depth
- AirPerm = Air permeability of drainable pores > 30µm (Macro + Transmission pores + Fissures)
- Pores > 30µm = Drainable pores (Macro + Transmission pores + Fissures) = Air-filled porosity at -100 hPa
- Pores < 3µm = FineMedium + Micro pores = Volumetric (vol) water content at -1000 hPa matric potential
- Pores 3 - 30µm = Coarse medium pores
- Pores < 30µm = CoarseMedium + FineMedium + Micro pores = Vol water content at -100 hPa
- Pores < 60µm = Transmission + Macro + CoarseMedium + FineMedium + Micro pores = Vol water content at -50 hPa
- Pores < 0.2µm = Micro pores
- Pores 0.2 - 3µm = Fine medium pores
- Pores < 150µm = Transmission + Macro + CoarseMedium + FineMedium + Micro pores = Vol water content at -20 hPa
- Pores 0.2 - 30µm = CoarseMedium + FineMedium pores = Plant available water

3.2. Effects on cereal yield

3.2.1. Actual and simulated yield

There was no significant effect of timing or traffic intensity on actual cereal yield, except for the effect of timing (p = 0.02) in 2016 (Table 6). In 2016, actual cereal yield was significantly smaller after early fieldwork than after medium (p=0.02) and late fieldwork (p=0.03).

Table 6: Lsmean values of actual yield (ActYield [1]) and simulated yield (SimYield [2]) affected by timing (Sowing date: A1 = early, A2 = medium, A3 = late).

	2014: wheat		2015: barley		2016: oats		2017: barley	
Timing	ActYield	SimYield	ActYield	SimYield	ActYield	SimYield	ActYield	SimYield
A1	0.92	1.00	0.89	0.86	0.75 [a]	0.71	0.74	0.76
A2	0.82	1.00	0.91	0.97	0.96 [b]	0.96	0.88	0.97
A3	0.66	0.96	0.85	0.98	0.93 [b]	0.80	0.85	0.89

[1] Expressed as relative to highest yield in respective replication; different letters indicating significant difference in Tukey comparison.

[2] Based on average recorded moisture content at 5-10 cm depth during spring fieldwork and optimum sowing date 15th April used in combined functions of yield loss due to too wet and too late spring fieldwork (Figure 1).

3.2.2. Correlations between physical properties and yield

In order to get an impression of the importance of a number of other soil physical properties for the simulated yield and the actual yield, correlation coefficients for their relationship are presented in Table 7. The strongest relationship with actual yield was observed for the proportion of 2-6 mm aggregates. The strongest relationship with simulated yield was observed for penetration resistance at 5-10 cm depth, if we disregard the strong relationship with moisture content at 5-10 cm depth. The latter was used as simulation input and is therefore found to be highly correlated. Correlation coefficients for 2016 were larger than for 2014-2017 collectively.

4. Discussion

4.1. Effects of timing and traffic intensity of spring fieldwork on physical properties in spring and summer

The observed treatment effects on aggregate size distribution shortly after spring fieldwork are mostly similar to results of previous seedbed research. The larger aggregates after spring fieldwork in wet soil (Figure 2 and Figure 3) are in line with a number of earlier studies (Tisdall and Adem, 1986; Bakken et al., 1987; Braunack and McPhee, 1991; Adam and Erbach, 1992; Håkansson et al., 2002; De Toro and Arvidsson, 2003; Dexter and Birkas, 2004; Keller et al., 2007). The larger aggregates after higher traffic intensity in the wettest conditions are in line with Marti (1983) and Njøs (1978).

Table 7: Correlation coefficients for relationship between actual yield (ActYield [1]) and simulated yield (SimYield [2]) and physical properties in spring [a] and autumn [b] for 2016, and for 2014-2017 collectively. Increasing shading illustrates increasing strength of relationship between respective properties. Ranked from strong to weak correlation with actual yield in 2016. *Coefficients in italics based on 2016-2017 data only*.

	2016		2014-2017	
	ActYield	SimYield	ActYield	SimYield
Agg 2-6 mm [a]	0.74	0.76	0.27	0.23
Pen5cm [b]	-0.72	-0.77	*-0.11*	*-0.48*
Agg 0.6-6 mm [a]	0.70	0.67	0.16	0.25
MWD [a]	-0.69	-0.47	-0.08	-0.31
Soil moisture [a]	-0.69	-0.88	-0.02	-0.78
Agg 0.6-2 mm [a]	0.69	0.48	0.06	0.31
Agg >6 mm [a]	-0.66	-0.45	-0.11	-0.28
Agg >20 [a]	-0.64	-0.62	-0.06	-0.33
Pen10cm [b]	-0.64	-0.82	*-0.17*	*-0.56*
Pen15cm [b]	-0.64	-0.77	*-0.40*	*-0.57*
Agg <0.6 mm [a]	0.62	0.36	0.12	0.32
JulianDay [a]	0.59	0.24	0.07	-0.14
Agg 6-20 mm [a]	-0.55	-0.32	-0.13	-0.18
AirPerm (> 30µm) [b]	0.49	0.49	0.13	0.22
Pores < 0.2µm [b]	-0.33	-0.10	-0.03	0.03
Pores > 30µm [b]	0.26	0.42	0.07	0.13
Pores 0.2 - 30µm [b]	0.24	-0.05	-0.14	-0.05
Total porosity [b]	0.19	0.39	-0.05	0.18
Bulk density [b]	-0.17	-0.45	-0.03	-0.11
Pores < 3µm [b]	-0.16	-0.26	-0.14	-0.01
Pores < 60µm [b]	-0.15	-0.22	-0.21	0.17
Pores 0.2 - 3µm [b]	0.14	-0.09	-0.11	-0.08
Pores < 30µm [b]	-0.13	-0.22	-0.16	0.02
Pores 3 - 30µm [b]	0.11	0.25	-0.03	0.13
Pores < 150µm [b]	-0.03	0.01	-0.08	-0.15
Sim	0.63	-	0.16	-

[1] Expressed as relative to highest yield in respective replication.

[2] Based on average recorded moisture content at 5-10 cm depth during spring fieldwork and optimum sowing date 15th April used in combined functions of yield loss due to too wet and too late spring fieldwork (Figure 1).

[a] Physical properties measured in spring:
- Agg = proportion of specified aggregate size fraction
- MWD = mean weight diameter of aggregates
- Soil moisture = volumetric soil moisture content at 5-10 cm depth at the time of spring fieldwork
- JulianDay = Julian day of spring fieldwork

[b] Physical properties measured in autumn:
- Pen5cm = penetration resistance at 0-5 cm depth
- Pen10cm = penetration resistance at 5-10 cm depth
- Pen15cm = penetration resistance at 10-15 cm depth
- AirPerm = Air permeability of drainable pores > 30µm (Macro + Transmission pores + Fissures)
- Pores > 30µm = Drainable pores (Macro + Transmission pores + Fissures) = Air-filled porosity at -100 hPa
- Pores < 3µm = FineMedium + Micro pores = Volumetric (vol) water content at -1000 hPa matric potential
- Pores 3 - 30µm = Coarse medium pores
- Pores < 30µm = CoarseMedium + FineMedium + Micro pores = Vol water content at -100 hPa
- Pores < 60µm = Transmission + Macro + CoarseMedium + FineMedium + Micro pores = Vol water content at -50 hPa
- Pores < 0.2µm = Micro pores
- Pores 0.2 - 3µm = Fine medium pores
- Pores < 150µm = Transmission + Macro + CoarseMedium + FineMedium + Micro pores = Vol water content at -20 hPa
- Pores 0.2 - 30µm = CoarseMedium + FineMedium pores = Plant available water

These effects are also consistent with tendencies shown in Obour et al. (2018) who reported larger fragmentation of soil samples during drop shatter test in plots of later spring fieldwork, and in non-compacted plots compared to once compacted plots of the present field experiment in 2016. An explanation for differences in aggregate size after wet and dry fieldwork may be that compaction of dry aggregates leads to wear of contact points, while compaction of wet aggregates leads to plastic deformation and an even larger increase in contact area (Braunack et al., 1979; Day and Holmgren, 1952). Larger contact area and larger cohesion again lead to formation of larger aggregates during fragmentation (Lyles and Woodruff, 1961), e.g. as during sampling.

In contrast to Obour et al. (2018), the present methods of data pre-processing and statistical analyses did not reveal any significant treatment effects on air-filled porosity, air permeability (Table 3) or tensile strength of air-dried 8-16 mm aggregates sampled at 0-5 cm (Table 4) in May 2016. The most important reason for this is probably that considering the experiment's split plot design in the statistical analyses provides less information on the main plot factor "timing".

On the other hand, with the present method, we observed stronger treatment effects than Obour et al. (2018) on aggregate tensile strength at 5-10 cm depth. At this depth, we observed an increase in aggregate tensile strength after early spring fieldwork and after one wheeling. These results are in line with Munkholm and Schjønning (2004), although in their study the effect of wet soil is not easily differentiated from the effect of traffic intensity.

In addition to increases in soil strength at the aggregate level, the more compacted state of the soil after early spring fieldwork is confirmed by increased penetration resistance in July 2016 at all depths and at 5-10 cm depth after one wheeling (Table 4). The effect of wheeling on penetration resistance is in line with Reintam et al. (2009), even though their study reported significant effect only after more than three wheelings. The effect of soil moisture content during spring fieldwork is similar to tendencies observed by Lapen et al. (2004). However, earlier research does not usually explore the effect of timing (moisture content) on soil strength in terms of penetration resistance, but shear strength sometimes is reported. In that sense, our observed increases in penetration resistance after too wet spring fieldwork are consistent with findings of increased shear strength in Njøs (1978), with parts of the study by Hofstra et al. (1986) and with tendencies in Marti

(1983). In any case, the medium penetration resistance values after late fieldwork are consistent with the medium soil moisture content during late fieldwork (Table 2).

Similar to our results, many studies have reported a positive relationship between aggregate tensile strength and penetration resistance in the topsoil (Materechera and Mkhabela, 2001; Munkholm and Schjønning, 2004; Munkholm et al., 2001; Kumar et al., 2012). The observed tendency of increased aggregate tensile strength after too wet (early and late) spring fieldwork in 2016 is in line with Munkholm and Schjønning (2004). Similarly, larger timing effects (p-values) on penetration resistance in July than on aggregate tensile strength in May are in line with Munkholm and Schjønning (2004) who found larger increases in penetration resistance in their second year of high traffic intensity, in contrast to the opposite after high tillage intensity. This may be interpreted as a larger increase of soil strength with increasing traffic intensity at the bulk level than at the aggregate level.

Altogether, too early spring fieldwork, especially when combined with wheeling, reduced the physical seedbed quality for early plant growth in spring. Larger and stronger aggregates or higher penetration resistance can be negative for plant growth and nutrient uptake under normal conditions after sowing (Håkansson et al., 2002; Nasr and Selles, 1995; Barley et al., 1965; Bengough and Mullins, 1991; Martino and Shaykewich, 1994; Misra et al., 1988; Braunack and Dexter 1989; Dexter, 2004; Taylor et al., 1966; Taylor and Ratliff, 1969; Arvidsson, 1999). Larger and stronger aggregates and higher penetration resistance may also be one of the reasons for risk of yield loss in soil tilled when still too wet, as described by Riley (2016).

4.2. Effects of timing and traffic intensity of spring fieldwork on physical properties in autumn

Generally, air-filled porosity and air permeability decreased, while penetration resistance increased between May and September (Table 3 and Table 4). The changes in these parameters from spring to autumn fit well with each other, but they may have several explanations. The measurements were done in different labs with different routines and methods. For example, to obtain air permeability in spring 2016, the Forchheimer approach was used (Schjønning and Koppelgaard, 2017), which considers deviation of very high or low flow conditions from the linear relationship to pressure, while in autumn air permeability was measured with the method described by Green and Fordham (1975), which assumes a linear Darcian flow pressure relationship. Another and probably more important explanation may be soil settlement throughout the crop growing season, due to wetting and drying cycles as described in Lapen et al. (2004) and Daigh and DeJong-Hughes (2017).

In general, there were smaller differences between the different treatments in soil pore characteristics measured in autumn than in aggregate size distribution measured in spring. However, there were more distinct differences in air-filled porosity between sowing dates in autumn than in spring. The question is whether this increase in treatment effect is relevant for crop growth. It probably would be relevant, if the effects are strong enough in spring or if they persist after ploughing in autumn. The missing effect on air permeability in September 2016 (Table 3) shows that this property is not necessarily directly related to air-filled porosity, as observed by Tang et al. (2011) and discussed by Ball (1981).

Smaller volumetric water content in autumn 2015 and 2016 after late than after early fieldwork at the highest matric potentials (lowest pressure) indicates that there were more of the very large pores after late than after early fieldwork, similar to findings at greater soil depths after heavy traffic in Berisso et al. (2012). In 2015, this had no influence on total porosity or any of the calculated pore sizes (Micro, FineMed, CoarseMed, Macro), and is not consistently reflected in the effects on total porosity or macropores in 2016.

Lower Bulk density and higher total porosity in autumn 2016 after medium than after early and late spring fieldwork are in line with Reintam et al. 2009 who found a higher bulk density when soil was compacted under higher soil moisture conditions, even though they did not find any difference between one and three wheelings after seedbed preparation. High bulk density and low porosity indicate soil compaction (Håkansson et al., 1988) during early spring fieldwork.

Only considering the zero and once-compacted plots (Greek letters in Table 4), the significant differences at 0-5 cm depth from July were no longer present in September, and also the effect of wheeling disappeared at 5-10 cm depth. At 5-10 and 10-15 cm depth, penetration resistance was still significantly greater after early than after medium spring fieldwork, but no longer greater after early than after late fieldwork. When considering all plots (Latin letters in Table 4), the increased penetration resistance in September 2016 after early fieldwork at all depths is in line with deToro and Arvidsson (2003). As mentioned earlier, according to short-term results in spring in Munkholm and Schjønning (2004), intensive tillage and intensive traffic created denser aggregates and larger penetration resistance at 0-20 cm depth. However, according to their long-term results in autumn, intensive tillage seemed to densify single aggregates, whilst the intensive traffic effect on aggregate tensile strength did not last as long. Therefore, an interesting question would be whether the densification of bulk soil, in terms of penetration resistance, is as persistent as the densification of aggregates, in terms of tensile strength. Unfortunately, in the present study, we did not measure both properties in spring and autumn.

All in all, our results show that soil degrading effects of timing and traffic intensity of spring fieldwork on physical properties can persist until autumn, some becoming weaker (penetration resistance), some becoming even stronger (air-filled porosity). The effect of traffic intensity is not as strong as the effect of timing in the present study. This is probably due to the still relatively low traffic intensity of three wheelings, in contrast to soil degrading effects and impaired plant growth observed after up to six wheelings (Reintam et al. 2009).

4.3. Relationship between aggregate size distribution (in spring) and other physical properties (in autumn)

Within the moisture content range on the different sowing dates of the present study, the year 2016 stands out with its effect of timing on soil physical quality and yield. This is also reflected in the much higher correlation coefficients for relationships between physical properties and yield in that year compared to when all years are considered together (Table 7). In 2016, the proportion of 2-6 mm aggregates in the seedbed was the most important physical property for actual yield and the second most important for simulated yield. This fits in well with the strongest correlations of the 2-6 mm fraction to the other physical properties (Table 5). Therefore, the proportion of 2-6 mm aggregates may be interpreted as the most important physical property in the present study, which is consistent with the predominant conclusion in Scandinavian seedbed research that this size fraction is of prime importance for seedbed quality and crop establishment (Håkansson et al., 2002; Håkansson et al., 2011b; Njøs and Børresen, 1991; Keller et al., 2007).

The opposite correlations for penetration resistance to smaller size fractions compared to larger size fractions (Table 5) illustrate that smaller aggregates are related to lower penetration resistance. This relationship has also been reported by Misra et al. (1988), amongst others. Furthermore, aggregate size distribution was most highly correlated with penetration resistance, and especially with the proportion of 2-6 mm aggregates (Table 5). If we assume, based on earlier research and its strong correlation with yield (Table7), that the proportion of 2-6 mm aggregates is a very important physical property, this means that penetration resistance is also a very important property in order to describe seedbed quality. This is in line with Bölenius, Stenberg and Arvidsson (2017) who found penetration resistance to be the most important property for variations in cereal yield and several authors who considered it to be a property representative of soil quality (Lapen et al., 2004).

Other properties that are quite strongly correlated with aggregate size distribution are Water1000 (pores < 3µm), total porosity, bulk density, air-filled porosity and air permeability, the latter especially in the case of 2-6 mm fraction. Compared to penetration resistance, bulk density and especially total porosity are only weakly correlated with yield (Table 7). This fits in well with the work of Lerink (1990) who found that such properties alone are not good indicators of soil physical quality. Altogether, since a number of other soil physical properties can influence penetration resistance, it is a good indicator of overall soil physical quality and yield potential (Bölenius et al., 2017).

4.4. Effects on simulated and actual yield

In contrast to Obour et al. (2018), we did not find any effect of traffic intensity on actual cereal yield in any of the experimental years and we found an effect of timing on actual yield in 2016 instead of 2015 and 2014. As mentioned for some of the physical properties, these deviating results are caused by differences in statistical methods and corrections of the raw yield data in 2015. The missing effect of traffic intensity on actual yield in the present study is in line with Reintam et al. (2009) who did not find any difference in plant growth or yield between one and three wheelings with a tractor of similar size.

There may be multiple reasons for why 2016 was the only year with an effect of timing on actual yield. The missing effect in 2014 was consistent with low soil moisture content during spring fieldwork on all three sowing dates. In 2015, with the relatively high soil moisture content during early spring fieldwork, we expected an effect of timing on actual yield that year. As discussed above, a small effect could be seen in physical properties that year, but this effect was probably outweighed by other factors. In 2017, based on the soil moisture content during spring fieldwork, we expected certain effects on actual yield. Even though the lack of effect on actual yield that year is consistent with small effects on physical properties, it may partially be explained by the soil moisture content during spring fieldwork, which was exceptionally high on early and late sowing dates and relatively high on medium sowing date. This is not very well reflected in soil physical properties, but in the values of the actual yields, and led to a smaller difference in actual yield between wettest and driest treatment.

Despite the previous attempt to explain the lack of yield effects, there seem to be other unknown factors involved. A comparison of actual yield with simulated yield may reveal some of these. Comparing actual yield to the simulated yield gives an impression of how much the actual yield is influenced by spring fieldwork timeliness (Figure 1) and how much it is influenced by other yield forming factors. Deviations between actual yield and simulated yield mean that the model did not represent well the realization of yield potential in a given year, e.g. after late sowing in 2014 and 2015 (Table 6), due to year-to-year variability in interactions between climatic conditions and soil physical properties. Similarly, Bölenius et al. (2017) found year-to-year variability in the relationship between yields and soil physical properties. The reason for the deviation between actual and simulated yield after late sowing date may be that the assumption of 15th April as the optimum sowing date was not appropriate in a given year. This was probably the case in 2014, and to a smaller degree in 2015, when the increasing effect of delayed sowing with later sowing date was larger than expected (Table 6). This is also reflected in the stronger relationship between JulianDay and actual yield than between JulianDay and simulated yield (Table 7), even though JulianDay was one of the inputs to the simulation. Weak correlation between Julian days and simulated yield (Table 7) shows that in the experimental years delayed sowing had only a small influence on the risk of yield loss. This is probably due to a relatively small range of data with regard to number of days in sowing delay. Thus, the higher correlation between Julian days and actual yield is in contrast to Peltonen-Sainio (1996) who studied a wider range of days in sowing delay.

Another, more substantial, reason for deviations between actual and simulated yield is that the model considers only risk of yield loss due to timeliness of spring fieldwork, i.e. compaction loss in too wet soil and loss due to delayed sowing. The model *disregards* other factors involved in yield formation throughout the crop growing season. This is a slight modification of the definition in Kolberg et al. (2019), where other factors were defined as *optimum.* These factors may be related to management or climate. For example, May 2015 was unusually wet and cold (Table 1). The absence of early summer drought and low temperature may have been advantageous for the crop to compensate by increased tillering for initial limitations related to spring fieldwork timeliness. Cereals have a great capability to compensate for such limitations by a number of yield-forming components, especially those that contribute to the number of grains per square meter (Peltonen-Sainio et al., 2007), i.e. number of tillers, spikes per plant, spikelets per spike and grains per spikelet. The actual yield depends on the combination of specific weather conditions through all growth stages. In cases where the actual yield is larger than the simulated yield, other yield forming factors throughout the season (e.g. management or climate) may have given perfect conditions for the crop to compensate for timeliness related increased risk of yield loss in terms of inadequate establishment.

The comparison (Table 6) shows that the model would be further improved by adjusting optimum sowing date to local and year-specific climatic conditions. Further, as discussed earlier, it shows that actual yield was influenced by other factors, especially in 2015, and that actual yields are not necessarily a good measure to evaluate spring fieldwork timeliness. Similarly, the stronger relationship between relative recorded and simulated yield in 2016 than in 2014-2017 and the stronger correlations with physical properties (Table 7) means that growth conditions in 2016 were closer to the experimental conditions upon which the simulation functions were based. Furthermore, many of the physical properties identified as important for soil physical quality (Pen, AirPerm, Pores > 30µm, TotalPor, BulkDens, Pores < 3µm, 2-6 mm in Table 5) have a stronger relationship to simulated yield than to actual yield, especially for 2014-2017 together, but also for 2016 separately (Table 7). Thus, depending on the purpose, a theoretical approach on yield or risk of yield loss based on soil physical properties or the recording of emergence would possibly be a better indicator than actual yield to evaluate physical conditions in spring.

In addition, deviations between simulated and actual yields may also be caused by a discordance in moisture content input to the yield loss function (Figure 1a). The empirical function is based on recorded soil moisture content at 0-20 cm depth during spring fieldwork (Riley, 2016), whilst we decided for soil moisture content at 5-10 cm depth as input. This decision was based on the expectation that average soil moisture content at 5-10 cm depth represents soil moisture content at 0-20 cm depth better than soil moisture content at 0-10 cm depth. Furthermore, since soil water contents were measured on a volumetric base after compaction, with its potential influence on bulk density, only mean values have been used as input to the simulations.

Altogether, in the present study, performing spring fieldwork too early affected actual yield significantly in autumn if the physical seedbed quality was impaired. Spring fieldwork performed too late gave lower actual yields, though non-significantly, possibly because the optimum sowing date potentially differs from year to year. In addition, it is difficult to separate the effect of soil degradation from the effect of delayed sowing in this study. The latter effect may even partially mask the former.

4.5. Implications and applications

In cereal production, seedbed preparation is a bottleneck, which is going to gain importance in the future, as we expect an increasing incidence of extremely unfavourable spring conditions. Unfortunately, in the present study, we did not experience such climatic conditions in all experimental years. One needs luck or a large number of experimental years to capture the relevant climatic variability. This illustrates the importance of having a large number of experimental years in this type of research. Possibly, placement of the field experiment in Central Norway, instead of at Ås in SE Norway, or on a clay soil instead of a loamy soil, could have given us more of the relevant challenging years (Kolberg et al., 2019).

Consequently, the focus of this study was on the most unfavourable year 2016, when weather conditions and timing resembled potential future conditions. Under such high soil moisture conditions in spring, besides the proportion of 2-6 mm aggregates, soil strength is the most important physical property for seedbed quality. In order to limit yield losses caused by soil degradation, timing and traffic intensity of spring fieldwork should in the future avoid topsoil compaction even more than is the case today.

For further research, it would be interesting to explore a larger range of traffic intensities, similar to the study by Reintam et al. (2009), who also reported accumulated effects on penetration resistance after several years. Furthermore, it should be studied whether the ranking of soil physical properties changes if the experimental range of traffic intensity or soil moisture content is widened or if high soil moisture conditions continue after sowing. Lastly, other physical properties should be included, such as aggregate stability, which is an important physical property for seedbed quality (Filho et al., 2013), because it is closely related to crusting (Gallardo-Carrera et al., 2007).

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Paper III

Photographer: Dorothee Kolberg (2016)

Adaptation of seedbed preparation to unfavourably high soil moisture conditions

Dorothee Kolberg [a,b,*], Hans Christian Endrerud [a], Trond Børresen [b]

[a] *Department of Agricultural Sciences, Inland Norway University of Applied Sciences, P.O. Box 400, NO-2418 Elverum, Norway.*

[b] *Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Norway.*

[*] Corresponding author. E-mail addresses: dorothee.kolberg@inn.no, dorothee.kolberg@nmbu.no

Abstract

In the future, increased precipitation in spring may force Scandinavian farmers to prepare their cereal seedbeds under conditions with excessive soil moisture, and thereby risk soil compaction, oxygen deficiency and yield loss. To adapt to climate change and avoid yield loss, a possible strategy may be to increase moisture loss from the seedbed, in contrast to earlier seedbed research, which has focused on minimising moisture loss. In this study, we compared light and heavy mechanisation alternatives for secondary tillage in an experiment with relatively dry and excess moisture conditions. The mechanisation alternatives' suitability for excess moisture conditions was assessed in terms of resultant aggregate size distribution, penetration resistance, bulk density, air-filled porosity, air permeability, soil moisture content and cereal emergence. In general, lighter mechanisation created more favourable seedbed characteristics and seemed to be more suitable under excess soil moisture conditions. Larger aggregates after heavier mechanisation did not result in lower soil moisture content, probably because of compaction in the seedbed. We conclude that, under Norwegian conditions, the most important adaptation to climate change in seedbed preparation for spring cereals is the avoidance of compaction. Implement management for seedbed preparation should be more differentiated.

Keywords: compaction, mechanisation strategy, secondary tillage, sowing, spring cereals, workability

Introduction

In the future, we expect more frequent extreme weather events and more precipitation during winter and spring in the northern regions of North America and Europe (Bedard-Haughn 2009; Hov et al. 2013). Higher soil moisture content in spring reduces the number of days when the soil can be tilled, and thus constricts the already narrow time window of opportunity for soil tillage described by Braunack and Dexter (1989b) and Edwards et al. (2016). Obour et al. (2017) associate the window of opportunity with the moisture range at which the soil is workable, i.e. in a state where tillage creates favourable conditions for plant growth without any deterioration of the soil's agrophysical qualities. In Norway, due to a short growing season, the lower moisture limit of the window of opportunity is seldom reached in spring, as described by Riley (2016), and the upper moisture limit is therefore considered more important.

On account of a narrower window of opportunity, future farmers may face the choice between yield loss caused by early tillage of unfavourably moist soil (here defined as soil with moisture content at or above Atterberg's lower plastic limit), with consequent soil compaction, or loss of yield potential caused by delayed sowing (Riley 2016). Consequently, together with the general trend towards larger and heavier machinery, a smaller time window of opportunity in the future will increase the risk of soil compaction, oxygen deficiency and yield loss.

To avoid yield loss, we need to adapt to climate change by adjusting our methods of seedbed[1] preparation (Hov et al. 2013). However, most of the previous research on seedbed preparation in Scandinavia has focused on early summer drought (Henriksson 1974; Håkansson and von Polgar 1984; Håkansson et al. 2002; Arvidsson et al. 2012) and how to minimise moisture loss from the seedbed.

To minimise moisture loss from the seed zone and ensure enough moisture for germination, the literature suggests minimising evaporation and maximising capillary water transfer from the subsoil to the seed. Evaporation is minimised by creating small aggregates[2] in the loose layer of the seedbed (Johnson and Buchele 1961; Heinonen 1985;

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[1] A seedbed is here "defined as a loose and usually shallow surface layer, tilled by harrowing prior to sowing (seedbed preparation). The basal layer underneath, untilled during seedbed preparation, is usually firm" (Håkansson et al. 2002).

[2] An aggregate is here a secondary soil structure unit, i.e. an assembly of "soil particles that cohere to each other more than to other surrounding particles", irrespective of its origin (Dexter 1988; Diaz-Zorita et al. 2002), including sizes which otherwise might be defined as peds, crumbs, fragments or clods.

Håkansson et al. 2011; Braunack and Dexter 1989a, 1989b). Water uptake is maximised by placing the seed on a firm seedbed bottom, also called the basal layer, (Håkansson and von Polgar 1976, 1984; Håkansson et al. 2011) and by re-compacting the loose layer by rolling or attaching press wheels to the seed drill (Håkansson et al. 2011). Light rolling is still common on smaller Norwegian farms, whilst larger and heavier seed drills with press wheels have taken over on larger farms lately, irrespectively of the soil type.

Nevertheless, in the future, farmers may have to adapt seedbed preparation in spring to unfavourably high soil moisture conditions. In soil with excess moisture after sowing, the ultimate goal is to ensure sufficient oxygen supply for germination. In theory, this would mean that we have to *increase* moisture loss from the seedbed, by increasing evaporation, infiltration and internal drainage and to decrease capillary transfer. Consequently, we might have to create the opposite seedbed characteristics, i.e. larger aggregates and a less compact seedbed. Furthermore, we need to explore which kinds of implement create these seedbed characteristics and thus give good germination at high soil moisture contents.

The objective of this study was therefore to compare common but contrasting mechanisation alternatives for seedbed preparation in Norway, namely a heavy implement combination and a lighter alternative, in a field experiment including normal conditions and unfavourably wet conditions. To compare the applicability of these implement combinations under excess moisture conditions, their attained seedbed quality and plant response were assessed, in terms of aggregate size distribution, penetration resistance, bulk density, air-filled porosity at field capacity (FC, -100 hPa), air permeability at FC, soil moisture content and the emergence of spring barley (*Hordeum vulgare* L.).

Material and methods

Study sites

Three field experiments were conducted in spring 2016, two at Inland Norway University of Applied Sciences at Blæstad (60° 49 N, 11° 10 E; 221 m above sea level) and one at the Norwegian Agricultural Extension Service in Solør (60° 15 N, 12° 5 E; 156 m above sea level). The soil at Blæstad is a morainic Endostagnic Cambisol (Eutric) (FAO 2006; NGU 2017) with a sandy loam (55 % sand, 31 % silt, 14 % clay) top layer. The soil in Solør consists of marine deposits classified as Haplic Stagnosol (Siltic) (FAO 2006; NGU 2017) with a silt loam (79 % silt, 15 % sand, 6 % clay) top layer. The soil at Blæstad has imperfect natural drainage whilst the soil in Solør has poor natural drainage; both are artificially drained. Additional characteristics of the experimental soils are given in Table 1. At both sites, crop rotations are cereal dominated. Prior to experiment, the soil at Blæstad was ploughed after barley with undersown ley (glyphosate terminated) in autumn 2015, whilst the Solør site was untilled after potato harvest. The climate at both sites is classified as continental subarctic (Dfc) after Köppen and Geiger (1936) with precipitation in all seasons and with cool and short summers.

Table 1. Initial physical and moisture characteristics of the topsoil at Blæstad 1 (B1), Blæstad 2 (B2) and Solør (S).

			Water content							
	Dry bulk density (g cm^{-3})	Tot. porosity (vol%)	100 hPa[a] /FC (vol%)	15000[b] hPa (vol%)	LPL[c] (vol%)	UPL[d] (vol%)	At harrowing & sowing			
							non-workable		workable	
							(vol%)	(%LPL)	(vol%)	(%LPL)
B1	1.08	62.2	27.0	10.5	26	32	26.0	99	22.4	86
B2	1.05	61.3	26.6	9.8	26	32	25.6	98	19.6	75
S	1.41	45.5	41.0	4.0	41	41	42.2	103	34.0	83

[a] Water retention after desorption to matric potential of -100 hPa (field capacity, FC).
[b] Water retention after desorption to matric potential of -15000 hPa.
[c] Volumetric water content at lower plastic limit.
[d] Volumetric water content at upper plastic limit.

Initial soil conditions - sampling and analyses

Texture and plastic limits of the soil (Table 1) were obtained from soil sampled the previous autumn at Blæstad, and from soil sampled in 2012 (Seehusen et al. 2017) at Solør, and stored air-dry. The samples were ground and sieved to 2 mm. Texture was determined on subsamples, using a pipette method and sieving (Elonen 1971). Other subsamples were wetted to find their lower and upper plastic limits, by Atterberg and Casagrande methods (McBride 1993), respectively. The remaining initial physical and moisture characteristics of the soil (Table 1) were obtained from four soil cores sampled at a depth of 1-5 cm at each site just before trial establishment and analysed with the methods described in section “In-situ measurements, sampling and analyses”.

Mechanisation

For comparison of common but contrasting mechanisation alternatives, we resembled a light and a heavy implement combination, and, in addition, the latter used in a headland situation. Our mechanisation choices are justified and described in more detail in appendices A and B. In our experiment, light mechanisation was represented by a spring tine harrow (Figure B.1a) combined with a light Cambridge roller (Figure B.1b). Heavy mechanisation was mimicked by a disc harrow (Figure B.2a) combined with a heavy test roller (Figures B.2b and B.3). Extra heavy mechanisation on headlands was mimicked by either doubling the test roller load (Blæstad 2) or rolling in tandem (Blæstad 1 and Solør) (Table 2), which represent two different aspects of headland compaction by modern seeders, as described in appendix A. Sowing of barley and fertilising was done in one operation, using the same plot seeder with disc coulters for all treatments.

Table 2. Trial implement combinations used in different mechanisation treatments, light, heavy and extra heavy (Xheavy), at Blæstad 1, Solør and Blæstad 2.

Treatment	Blæstad 1 and Solør	Blæstad 2
light	Spring tine harrow & Cambridge roller	Spring tine harrow & Cambridge roller
heavy	Disc harrow & Test roller II single	Disc harrow & Test roller I
Xheavy	Disc harrow & Test roller II in tandem	Disc harrow & Test roller I + load

Experimental design and treatment

The experiments had a 2-factor randomised complete block design with 3 replications at each site, with experimental factors workability (no or yes) and mechanisation (light, heavy or extra heavy). However, in Blæstad 1 and Solør, use of the non-liftable test roller II, did not allow randomisation of the plots.

On the silt loam in Solør, preparatory harrowings were done before trial establishment (Table 3), due to farmers' mulching practice on this silt soil type. In all cases, prior to seedbed preparation, the soil was considered favourable for tillage (workable) or unfavourable (non-workable), based on perception of soil moisture content during manual kneading as practiced by farmers. In addition, actual soil water contents at workable and non-workable establishment in the three experiments (Table 1) were obtained from soil core samples mentioned in "Initial soil conditions". Contrasting soil moisture conditions in non-workable and workable treatment were a result of natural precipitation prior to establishment of the experiment.

Table 3. Dates and day degrees (DD[a]) for the different treatment and sampling operations with light, heavy and extra heavy (Xheavy) mechanisation in non-workable (no) and workable (yes) soil at Blæstad 1, Blæstad 2 and Solør.

		Blæstad 1		Solør		Blæstad 2	
	Operation	date	DD[a]	date	DD[a]	date	DD[a]
No	- harrowing & sowing (light/heavy/Xheavy) & rolling (heavy/ Xheavy)	20/04	0	27/05	0	21/06	0
	- delayed rolling (light)	28/04	27	01/06	77	23/06	32
	- emergence recording start	05/05	70	02/06	97	25/06	67
	- soil penetration & sampling	06/05	81	03/06	117	26/06	84
	- emergence recording end	19/05	221	11/06	222	05/07	209
Yes	- preparatory harrowing I	-	-	27/05	0	-	-
	- preparatory harrowing II	-	-	01/06	0	-	-
	- harrowing & sowing & rolling (light/ heavy/ Xheavy)	09/05	0	01/06	0	23/06	0
	- emergence recording start	17/05	70	05/06	70	27/06	68
	- soil penetration & sampling	18/05	90	06/06	85	28/06	84
	- emergence recording end	09/06	250	15/06	200	07/07	191

[a] Accumulated degrees (C°) after sowing.

The 12 m by 1.25 m plots were established between the tractor and implement wheels. The plots were harrowed and seeded to a target depth of 4 cm (Håkansson et al. 2011), and rolled on the same day, except on the non-workable plots with light mechanisation, where the rolling was delayed until conditions were drier (Table 3), in line with farmers' practice when using this type of mechanisation in wet conditions. Dates and day degrees for establishment and management of the experiment are given in Table 3.

Precipitation between sowing and germination for the three experiments are given in figure 1. Even though the two experimental sites are in the same climate class, the three experiments reflect local differences in climate due to locality (Blæstad vs Solør) and time of season (Blæstad 1 in early spring vs Blæstad 2 in late spring) (Figure 1).

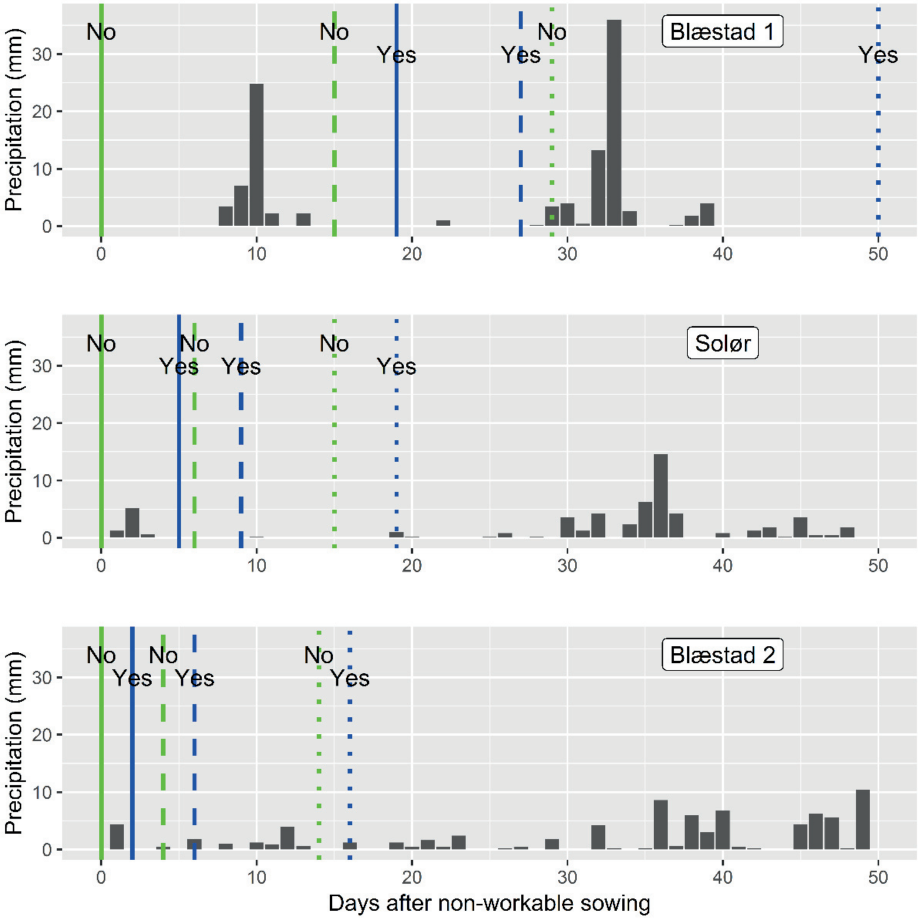

Figure 1. Precipitation on a given number of days after non-workable sowing for non-workable (no) and workable (yes) treatment in Blæstad 1, Solør and Blæstad 2. Vertical lines indicating sowing (solid), emergence start (dashed) and last emergence recording (dotted). Precipitation data obtained from weather stations Ilseng (60° 48 N, 11° 12 E; 182 m above sea level) and Roverud (60° 15 N, 12° 5 E; 172 m above sea level) for Blæstad and Solør, respectively (NIBIO, 2016).

In-situ measurements, sampling and analyses

To assess the plants’ response to the treatments, emergence was recorded by counting the seedlings daily, in two stationary frames à 0.25 m^{-2} per plot. Daily counts, averaged for each plot, were fitted to Gompertz growth curve $y = \alpha e^{-e^{(\beta-\gamma x)}}$, where y = cumulative emergence (%), x = days after sowing and α, β and γ were parameters estimated by iteration (Minitab 17). Based on the fitted curves, we found degree (maximum y-value = α), speed (inflection point = $\beta*\gamma$-1) and uniformity of emergence (slope at inflection point = ($\alpha*\gamma$)/e), equivalent to processing of germination data in Bewley et al. (2013).

To assess the seedbed quality attained by our treatments, soil moisture and penetration resistance were measured on the day after the first emergence. At the same time, samples for analyses of aggregate size distribution and pore characteristics were taken. Soil penetration resistance was measured in the field with Eijkelkamp Penetrologger 06.15.31 (Giesbeek, NL), to a depth of 30 cm, using a 60° cone with 11.28 mm base diameter and 2 cm s^{-1} penetration speed. Each plot was penetrated fifteen times with 30-60 cm spacing. The fifteen penetration resistance measurements were used to determine the geometric mean for each plot for the depths of 1-2 cm, 3-7 cm and 23-27 cm. Zero and negative measurements were discarded. Soil moisture content was measured the day after the first emergence, four times per plot with Vegetronix VG-meter-200 (Riverton, UT) to a depth of 10 cm.

For analysis of aggregate size distribution, two litres of bulk soil per plot were collected with a spade from the upper five cm, air-dried without further manipulation, and later sieved for 3 min (240 shakes min-1, 12 mm amplitude) in a set of sieves with mesh sizes of 0.6, 2, 6 and 20 mm. The largest stones of the > 6 mm fractions were excluded from the measurements of the morainic Blæstad soil. The different fraction percentages were calculated of soil minus stones. Mean weight diameter was estimated and adjusted with the method described by White (1993).

For measurements of soil pore characteristics, water retention and bulk density, four undisturbed core samples (100 cm3) per plot were collected the day after the first emergence, at a depth of 1-5 cm and stored cool (4 °C) until further processing. Thereafter, the samples were weighed and saturated from below. Their volumetric water contents were determined at matric potentials of -20 hPa, using an Eijkelkamp sandbox (Giesbeek, NL), -100 hPa and -15000 hPa, using ceramic pressure plates (Richards 1948). Air-filled porosity was measured, at -20 hPa and -100 hPa with an air pycnometer (Torstensson and Eriksson 1936). Total porosity was calculated by summing air-filled porosity and volumetric water content at -100 hPa matric potential. Air permeability was measured at -20 and -100 hPa, with the method described by Green and Fordham (1975). Finally, the cores were dried at 105 °C and bulk density was calculated.

Statistical analyses

All responses were described by linear models of the experimental fixed factors, their interaction and a random block factor in R version 3.2.3 (R Core Team, 2015). Null hypotheses of main effects and interactions were tested by ANOVA F-test in mixlm package (Liland and Sæbø 2016) with rejection level α = 0.05. In cases of rejection, Tukey HSD tests were done in lsmeans package (Lenth 2016). Plots were created with ggplot2 (Wickham 2009), gcookbook (Chang 2012) and gridExtra (Auguie and Antonov 2016) packages.

Because of the lacking randomisation in Blæstad 1 and Solør statistical tests on these data might have revealed false significant treatment effects or overlooked existing effects. Therefore, only group mean values were generated for these data.

Results

Aggregate size distribution

In general, use of heavier mechanisation and non-workable tillage conditions created larger aggregates than lighter mechanisation or workable conditions. Mechanisation and workability at the time of seedbed preparation had a significant interaction effect on the amount of large (6-20 mm, p=0.03) and small aggregates (0.6-2 mm, p=0.02) in the seedbed at the time of emergence at Blæstad 2. There were more large aggregates after extra heavy mechanisation than after light mechanisation on non-workable soil (Figure 2a), while there was no significant effect of mechanisation in workable soil. There was a similar pattern for the large aggregates in Blæstad 1 (Table 4).

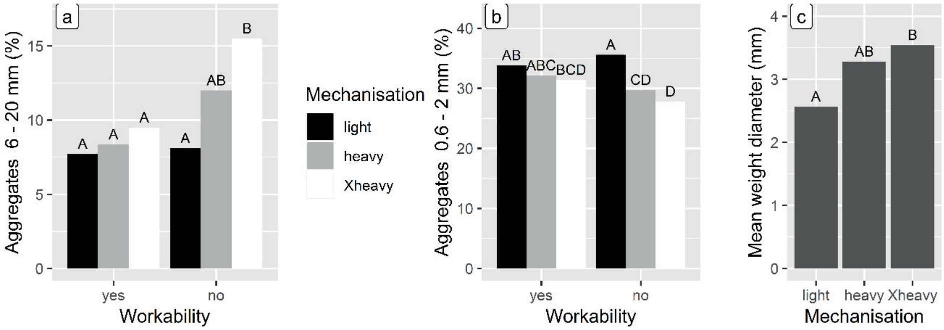

Figure 2. Proportion of aggregates of 6–20 mm (a) and 0.6–2 mm (b) size, and mean weight diameter of aggregates (c) after workable (yes) and non-workable (no) seedbed preparation with light, heavy and extra heavy (Xheavy) mechanisation at Blæstad 2. Subfigures a and b show interaction between mechanisation and workability, while c shows main effect of mechanisation. Means with different capital letters differ significantly (Tukey HSD, $p < 0.05$).

At the same time, heavy and extra heavy mechanisation led to fewer small aggregates than light mechanisation on non-workable soil in Blæstad 2, while there was no significant difference between mechanisations on workable soil (Figure 2b). Also at Solør, the small aggregates showed the same tendency (Table 4). The mean weight diameter (MWD) of the aggregates at Blæstad 2 was larger after seedbed preparation in non-workable soil than in workable soil (p=0.04), which was also the case at Blæstad 1 and Solør (data not shown). MWD at Blæstad 2 increased also with increasing mechanisation, with a significant (p=0.02) difference between light and extra heavy mechanisation (Figure 2c). The MWD values for the different mechanisation levels at Blæstad 1 and Solør showed the same pattern (Table 4).

Air-filled porosity and air permeability

Heavier mechanisation and non-workable tillage conditions generally led to smaller air-filled porosity and lower air permeability than lighter mechanisation or workable conditions, measured at field capacity (FC, -100 hPa matric potential). At Blæstad 2, heavy and extra heavy mechanisation led to a significantly (p<0.01) lower air-filled porosity at FC than light mechanisation (Figure 3a). Similar results were obtained at Blæstad 1 and Solør (Table 4). Air permeability was significantly (p=0.04) lower after heavy than after light mechanisation, with intermediate values after extra heavy mechanisation (Figure 3b). In Blæstad 1 and Solør, air permeability decreased with increasing mechanisation (Table 4). The mechanisation effect on air-filled porosity had the same pattern after desorption to matric potential of -20 hPa (p<0.01) as after desorption to FC (Figure 3a and c).

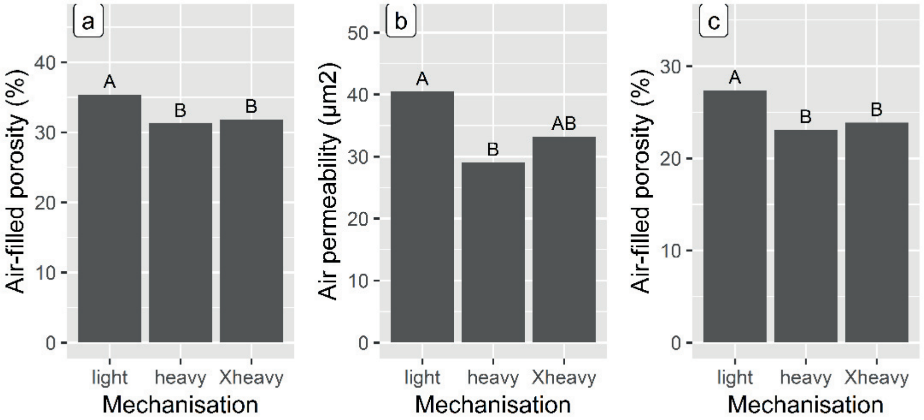

Figure 3. Air-filled porosity (a) and air permeability (b) at – 100 hPa matric potential, and air-filled porosity at -20 hPa matric potential (c), after seedbed preparation with light, heavy and extra heavy (Xheavy) mechanisation at Blæstad 2. Means with different capital letters differ significantly (Tukey HSD, $p < 0.05$).

Penetration resistance

At the time of emergence, there was a general increase in penetration resistance with increasing mechanisation and after non-workable tillage compared to workable tillage. At Blæstad 2, the upper layer of the seedbed (1-2 cm depth) had greater penetration resistance after heavy (p=0.01) and extra heavy (p<0.01) mechanisation than after light mechanisation (Figure 4a) and after seedbed preparation on non-workable than on workable soil (p<0.01, data not shown). At the seedbed bottom (3-7 cm depth), there was a significant interaction (p=0.04) between workability and mechanisation. As in the upper layer, the penetration resistance there was significantly greater after heavy (p<0.01) and extra heavy (p<0.01) mechanisation than after light mechanisation, but this was only the case in non-workable soil (Figure 4b). Further down in the soil (23-27 cm), the extra heavy mechanisation caused a larger penetration resistance than the light and heavy mechanisations (p<0.01, Figure 4c). All described effects on penetration resistance in Blæstad 2 were affirmed by the mean values in Blæstad 1 and Solør (Table 4).

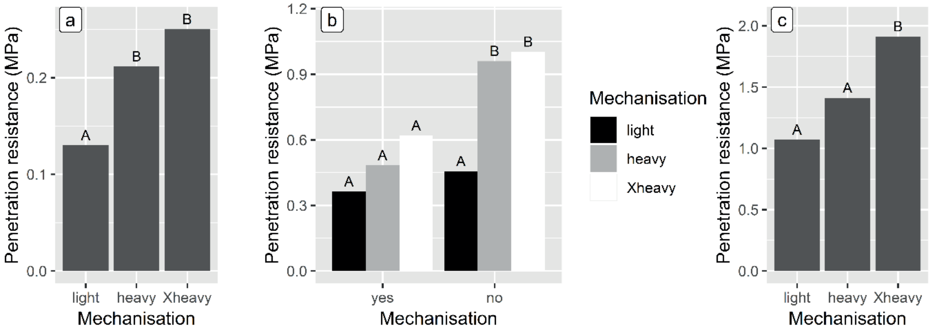

Figure 4. Penetration resistance at 1-2 cm (a), 3-7 cm (b) and 23-27 cm (c) depth on the day after emergence start, after seedbed preparation with light, heavy and extra heavy (Xheavy) mechanisation at Blæstad 2. Means with different capital letters differ significantly (Tukey HSD, p < 0.05).

Soil moisture content

The heavier mechanisation resulted in a generally higher soil moisture content at the time of emergence. The soil at Blæstad 2 had significantly (p<0.01) higher moisture content where the seedbed was prepared with heavy and extra heavy mechanisation than with light mechanisation (Figure 5a). This difference was most pronounced in the non-workable plots (Figure 5b). Similar mechanisation effects were found at Blæstad 1 and Solør (Table 4). In addition, there was significantly (p<0.05) higher soil moisture content after non-workable than after workable seedbed preparation (data not shown), which was resembled in Solør.

The differences in soil moisture content were not caused by differences in bulk density, because there were no significant differences in bulk density between treatments (data not shown).

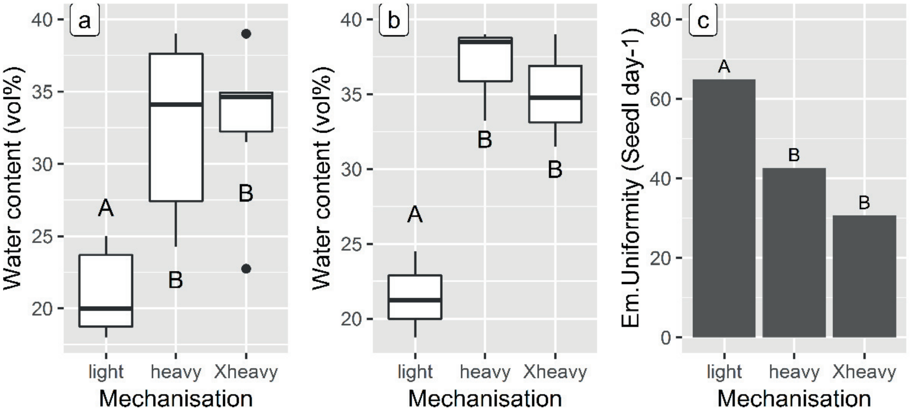

Figure 5. Soil water content (vol%) at 0-10 cm depth on the day after emergence start, averaging all treatments (a) and averaging non-workable treatment (b), and emergence uniformity (seedlings day-1) (c), after light, heavy and extra heavy (Xheavy) mechanisation at Blæstad 2. Boxplots (a, b) showing minimum, 1st quartile, median, 3rd quartile and maximum, with the box encompassing 50% of the observations, and dots representing outliers. Means with different capital letters differ significantly (Tukey HSD, $p < 0.05$).

Table 4. Group mean values for responses at Blæstad 1 and Solør, averaged over workability.

		Blæstad 1			Solør		
Response *	Unit	light	heavy	Xheavy	light	heavy	Xheavy
Agg6-20	%	14.2	14.6	16.2	25.0	23.4	25.5
Agg0.6-2	%	20.8	28.9	28.2	17. 8	16.9	13.2
MWD	mm	4.0	4.3	4.3	6.7	7.2	8.6
AirPor100	%	37.2	32.0	31.9	25.0	20.7	17.9
AirPor20	%	30.7	25.3	24.8	20.2	15.9	12.9
AirPerm100	μm^2	40.2	33.8	32.6	14.5	13.3	7.2
Pen2	MPa	0.2	0.3	0.3	0.2	0.3	0.4
Pen7	MPa	0.4	0.7	0.8	0.6	0.8	1.0
Pen27	MPa	1.0	1.3	1.4	2.1	2.2	2.5
Moist:all	vol%	10.3	15.6	17.7	42.9	46.5	48.9
Moist:no	vol%	7.5	9.9	17.3	43.4	52.4	55.0
EmUniform	seedl day^{-1}	37.0	35.6	22.5	40.4	37.0	25.5

* Agg6-20 = fraction of aggregates with size 6-20 mm; Agg0.6-2 = fraction of aggregates with size 0.6-2 mm; MWD = aggregate mean weight diameter; AirPor100 = air-filled porosity at matric potential of -100 hPa; AirPor20 = air-filled porosity at matric potential of -20 hPa; Airperm100 = air permeability at matric potential of -100 hPa; Pen2 = penetration resistance at depth of 1-2 cm; Pen7 = penetration resistance at depth of 3-7 cm; Pen27 = penetration resistance at depth of 23-27 cm; Moist:all = moisture content at emergence for all data; Moist:no = moisture content at emergence for non-workable seedbed preparation; EmUniform = emergence uniformity.

Emergence

At Blæstad 2, heavy and extra heavy mechanisation during seedbed preparation led to significantly less uniform emergence of the barley seedlings than light mechanisation (Figure 5c), with p-values of $p=0.02$ and <0.01, respectively. We found the same pattern in Blæstad 1 and Solør (Table 4). There was no significant treatment effect on degree and speed of emergence (data not shown).

Discussion

Because the traditional approach to seedbed preparation is to protect the seed against drought (Heinonen 1985), under moister spring conditions we might have to aim at the opposite - soil characteristics that increase moisture loss from the seedbed. According to the literature, moisture loss is dependent upon (1) evaporation from the loose layer and (2) capillary transfer from the basal layer into the seedbed (Lemon 1956). In addition, if precipitation prevails during germination and emergence, moisture loss is dependent upon (3) infiltration and internal drainage from the loose layer into the basal layer (Wesseling and van Wijk 1957; Hillel 2004). Therefore, we discuss the different seedbed characteristics that result from our contrasting mechanisation in the light of these three processes of potential moisture loss.

Evaporation

A larger amount of large aggregates in the seedbed may potentially increase evaporation. In earlier studies, larger aggregates in the seedbed led to lower soil moisture content (Johnson and Buchele 1961; Atkinson et al. 2007), due to an increase in evaporation (Heinonen 1985; Braunack and Dexter 1989b; Håkansson et al. 2011). Evaporation is depending on properties of pores between and within aggregates. Since intra-aggregate porosity does not reflect short-term effects of tillage (Allmaras et al. 1977), we discuss only interaggregate porosity. An increase in evaporation from larger aggregates can be explained by an increase in aeration (Braunack and Dexter 1989a, 1989b), in terms of air-filled porosity (Voorhees et al. 1966) and air permeability at constant level of compactness (Lipiec 1992 cited in Lipiec and Hatano 2003). In our study, larger aggregates did not increase aeration. Heavier mechanisation led to larger aggregates (Figure 2a-c), but, at the same time and same depth

(0-5 cm), to less air-filled porosity (Figure 3a) and lower air permeability (Figure 3b) at FC.

Compaction may explain this inconsistency between aggregate size and aeration. Due to the close relationship between compaction and aeration (Lipiec and Hatano 2003), air-filled porosity and air permeability serve as indicators for soil compaction (Nawaz et al. 2013). Earlier studies have shown that a compacted seedbed has lower air permeability (Sanchez-Giron et al. 1998) and less air-filled porosity (Braunack et al. 1979). The larger the load and the larger the aggregates, the more easily is the soil compacted (Braunack and Dexter 1989a), especially under moist conditions as in our experiment. Due to early sampling and shallow sampling depth, measured air-filled porosity and air permeability at field capacity were not below critical limits reported in the literature (Ball et al. 1988; Fish and Koppi 1994; McQueen and Shepherd 2002). However, because of its effect on porosity and permeability, compaction leads to less aeration, less vapour diffusion, less convection (Currie 1984) and consequently less evaporation (Johnson and Buchele 1961). Therefore, after heavier mechanisation, the lower air-filled porosity (Figure 3a) and air permeability (Figure 3b) at FC both suggest that the seedbed was compacted and had lower evaporation.

Another indicator for compaction is penetration resistance (Bachmann et al. 2006). In our experiment, heavier mechanisation gave greater penetration resistance at 1-2 cm depth (Figure 4a), in spite of higher soil moisture content at penetration (Figure 5a and b). If adjusted for moisture content, we would expect an even bigger difference in penetration resistance between the mechanisation alternatives. Thus, also our penetration resistance results suggest compaction of the top soil and potentially smaller evaporation after heavier mechanisation.

Capillary supply

An equally important approach to decrease moisture content in the seedbed is to decrease the capillary supply. The already discussed evaporation removes moisture from the seedbed, but the upper layer stays moist as long as there is capillary supply from the basal layer. Thus, this means that we can reduce the moisture content in the seedbed by increasing evaporation only if we reduce capillary rise to a greater extent.

In theory, capillary supply decreases with increasing aggregate size. Holmes et al. (1960) and Hubbell (1947) showed that larger aggregates result in slower capillary rise. At a given potential evaporation rate, a slower capillary rise could mean a lower moisture content in the loose layer. Therefore, we expect the larger aggregates after heavier mechanisation to reduce the moisture content in the seedbed faster. However, the question is whether this also applies in our experiment where those larger aggregates were compacted.

Compaction may counteract the slower capillary transfer resulting from larger aggregates. From compacted soil, in terms of soil with less porosity and permeability, one expects greater capillarity (Stenberg 2000) and hence higher soil moisture content resulting from heavier mechanisation. Because the compaction by heavier treatment in our study results in lower air-filled porosity (Figure 3a) and air permeability (Figure 3b) at FC, we might expect the heavier treatment to result in greater water-holding capacity, faster capillary transfer and hence higher soil moisture content.

Infiltration and internal drainage

If wet conditions continue after sowing, infiltration and internal drainage may be at least as important as evaporation to avoid oxygen deficiency. During germination and emergence, cereals are at their most sensitive with respect to oxygen deficiency (Cannell et al. 1980; Burgos et al. 2001). Therefore, heavy mechanisation, as in our experiment, may more easily cause oxygen deficiency if precipitation prevails after sowing, a situation that we expect more often in the future. In a persisting wet seedbed, evaporation, in its first and maybe second stage, is still an important process for moisture loss, but even more important in this situation are (rainpond) infiltration and internal drainage.

Infiltration and internal drainage are controlled by the soil's saturated hydraulic conductivity (Hillel 2004), which increases with increasing aggregate size and increasing air-filled porosity (Benoit 1973; Kuncoro et al. 2014). Hence, infiltration and internal drainage can be increased by increasing air-filled porosity at FC and aggregate size in the seedbed.

In theory, larger aggregates would lead to higher porosity. However, there is no benefit of large aggregates in the seedbed, if the seedbed bottom is compacted at the same time, which can be seen when comparing figure 2 and figure 3. A compacted layer reduces infiltration and internal drainage, because they are controlled by the profile's layer of least conductivity (Hillel 2004). Therefore, compaction at the seedbed bottom or below can reduce the profile's porosity, air permeability (Berisso et al. 2012; Chen et al. 2014), saturated hydraulic conductivity (Horn et al. 1995), and hence its infiltration and internal drainage. In like manner, Stenberg (2000) observed higher moisture content in a compacted seedbed compared to a seedbed with loose bottom. Thus, in spite of artificial drainage at our study sites, a seedbed bottom or subsoil compacted by heavy mechanisation (Figure 4b and c) might hamper infiltration if precipitation continued after sowing.

With persisting precipitation, reduced infiltration and drainage in a compacted layer potentially increase oxygen deficiency during germination and emergence. By compacting wet aggregates and keeping them wet afterwards, Curie (1984) created conditions potentially thirty times more oxygen deficient at -50 hPa than in the non-compacted reference treatment. When we extrapolate aeration conditions in our experiment, by measuring air-filled porosity in wet conditions at -20 hPa (Figure 3c), the mechanisation effect pattern is the same as for FC (Figure 3a), but with lower values, especially in the silt soil (Table 4). Even though we do not know our soils` critical aeration limits, these lower values mean less aeration and potentially higher risk of oxygen deficiency during germination and emergence.

Effect on soil moisture content and emergence

We attribute our observed treatment effects on soil moisture content to evaporation and capillarity, because with the dry conditions after sowing in our study, infiltration and internal drainage were probably less important for both moisture content and emergence. Even though our approach does not reveal the proportional impact of smaller evaporation and larger capillary transfer, we consider that both were important in the higher soil moisture content at emergence (Figure 5a and b) after heavier mechanisation, because they naturally interact.

Compaction seems to override the effect of aggregate size on moisture content in our study. After heavier mechanisation, we expect a larger evaporation and less capillarity, because of larger aggregate size (Figure 2a-c). On the other hand, we expect less evaporation and more capillarity, because of more compaction (less air-filled porosity in Figure 3a and less air permeability in Figure 3b at FC, and larger penetration resistance in Figure 4a-c). In spite of no significant differences in bulk densities ($p = 0.2$), the latter is the case when we examine the moisture content after different mechanisations (Figure 5a and b). The moisture content at emergence is greater after heavier mechanisation, which has caused more compaction. This means that there is no benefit from larger aggregates if they are compacted at the same time.

Although our mechanisation treatment had an effect on moisture content, there was probably no oxygen deficiency during germination and emergence in our study.

Mechanisation had only a small effect on emergence (Figure 5c). A possible reason for this is the dry conditions after sowing and during germination in our study. Under such conditions and up to field capacity (Figure 3a), mean air-filled porosity was probably above this soil's critical level.

Implications from the study

In our study, the lighter mechanisation gave lower soil moisture content at the time of emergence and better emergence uniformity, and was hence better suited for seedbed preparation in wet soil. However, because of our experimental design with a combined mechanisation factor (harrowing and sowing), we cannot make conclusions about any specific implement. Thus, studies are needed that test different types of harrows and seeders separately under wet conditions.

Furthermore, our results indicate that heavy modern seed drills with press wheels are not as well performing under unfavourably wet conditions as under normal dry conditions. However, due to their design, modern seed drills cannot function without press wheels. Therefore, future climate may require new designs or the reintroduction of older implement, in order to allow selective use of rolling, as applied in this study.

The importance of avoiding compaction must also be taken into consideration in implement management when optimising the working capacity for spring sowing at the farms. From our study we infer that, when increasing working capacity, it is necessary to consider increasing the number of machines and operators instead of increasing machinery size (and weight), thus avoiding compaction, oxygen deficiency and potential yield loss at the same time.

Our study not only shows that existing theory is not necessarily applicable under wet conditions, but also that its methods need to be re-evaluated for wet conditions. The relationship between size and compaction of aggregates with other structural soil properties, directly affecting the movement of water and air in soils, is likely different in dry and wet soil. Therefore, established seedbed knowledge should be tested specifically under wet conditions, during and after seedbed preparation, including direct measurements of evaporation, infiltration and internal drainage.

The well-structured soil in this study did probably moderate our results. The soil at Blæstad is among the best agricultural soils in Norway, with a hierarchical structure, as described by Diaz-Zorita et al. (2002). This was noticeable during sampling, as the soil was well structured, even after unfavourably moist compaction, and manual manipulation prior to sieving was unnecessary. Therefore, we would expect a more severe treatment effect on less well-structured soil types.

In conclusion, lighter implements are generally better suited for seedbed preparation in wet conditions. As expected, seedbed preparation in unfavourably moist soil led to impaired seedbed quality and emergence in our study. Nonetheless, lighter implements caused less damage under wet conditions, in terms of greater air-filled porosity and higher air permeability at FC, lower penetration resistance, lower moisture content at emergence and greater emergence uniformity. With better emergence, the light implement decreases the potential yield loss caused by unfavourably moist conditions during seedbed preparation.

Avoidance of compaction seems to be the most important adaptation to climate change in seedbed preparation. Even though heavier mechanisation created larger aggregates in the seedbed under unfavourably moist conditions, it also led to higher soil moisture content and less uniform emergence. Larger aggregates after heavier mechanisation did not increase the desired moisture loss, because they were compacted at the same time. Even though air-filled porosity and permeability were not critically low in any of the treatments in this study, the least compacted seedbed preserves the best oxygen supply for germination and thus constitutes a potential adaptation to projected future increase in spring precipitation, especially if precipitation prevails after sowing.

To avoid compaction and adapt to climate change, future mechanisation management for seedbed preparation should focus on differentiated implement use with lighter implement and selective rolling in years with unfavourably high soil moisture conditions in spring. For maximising working capacity, farmers should consider increasing number of machines and operators instead of increasing machinery size. In addition, there is a need for developing new designs and testing applicability of specific (in contrast to our study) implements under wet conditions. Finally, in future research, established seedbed theory and its methods, which are based on relatively dry conditions, should be tested under wet conditions.

Disclosure statement

We have no conflicts of interest to disclose.

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Appendix A. Mechanisation - justification of the choices made

For seedbed harrowing, we selected disc harrow and spring tine harrow with their contrasting design and functionality. The disc harrow does not force itself into the soil and hence needs to be relatively heavy. Its function is based on soil friction, which can lead to soil compaction just beneath its working depth (Birkas et al., 2004). The spring tine harrow on the other hand, is built up of tines that force into the soil, and therefore it can be lighter (Chamen et al., 2003). Furthermore, its tines loosen the soil by a shattering movement without any soil compaction (Bell, 1996).

For sowing, we chose to resemble a heavy modern combi seeder and a lighter alternative. We assume that the important difference between heavy and light seeder is not the sowing operation itself, but the presence of press wheels in the heavy alternative. Therefore, we resemble the sowing operation with the same plot seeder for all treatments, in combination with treatment specific compaction by rolling.

In practice, light seeders are commonly combined with light rollers, e.g. of Cambridge type, in Norway, in order to ensure seed-soil contact and by that capillary supply and thermal conduction. Furthermore, especially on morainic soil, like at Blæstad, rolling prevents stones from complicating combine harvesting. In addition to their light weight, the advantage of light rollers in this context is that their use can be postponed or even omitted if sowing is done under unfavourably wet conditions.

However, larger and heavier combi seeders with press wheels have replaced this light equipment on many farms in recent years. To get an impression of the compaction effect of such press wheels, we consulted manufacturer data of a random brand of modern combi seeders, with 3 m working width and 12 press wheels, common in Norway. Based on this data, we calculated a contact stress of 1.4 t per m tyre working width for the press wheels during sowing and 2.4 t per m during turning on headland with maximum cargo. A similarly large increase in contact stress during turning was mimicked by adding a concrete load to test roller I (Table A.1). However, with test roller II, this was not possible, and this roller was used in tandem instead. Thus, the different test rollers resembled two different aspects of headland compaction by modern seeders, increased contact stress and increased coverage by press wheel traffic. The test rollers used were more or less rigid rollers, which do not accurately mimic the effect of pneumatic press wheels. Therefore, we tried at least to keep the test roller radius close to common press wheel radius to enable comparison.

Seedbed preparation was done with the same tractor (Blæstad: 2.9 t weight, 52 kW effect; Solør: 4.5 t, 60 kW) in all treatments.

Table A.1. Characteristics of the trial implement.

Implement	Tot. weight (kg)	Working width (cm)	Weight width^{-1} (kg m^{-1})	Length (cm)	Tool space [a] (cm)	Max. diameter (cm)	Operating speed (km h^{-1})	Support mode [b]
Spring tine harrow[1]	420	132	-	160	10	-	5-8	mounted
Disc harrow[2]	500	140	-	190	10	50	5-8	mounted
Combi plot seeder[3]	750	125	-	192	12.5	-	3	mounted
Cambridge roller	350	130	269	-	-	37	3-5	trailed
Test roller I	1400	130	1077	-	-	68	3-5	trailed
Test roller I + load	2640	130	2031	-	-	68	3-5	trailed
Test roller II, single	1350	201	672	-	-	67	3-5	trailed
Test roller II, tandem	1350 & 1400	201	672 & 697	-	-	67	3-5	trailed

[a] Effective space between operating tools in the direction of travel, with all rows included.

[b] Operation support mode (not necessarily the same as for transport).

[1-3] Rows/ tools = number of rows/ number of operating tools (arranged in number per row, from front to back).

[1] Rows/ tools: 5/ 4 + 4 + 3 + 3 (S-tines, 37 mm) + 12 (teeth).

[2] Rows/ tools: 2/ 8 + 8 (notched discs, 20 ° angle).

[3] Rows/ tools: 2/ 10 (sowing discs) + 5 (fertilising tines)

Appendix B. Mechanisation details

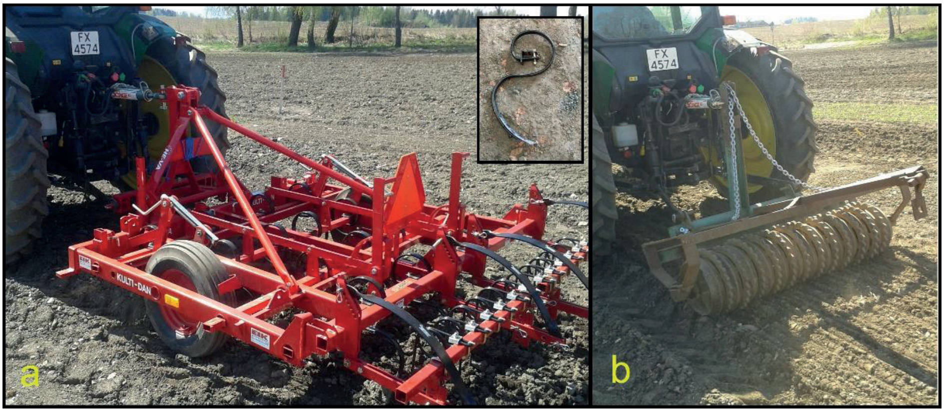

Figure B.1. Spring tine harrow modified in width (a), and Cambridge roller, middle section of an older three-piece roller, modified with a chain to be three-point liftable (b).

Figure B.2. Disc harrow, modified in width, frame and support wheels for depth control attached (a), and test roller I, custom built with 3-point hitch and liftable by hydraulic support wheels during transport, used with (extra heavy mechanisation) or without (heavy mechanisation) concrete load at Blæstad 2 (b).

Figure B.3. Test roller II, non-liftable, used as either single (heavy mechanisation) or tandem (extra heavy mechanisation) roller at Blæstad 1 and Solør.

Paper IV

Photographer: Unni Abrahamsen (2013)

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

Dorothee Kolberg [1,2,*], Tomas Persson [3], Kjell Mangerud [3], Hugh Riley [3]

[1] *Department of Agricultural Sciences, Inland Norway University of Applied Sciences, P.O. Box 400, NO-2418 Elverum, Norway.*
[2] *Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Norway.*
[3] *Norwegian Institute of Bioeconomy Research – NIBIO, P.O. Box 115, NO-1431 Ås, Norway.*
** Corresponding author. E-mail addresses: dorothee.kolberg@inn.no, dorothee.kolberg@nmbu.no*

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

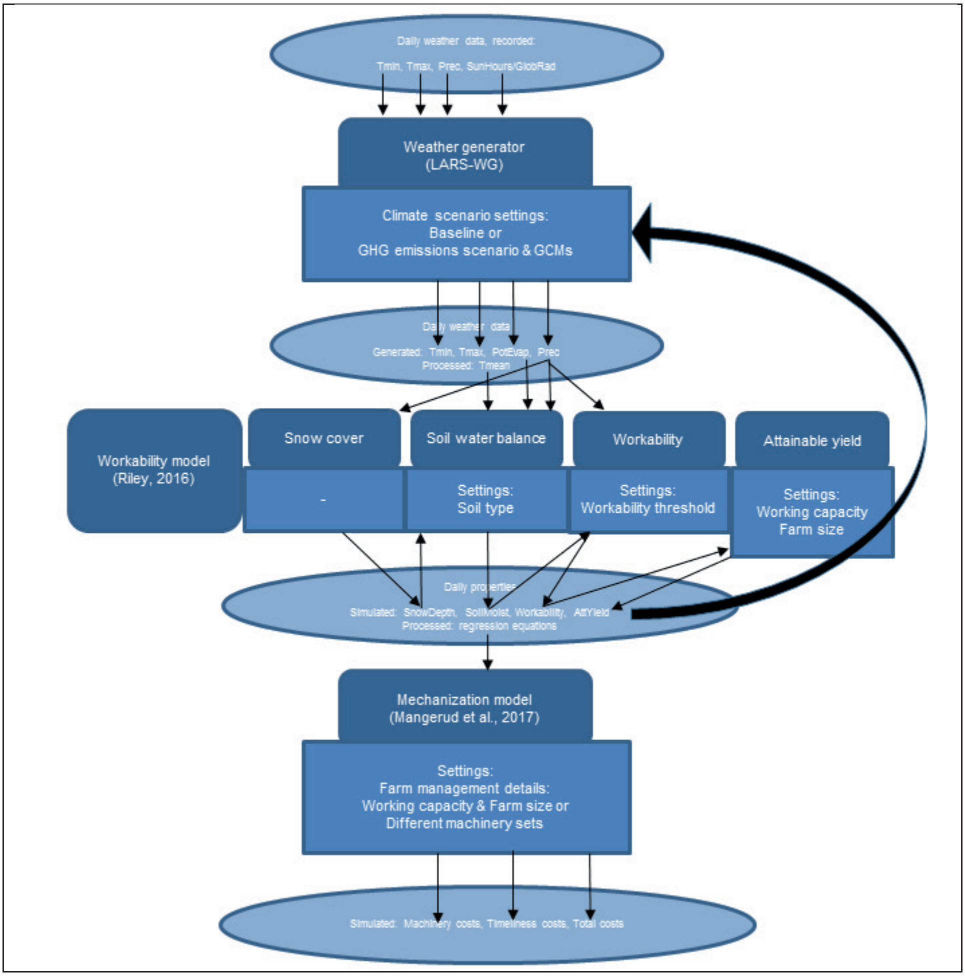

Figure 1: Overview over working steps (Rounded rectangles) and their associated data in- and output (Ellipses), and settings (Rectangles), for simulations of attainable yield, timeliness costs and total costs under Baseline and future (2046-2065) climate scenarios in South-eastern and Central Norway.

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.

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.

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).

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.

2.2.3 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 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)

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.

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 Norwaycompared 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.

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 (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
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.

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.

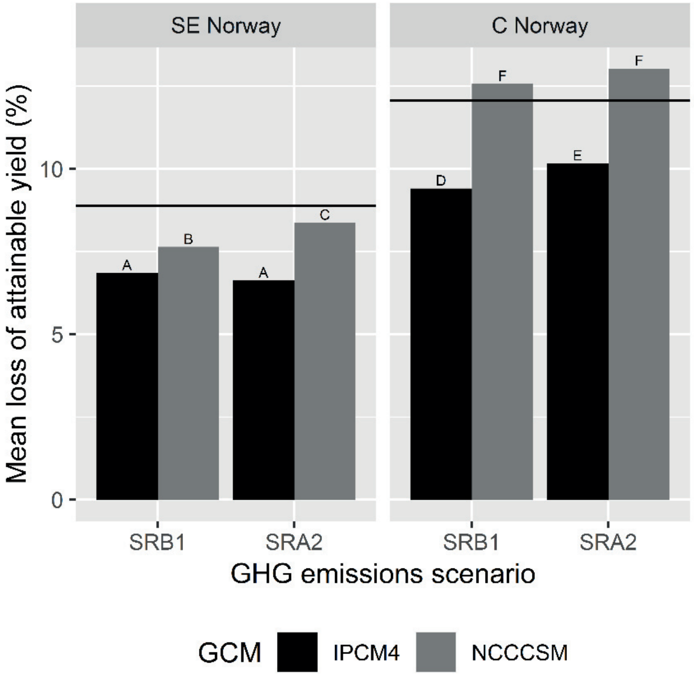

Figure 2: Interaction effect of region (SE, C Norway), greenhouse gas emissions scenario (SRB1, SRA2) and global climate model (IPCM4, NCCCSM) on loss of attainable yield (%) in South-eastern (SE) and Central (C) Norway; represents mean of 300 simulated years for the period of 2046-2065, averaged over 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.

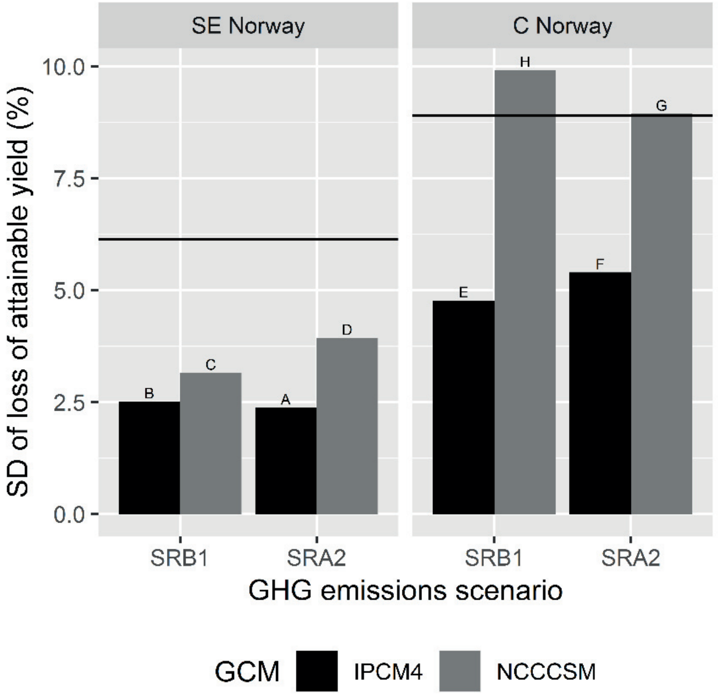

Figure 3: Interaction effect of region (SE, C Norway), greenhouse gas emissions scenario (SRB1, SRA2) and global climate model (IPCM4, NCCCSM) on standard deviation (SD) of loss of attainable yield (%) in South-eastern (SE) and Central (C) Norway; represents variability within 300 simulated years for 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.

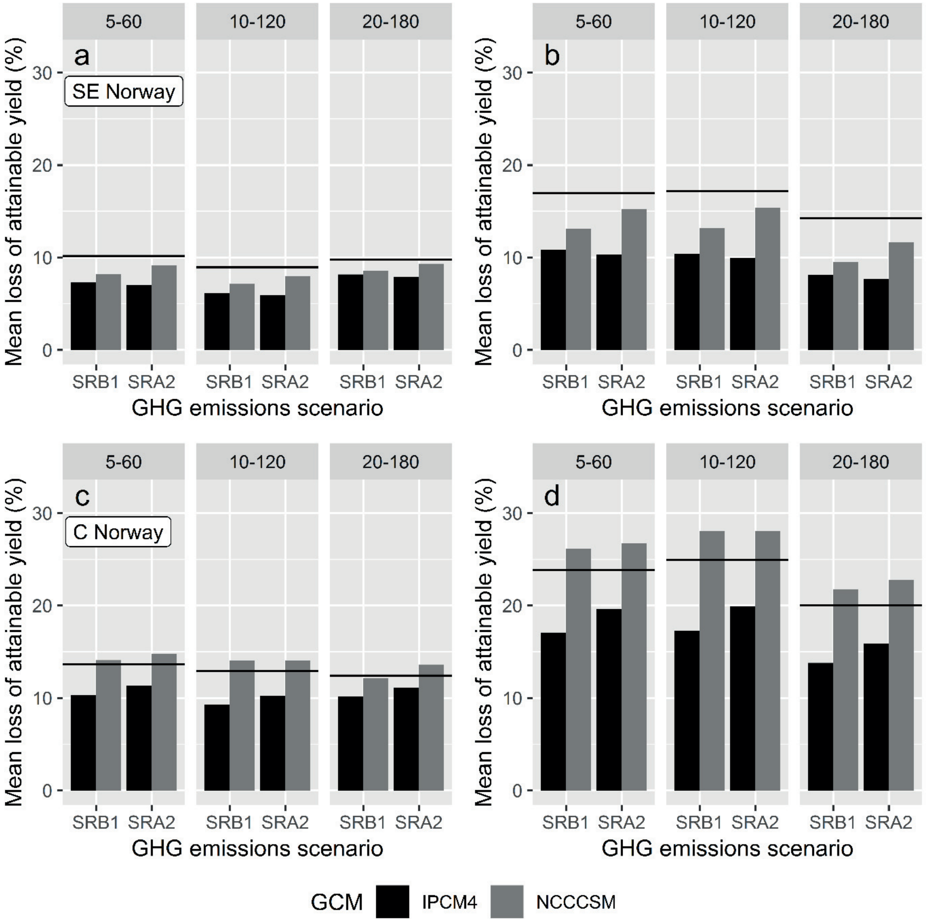

Figure 4: Predicted loss of attainable yield for three different examples of working capacity & farm size (5 ha d^{-1} & 60 ha, 10 ha d^{-1} & 120 ha, 20 ha d^{-1} & 180 ha) on loamy sand (a, c) and clay/silt (b, d) in different greenhouse gas emissions scenarios (SRB1, SRA2) and global climate models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

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 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).

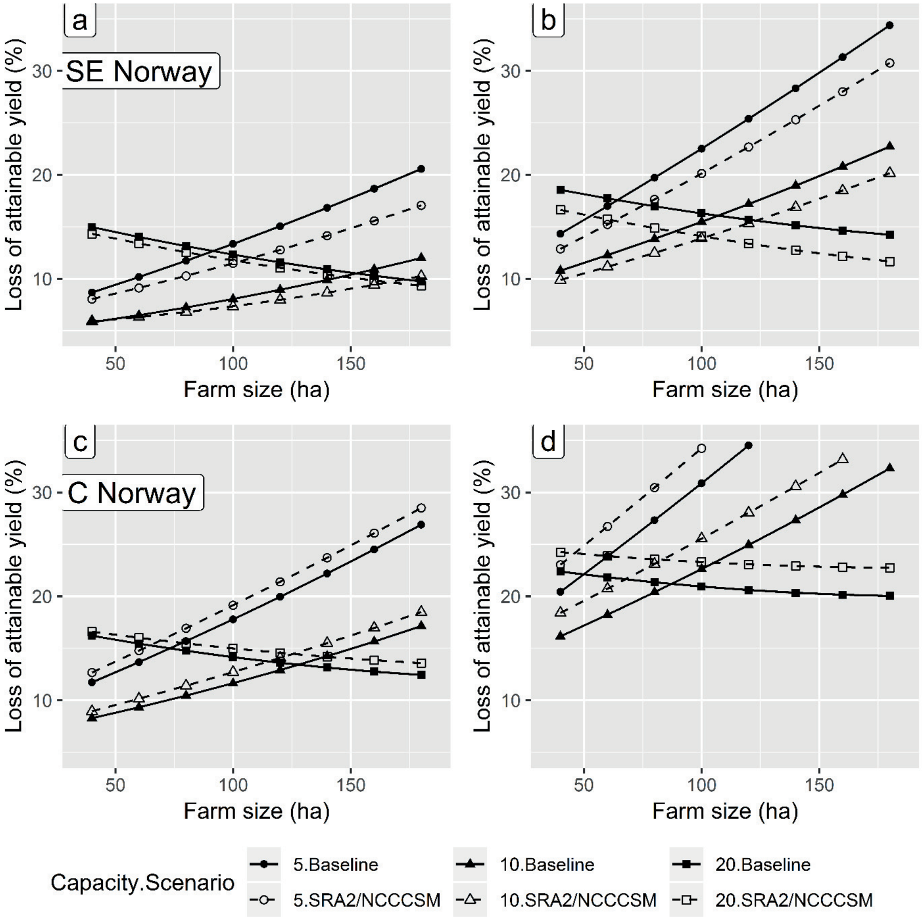

Figure 5: Predicted loss of attainable yield for different working capacities (5, 10, and 20 ha d^{-1}) with increasing farm size for historical (Baseline) and worst-case future (2046-2065) climate (greenhouse gas emissions scenario SRA2/ global climate model NCCCSM) on loamy sand (a, c) and clay/silt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

3.4.1 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).

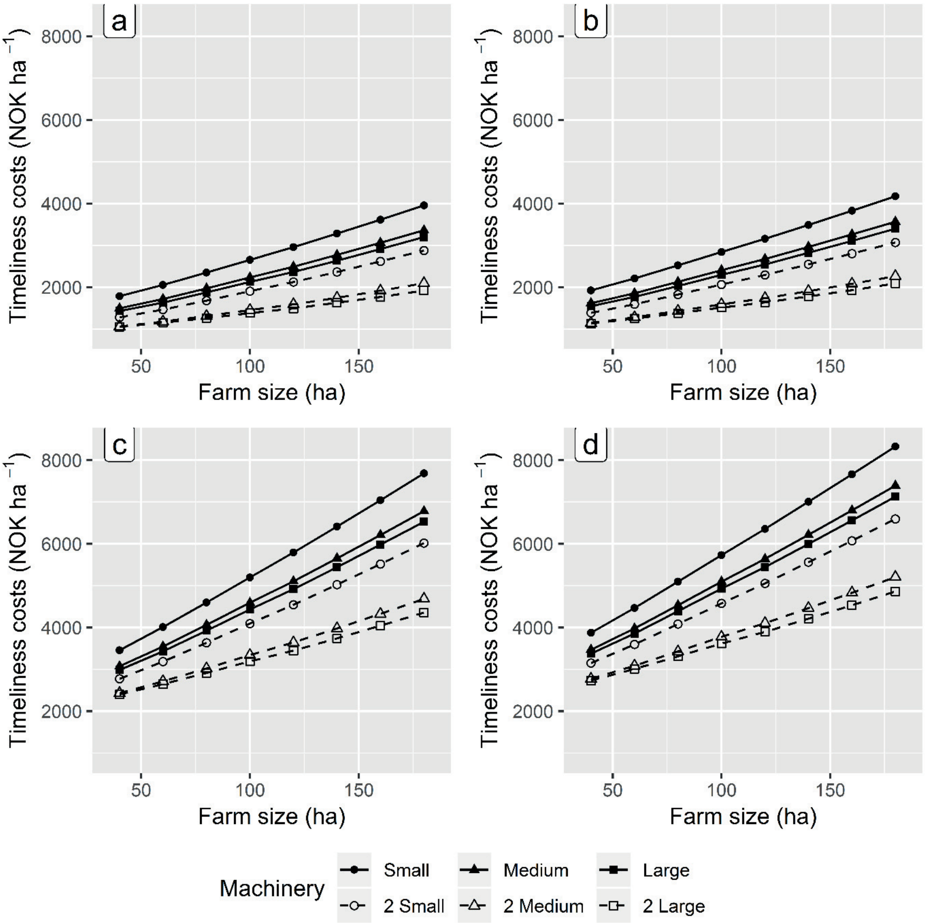

Figure 6: Simulated timeliness costs depending on farm size and machinery sets of 1 or 2 small, medium or large tractors and corresponding implement for Baseline (a, c) and worst-case future (2046-2065) climate SRA2/NCCCSM (b, d) on loamy sand (a, b) and clay/silt (c, d) in Central Norway.

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.

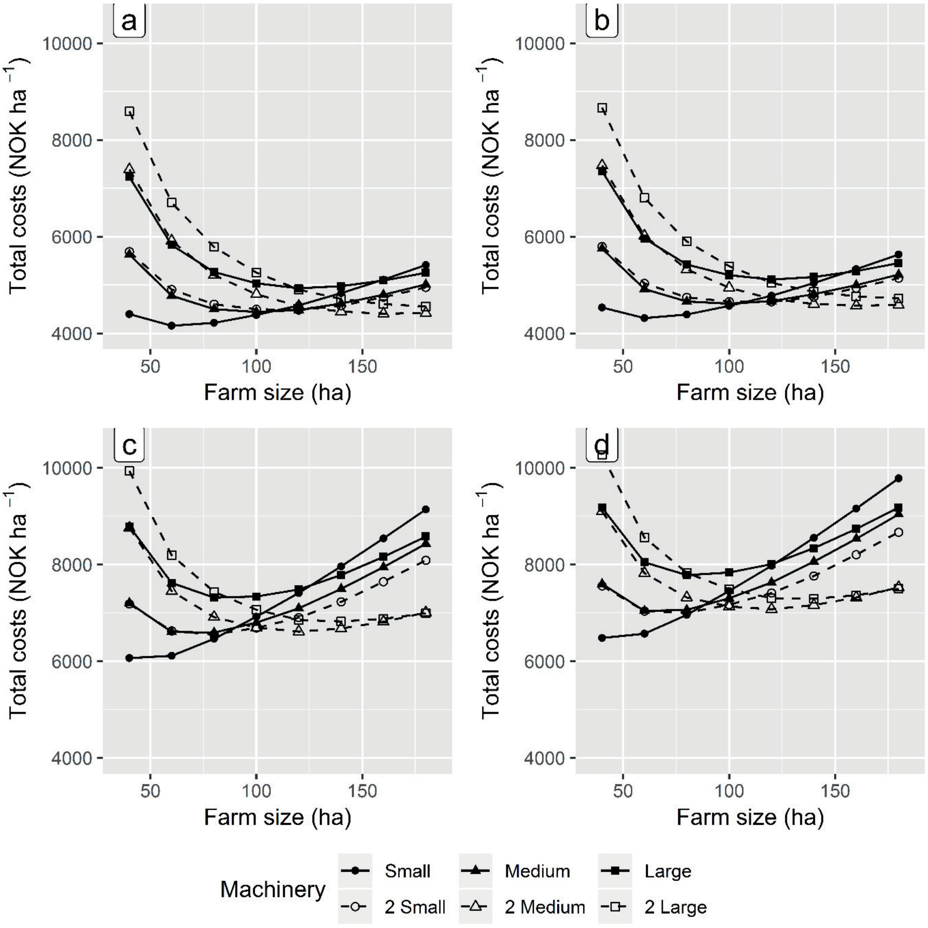

Figure 7: Simulated total costs depending on farm size and machinery sets of 1 or 2 small, medium or large tractors and corresponding implement for Baseline (a, c) and worst-case future (2046-2065) climate SRA2/NCCCSM (b, d) on loamy sand (a, b) and clay/silt (c, d) in C Norway.

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.

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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.

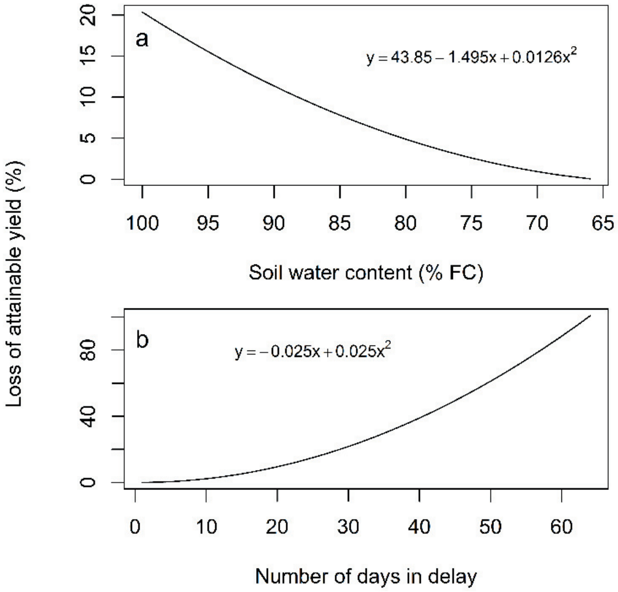

Figure A1: Functions for calculation of loss of attainable yield affected by soil water content in % of field capacity (FC, pF2, -10 kPa) in 0-20 cm soil depth during spring fieldwork (a), and number of days after optimum sowing date April 20 (b), used in the workability model (Riley, 2016).

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
$(\text{Capacity})^2$	-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
$(\text{Farmsize})^2$	-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

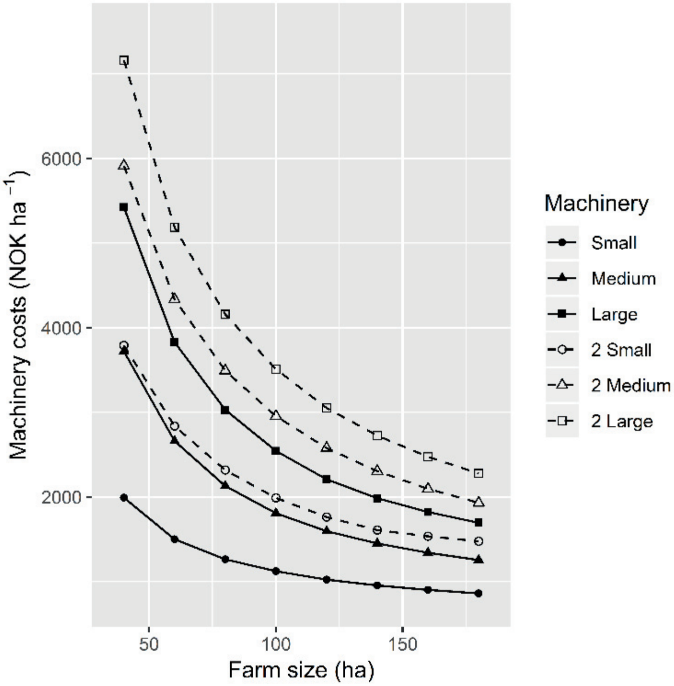

Figure A2: Simulated machinery costs depending on farm size and machinery sets of 1 or 2 small, medium or large tractors and corresponding implement, independent from climate scenario and region.

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	
	Mean (SD)	IPCM4 Mean (SD)	NCCCSM Mean (SD)	IPCM4 Mean (SD)	NCCCSM Mean (SD)	Mean (SD)	IPCM4 Mean (SD)	NCCCSM Mean (SD)	IPCM4 Mean (SD)	NCCCSM 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).

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INLAND NORWAY UNIVERSITY OF APPLIED SCIENCES

P.O. Box 400
NO-2418 Elverum, Norway
+47 62 43 00 00
www.hinn.no

Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no

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