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Yield losses due to soil compaction and sowing delay and their consequences for optimal mechanisation in relation to crop area

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SAMMENDRAG/SUMMARY:

Det er kjent at kornavlingene avtar både med utsatt såing og ved jordpakking som oppstår i jord med for høyt vanninnhold på tidspunktet våronna utføres. Dette gir utfordringer mht. når våronna kan begynne og hvordan maskinparken tilpasses de rådende jord- og klimaforhold.

Tidligere forsøksresultat er brukt for å modellere effektene av utsatt såing og jordpakking på kornavling. Jordpakking er relatert til jordas vanninnhold, uttrykt som prosent av feltkapasitet. En vannbalansemodell er brukt med 40 års værdata (1973-2012) fra tre av Norges viktigste korndyrkingsdistrikt. Beregninger er gjort for flere jordtyper med ulik vannlagringsevne.

Resultatene gjenspeiler de klare forskjellene mellom regioner, med den sørligste regionen som enklest og Midt-Norge som mest krevende. Antall laglige dager for jordarbeiding er presentert for hver jordtype og region, med ulike krav til opptørking av jorda. I all regioner var det i middel relativt få dager hvor jorda hadde tørket opp nok til at det var ingen risiko for jordpakking. Det ble ansett at 90% av feltkapasitet er et realistisk maksimalt vanninnhold for jordarbeiding.

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Effekten av våronnkapasitet på andelen av potensiell avling som er oppnåelig på ulike jordtyper ble evaluert for økende kornareal. Relative tall ble konvertert til absolutte avlingsverdier, basert på antakelser om hvordan potensiell avling påvirkes i Norge av temperaturregime og tørke. Til slutt er det gitt noen eksempler på hvordan ulike våronnkapasiteter kan oppnås, og av kostnadene som dette medfører. Disse ble brukt i an analyse av balansen mellom endringene i kornverdien ved overgang fra lavere til høyere våronnkapasitet og kostnadene dette medfører. Analysen viste at økning i arbeidskraft kan være mer kostnadseffektiv enn økt maskinstørrelse.

Et mer fullstendig sammendrag av de enkelte avsnittene i rapporten er gitt på norsk etter forordet.

Summary

Previous studies in Norway have clearly shown that cereal yields decline both with delay in sowing time in spring and with increasing soil moisture content at the time at which tillage and sowing is performed. These opposing trends represent a challenge for farmers, with relation to decisions about when to begin tillage in spring and how to adapt their investment in machinery to the prevailing soil and climatic conditions and to their own cereal area. This study is an attempt to illustrate the relative importance of delay in sowing time versus the soil moisture content at which tillage is performed, and to evaluate ways of optimising cereal profitability by choosing suitable levels of mechanisation for spring tillage and sowing.

The results of earlier field trials were used to model the effects of both sowing delay and soil compaction on relative cereal yields. The effect of compaction was related to the soil's moisture content at the time spring-work was performed, expressed as a percentage of field capacity. A soil moisture balance model was used to calculate daily topsoil moisture contents for the whole spring and early summer period, using forty years of weather data (1973-2012) from three representative weather stations in Norway's main cereal-growing regions. Calculations were made for four typical soil types, with different moisture-holding capacities.

The results reflected the marked differences in weather conditions between regions, with the southernmost area being most favourable and that in central Norway most demanding. Results presented include the number of trafficable days on each soil in each region, assuming different levels of prerequisite soil moisture. The average number of days on which the soil had dried up enough to completely avoid all risk of yield loss due to compaction was low in all regions. As a realistic starting point, 90% of field capacity was chosen as the maximum level for spring tillage.

Effects of spring-work capacity on the percentage of potential yield obtainable on different soil types were assessed for increasing cereal areas. These were converted to absolute yield levels, on the basis of assumptions about how potential yield in Norway is affected by temperature regime and drought proneness. Finally, some examples were given of ways in which various levels of spring-work capacity may be achieved, and to illustrate their costs. These were used in an analysis of the balance between changes in mean grain value following changes from lower to higher spring work capacities and the costs involved. This analysis suggested that in some cases increases in manpower may be more cost-effective than increases in the size of machinery used.

GODKJENT /APPROVED	PROSJEKTLEDER /PROJECT LEADER
Trond Børresen	Lillian Øygarden
NAVN/NAME	NAVN/NAME

Forord

Prosjektet «AGROPRO - Agronomi for økt matproduksjon: Utfordringer og muligheter» pågår i perioden 2013- 2017. I prosjektet deltar forskergrupper fra NMBU, NIBIO, Bygdeforskning, Norsk landbruksrådgivning og Høgskolen i Hedmark, sammen med internasjonale forskergrupper. Prosjektet er finansiert av Bionærprogrammet i Norges Forskningsråd (prosjektnummer 225330/E40) og med egeninnsats fra forskningsinstitusjoner. I prosjektets referansegruppe deltar Norges bondelag, Tine, Felleskjøpet, Nortura, Statens landbruksforvaltning og Norsk landbruksrådgivning. I AGROPRO er målet å undersøke muligheter og begrensinger for at forbedret agronomisk praksis kan bidra til økt og bærekraftig matproduksjon i Norge. For kontaktpersoner og mer om prosjektet, se www.agropro.org.

Arbeidet som presenteres i denne rapporten inngår i AGROPRO arbeidspakke nr. 1, som heter *Forbedret agronomisk praksis,* under oppgave 2 (*Bedre jordstruktur*), deloppgave 2.2 (*Utvikle beslutningsverktøy for jordas laglighet og risiko for jordpakking*). Denne deloppgaven fokuserer på de til dels motstridende målsettingene av tidligst mulig såing om våren for å utnytte kornets vekstpotensial, og ønsket om å minimalisere mest mulig jordpakkingsskader som oppstår når man kjører for tidlig på jorda. Problemet søkes belyst ved hjelp av beregninger av jordas laglighet for jordarbeiding over en 40-års periode i de viktigste kornregionene i landet. Disse beregningene kobles opp mot mekaniseringsgraden som trengs for å gi optimal avling og økonomi på kornbruk av ulik størrelse.

Stor takk til Kjell Mangerud (tidl. førsteamanuensis ved Høgskolen i Hedmark) for verdifull bistand vedrørende vurdering av mekaniseringsbehov og beregning av kostnader (kapittel 5).

Apelsvoll, 05.01.17

Hugh Riley

UTVIDET SAMMENDRAG

1. Målsetting: Hensikten med studiet er å estimere potensielle avlingstap som følge av utsatt såing om våren kontra tap ved jordpakkingen som skjer ved såing under ulaglige jordforhold. I tillegg er det ved modellberegninger søkt å belyse hvor stor mekaniseringsgrad som trengs for å oppnå et økonomisk tilfredsstillende avlingsnivå på gårder av ulik størrelse.

2. Bakgrunn: En vesentlig betraktning knyttet til jordas laglighet for jordarbeiding er å fastsette graden av opptørking som trengs for å unngå jordpakkingskader. Et sentralt begrep er den nedre plastisitetsgrensen, som beskriver fuktighetsnivået hvor jorda går fra å være formbar til å bli smuldrende. Erfaring fra både Norge og Sverige tilsier at jordas nedre plastisitets-grense inntreffer ved et gjennomsnittlig vanninnhold på ca. 90 % av feltkapasitet.

   Ulike metoder er blitt foreslått for å bestemme det optimale vanninnholdet i jorda for jordarbeiding, basert på målinger av f.eks. jordas vannretensjonskarakteristikk eller dens mekaniske styrke. Slike metoder krever opplysninger om jordfysiske størrelser som ofte er lite tilgjengelige. I dette arbeidet er det i stedet valgt å benytte en metode som tar utgangspunkt i jordas vanninnhold sett i relasjonen til jordas dreneringslikevekt (såkalt feltkapasitet). Det er brukt en vannbalansemodell for bar jord (ubevokst og uten planterester på overflaten) for å beregne vanninnholdet i matjorda og derved å få et mål på nivået av jords laglighet på en dag til dag basis.

   Litteraturen oppgir ulike verdier for det optimale vanninnholdet for jordarbeiding, fra ca. 70 % til >90 % av feltkapasitet. Etter vår erfaring er vanninnholdet i hele matjordlaget ved såing ofte ca. 80-85 % feltkapasitet. Dette samsvarer med 90 % av nedre plastisitetsgrense, som av mange brukes som et ønskelig nivå for å unngå skade på jordstrukturen. I praksis blir jordarbeiding ofte startet under noe fuktigere forhold, for å kunne rekke over et stort areal. Datoene som ble notert for oppstarten av våronna ved Apelsvoll forskningsstasjon over en periode på ca. 30 år er beregnet til å samsvare med et gjennomsnittlig vanninnhold i jorda på 90 % av feltkapasitet, dvs. akkurat ved nedre plastisitetsgrense.

3. Metoder:

   3.1 Vær: Det er brukt værdata for perioden 1978-2012 til modellberegningene som er gjort i denne rapporten. Beregningene er gjort på døgnbasis hvert år fra 16. mars til slutten av juni. Værdataene er fra Ås (Sør-Østlandet), Kise (Nord-Østlandet) og Kvithamar (Midt-Norge).

   3.2 Vannbalanse: En enkel og velprøvd dansk modell er brukt for å beregne den aktuelle fordampinga fra matjordlaget, på grunnlag av potensiell fordamping og nedbør, samt jordas vannlagringsevne. Beregningene er gjort for de fire mest utbredte jordteksturgrupper som brukes til korndyrking i Norge (sand, siltig sand, lettleire og mellomleire/siltjord). Fra disse må det fordampes hhv. 3 mm, 5 mm, 7 mm og 9 mm vann for at de skal tørke til 90 % av feltkapasitet. Modellberegningene forutsetter at jorda er fritt drenert eller at den har velfungerende grøfter.

   3.3 Avlingstap ved utsatt såing: En kurve basert på mange års norske såtidsforsøk er brukt for å gi prosentvis tap av potensiell avling når såing skjer seinere enn 20. april. Kurven tilsier ca. 5 % tap ved såing 5. mai, 15 % tap ved såing 15. mai, 30 % tap ved såing 25. mai og total avlingssvikt ved såing >24. juni.

   3.4 Avlingstap ved pakking av matjorda: En kurve basert på en rekke norske forsøk med jordpakking i korn og gras er brukt for å gi prosentvis tap ved kjøring på jord med ulik fuktighet. Kurven tilsier at det ikke blir tap av potensiell avling når våronna gjøres på jord med vanninnhold <70 %, 4-7 % tap ved 80-85 % og 10-15 % tap ved 90-95 % av feltkapasitet.

3.5 Kombinert effekt av såtid og jordpakking: De to kurvene er kombinert multiplikativt. Dette betyr at ved såing før 21. april på jord som har tørket til 70 % av feltkapasitet, forventes det at man kan oppnå hele det potensielle avlingsnivå for vedkommende region og jordart, så lenge forholdene seinere i veksttida ikke er begrensende. Ved såing i midten av mai på jord som har tørket til 85 % av feltkapasitet, vil man kunne oppnå ca. 80 % av potensiell avling, mens såing til samme tid på jord som har bare tørket til 95 % av feltkapasitet vil gi ca. 75 % av potensiell avling pga. pakking. Hvis såing utsettes til 30. mai, vil de tilsvarende tallene være ca. 60 %, 55 % og 50 % ved hhv. 70 %, 85 % og 95 % av feltkapasitet.

4. Resultater:

4.1 Værforhold: Temperaturen på Nord-Østlandet er som regel under null fram til slutten av mars, slik at snøen ligger lengst der. Sør-Østlandet har gjennomgående høyest temperatur. Tidlig på våren er den lavest på Nord-Østlandet, mens i juni er den lavest i Midt-Norge. Nedbøren er lavest på Nord-Østlandet, og som regel høyest i Midt-Norge. Potensiell fordamping er høyest på Sør-Østlandet, og på omtrent samme nivå de andre stedene. Aktuell fordamping ble beregnet til gjennomsnittlig 56 % av potensiell fordamping på Sør-Østlandet, 61 % på Nord-Østlandet og 74 % i Midt-Norge. Forskjellene skyldes ulike jordfuktighetsforhold.

4.2 Jordfuktighet: Gjennomsnittlig vanninnhold i jorda rundt 1. mai var 85-90 % av feltkapasitet på Sør-Østlandet, 87-93 % på Nord-Østlandet og 90-95 % i Midt-Norge. På Østlandet tørker den letteste jorda til ca. 75 % av feltkapasitet i løpet av mai, mens den tyngste jorda holder seg rundt 80-85 % av feltkapasitet. I Midt-Norge er opptørkinga mindre, i gjennomsnitt til ca. 80 % av feltkapasitet på lett jord og 90 % på tung jord. Det er store variasjoner i opptørkinga fra år til år i alle regioner, slik at jordfuktigheten i enkelte år kan variere fra ca. 75 % til ca. 95 % av feltkapasitet mot slutten av mai. En oversikt er gitt over hvor ofte (% av alle år) jordfuktigheten tørker til hhv. 95 %, 85 % og 75 % av feltkapasitet til ulik tid utover våren. I slutten av april har jorda tørket til <95 % av feltkapasitet i 70-80 % av åra på Sør-Østlandet, 60-70 % av åra på Nord-Østlandet og 50-60 % av åra i Midt-Norge. Forskjellen mellom jordarter øker med kravet man stiller til opptørking. På Nord-Østlandet, for eksempel, tørker sandjord til <85 % av feltkapasitet innen midten av mai i 70 % av åra, mens tilsvarende tall for leirjord og siltjord er bare 45 %. Tørking til < 75 % av feltkapasitet skjer der i ca. 40 % av åra på sandjord, men i mindre enn 10 % av åra på den tyngste jorda. De tilsvarende tall for Sør-Østlandet er noe høyere, mens de i Midt-Norge er betydelig lavere.

4.3 Antall laglige dager for jordarbeiding: Antall dager med jordfuktighet under ulike terskelverdier viser flest dager i hver gruppe på Sør-Østlandet og færrest i Midt-Norge. Det er dobbelt så mange laglige dager i mai som i mars og april til sammen, og like mange i juni som i mai. Antall dager som er laglige for jordarbeiding synker markert i alle regioner hvis det stilles krav om opptørking til < 85 % av feltkapasitet, særlig på tyngre jord. Plotting av antall laglige dager i enkeltår viser store svingninger mellom år, men det er ikke funnet noen klar tidstrend. Fram til slutten av mai, var antall dager med jordfuktighet <90 % av feltkapasitet på sandjord funnet å variere i gjennomsnitt fra 28 i Midt-Norge til 40 på Sør-Østlandet. Den tilsvarende variasjonen for leirjord/siltjord var fra 15 i Midt-Norge til 26 på Sør-Østlandet. Det var altså omtrent like stor forskjell mellom regioner innen jordart som mellom jordarter i samme region. Standardavvikene for alle disse middeltallene, dvs. variabiliteten mellom år, var ca. 10 dager.

4.4 Avlingstap ved utsatt såing kontra jordpakking: Potensielt avlingstap som følge av jordpakking avtar fra 20 % tidlig i våronna til omtrent 10 % fra begynnelsen av mai. Etter ca. 10. mai begynner risikoen for avlingstap pga. sein såing å bli større enn risikoen for tap som følge av jordpakking. Jordpakkingsrisikoen på samme type jord er størst i Midt-Norge og minst på Sør-Østlandet, og den er nesten dobbelt så stor på leirjord/siltjord som på sandjord. Når begge faktorene er sett under ett, ser det ut til at den største andelen av potensiell avling kan oppnås ved såing fra midten til slutten av april. Såing etter midten av mai medfører relativt store tap.

4.5 Areal som kan sås ved ulik arbeidskapasitet: Mer enn halvparten av norske korndyrkere har et kornareal på 200-400 dekar. Den totale våronnkapasiteten estimeres å ligge i området 25-100 dekar pr. laglige dag. Valg av opptørkingsgraden som kreves for jordarbeiding har stor innflytelse på arealet som kan sås innen rimelig tid. For eksempel, vil krav om tørking til 85 % av feltkapasitet redusere arealet som kan sås på Nord-Østlandet før 25. mai med 20 % på sandjord og 40 % på leirjord/siltjord, sett i forhold til krav om 90 % av feltkapasitet. Et mer liberalt kriterium, derimot, vil gi økte avlingstap pga. jordpakking.

Det er også store regionale forskjeller. Ved krav om opptørking til 90 % av feltkapasitet før jordarbeiding, kan det sås et 20 % større areal på sandjord før 25. mai på Sør-Østlandet enn på Nord-Østlandet, mens forskjellen for leirjord/siltjord er nesten 40 %. Tilsvarende kan det i Midt-Norge sås 15 % mindre areal på sandjord og 25 % mindre areal på leirjord/siltjord enn på Nord-Østlandet med samme valg av laglighetskriterium.

Ved bruk av en middels stor våronnkapasitet, 50 dekar pr. laglige dag, er midlere dato for å være ferdig med våronn på 400 dekar på Nord-Østlandet beregnet til 27. april på sandjord og 11. mai på leirjord/siltjord, når det stilles krav om tørking til 90 % av feltkapasitet. Dersom arealet økes til 800 dekar, er de tilsvarende datoene 9. mai og 24. mai. Med en slik kapasitet og et areal på 400 dekar, vil man alltid være ferdig med våronna på sandjord før 25. mai, mens en på leirjord/siltjord ikke vil være ferdig innen 25. mai i 17 % av årene. Økes arealet til 800 dekar, blir man ikke ferdig på sandjord før 25. mai i 7 % av åra og i hele 50 % av åra på leirjord/siltjord. Det gis flere eksempler for alle regioner og for areal fra 150 til 900 dekar.

4.6 Avlingsrespons ved ulik våronnkapasitet på gårder med ulike kornareal: Avlingsnivået som kan oppnås som prosent av det potensielle man kan få uten begrensninger ved utsatt såtid eller jordpakking ble estimert. Beregninger er gjort for kornareal fra 150 til 900 dekar og med våronnkapasiteter fra 25 til 75 dekar pr. laglige dag. Våronnkapasiteten har større betydning jo lenger nord i landet man kommer, og effekten er større på tyngre enn på lett jord. Med sandjord på Sør-Østlandet ser det ut til å ha lite for seg å ha større våronn-kapasitet enn ca. 35 daa/dag, uansett areal, mens på leirjord/siltjord er det trolig nok med 50 daa/dag på areal opp til 500 dekar. På Nord-Østlandet ser en kapasitet på 50 daa/dag ut til å være tilstrekkelig på sandjord, selv på større kornareal, mens på leirjord/siltjord rekker dette bare til 300 dekar. Ved større areal trengs det en kapasitet på minst 75 daa/dag. I Midt-Norge er det større sjanse for avlingstap, og det er behov for stor våronnkapasitet selv på relativt små kornareal.

For hver region er det ut fra simuleringsresultatene utledet regresjonslikninger som trolig kan brukes til enkle applikasjoner for å bestemme hvor stort tap av potensiell avling man kan forvente ved bruk av ulike våronnkapasiteter. Likninger inneholder termer for kornareal, jordas vannlagringsevne, våronnkapasiteten og samspillene mellom disse. De forklarer 93-97 % av variasjonen i materialet og predikerer relativt avlingsnivå med en middelfeil på <2 %.

4.7 Estimering av aktuell avling fra relativ avling uttrykt som % av potensiell avling: For å dra nytte av de relative avlingsnivå som er omtalt i forrige avsnitt, er det nødvendig å finne passende verdier for det maksimale avlingsnivå man kan forvente i ulike klimasoner på jord med ulik vannlagringsevne. Det potensielle avlingsnivået antas her å gjelde for kornavlingen som kan oppnås uten andre begrensninger enn det som forutsettes av temperaturforholdene i den aktuelle regionen. Med utgangspunkt i tidligere publiserte vurderinger av effekten av temperatur og tørke på kornavlinger i Norge, er det satt opp et forslag på hvordan potensiell avling varierer mellom kornregionene og jordartene som er brukt i denne rapporten.

Det potensielle avlingsnivået er satt til hhv. 7,5 % og 15 % mindre på Nord-Østlandet og i Midt-Norge enn på Sør-Østlandet, og til hhv. 7,5 %, 15 % og 25 % mindre på lettleire, siltig sand og sandjord enn på leirjord/siltjord. Med dette utgangspunktet og med de maksimale prosentverdiene som ble funnet i forrige avsnitt, er det beregnet de maksimale avlingene som kan forventes for hver region og jordart når våronnkapasiteten ikke er begrensende.

4.8 Verdien av meravlingen som oppnås ved å øke mekaniseringsgraden: Beregninger er gjort av midlere avlinger i de tre regioner som kan forventes oppnådd på kornareal fra 150 til 900daa, ved arbeidskapasiteter i våronna på mellom 25 og 100 daa/dag. Beregningene tar utgangspunkt i et middels potensielt avlingsnivå på 700 kg/daa på Nord-Østlandet, justert for jordart og region som beskrevet ovenfor. Omregning til andre valg av potensiell avling gjøres med passende faktorer. Videre er det tabulert gevinstene ved å øke kapasiteten fra et nivå til det neste, både i kg/daa og i kr/daa ved dagens gjeldende gjennomsnittlige kornpris.

På Sør-Østlandet, er det ved kornareal opp til 300 dekar relativt liten økning i avling uansett jordtype når våronnkapasiteten økes utover 37.5 daa/dag. På større areal gir en kapasitet på 50-75 daa/dag avlingsøkning, spesielt på tyngre jord, men det er lite å hente ved å øke kapasiteten enda mer. Generelt større fordeler ved å øke våronnkapasiteten oppnås jo lenger nord i landet man kommer og de er større på tyngre enn på lettere jord. På Nord-Østlandet, har avlingsøkningene på den dominerende jordart i regionen, lettleire, av omtrent samme størrelsesorden som de beregnet for leirjord på Sør-Østlandet, hvor slik jord dominerer. Relativt store avlingsøkninger oppnås ved å øke kapasiteten til 75 daa/dag når kornarealet er 600 daa. Videre kapasitetsøkning opp til to 100 daa/dag øker kornverdien med kr 15/daa ved et kornareal på 750 daa, og med dobbelt så mye ved et areal på 900 daa.

I Midt-Norge er betydningen av å ha tilstrekkelig våronnkapasitet enda større. Det finnes flere jordarter i denne regionen, men arealene som brukes til korndyrking er hovedsakelig på leirjord. En gjennomsnittlig økning i kornverdien av kr 38/daa oppnås på slik jord når kapasiteten økes fra 50 til 75 daa/dag ved et kornareal på 300 daa, mens for et areal på 600 daa, kan det oppnås nesten like mye igjen ved å øke fra 75 til 100 daa/dag.

5. <u>Optimalisering av våronnarbeidet</u>:

5.1 Eksempel på kapasiteter ved ulike jordarbeidingsalternativ: Relativt lite informasjon finnes om tidsbehovet for ulike jordarbeidings-operasjoner under norske forhold. Noen egne målinger er presentert, og disse er sammenliknet med tall beregnet med et dansk dataprogram.

Det ble funnet rimelig overenstemmelse og det danske programmet er brukt for å illustrere effektene av skiftestørrelse, skifteform og kjørehastighet på tidsforbruket for en rekke arbeids-operasjoner med ulik redskapsstørrelse.

På basis av dette, ble det estimert at tidsbehovet for tillaging av såbed og såing om våren ofte er ca. 20-30 minutt/daa, eller 20-30 daa/dag. Dette forutsetter at utgangspunktet er jord som har blitt høstpløyd eller høstharvet. Erfaringene tilsier at eventuell vårpløying vanligvis kan startes 1-3 dager tidligere enn sekundær jordarbeiding, uten stor risiko for jordpakking. For at ikke såtida skal utsettes ved vårpløying, bør pløyekapasiteten derfor være av omtrent samme størrelsesorden som kapasiteten som trengs til de øvrige arbeidsoperasjoner.

5.2 Eksempel på kostnader ved ulike jordarbeidingsalternativ: Traktorkostnaden utgjør en viktig del av de totale kostnadene ved jordarbeiding. Med hjelp fra førsteamanuensis Kjell Mangerud er det satt opp eksempler som viser sammenhengene mellom traktorpris og trekkraft, samt trekkrafts-behovet til harver og såmaskiner med ulik bredde. På bakgrunn av dette er det satt opp eksempler på traktorer og tilpasset redskap for tre nivå av våronnkapasitet (hhv. 30, 50 og 100 daa/dag), med tilhørende investeringskostnader. Dette tyder på at det kreves en estimert økning i investering på kr. 66.000 for å øke arbeidskapasiteten med 25 daa/dag.

Det ble også beregnet totale årlige kostnader for de tre alternativene, inklusive nedskriving, vedlikehold, drivstoff og arbeidsinnsatser, ved hjelp av et beregningsprogram utviklet av Kjell Mangerud. I hvert tilfelle ble beregningene gjort for tilfeller med både én og to traktorer, for å simulere effekten av å øke arbeidskapasiteten fram for å øke maskinstørrelse. Kostnadene pr. daa øker raskt ved alle alternativene når kornareal er mindre enn 300 daa. Kostnadene ved bruk av hhv. en eller to traktorer blir relativt like når det er snakk om store kornareal, fordi bruk av bare én traktor senker traktorens livstid og øker vedlikeholdskostnadene.

Til slutt ble det satt opp en oversikt over balansen mellom endringen i kornverdien som oppnås ved ulik våronnkapasitet (jfr. pkt. 4.8), og kostnadene som dette medfører. For et kornareal på 300 daa var balansen stort sett negativ når man gikk fra en lavere til en høyere våronnkapasitet. For et kornareal på 900 daa, derimot, var det store positive balanser for å øke kapasiteten fra 25 til 50 daa/dag, og i mange tilfeller også for å øke kapasiteten videre til 100 daa/dag. Dette gjaldt særlig situasjonen på tyngre jordarter og spesielt i Midt-Norge. Beregningen tydet på at det var generelt mer lønnsomt å øke kapasiteten ved å bruke to traktorer med samme maskinpark enn å øke størrelsen på både den ene traktoren og maskinparken. En slik løsning forutsetter selvfølgelig at den nødvendige arbeidskraften finnes for å betjene to traktorer i våronna.

6. Diskusjon og framtidig forskning:

Styrken ved modellen som er brukt er at den tar med effektene av både jordpakking og såtid. Den empiriske såtidsfunksjon kan imidlertid bli endret ved evt. klimaendringer. Hvis vårpløying vekt-legges mer i framtida, må det tas hensyn til kjedeeffektene av avbrudd i jordarbeidingssekvenser. Det bør også sees nærmere på logistiske og topografiske begrensninger. Langtidseffekten av dyp jordpakking ved bruk av tyngre maskiner bør kobles inn i modellen, og det er behov for mer informasjon om effektiviteten av nyere jordarbeidingsredskap, sett i forhold til kostnadene.

Contents

1 AIMS

The first aim of this study was to estimate potential yield losses associated on the one hand with delayed sowing and on the other hand losses due to soil compaction resulting from untimely sowing. A further purpose of these calculations was to enable an analysis of the optimum amount of spring tillage mechanisation that is required in order to obtain satisfactory mean cereal yields on farms of different size in the three main cereal-growing regions of Norway.

Optimal avoidance of soil compaction – suboptimal sowing time?

Optimal sowing time – suboptimal avoidance of soil compaction?

2 BACKGROUND

Farmers aim to sow cereals in spring as soon as the soil has dried up enough to avoid harmful compaction. This implies that the topsoil should become 'friable' (Norwegian 'laglig') before tillage commences. This condition is defined as the lower plastic limit (LPL), i.e. that at which the soil consistency is no longer plastic. Opinions vary as to the optimum soil moisture content for tillage. Many authors (e.g. Keller et al. 2007) have used the criterion 0.9LPL as a rough estimate of the upper moisture level at which tillage will not adversely affect soil structure.

Dexter & Bird (2001) proposed the use of the 'inflection point' in the soil moisture retention curve to predict optimum conditions for tillage. However, in a study of 80 German and US soils, Mueller et al. (2003) found that at the inflection point, the soil would in many cases be too wet for tillage. In any case, determination of the latter requires detailed soil physical information.

Another approach is to relate the soil's mechanical strength (as measured by penetrometer resistance) to soil moisture deficit (Earl 1996). Earl considered soils to be 'trafficable' (i.e. dry enough to be driven on) and 'workable' (i.e. dry enough to be tilled) at average deficits of 9 mm and 17 mm, respectively, in the upper 20 cm of soil. Unfortunately, systematic data on the relationship between penetrometer resistance and the moisture content of Norwegian soils is not available. In practice, it is difficult to distinguish between the stage at which soil is trafficable and that when it becomes workable. In this report the term 'trafficability' is used to encompass both stages.

In addition to drainage, some water must be evaporated before the soil is fit to be tilled. An approach which is easy to use in simple moisture balance models is to define the optimum soil moisture content for tillage as the percentage of the moisture content at a specified drainage equilibrium. This approach implies that the amount of evaporation required before the friable state is reached increases with the soil's moisture-holding capacity (i.e. clay and silt soils take longer to dry up enough for tillage than do more sandy soils).

Mueller et al. (2003) found that 70% of the soil moisture content at -5 kPa (pF1.7) was a suitable average value to describe the maximum water content for optimum tillage. In Norway, the soil moisture (SM) at -10 kPa (pF 2) is often used to define the field capacity (FC) of arable soils. The corresponding optimum SM, based on the soil data of Riley (1996), is about 75% of FC. The critical deficits found by Earl, mentioned above, are roughly equivalent to about 85 % and 75% of FC at pF 2. Kohnke (1968) considered the best tillage range to lie between pF values of 2.8 and 4.4, with pF 2.8 as the wet limit, at which the soil becomes friable. The latter is equivalent to SM levels of 80-90 % of FC for many Norwegian soils (Riley 1996).

Data on the soil consistency of Norwegian soils is rather scarce, but in the case of 8 fairly typical soils from Hedmark, Romerike (in Akershus) and Østfold, the LPL was found at pF 2-3.5 (Fig. 2.1). In relation to field capacity, the LPL of these soils was found on average at 89±4 % of FC (mean±se). When expressed as 0.9LPL, the corresponding average figure is 80±3 % of FC.

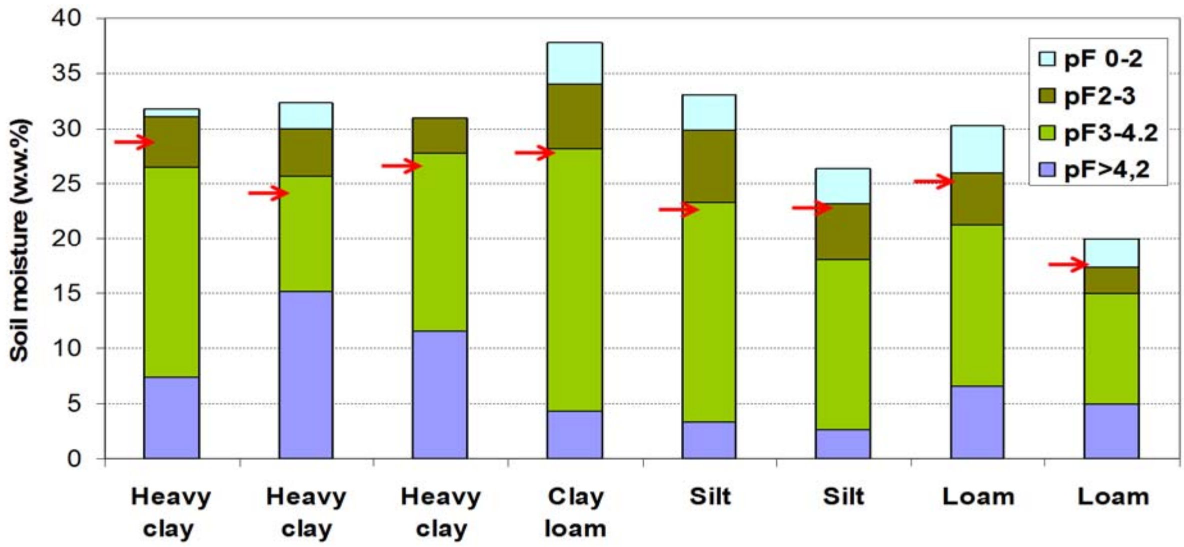


Fig. 2.1. The lower plastic limit (red arrows) in relation to the moisture retention characteristic of some typical arable soils in SE Norway (Riley, unpublished data).

With the exception of one soil, these data suggest that the LPL expressed as % of FC declined with increasing clay content. However, our data are too few to make a definite conclusion. When data was included for 14 Swedish soils, published by Keller & Dexter (2012), a trend in the opposite direction was found (Fig. 2.2), but the mean figure remained the same (89±3 %). The variability found in LPL may be due to its relatively imprecise method of measurement (i.e. by finding the water content at which a rolled-out thread of 3 mm diameter is deemed to become unstable).

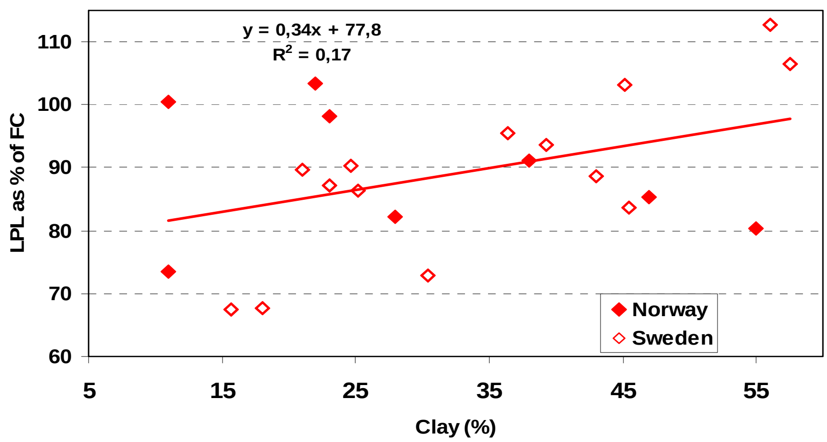


Fig. 2.2. The relationship of LPL (expressed as % of FC at -10kPa) with increasing clay content in 8 Norwegian and 14 Swedish soils.

We found that both the plasticity index (upper minus lower plastic limit) and the aggregate size of these soils increase with increasing clay content (Fig. 2.3). This is a clear illustration of the well-known fact that clay soils are most demanding with relation to their ease of tillage.

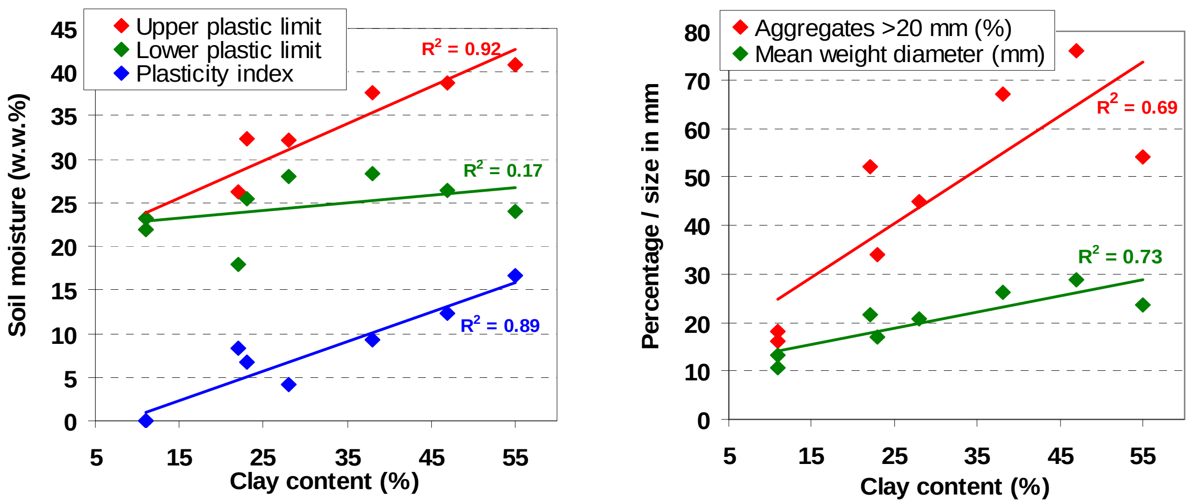


Fig. 2.3. The plasticity (left) and aggregate size (right arrows) of typical soils in relation to their clay content (Riley, unpublished data, same soils as those in Fig. 2.1).

In the light of the above discussion, it was decided in this report to use the percentage of topsoil moisture, relative to that held at field capacity, as the criterion for trafficability. There is, however, variation in the literature with regard to suitable values. Elliot et al. (1977) considered that the critical point for soil tillage may be assumed to lie between 70 and 95 % of FC, whilst Babeir et al. (1986) used a criterion of 99% of FC as the upper limit for trafficability. However, in the latter case, FC was defined as the SM content at -33 kPa (pF 2.5) rather than at -10 kPa (pF 2). Based on the soil data of Riley (1996), the corresponding SM for FC defined as pF 2 would be ca. 89% of FC.

Little information exists in Norway about the soil moisture content at the start of spring tillage, but some authors have given the topsoil moisture content at sowing. In a study by Skjelvåg (1986), records were used of the first sowing date in southern Norway in 1957-1982. Topsoil (0-20 cm) moisture at that time was calculated to equal on average 70% of FC, but there were large variations between years (from <50% to >90%). The soil type in question was loamy sand, and on average more than ten days had passed after the stage at which the soil had dried to 90% of FC until sowing commenced. It seems likely, therefore, that 70% of FC is too stringent a criterion for deciding when tillage starts. In a study of the moisture content at sowing time measured on loam soil in 1977-1980, Riley (1989) found that this occurred at a mean value of 80% of FC (range 73-84%). About one week had then passed after the calculated moisture content was at 90% of FC.

Whilst for modelling it is convenient to consider the mean moisture content of the whole topsoil, the soil does not dry out uniformly throughout this depth. Normally, it dries considerably faster at the surface than at lower depths. In a study of seedbed conditions soon after sowing on ca. 300 fields in Sweden, Kritz (1983) measured soil moisture in several layers (0-2, 2-4, 4-6, 6-8 cm).

Using his data, grouped according to clay content, the measured moisture values are compared with the corresponding field capacity and wilting point of each soil group (Fig. 2.4, left).

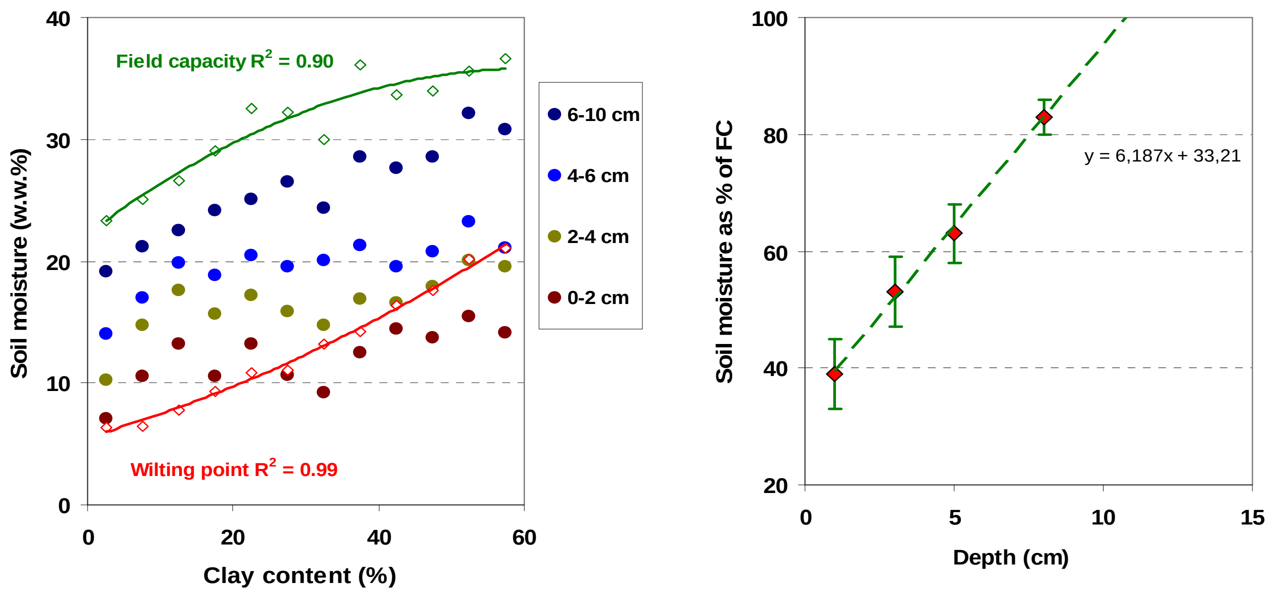


Fig. 2.4. Soil moisture content in cereal seedbeds plotted against clay content (left) and their mean values (± std. dev.) expressed as % of field capacity (FC) at different depths (right). Based on data collected on Swedish farms by Kritz (1983).

Although the soil moisture in all cases increased with clay content, we found little difference between soil groups in the relationship of measured moisture content versus field capacity. The average values were 39, 53, 63 and 83 % of FC at 0-2, 2-4, 4-6 and 6-8 cm depths, respectively. When plotted against mean depth, these mean values follow a linear trend (Fig. 2.4, right), suggesting that soil moisture below 10 cm is at 100% of FC. The mean content for 0-10 cm is 64 % of FC, whilst the corresponding value for the whole 0-20 cm layer would, on the latter assumption, be 82% of FC.

It is well-known that tillage in practice often commences somewhat sooner than the stage at which the soil moisture content of the whole topsoil layer is considered 'optimum for tillage', possibly at 85-95% of FC. Such a practice is probably unavoidable in order to allow farmers to sow adequate areas within a reasonable time span. The above findings imply that, while the layer closest to the surface may appear to be relatively friable, the moisture content of the lower topsoil will often be somewhat higher than that at which the soil is friable. As will be seen in the next section, a certain reduction of yield may thus often be expected to occur as a result of compaction even when the damage is hardly visible at the soil surface.

Confirmation that tillage and sowing often commence within the range 85-95% of FC was found in the dates for the first day of tillage and first day of sowing noted by farm manager Petter Lunde at Apelsvoll Research Station, Østre Toten, between 1979 and 2007. Using weather data from nearby Kise weather station, calculations were made for the moisture content in loam soil on these dates, using the model described in section 3.2.

The moisture content on the first day of tillage in this period was on average 90.1% of FC (std. dev. 4.5%), whilst the corresponding mean on the first day of sowing was 87.7% of FC (std. dev. 4.1%). The distribution in the values calculated for individual years is shown in Fig. 2.5. The first day of tillage was at soil moisture contents between 85 and 95% of FC in 22 of the 28 years in which it was noted, whilst the first day of sowing was between 80 and 90% of FC in 15 of the 24 years noted.

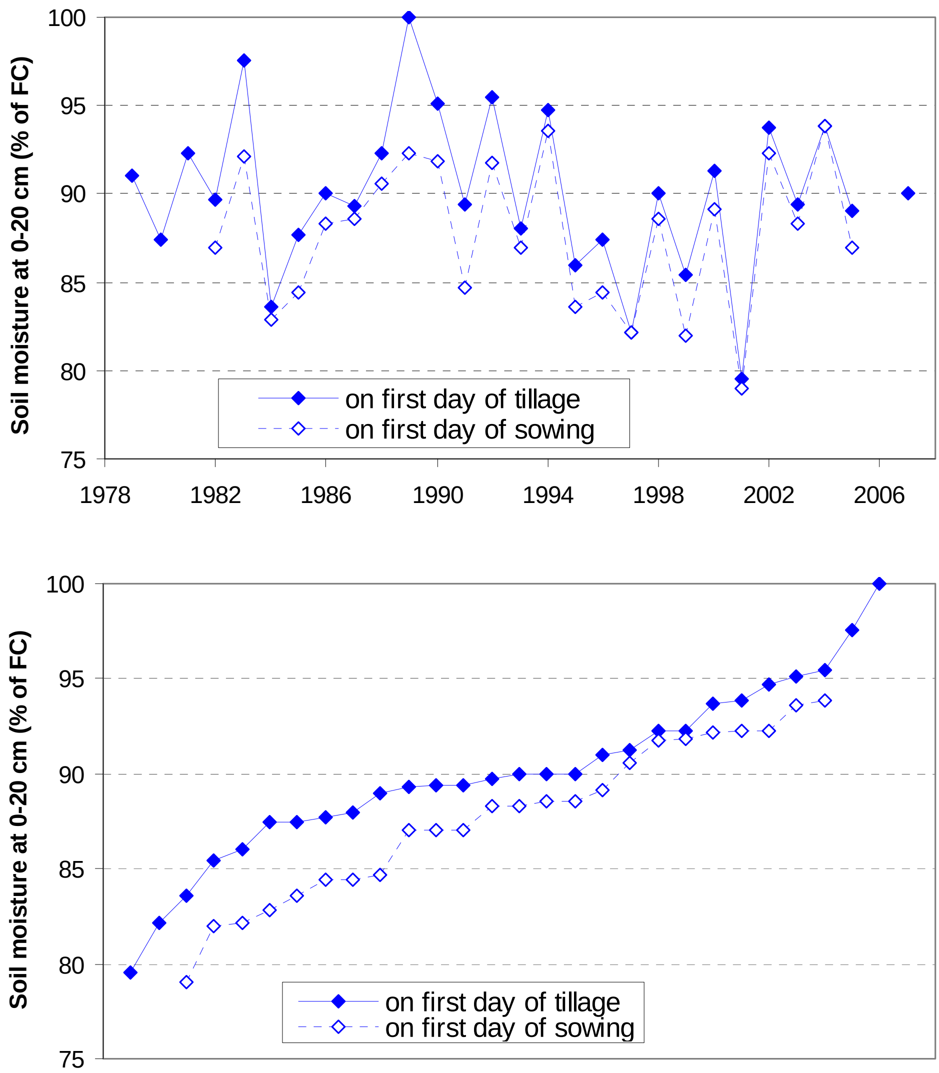


Fig. 2.5. Calculated soil moisture content at 0-20 cm depth, expressed as % of field capacity (FC), on the first day of tillage and on the first day of sowing at Apelsvoll Research Station, Østre Toten (dates noted by farm manager Petter Lunde during the period 1979-2007).

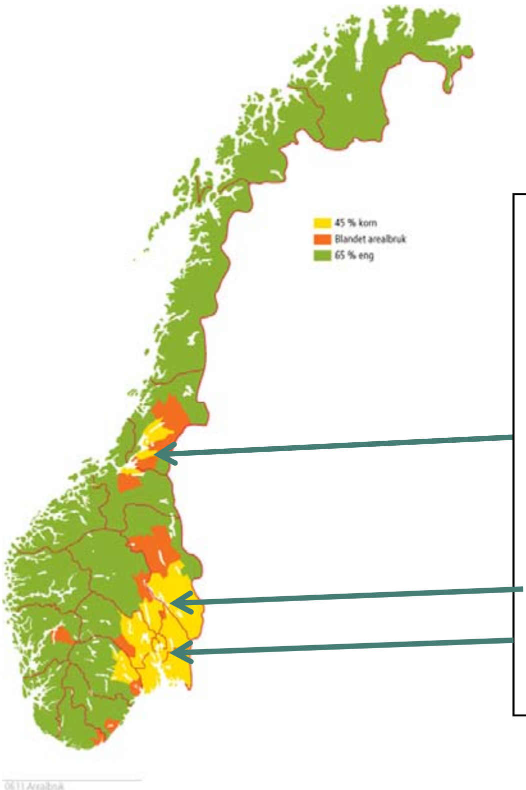
3 Methods

3.1 Localities and weather data

The calculations are made with daily weather data for 1973-2012 from three weather stations:
Ås: representative for much of the arable area in eastern Norway to the south of Oslo.
Kise: representative for much of the arable area in eastern Norway to the north of Oslo.
Kvithamar: representative for much of the arable area in Central Norway (Trøndelag).

The data used cover the 15-week period from 16th March (Julian day number 75) until 28th June. The normal sowing time for cereals is in all three regions from late April to mid/late May.

The potential evaporation (Ep) values used here were, in the case of Kise, open water evaporation measured until 2003 with a Thorsrud 2500 evaporimeter, and thereafter calculated using an equation derived from weather data at the same station (see Riley & Berentsen 2009, appendix II). The latter equation was used in all years in the case of the other two stations. Data for snow cover were measured values at Kise, whilst for the other stations values were calculated using a Finnish model adapted and calibrated for Norwegian conditions by Riley and Bonesmo (2005).



The regions (yellow/brown areas) in which most cereal growing takes place, and the location of the weather stations:

Central Norway
(17 % of cereal area)

Kvithamar

Eastern Norway
(82% of cereal area)

Kise

Ås

3.2 Moisture model

The moisture balance calculations are made using the 'bare soil module' in the hydrology model of Kristensen & Jensen (1975). This module calculates the daily actual evaporation (Ea) from daily amounts of rainfall and potential evaporation (Ep), assuming that Ea=Ep at soil field capacity, declining linearly to 15% of Ep when 20% of the topsoil (0-20 cm) moisture held at FC has been evaporated (Fig. 3.1). This calculation method has previously been found to give good agreement with measured values of the moisture in bare soil at Kise (Riley 1989).

Daily precipitation is allocated first to make up the difference between Ea and Ep, and the remainder to topsoil moisture. Any excess over the latter's FC passes to depth. It is assumed that the topsoil is at (or above) FC on 15th March each year, as soils in Norway are normally saturated at the time of snow-melt in spring (Picture 1). Further it is assumed that hydraulic conductivity in the subsoil is rapid enough to prevent delay in topsoil drying due to poorly functioning drains. Poorly drained soils would thus have lower trafficability than that shown by these calculations.

Calculations are made for the following soil textures, representing different moisture-holding capacities, expressed here as mm of water held at FC in the 0-20 cm topsoil layer, with corresponding amounts of evaporation required to reach 90% of FC (in brackets) :

Coarse sand: 30 mm (3 mm held between FC and 90% of FC)
Loamy sand: 50 mm (5 mm held between FC and 90% of FC)
Loam: 70 mm (7 mm held between FC and 90% of FC)
Clay loam/silt: 90 mm (9 mm held between FC and 90% of FC)

Picture 1. A typical scene during snow-melt in early spring in Norway, showing run-off from near-saturated loam soil (foreground) and ponding of water above frozen subsoil (background).

(Photo: H. Riley)

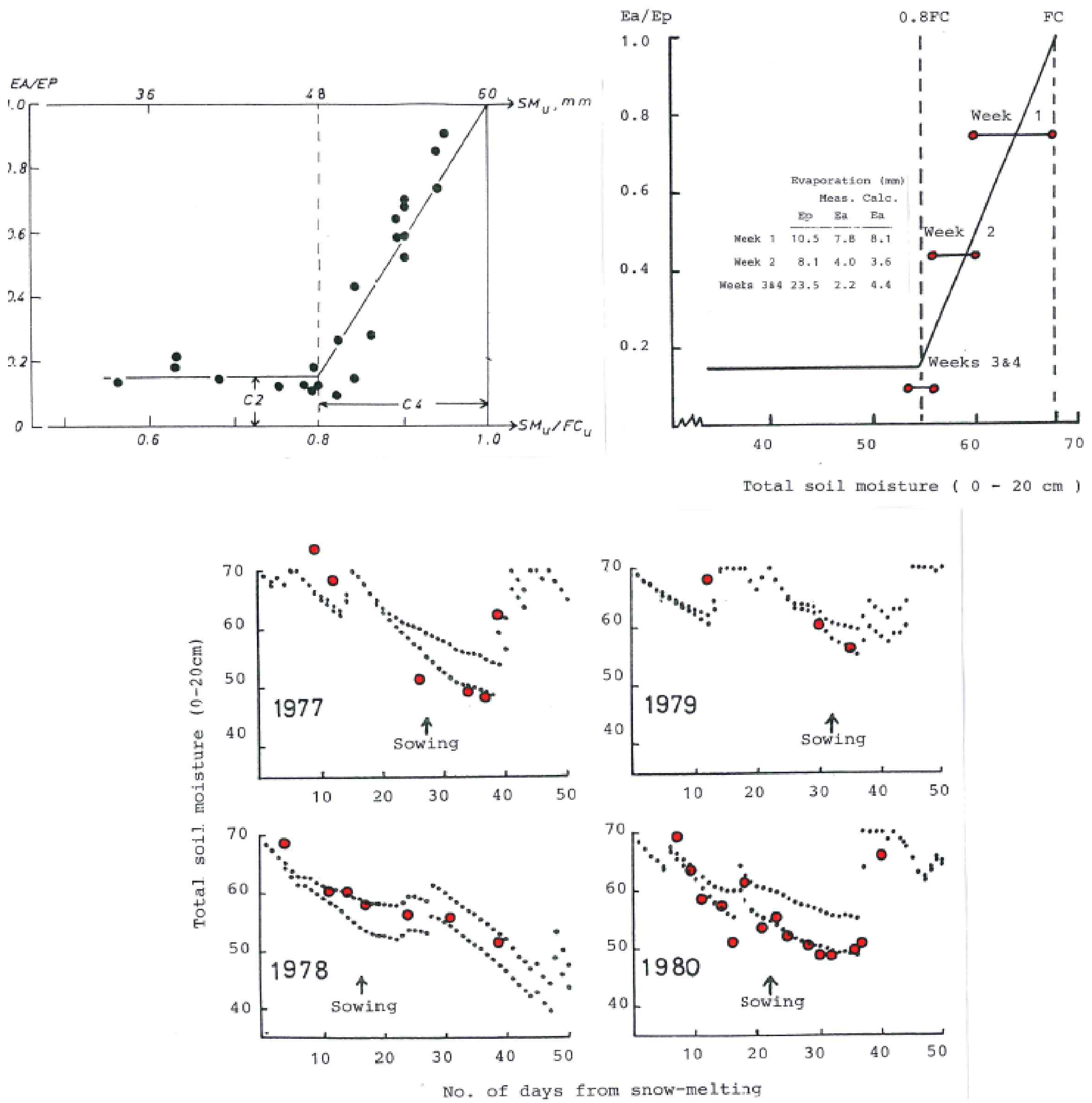


Fig. 3.1. Illustration of the way in which the ratio of actual to potential evaporation (Ea/Ep) declines with decreasing topsoil moisture content in the bare soil model used in this study.

Top left: Data (●) from clay loam on which the model is based (Kristensen & Jensen 1975).
Top right: The decline in Ea/Ep measured over four weeks on bare loam soil at Kise after a heavy rainfall in 1987 (Riley 1989). Changes in topsoil moisture denoted by ●---●.
Bottom: Changes in topsoil moisture on loam soil in spring 1977-1980 at Kise (Riley 1989). The upper and lower dotted lines indicate values calculated with the model using values of 10 and 18 mm, respectively, equivalent to 14 and 26% of field capacity rather than the stipulated 20%, as a sensitivity test of this parameter. The red circles indicate measured values.

3.3 Yield decline due to delayed sowing

The decline in yield potential due to delayed sowing is estimated using a function derived by Ekeberg (1987) on the basis of a large number of trials in which the sowing time of spring cereals was studied in Norway in the period 1964-1986 (Fig. 3.2). The curve shows that the yield decline per day of delayed sowing is considerably greater in late May than in late April. This is because late sowing is commonly associated with greater moisture deficits during early growth and lower solar radiation later in the growing season (in SE Norway there is 20% lower incoming global radiation in the 100 days between 19th June and 26th Sept. than between 5th May and 17th Aug.). Delayed harvesting of late sown crops due to wet autumn weather may also cause further loss of yield (Hoel & Abrahamsen 2013). The average date of first sowings compared in this figure was 24th April, but a starting date of 20th April may be assumed to be more relevant in Norway today.

It is assumed that there is no direct benefit of sowing times earlier than around 20th April, as soil temperatures at that time are normally low, resulting in slow germination. Such early sowing may nevertheless be beneficial if it allows farmers to achieve an earlier average sowing time on the whole farm area. Extrapolation of the curve to a sowing delay of 65 days after 20th April suggests that complete crop failure will occur when sowing is delayed until almost the end of June.

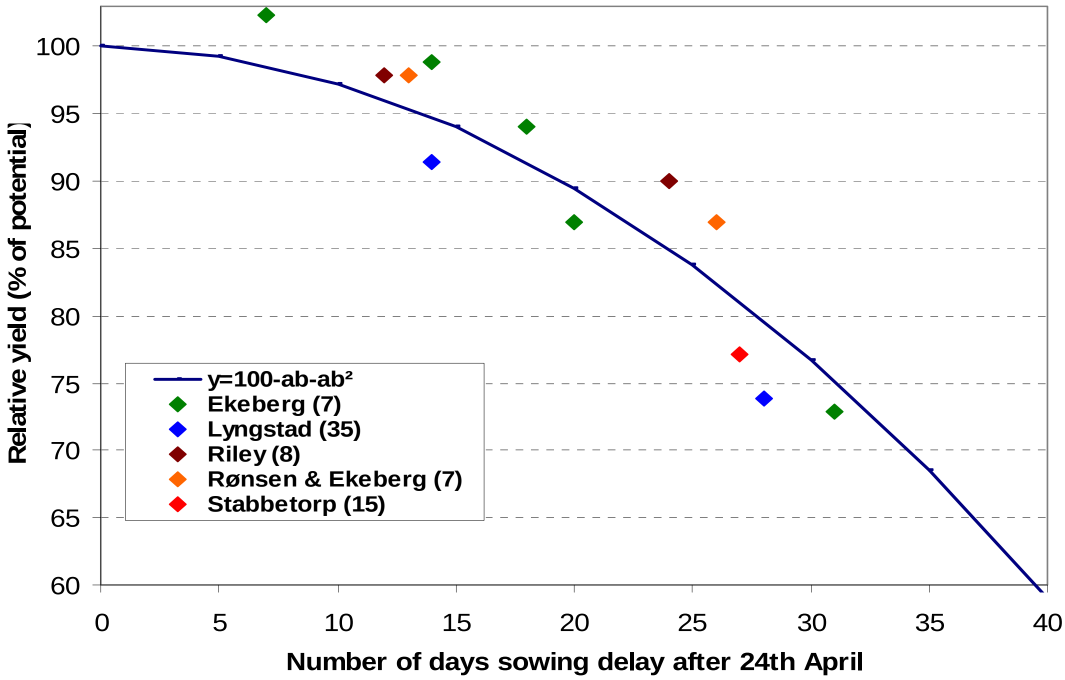


Fig. 3.2. Relative grain yield (% of maximum) expected with delayed sowing of spring cereals in Norway. The curve $y=100-ab-ab^2$ was proposed by Ekeberg (1987) with a=0.025 and b=no. days delay. Points are mean measured values reported by various researchers (no. of trials in brackets). Sources: Ekeberg (1987), Lyngstad (1973), Riley (1985), Rønsen & Ekeberg (1979), Stabbetorp (1980).

Similar curves for yield decline as a result of delayed sowing have been proposed in Sweden by R. Mattson (cited by Ekeberg, 1990) and in England by Smith (1972), both on the basis of sowing time trials in spring barley, as well as by Nafziger (2008) on the basis of maize trials in Illinois, USA. These are compared with the Norwegian yield decline curve in Fig. 3.3. There was close agreement between the Swedish and the Norwegian curves. Ekeberg (1990) showed very similar results also from Finland.

Under English conditions, Smith's model assumed there to be no yield decline when sowing occurred before 15th March, and he assumed complete failure to occur when sowing was delayed beyond 15th May. The slope of his curve was slightly less steep than the Norwegian one. This would seem plausible as the cereal growing season in England is considerably longer than in Norway.

Nafziger's curve showed only a very light decline in yields for maize crops sown before mid-April, but increasingly large declines for crops sown later than that date. The steepness of the declines with length of delay was in this case lower than that shown by the Norwegian trials, but again this may be accounted for by longer and warmer growing seasons in USA than in Norway. Nafziger gave no indication of the sowing time after which complete failure may be expected, but the length of time suggested by Smith for English conditions (60 days delay after 15th March) corresponds well with the suggestion made for Norwegian conditions (ca. 60 days after 20th April). Although crops may develop after such late sowing, the risk of not being able to harvest them is very high.

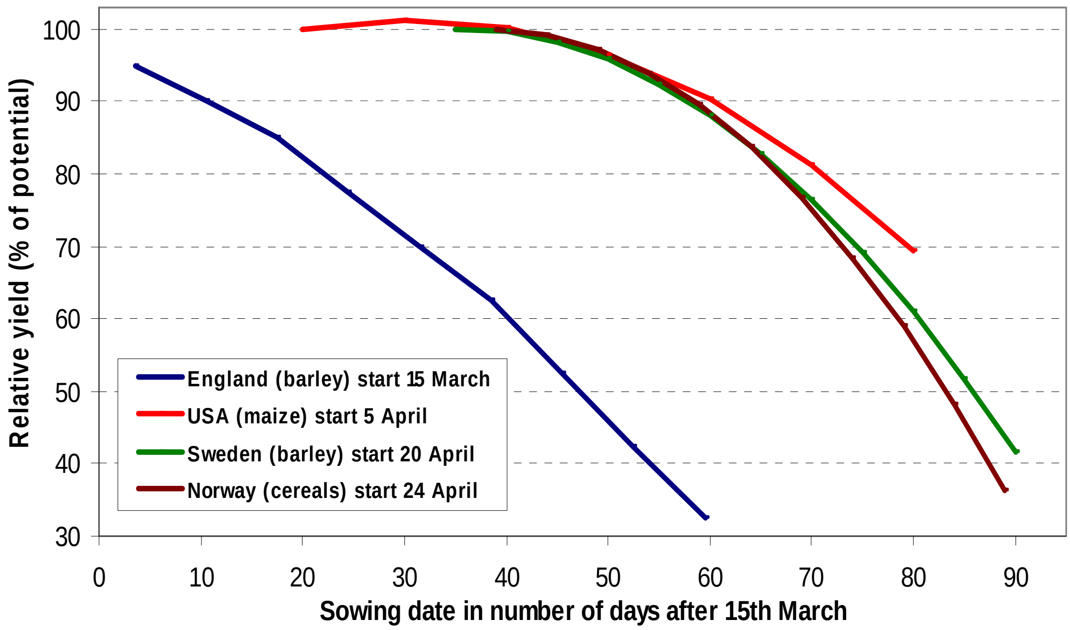


Fig. 3.3. Comparison of the Norwegian curve for yield decline as a result of delayed sowing with curves based on sowing time trials in spring barley in Sweden and England and maize in USA.

Further support for the use of the Norwegian yield decline curve with delayed sowing was found in the results of a 10-year experiment on silty clay soil in SE Norway, in which the effect of drain spacing from 4 m to 32 m on soil trafficability in spring was studied (Hove 1986). Cereals were sown on the first day on which an adequate soil bearing capacity was reached. Table 3.1 shows the mean effect of the resulting delays in sowing on measured yields, compared with predictions calculated from the curve in Fig. 3.1. The latter actually suggest slightly lower yield declines than those observed, possibly due to yield limitation caused by other factors related to poor drainage status. Nevertheless, the results confirm that the proposed curve probably does not overestimate the likely losses that may be incurred due to delayed sowing under Norwegian conditions.

Table 3.1. Measured relative cereal yields (mean of 1976-1985, % of closest drain spacing) with different drain spacings and their resulting mean sowing dates (Hove 1986), compared with values by the Norwegian yield decline curve (Ekeberg 1987)

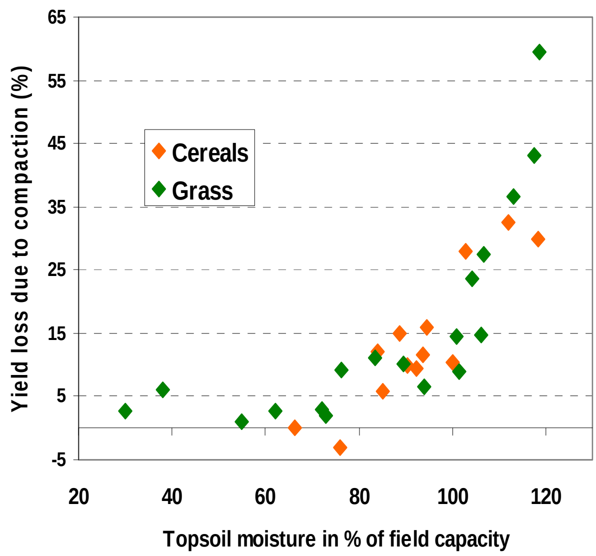
Drain spacing	Mean sowing date	Measured yield	Predicted by curve
4 m	30th April	100	97
8 m	7th May	91	92
16 m	14th May	80	85
32 m	21st May	66	75

3.4 Yield decline due to topsoil compaction

The effect of soil compaction on yield potential due to secondary tillage (harrowing etc.) of ploughed soil under suboptimal (= too moist) conditions is estimated on the basis of results obtained in some Norwegian trials with tractor wheeling in spring cereals (Marti 1983; Riley 1983) and on grassland (Rivedal et al. 2014). These data were obtained from trials on a wide range of soils, including clay loam, loam, silt and sand.

The cereal trials were performed with tractor wheeling over the whole soil surface before subsequent harrowing and sowing, in order to simulate the amount wheeling experienced with spring tillage. For Nordic conditions, this was estimated to represent 200-300 % surface cover by Håkansson (2000). In practice, the distribution of wheeling may be uneven, but the function used is nevertheless thought to be fairly representative of the average traffic intensity including all field operations in spring.

The percentage yield losses found at various topsoil moisture contents, expressed as % of FC, are shown in Fig. 3.4. This shows that wheeling in soil moister than FC gives a large loss of potential yield (>20%). Losses decline to 10% at 90% FC, 4% at 80% FC and 0% at 70% FC. As tillage in spring normally starts before soil drying reaches values below 80% of FC, this implies that some loss of yield potential due to tractor traffic will nearly always occur.



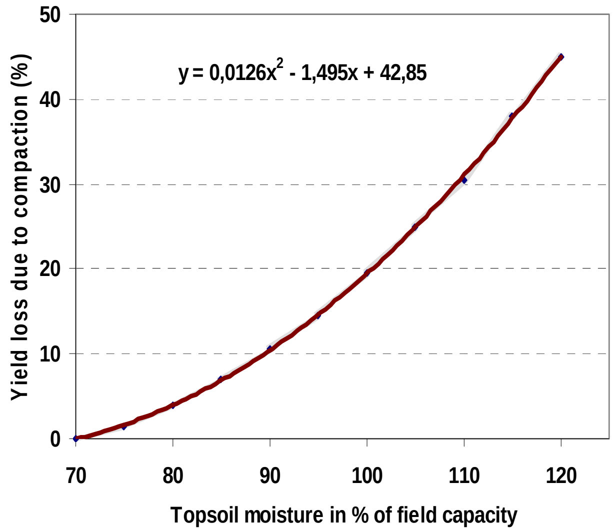


Fig. 3.4. Yield losses found in compaction trials after tractor wheeling on soil with varying moisture content. The left-hand figure shows measured losses relative to topsoil moisture (% of FC) at the time of wheeling. To the right is the function used in model calculations.

3.5 Combined factor for sowing delay and soil compaction

The functions for sowing delay and soil compaction are combined in a multiplicative factor for the potential yield obtainable when spring fieldwork is performed on particular dates and soil moisture contents (i.e. % of pot. yield = (100-%delay loss)*(100-%compaction loss)/ 100).

This simplification ignores the fact that in practice tillage and sowing may occur on different days. However, such time intervals are assumed normally to be short. Examples of combined losses are shown in Table 3.2. This model thus implies that a certain yield reduction due to tilling under moist soil conditions may in some case be preferable to the loss which would be incurred by delaying sowing until conditions are more favourable, especialy when sowing is delayed towards the end of May. How often this situation occcurs in practice will vary between years and between soil types.

Table 3.2. The percentage of potential yield that is obtained with various combinations of sowing date and topsoil moisture content expresed as percentages of field capacity

Moisture/Date	< 21st April	30th April	14th May	30th May
95 % of FC	85	83	73	50
90 % of FC	90	87	76	53
85 % of FC	93	91	79	55
80 % of FC	96	93	82	57
75 % of FC	98	96	84	58
70 % of FC	100	97	85	59

4 Results

4.1 Weather conditions

Mean weekly values for the weather variables used are shown in Table 4.1. At Kise (Eastern region, north of Oslo) snow normally lies until mid-late April, and mean temperatures are below zero until the end of March. In the other regions temperatures are normally above zero from mid-March, and the snow cover disappears somewhat earlier. The temperature level for most of the spring period is highest at Ås (Eastern region, south of Oslo) and lowest until late May at Kise (Eastern region, north of Oslo), with about 1-2° C difference between these two regions. The rainfall during the whole period is highest (219 mm) at Kvithamar (Central region, Trøndelag), lowest at Kise (156 mm) and intermediate (197 mm) at Ås.

In this study, potential evaporation (Ep) was set to zero until snow disappeared and on days with temperature <0° C. In April mean Ep was <1 mm/day at Kise and at Kvithamar, and around 1 mm/day at Ås). In May the mean Ep was ca. 2.8 mm/day at Ås, 2.2 mm/day at Kise and 2.0 mm/day at Kvithamar. In June the corresponding figures were 3.3, 2.6 and 2.4 mm/day. Actual evaporation (Ea), calculated for loam soil, was found on average to be 56% of Ep at Ås, 61% of Ep at Kise and 74% of Ep at Kvithamar. The differences between regions in the Ea/Ep ratio reflect the higher temperature at Ås than at Kise which gives most rapid soil drying, whilst at Kvithamar both lower temperature and higher rainfall give slower soil drying. Rapid drying leads to a rapid decline in the Ea/Ep ratio, and vice-versa.

4.2 Soil moisture

The mean topsoil moisture, calculated daily for four texture groups, is shown in Fig. 4.1. In all regions, except on very light soil, average soil moisture remains above 90% of FC in most of April. Drying speeds up in early May, and differences between regions start to become more marked. Drying is most rapid in the southernmost region, and slowest in the central region of Norway. In the eastern regions, it remains on average around 80% of FC on most soils throughout the month of May, and only approaches the 'zero compaction' level of 70% on very light soil in the southernmost region. In the regions north of Oslo it remains on average around 75% of FC even on light soil. In the central region, most soils are on average moister than 85% of FC in most of May, whilst very light soil is on average slightly moister than 80% of FC.

Mean values mask, however, the considerable variation that occurs between years, due to variation between years in the earliness/lateness of the spring and in the amount of rainfall that occurs in this period, as shown for loam soil in Fig.4.2. This indicates that in the eastern regions, soil moisture values are most frequently within the range 85-100% of FC in April, but that the range increases somewhat in May, to 75-95% of FC. In the central region, the corresponding ranges are 90-100% in April and 80-95% in May. In June, the lower range extends to ca. 65% and 70% in the eastern regions south and north of Oslo, whilst in the central region the soil moisture content is seldom below 80% of FC.

Table 4.1. Mean weekly weather 1973-2012 at three weather stations during the spring period

	Dates	Snow (cm)	Air temp. °C	Rain mm	Ep mm/day	Ea mm/day
ÅS	16.3 - 22.3	7.6	0	11.5	0.1	0.1
(Eastern	23.3 - 29.3	5.2	1.3	12.4	0.2	0.1
region,	30.3 - 5.4	3.3	2.7	15.1	0.6	0.5
to south	6.4 - 12.4	1.4	3.3	10.8	0.9	0.7
of Oslo)	13.4 - 19.4	0.3	4.8	9.3	1.3	0.8
	20.4 - 26.4	0	6.1	8	1.3	0.8
	27.4 - 3.5	0	7.7	14.2	1.8	1.2
	4.5 - 10.5	0	9.4	10.3	2.6	1.5
	11.5 - 17.5	0	10.2	11	2.7	1.3
	18.5 - 24.5	0	11.4	12.4	2.9	1.5
	25.5 - 31.5	0	12.3	16.1	2.9	1.6
	1.6 - 7.6	0	13.6	12.5	3.3	1.6
	8.6 - 14.6	0	13.9	17	3.3	1.9
	15.6 - 21.6	0	14.4	15.5	3.3	1.7
	22.6 - 28.6	0	15.1	20.8	3.3	1.8
KISE	16.3 - 22.3	26	-1.9	5.8	0	0
(Eastern	23.3 - 29.3	22.4	-0.3	5.2	0	0
region,	30.3 - 5.4	17.7	1.2	8	0.2	0.2
to north	6.4 - 12.4	12.6	1.9	7.5	0.4	0.3
of Oslo)	13.4 - 19.4	6.7	3.3	7.1	0.7	0.5
	20.4 - 26.4	2.3	4.6	5.8	0.8	0.6
	27.4 - 3.5	0.6	6.1	11.3	1.2	0.9
	4.5 - 10.5	0.1	7.7	7.2	2	1.3
	11.5 - 17.5	0	8.8	9.4	2.1	1.2
	18.5 - 24.5	0	10	10.2	2.1	1.2
	25.5 - 31.5	0	11	15.1	2.3	1.3
	1.6 - 7.6	0	12.7	11.8	2.6	1.5
	8.6 - 14.6	0	13.2	16.9	2.6	1.6
	15.6 - 21.6	0	13.6	15.2	2.8	1.6
	22.6 - 28.6	0	14.3	18.5	2.6	1.5
KVITHAMAR	16.3 - 22.3	5.5	0.7	16	0	0
(Central	23.3 - 29.3	4.2	1.7	13.3	0	0
region,	30.3 - 5.4	1.6	2.9	13.6	0.4	0.4
Trøndelag)	6.4 - 12.4	0.6	3.3	14.9	0.6	0.5
	13.4 - 19.4	0.2	4.2	15	0.8	0.7
	20.4 - 26.4	0.1	5.8	10.3	0.9	0.8
	27.4 - 3.5	0	6.7	13.1	1.4	1.1
	4.5 - 10.5	0	8.1	10.6	1.9	1.3
	11.5 - 17.5	0	8.8	13	2	1.4
	18.5 - 24.5	0	10.4	15.2	2.1	1.5
	25.5 - 31.5	0	10.5	14.2	2	1.5
	1.6 - 7.6	0	11.8	14	2.4	1.7
	8.6 - 14.6	0	12	20.9	2.4	1.7
	15.6 - 21.6	0	12.3	19.8	2.3	1.8
	22.6 - 28.6	0	13.1	15.5	2.3	1.7

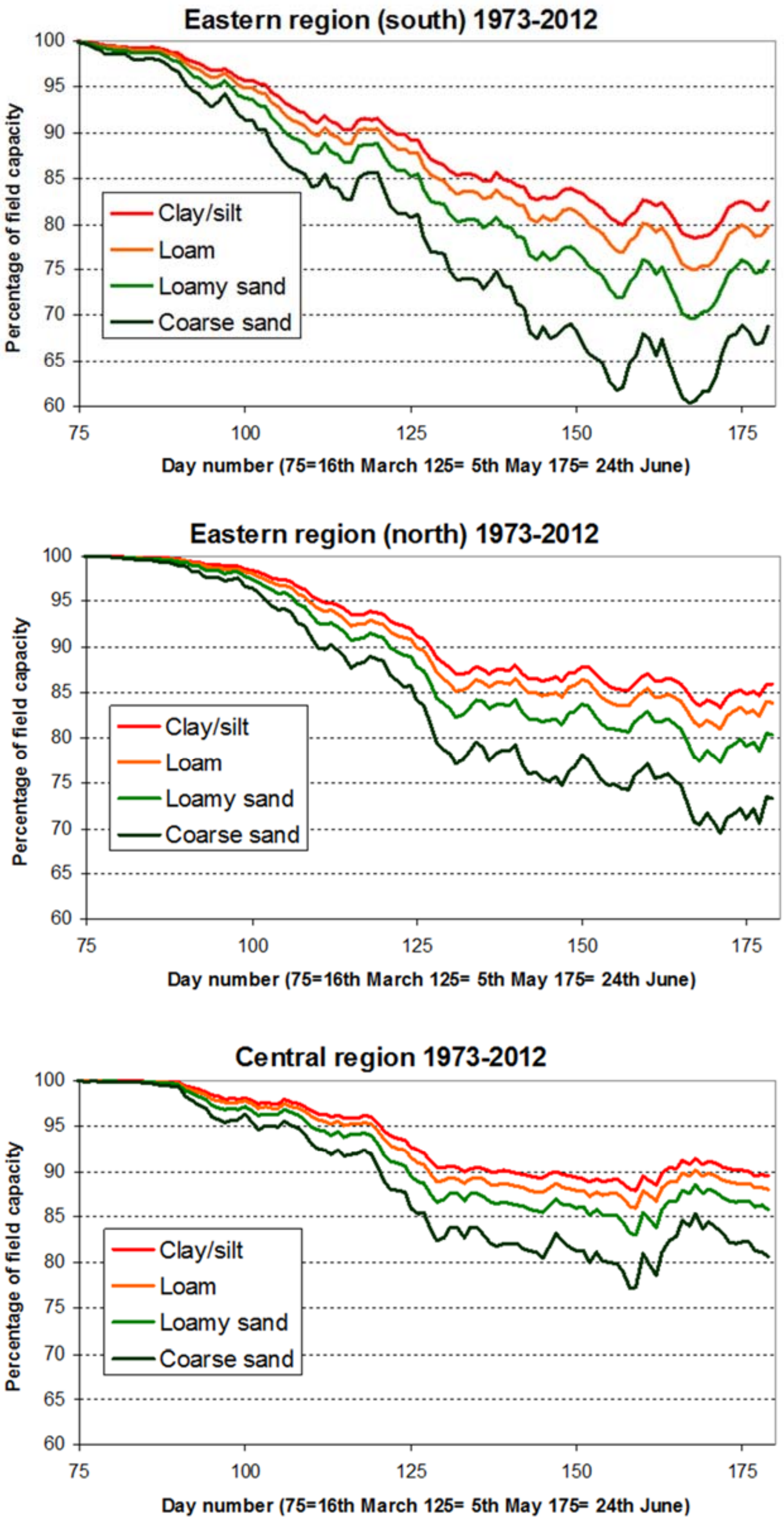


Fig. 4.1 Mean topsoil moisture in three regions, calculated as percentages of FC.

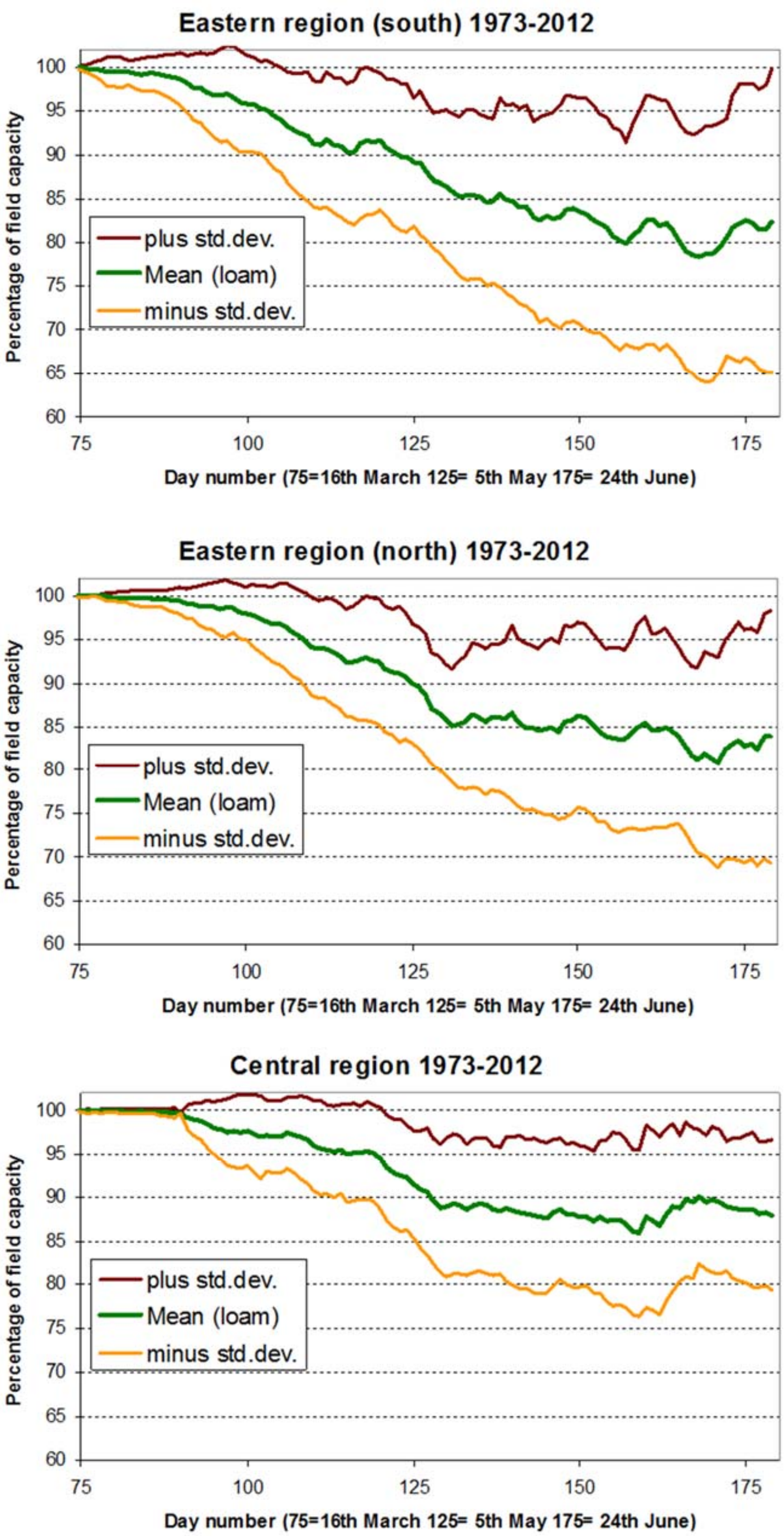


Fig. 4.2. Mean % of field capacity in loam topsoil, plus and minus 1 standard deviation.

Fig. 4.3 shows the percentage of years in which topsoil moisture is lower than the thresholds <95%, <85% and <75% of FC in each region for each type of soil. The proportion of years when soil moisture is <95% of FC at the end of April is around 70-80% in the region south of Oslo, 60-70% in that north of Oslo and 50-60% in the central region. In all cases it is lowest, as expected, on clay/silt and highest on coarse sand.

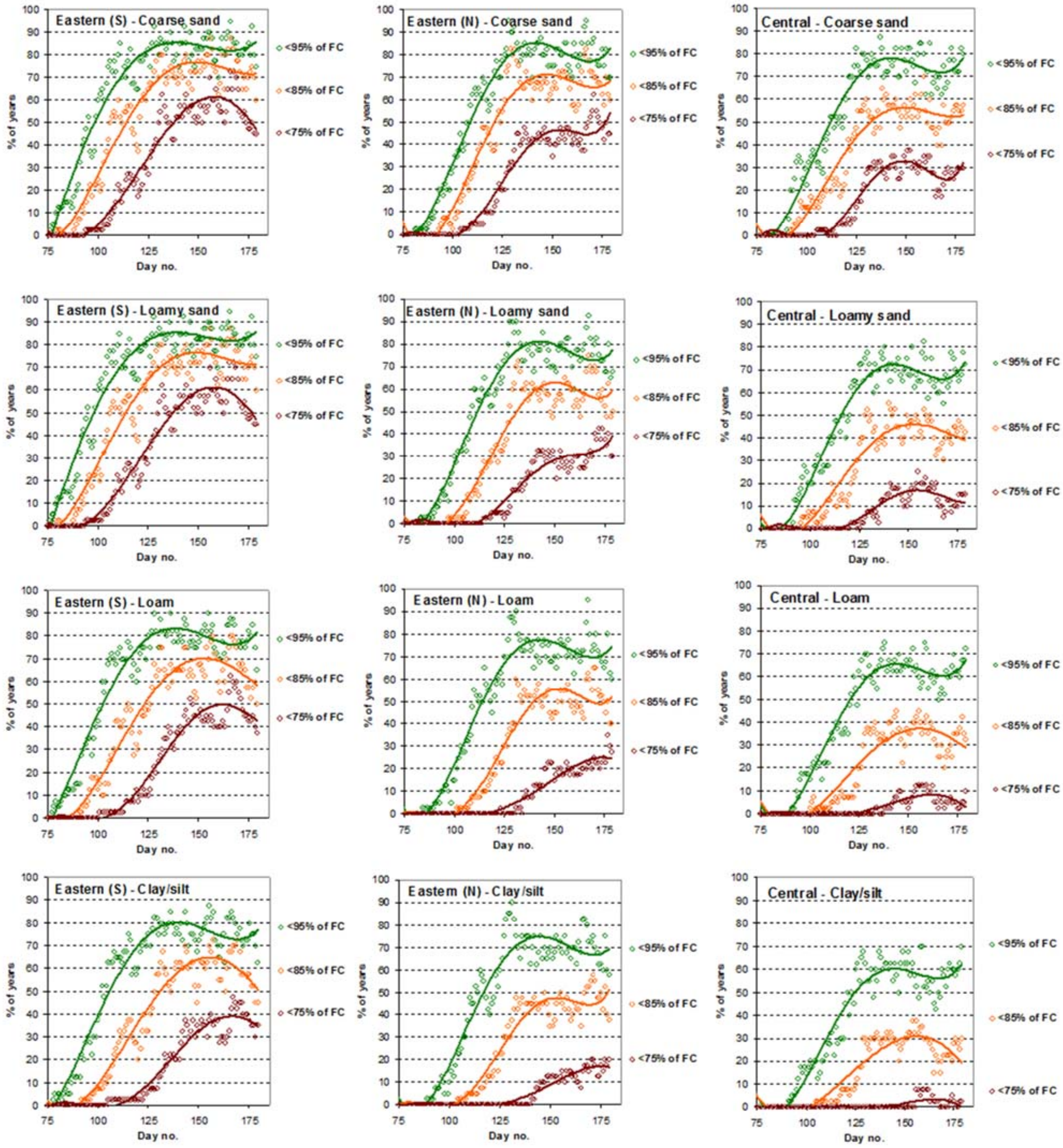


Fig. 4.3. The percentage of years (1973-2012) in which topsoil moisture is lower than three selected criteria (95%, 85% and 75% of FC) on soils with different texture in three regions.

Differences between soil textures become more pronounced in the proportion of years with lower moisture contents. In the region to the north of Oslo, for example, the percentage of years with moisture <85% of FC in mid-late May is around 70% on coarse sand, but it declines to 60% on loamy sand, 50% on loam and 45% on clay/silt. The corresponding percentages of years with soil moisture <75% of FC in this region are ca. 40% on coarse sand, 25% on loamy sand, 10% on loam and <5% on clay/silt.

There appears to be relatively little difference between the loam and the clay/silt groups when soil moisture is expressed as percentage of field capacity, whilst coarse sand exhibits a large difference. When comparing regions, the soil types that dominate in each region should be taken into account. Clay soils dominate in most cereal-growing areas in the eastern region south of Oslo, whilst loams dominate in the region north of Oslo, together with silt and loamy sand. All soil groups are present in the central region, but clay loams dominate there also. Differences in soil type affect the actual starting time for tillage in each region. There is thus often little difference between the two eastern regions in the starting time for spring tillage, as loam soils become tillable more rapidly than clays.

4.3 Number of trafficable days

The mean numbers of days when soil moisture is below various percentages of FC thresholds are shown in Table 4.2 for the four soil texture classes. It is considered that ploughing may normally be performed with relatively little compaction damage when it is performed at soil moisture contents of 95-100% of FC, provided suitable wheel equipment and tyre inflation pressures are used. Secondary tillage (soil levelling and harrowing) is commonly performed at moisture contents of 85-95% of FC, whilst for operations such as sowing and rolling, a moisture content of around 85% of FC is normal. To completely avoid any yield decline due to compaction, tillage should be performed when the soil has dried to 70% of FC, though in practice this level of drying may rarely be reached during the spring period.

There are very few years in any region in which the soil is tillable in March, and then only for very few days. If we assume that secondary tillage starts at around 90% of FC, we see that in April coarse sand may on average be tilled on 15 days in the eastern region south of Oslo, on 10 days in that north of Oslo and on 7 days in the central region. At the other extreme, on clay and silt soils, the corresponding numbers of days are only 7, 3 and 2. In that month only the lighter soils become dry enough for sowing (<85% of FC), and then only on relatively few days.

All soils are on average dry enough for secondary tillage much more frequently in May, with a range of around 60-80% of all days in the southernmost region, depending on soil type, and corresponding ranges of 55-65% and 45-65% of all days to the north of Oslo and Trøndelag. The mean proportions of days suitable for sowing are considerably lower (ca. 35-45% on heavy soil and 65-70% on very light soil in the eastern regions and 25%-50% in the central region). The number of trafficable days in June is in most cases only slightly lower than in May.

Table 4.2. Calculated mean number of days 1973-2012 when topsoil moisture content is below various percentages of field capacity (% of FC) in the period 16th March – 28th June in the three main cereal-growing regions of Norway

	Eastern region (south of Oslo)					Eastern region (north of Oslo)					Central region (Trøndelag)				
	Mar	Apr	May	Jun	Total	Mar	Apr	May	Jun	Total	Mar	Apr	May	Jun	Total
% of FC															
Clay/silt (FC = 90 mm)															
<95%	0.6	13.5	22.2	20.2	56.5	0.1	8.4	21.5	19.4	49.3	0.0	6.1	18.1	15.8	40.0
<90%	0.0	7.4	18.7	17.8	43.9	0.0	3.3	17.0	16.4	36.6	0.0	2.3	12.7	11.9	26.9
<85%	0.0	3.6	14.6	15.3	33.5	0.0	1.0	11.6	12.8	25.3	0.0	0.5	7.6	7.5	15.6
<80%	0.0	0.8	9.1	12.0	21.8	0.0	0.2	5.4	8.1	13.6	0.0	0.0	2.4	3.3	5.7
<75%	0.0	0.2	3.6	7.5	11.2	0.0	0.0	1.1	4.0	5.1	0.0	0.0	0.0	0.8	0.8
<70%	0.0	0.0	1.1	4.4	5.4	0.0	0.0	0.1	1.9	2.0	0.0	0.0	0.0	0.0	0.0
Loam (FC = 70 mm)															
<95%	1.0	15.0	23.5	21.1	60.5	0.2	9.8	22.6	20.2	52.8	0.0	7.4	19.8	17.2	44.3
<90%	0.1	9.4	20.5	18.9	48.9	0.0	4.7	18.7	17.4	40.9	0.0	3.6	14.8	13.3	31.7
<85%	0.0	5.1	16.7	16.9	38.6	0.0	1.6	14.0	14.4	29.9	0.0	1.1	9.8	9.5	20.3
<80%	0.0	1.8	11.8	14.1	27.7	0.0	0.5	8.1	10.1	18.7	0.0	0.1	4.6	5.4	10.0
<75%	0.0	0.4	6.3	10.2	16.9	0.0	0.0	2.6	6.0	8.6	0.0	0.0	0.8	2.1	2.9
<70%	0.0	0.0	2.7	7.0	9.7	0.0	0.0	0.6	3.3	3.9	0.0	0.0	0.0	0.7	0.7
Loamy sand (FC = 50 mm)															
<95%	1.4	16.7	24.7	22.0	64.8	0.3	11.2	23.6	21.2	56.3	0.0	9.3	21.7	18.9	49.8
<90%	0.4	11.7	22.1	20.4	54.6	0.0	6.7	21.0	18.9	46.6	0.0	5.0	17.0	15.5	37.5
<85%	0.0	7.4	19.1	18.5	44.9	0.0	3.2	16.7	16.4	36.3	0.0	2.3	13.1	11.8	27.2
<80%	0.0	3.5	15.0	16.1	34.6	0.0	1.1	11.7	12.9	25.6	0.0	0.5	7.7	7.9	16.1
<75%	0.0	0.9	10.0	12.9	23.8	0.0	0.2	6.0	8.7	14.9	0.0	0.0	3.0	4.2	7.2
<70%	0.0	0.4	6.1	10.2	16.6	0.0	0.0	2.6	5.6	8.1	0.0	0.0	0.8	2.1	2.9
Coarse sand (FC = 30 mm)															
<95%	2.0	18.9	25.6	23.3	69.8	0.4	13.0	25.0	22.3	60.7	0.0	11.3	23.6	20.5	55.4
<90%	1.0	14.7	24.0	22.1	61.7	0.3	9.5	22.9	20.5	53.1	0.0	7.3	20.3	17.8	45.4
<85%	0.3	11.1	21.9	20.8	54.0	0.0	6.3	20.4	18.8	45.6	0.0	4.7	16.6	14.9	36.1
<80%	0.0	6.8	18.8	18.6	44.2	0.0	2.9	16.3	16.3	35.5	0.0	1.9	12.5	11.4	25.8
<75%	0.0	3.3	14.7	16.0	34.0	0.0	1.0	11.3	12.9	25.2	0.0	0.5	8.0	7.8	16.2
<70%	0.0	1.6	11.1	13.7	26.4	0.0	0.4	8.1	9.9	18.4	0.0	0.1	4.4	5.6	10.1

Another way of studying the annual variation in soil trafficability is by summing the number of days above various threshold values at different times of the spring and early summer seasons. Figs. 4.4-4.6 show the annual variation in the number of days when topsoil moisture is lower than the thresholds of <95% and <85% of FC in each region for the soils with the highest and lowest moisture-holding capacities, respectively. Results for <75% of FC are not shown in these figures, because the number of days at this level is normally very low. The 15-week period considered here is divided into three equal periods, of which the first two are of most interest in cereals, as yields declined sharply when sowing takes place in the last period:

Early spring: Julian day number 75-109 (16th March–19th April)
Spring: Julian day number 110-144 (20th April–24th May)
Early summer: Julian day number 145-179 (25th May–28th June)

It is difficult to discern any marked trend over time in the number of trafficable days in any of the regions. In the eastern regions, there were fewest trafficable days during the first two periods in the years 1977, 1983, 1986-87, 1998-2001, 2006, 2010 and 2012. In the central region there have been several years with few trafficable days in all four decades. Since 2012, we have experienced a year (2013) with very low trafficability, a year (2014) with very high trafficability and a year (2015) with dry conditions in early spring followed by wet weather in May.

Table 4.3 shows the frequency distribution in the total number of days with soil moisture below the three % of FC thresholds in the first period and in first and second periods combined, grouped in various numbers of days. This highlights clear differences between regions as well as between soils. In the period up to 19th April, there were fewer than 6 days with moisture below 95% of FC in at least half of all years on coarse sand and three-quarters of years on clay/silt both in the eastern region north of Oslo and in Trøndelag. In the southern region, by contrast, corresponding figures were only 10% and 43%. There was rather less difference between regions in values <85% of FC.

The total number of days with soil moisture <95% of FC up to 25th May was on coarse sand normally more than 25 in the southern region and more than 15 in the other regions, whilst on clay/silt soils it was naturally less. On coarse sand, the total number of days with moisture below 85% of FC was 15 days or less in 8%, 33% and 42% of all years in eastern (south), eastern (north) and central regions, respectively. Corresponding data for clay/silt were 63%, 77% and 90%. With respect to moisture below 75% of FC, the number of days was less than 6 in almost all years on clay/silt soils, and in 20-50% of years on coarse sand.

In summary, it seems likely that the number of days with soil moisture <85% of FC are too few for farmers to postpone the start of spring tillage until such conditions occur. A starting point when soil is at 90% of FC is a likely compromise, roughly in accordance with the point at which the upper soil layer becomes friable. Most farmers aim to finish sowing by the end of May at the latest. The average number of days with such conditions, and the associated standard deviations, are shown in Table 4.4. It may be noted that the variation between regions within the same soil type is similar to the variation between soil types within the same region. The between-year coefficients of variation range from 20-30% on sandy soil to 40-60% on clay/silt soil. This further underlines the fact that the latter soils are more demanding than lighter soils with regard to their ease of tillage.

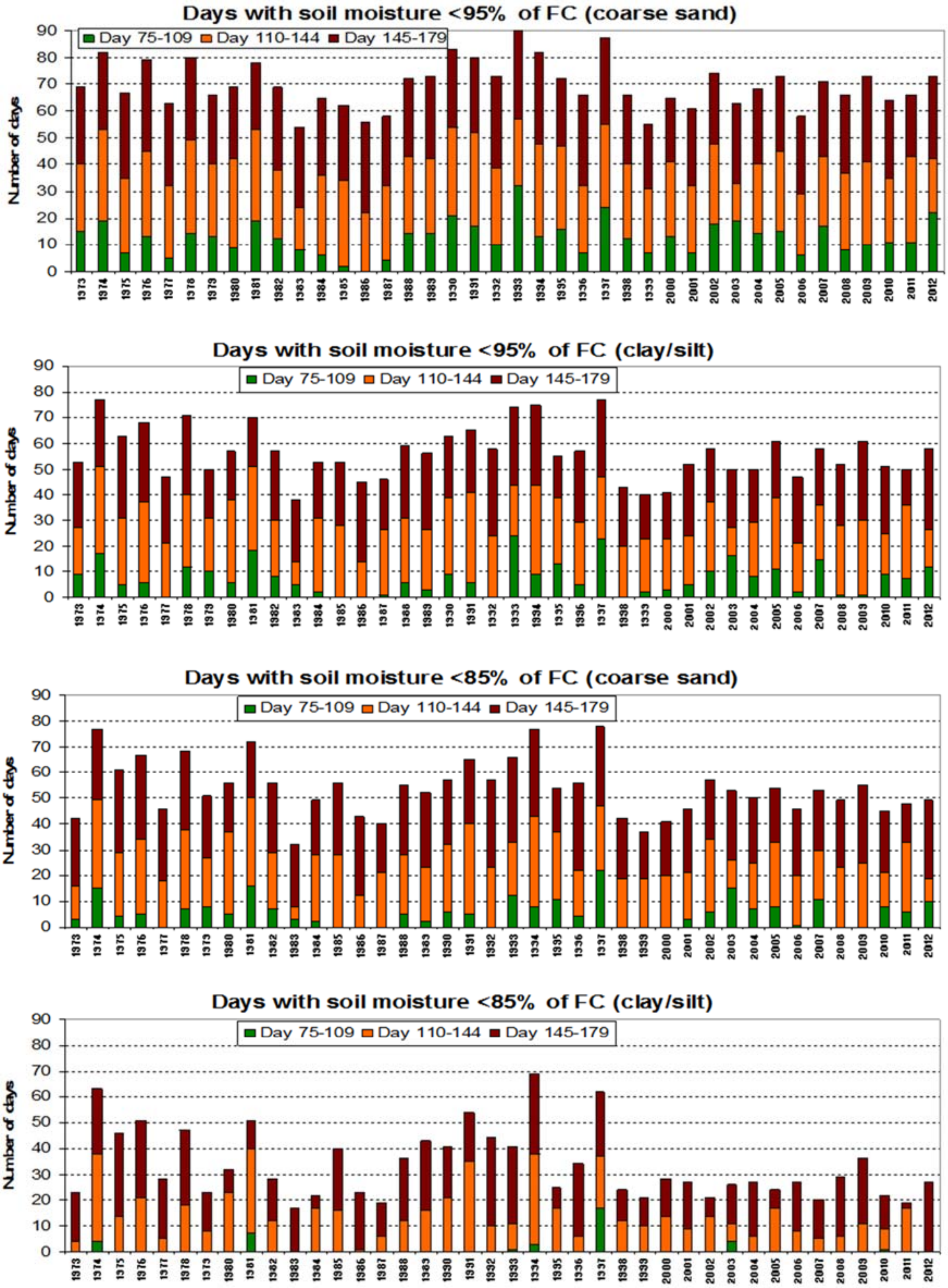


Fig. 4.4. The number of days when topsoil moisture in coarse sand and clay/silt in the Eastern region (south of Oslo) is below two thresholds (95% and 85% of FC) in early spring (day 75-109 = 16th March – 19th April), the normal sowing period (day 110-144 = 20th April–24th May) and the late sowing period (day 145-179 = 25th May–28th June).

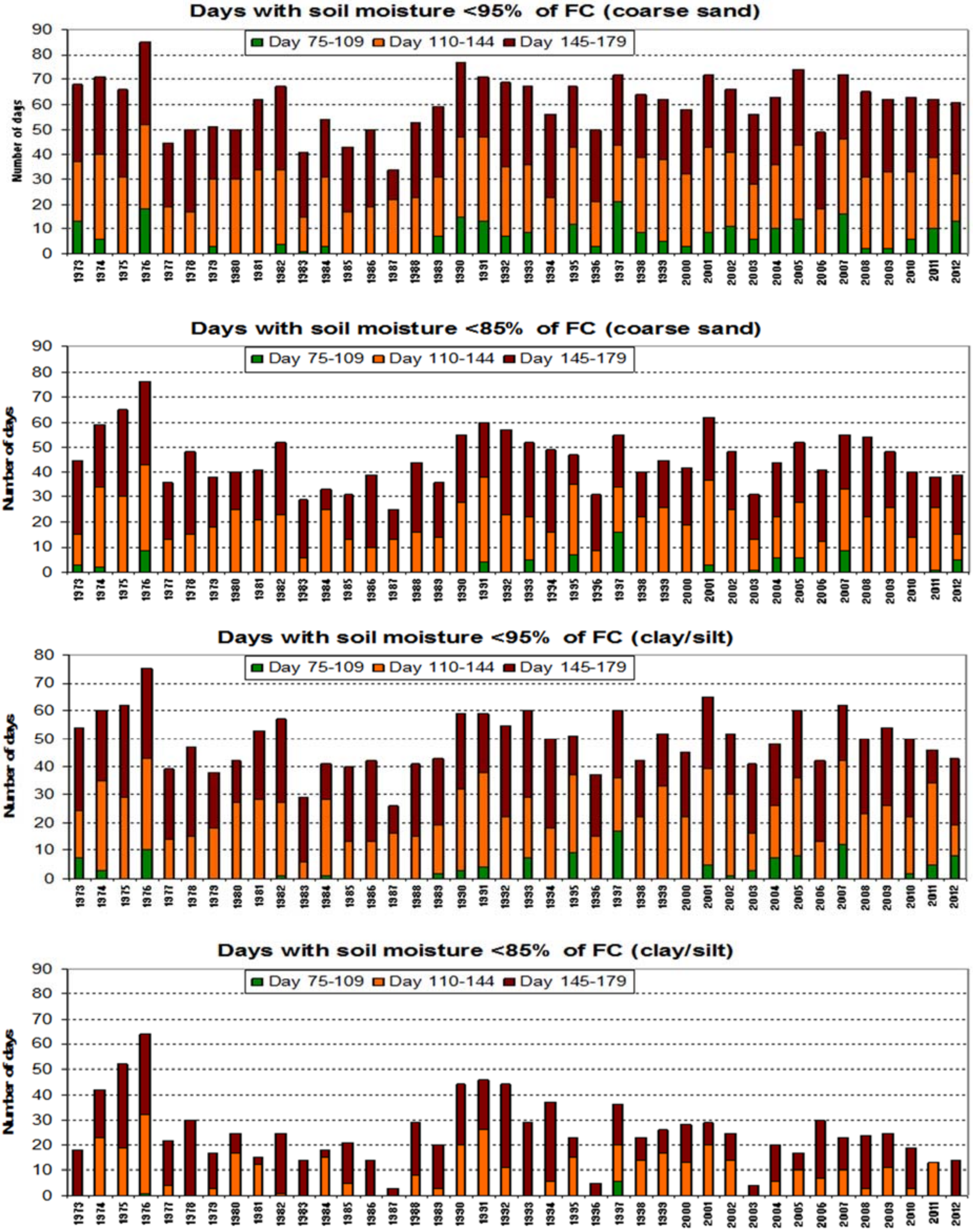


Fig. 4.5. The number of days when topsoil moisture in coarse sand and clay/silt in the Eastern region (north of Oslo) is below two thresholds (95% and 85% of FC) in early spring (day 75-109 = 16th March – 19th April), the normal sowing period (day 110-144 = 20th April–24th May) and the late sowing period (day 145-179 = 25th May–28th June).

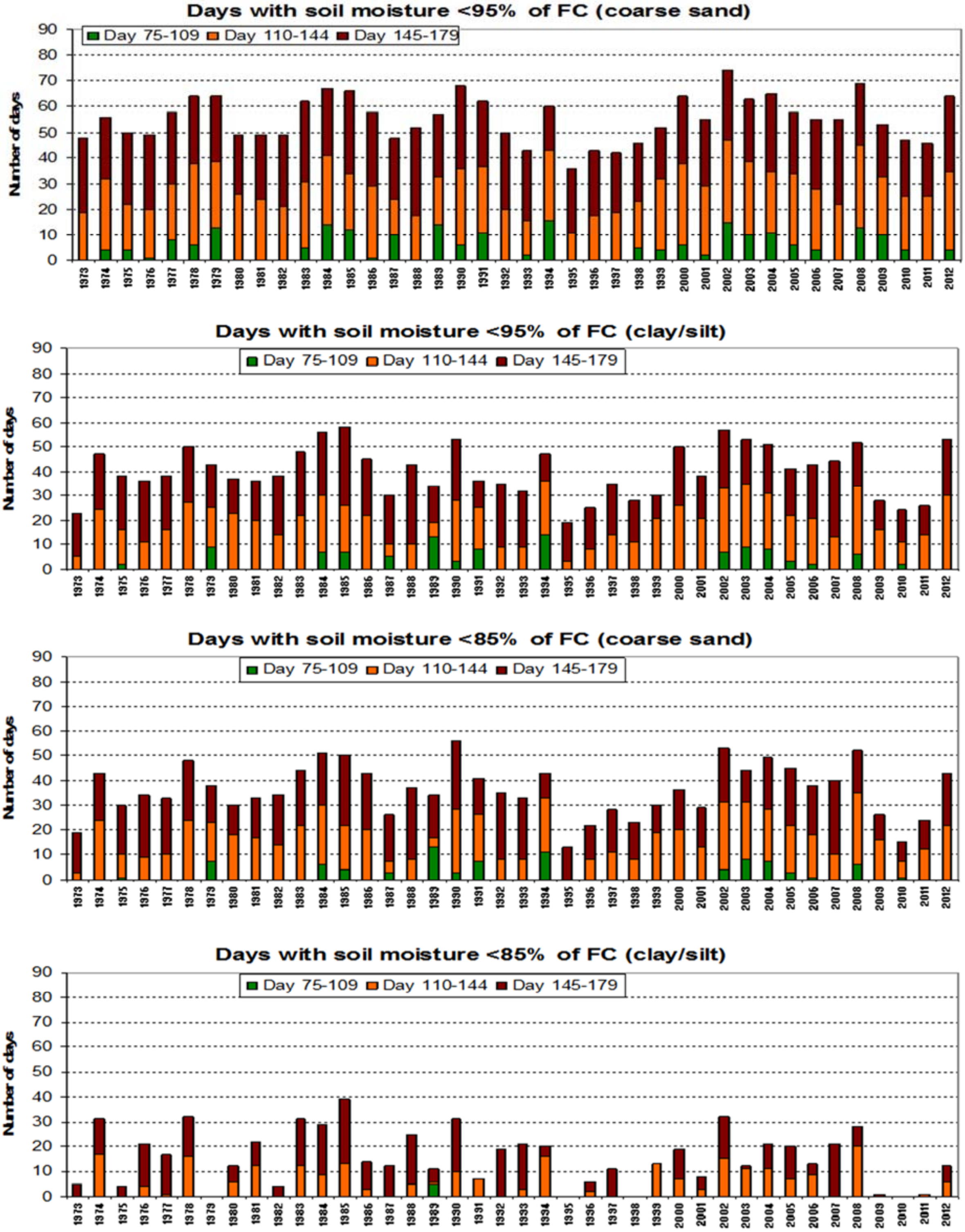


Fig. 4.6. The number of days when topsoil moisture in coarse sand and clay/silt in the Central region (Trøndelag) is below two thresholds (95% and 85% of FC) in early spring (day 75-109 = 16th March – 19th April), the normal sowing period (day 110-144 = 20th April–24th May) and the late sowing period (day 145-179 = 25th May–28th June).

Table 4.3. Percentage frequency distributions in three regions of the total number of days in various trafficability groupings before day 110 (= 20th April) and up to day 144 (= 24th May)

		Before 20th April			Before 25th May		
EASTERN	**Coarse sand**	**<95%**	**<85%**	**<75%**	**<95%**	**<85%**	**<75%**
(south of Oslo)	< 6 days	10	55	95	0	0	20
	6-15 days	62	40	3	0	8	48
	16-25 days	25	5	3	5	40	20
	> 25 days	3	0	0	95	52	12
	Clay / silt						
	< 6 days	43	94	100	0	15	84
	6-15 days	44	3	0	5	48	13
	16-25 days	13	3	0	20	24	3
	> 25 days	0	0	0	75	3	0
EASTERN	**Coarse sand**						
(north of Oslo)	< 6 days	50	84	97	0	0	43
	6-15 days	42	13	3	3	33	37
	16-25 days	8	3	0	23	35	15
	> 25 days	0	0	0	74	32	5
	Clay / silt						
	< 6 days	77	97	100	0	40	100
	6-15 days	20	3	0	20	37	0
	16-25 days	3	0	0	30	18	0
	> 25 days	0	0	0	50	5	0
CENTRAL	**Coarse sand**						
(Trøndelag)	< 6 days	57	80	97	0	5	52
	6-15 days	40	20	3	3	37	38
	16-25 days	3	0	0	38	38	10
	> 25 days	0	0	0	59	20	0
	Clay / silt						
	< 6 days	75	100	100	5	50	100
	6-15 days	25	0	0	30	40	0
	16-25 days	0	0	0	37	10	0
	> 25 days	0	0	0	28	0	0

Table 4.4. Mean number of days (± std. dev.) in period 16th March to 31st May 1972-2012, when the soil moisture content was below 90% of FC in different soil types and in different regions

	Coarse sand	**Silty sand**	**Loam**	**Clay/silt**
Eastern (S. of Oslo)	40 ± 9	34 ± 10	30 ± 11	26 ± 11
Eastern (N. of Oslo)	33 ± 9	28 ± 9	23 ± 10	20 ± 10
Central (Trøndelag)	28 ± 9	22 ± 9	18 ± 9	15 ± 9

4.4 Yield responses to compaction and sowing delay

The losses of yield potential that may be expected due to delayed sowing relative to those due to possible soil compaction are shown in Fig. 4.7. The loss due to delayed sowing is a fixed function of time, and becomes dominant in late May. The potential loss due to compaction is normally greatest in early spring and declines towards the end of April. The risk of compaction is on average similar throughout May and June, but there is naturally high variability between years during this period.

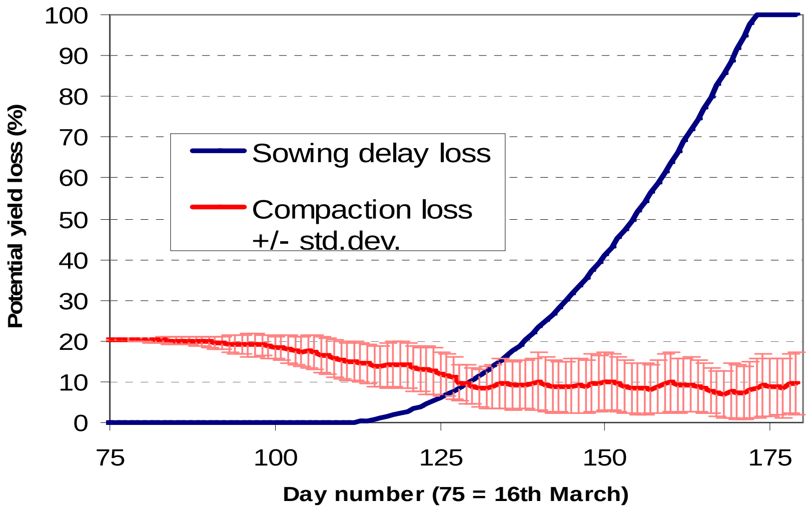


Fig. 4.7. Illustration of the potential yield losses due to delayed sowing and soil compaction, illustrated for loam soil using 1973-2012 weather data for the eastern region north of Oslo.

There is a somewhat lower risk of compaction in the eastern area south of Oslo than in the area to the north of Oslo, especially in April, and a slightly higher risk in the central region (Fig. 4.8).

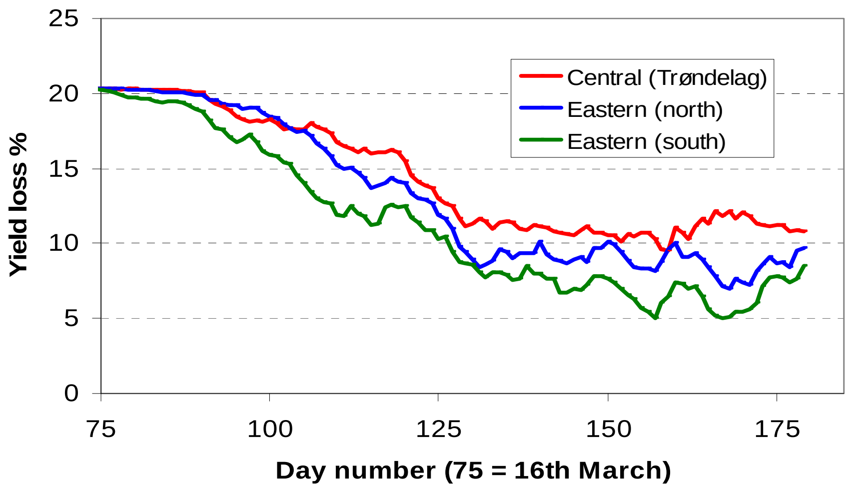


Fig. 4.8. Mean yield losses due to soil compaction when tillage and sowing is performed at different times in three regions, based on loam soil moisture calculated from 1973-2012 data.

There are also differences in compaction risk between soil types, as shown in Fig. 4.9. There is approximately the same difference between soil types with lowest and highest moisture content (coarse sand vs. clay/silt) as between regions with lowest and highest compaction risk.

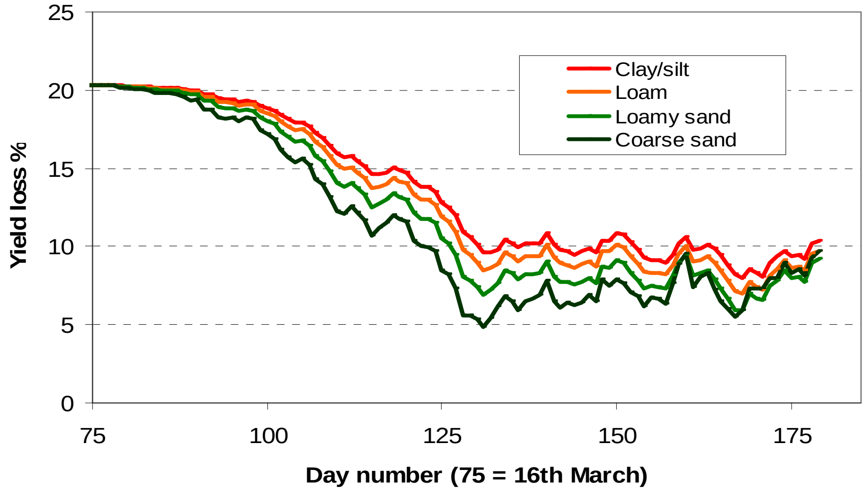


Fig. 4.9. Mean yield losses due to soil compaction when tillage and sowing is performed on different soils, based on soil moisture contents calculated using 1973-2012 weather data for the eastern region north of Oslo.

When the potential yield losses due to both soil compaction risk at different times and sowing delay are combined, it is possible to visualize the optimum time for spring tillage and sowing. This is illustrated in Fig 4.10 for the period of main interest to farmers, i.e. up to ca. 25th May, indicating that the risks of yield losses are lowest from late April to the middle of May.

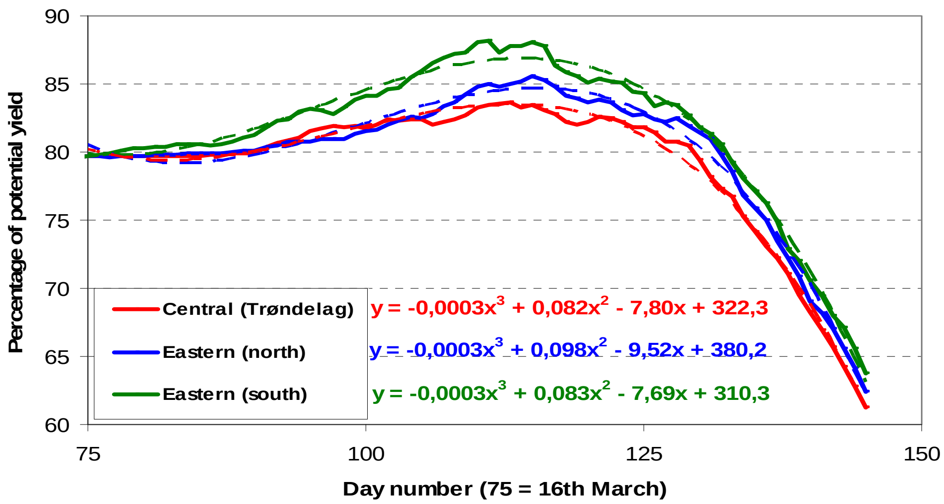


Fig. 4.10. Potential yield losses due to the combined effects of soil compaction risk and delayed sowing in different regions, based on loam soil moisture content calculated from 1973-2012 weather data. The dashed lines refer to the third order polynomials shown.

A similar illustration of the potential yield losses due to compaction risk and sowing delay on different types of soil is given in Fig. 4.11.

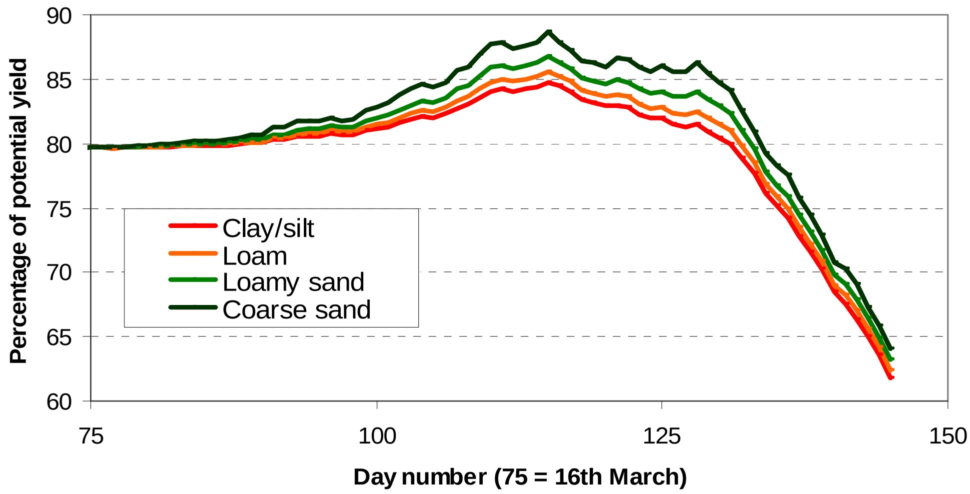


Fig. 4.11. Potential yield losses due to the combined effects of soil compaction risk and delayed sowing on different soils, based on soil moisture content calculated using 1973-2012 weather data for the eastern region north of Oslo.

4.5 Tillable area in relation to work capacity

According to 2014 data from Statistics Norway (SSB), 27% of Norwegian cereal farmers grow cereals on less than 100 daa, 56% have 200-400 daa and 17% have over 400 daa (1 daa=0.1 ha). The mean cereal and oilseed area per farm is 254 daa. We estimate the average total spring-work capacity (i.e. levelling and seedbed harrowing of land either ploughed or deeply harrowed in autumn, followed by sowing and rolling) to lie in the range of 25-100 daa per trafficable day for most cereal growers in Norway. At the lower level we assume the use of a small tractor and implements with working widths of 2.5 – 4 m, whilst at the highest we assume that a very large tractor and implements with working widths of 6-12 m would be necessary. Examples of the necessary machinary for such work capacities are given in section 5. A medium work capacity of around 50 daa/day is considered to be typical in many cases on larger Norwegian farms today.

The mean areas that may be sown day by day up to 25th May, assuming a work capacity of 25 daa/trafficable day, are shown in Fig. 4.12 with three alternative criteria for trafficability. This indicates that the choice of criterion affects the area sown by a certain date, less on sand than it does on clay/silt. Further we see that, as one moves north, considerably smaller areas may be sown by a certain date. If 90% of FC is chosen as the criterion for trafficability, around 850 daa can on average be sown before 25th May on sandy soil in the region south of Oslo, as opposed to around 700 daa in the region north of Oslo and less than 600 daa in the Trondheim region. The corre-sponding figures for clay/silt soils are ca. 550, 400 and 300 daa, respectively, for the three regions.

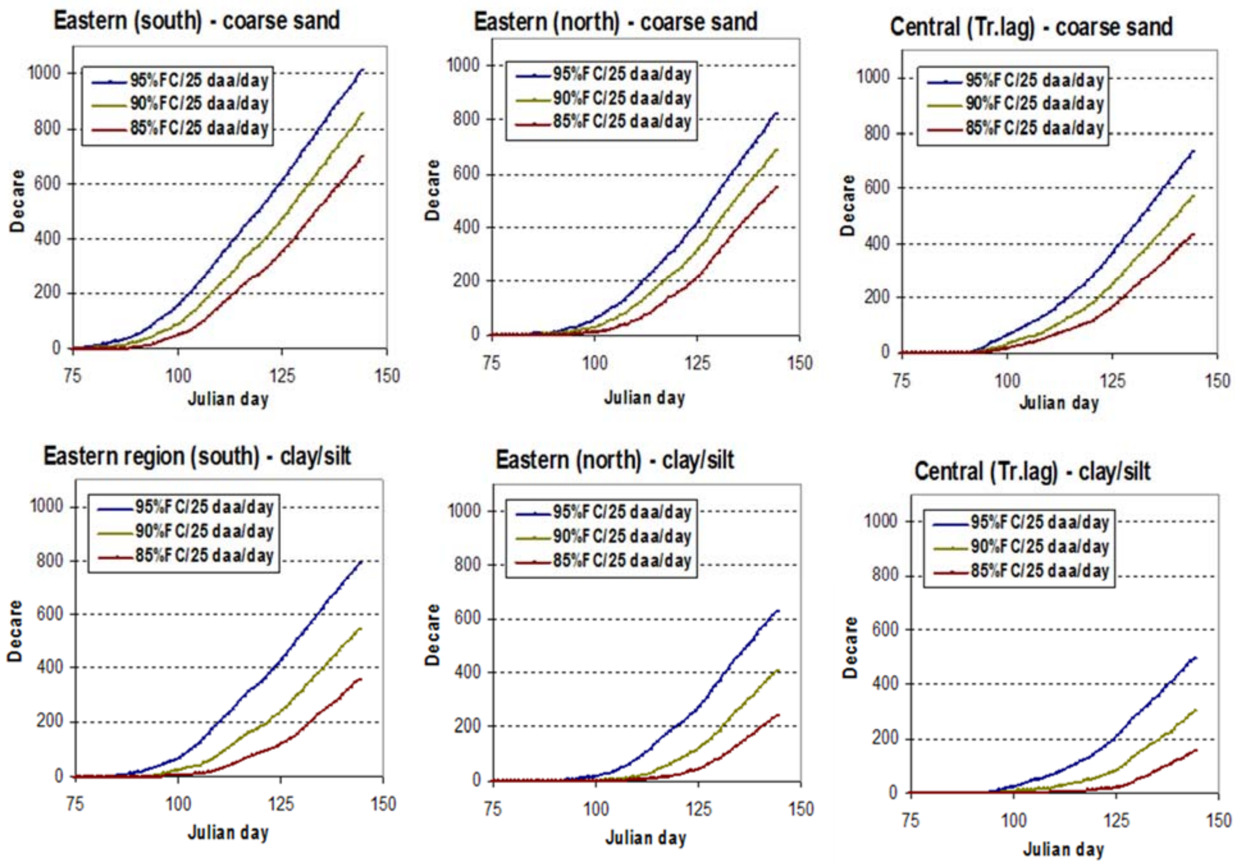


Fig. 4.12. Mean areas sown on coarse sand and clay/silt in three cereal regions, at a work capacity of 25 daa per trafficable day, assuming different trafficability criteria (% of FC). (Julian day number 75 =16th March, 100 =10th April, 125= 5th May, 150= 30th May).

The mean yield levels (% of potential yield without sowing delay or compaction) for the whole area sown by different dates (as indicated in Fig. 4.12) are shown in Fig. 4.13. Note that while a doubling of the work capacity doubles the areas sown by a certain date, the mean yield level for the whole area sown by that date remains the same. Although this figure shows that the highest mean yields are obtained when a stringent trafficability criterion is chosen, one must remember that this comes at the cost of only being able to sow a smaller area before a certain date. The figure also shows that the choice of criterion becomes relatively unimportant when the total area to be sown requires that the sowing period is extended beyond mid to late May.

We see from the figure that the highest yield levels are likely to be obtained in the southernmost region, and the lowest yield in the central region, due to differences in the combined effect of sowing delay and compaction risk. Higher yields are indicated in all regions on sandy soil than on clay/silt soils, but it should be borne in mind that other factors, such as drought resistance, may favour the latter soils and outweigh the potential advantage of early sowing on sandy soils, unless these are irrigated in periods with rainfall deficit.

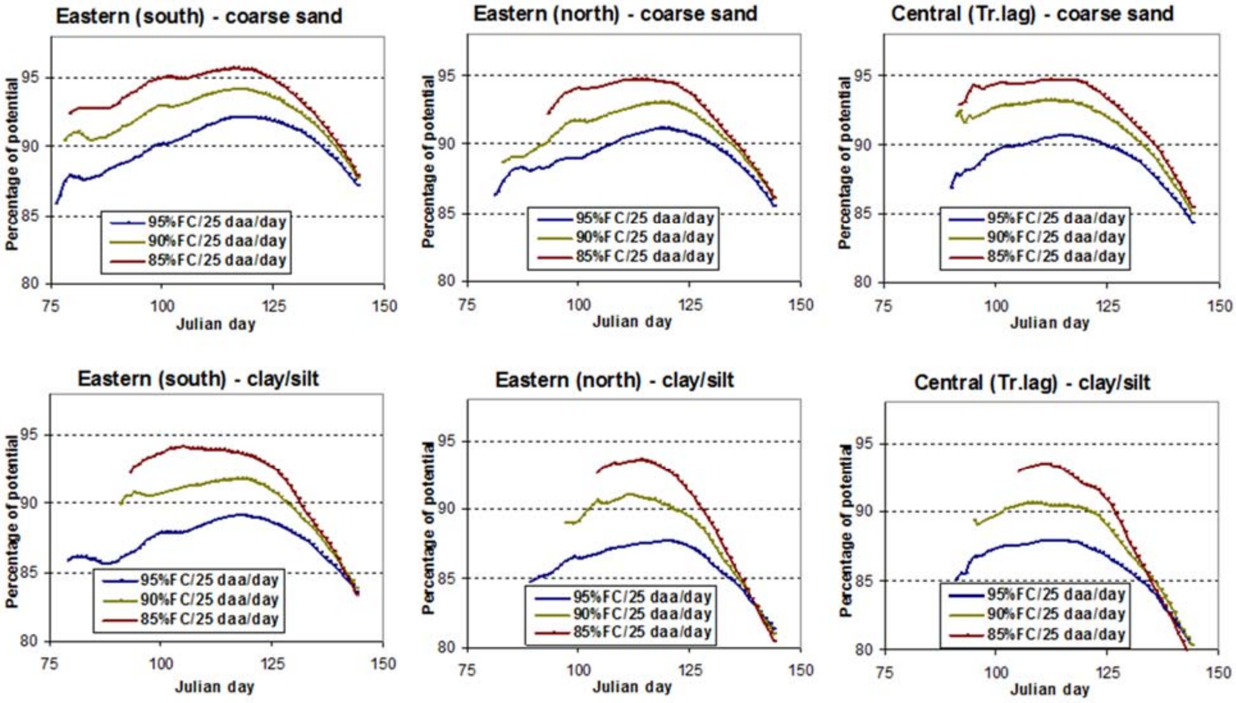


Fig. 4.13. Mean yield levels (% of potential) for the whole area sown by certain dates on coarse sand and clay/silt in three cereal regions, assuming different levels of trafficability criterion. (Julian day number 75 =16th March, 100 =10th April, 125= 5th May, 150= 30th May).

Table 4.5 shows for the Eastern region north of Oslo, the mean areas sown before 11th May (which is what most growers aim at) and before 25th May (which is when they are becoming very worried that delayed sowing will severely reduce their income), and the corresponding mean yield levels for the whole area sown by those dates. The example is for a spring-work capacity 25 daa/day. As stated above, a doubling of the capacity doubles the area sown, but gives the same mean yield for the whole area.

Table 4.5. Mean areas sown before 11th and 25th May, and corresponding yield (% of potential) in the Eastern region (north of Oslo) assuming a work capacity of 25 daa/trafficable day, with three trafficability criteria (% of FC)

	Coarse sand			Clay/silt		
Traffic criterion (% of FC)	85%	90%	95%	85%	90%	95%
Area sown (daa)						
Before 11th May	308	419	531	84	187	371
Before 25th May	549	685	819	238	419	531
Yield % of potential						
Before 11th May	92.1	91.2	90.0	89.1	88.0	86.0
Before 25th May	86.1	86.1	85.5	80.0	81.0	81.0

We see that the use of the most stringent criterion (85% of FC) severely reduces the area that may be sown by 20-25% on sandy soil and by 45-55% on clay and silt soils, relative to the use of 90% of FC, whilst the use of the least stringent criterion (95% of FC) allows considerably larger areas to be sown. With a trafficability criterion of 90% of FC, it normally takes two weeks longer on clay/silt soils to sow the same area as that sown by 11th May on coarse sand, while use of the 85% criterion severely restricts the area sown before 11th May on clay/silt. The differences in average yield obtainable with these different criteria are relatively small, especially for the areas sown by the latest date. Again, however, it must be remembered that these average yields refer to widely differing total areas sown. On clay/silt soils, for example, use of the most stringent criterion halves the area sown by a certain date, with little, if any, increase in average yield.

From the farmer's point- of-view it is not only the average area that may be sown by a certain date that is of interest, but also the work capacity that is required in order to be able to complete sowing early enough in a sufficiently high proportion of years on the area which applies to him. The level of mechanisation required is obviously dependent upon the area to be sown (farm size). Table 4.6 shows the mean date on which sowing is completed on farms of different size in the Eastern region north of Oslo, assuming two levels of mechanisation (low and moderately high work capacity), calculated for areas of 150-900 daa. This covers most of the range of cereal farms in Norway (where the mean cereal area/farm is ca. 250 daa, and 1 man-year in cereals is estimated at ca. 750 daa).

Table 4.6. Mean dates for the completion of sowing of different areas (200-800 daa) in the Eastern region (north of Oslo), with different trafficability criteria

	Coarse sand			**Clay/silt**		
Traffic criterion (% of FC)	85%	90%	95%	85%	90%	95%
Area and rate of sowing						
200 daa at 25 daa/day	4.5	27.4	22.4	21.5	11.5	29.4
400 daa at 25 daa/day	15.5	9.5	4.5	8.6	24.5	11.5
600 daa at 25 daa/day	27.5	19.5	13.5	>24.6	7.6	23.5
800 daa at 25 daa/day	8.6	30.5	23.5	>24.6	20.6	5.6
200 daa at 50 daa/day	25.4	19.4	14.4	12.5	2.5	21.4
400 daa at 50 daa/day	4.5	27.4	22.4	21.5	11.5	29.4
600 daa at 50 daa/day	10.5	4.5	28.4	30.5	17.5	12.5
800 daa at 50 daa/day	15.5	9.5	4.5	8.6	24.5	11.5

In the case of a farm with a low cereal area (200 daa), investment in a high working capacity brings forward the completion of sowing date on course sand by about a week. For this size of farm the effect is somewhat higher on clay/silt soils, especially when a strict trafficability criterion is used (85% of FC). The differences between soils increase as the size of the cereal area increases. Even the moderately high work capacity gives large delay in mean completion date on clay/silt when the strictest criterion is applied. At the higher work capacity, the use of the 90% trafficability criterion appears to give an acceptably early mean completion date in most cases except on very large farms. Table 4.7 shows the probability (% of years) that sowing will be completed before 25th May on cereal farms of different size and soil type in the same region as above.

Table 4.7. Percentage of years in which sowing is completed before 25th May on cereal farms of different size and soil type in Eastern region (north of Oslo), with the use of three trafficability criteria, assuming work capacities of 25 and 50 daa per trafficable day

	200 daa	400 daa	600 daa	800 daa
Coarse sand at 25 daa/day				
85% of FC	98	68	40	18
90% of FC	100	93	70	30
95% of FC	100	98	75	58
Coarse sand at 50 daa/day				
85% of FC	100	98	93	68
90% of FC	100	100	98	93
95% of FC	100	100	100	98
Clay/silt at 25 daa/day				
85% of FC	53	23	5	0
90% of FC	83	50	25	8
95% of FC	98	80	53	28
Clay/silt at 50 daa/day				
85% of FC	65	53	40	23
90% of FC	90	83	68	50
95% of FC	100	98	98	80

On coarse sand the lower work capacity gives completion of sowing before 25th May in most years on farms up to 400 daa when trafficability criteria of 90 or 95% are used, but only on smaller farms when the strictest criterion (85%) is used. On clay/silt soils the low work rate only gives a high proportion of years with completion earlier than 25th May on smaller farms. On such farms the use of the 85% criterion leads to sowing later than 25th May in a large proportion of years, even at the higher work rate. The higher work rate gives completion of sowing before 25th May in most years on clay/silt farms up to 600 daa when the 95% criterion is used, but in fewer years with 90% of FC.

It is difficult to make an objective decision as to which trafficability criterion is most beneficial in terms of maximising farmer income whilst maintaining good soil structure. However, the examples given above give the impression that use of the most stringent criterion limits farm profitability, whilst use of the least stringent criterion may in the long term be detrimental to soil structure, especially with the increases in tractor and machinery weight found nowadays.

For the remainder of the calculations presented in this report, the criterion of 90% of FC was chosen as the maximum soil moisture content at which tillage is performed (i.e. roughly equivalent to the lower plastic limit of many soils). This represents a compromise between ensuring early sowing to maximise crop productivity and safeguarding soil structure.

Completion of sowing by at latest the end of May is perceived as essential by farmers in Norway. Table 4.8 shows how often this is likely to be achieved on various types of soil in the three regions. On coarse sand a work capacity of 25 daa/day may be sufficient for areas up to 300-400 daa in all regions, whilst a greater capacity is required for larger areas, especially in the central region. On this soil a doubling of the work capacity to 50 daa/day may normally be sufficient. The work-rate required for completion increases both with soil moisture-holding capacity and from the south to more northerly regions. On clay and silt soils, the lowest work-rate is seldom sufficient to allow completion on areas above 150 daa/day, especially in Central Norway. In the latter region, a work capacity of 75 daa/day or more is often required on farms with a large cereal area.

Table 4.8. Percentage of years when sowing is completed before 1st June with increasing work-rates (daa/day) in three regions and on four soil types. The calculations are made for cereal areas per farm between 150 and 900 daa, assuming soil to be trafficable at or below 90% of FC

		Coarse sand			Loamy sand			Loam			Clay/silt		
Work-rate	Area (daa)	East (S)	East (N)	Cen-tral	East (S)	East (N)	Cen-tral	East (S)	East (N)	Cen-tral	East (S)	East (N)	Cen-tral
25 daa /day (low)	150	100	100	100	100	100	100	98	98	93	98	98	80
	300	100	100	100	98	98	93	95	90	73	93	85	60
	450	100	98	90	95	85	58	93	73	55	83	55	40
	600	98	95	63	88	63	43	75	43	30	60	33	23
	750	90	65	40	70	43	23	43	28	15	28	18	3
	900	55	43	23	38	23	10	23	10	3	18	10	0
50 daa /day (mod-erate)	150	100	100	100	100	100	100	100	100	100	98	98	93
	300	100	100	100	100	100	10	100	98	93	98	95	80
	450	100	100	100	100	98	93	98	98	83	95	88	73
	600	100	100	100	98	98	93	95	90	73	98	85	60
	750	100	98	95	98	95	78	93	83	55	90	73	50
	900	100	98	90	95	85	58	93	73	55	83	55	40
75 daa /day (high)	150	100	100	100	100	100	100	100	100	100	98	98	93
	300	100	100	100	100	100	100	100	98	98	98	98	88
	450	100	100	100	100	100	98	98	98	93	98	95	80
	600	100	100	100	100	100	98	98	98	90	98	93	75
	750	100	100	100	100	98	93	98	98	83	95	88	65
	900	100	100	100	98	98	93	95	90	73	93	85	60
100 daa /day (very high)	150	100	100	100	100	100	100	100	100	100	98	98	93
	300	100	100	100	100	100	100	100	100	100	98	98	93
	450	100	100	100	100	100	100	100	98	95	98	98	88
	600	100	100	100	100	100	100	98	98	93	98	95	80
	750	100	100	100	100	100	98	98	98	90	98	93	75
	900	100	100	100	100	100	93	98	98	83	95	88	73

4.6 Yield responses in relation to mechanisation level on farms of different size

The average relative yields (% of potential) obtained over the whole simulation period with spring work rates varying between 25 and 75 daa per trafficable day are shown in Fig. 4.14. A similar trend is seen as that mentioned in the previous section, with increasing influence of work capacity from the southernmost region northwards to Central Norway, and from soils with the coarsest texture to those with finer texture. These trends reflect differences in climate and soil moisture holding capacity.

On coarse sand in the eastern region south of Oslo, the average relative yields are slightly above 90% of the maximum potential irrespective of work rate on areas up to 450 daa. A very high work rate appears to involve a very slight yield penalty on small areas, due to the fact that it sometimes allows sowing whilst the soil conditions are still sub-optimal. In this region and on this soil a work capacity of 37,5 daa/day appears to be sufficient also on quite large areas. In the other regions, slightly higher work capacities are required even on light soil when the area to be sown increases.

In the southernmost region, the relative yields obtainable with a low work rate on small cereal areas decline from >90% on light soil to around 85% of the potential on the finest-textured soils. The corresponding declines in the eastern region north of Oslo are from 90% to around 80%, and in Central Norway from just under 90% to around 75% of the potential yield. In the eastern region south of Oslo, a work capacity of 50 daa/day seems to be sufficient for areas up to 450-600 daa even on the heaviest soils, whilst in the eastern region north of Oslo this capacity only suffices for a somewhat smaller area. In Central Norway, such a capacity seems to be sufficient for areas up to 300 daa on light and medium-textured soil, but a higher capacity is required on finer-textures soil. The yield losses associated with insufficient work capacity may become very great in this region.

The simulation results can be described by regression equations containing terms for the effects of cereal area, soil moisture-holding capacity, work capacity and their interactions. Such equations may be useful for the possible future development of simple internet applications to aid farmers in decisions about the amount of mechanisation necessary in their individual cases. Such equations are given in Table 4.9, using simulations with work capacity of 100 daa/day as well as the results presented in Fig. 4.14. The equations account for 93-97% of the variation in the simulated data and the standard errors of prediction of the estimated relative yields are 1.3-1.9%. Plots of the estimated relative yields versus the model simulations are given in Fig. 4.15. The greatest inaccuracy is seen at low levels of relative yield, which are probably below the levels of most interest in farmer decisions.

Table 4.9. Regression equations describing the simulated relative yields obtainable in each region on soil types[1] with different moisture-holding capacities, at varying work capacities (daa/day) and different total cereal crop areas (daa)

Region	Con-stant	Soil type	Work cap-acity	Cereal area	Soil type x cereal area	Work cap. x w. cap.	Work cap. x cer. area	Cereal area x cer. area	S. type x w. cap. x cer. area	R^2	s.e. (y)
East (S)	88.38	-1.04	0.193	0.0088	-0.0073	-0.0023	0.00014	-0.00001	0.00006	0.93	1.38
East (N)	85.39	-1.80	0.313	0.0001	-0.0086	-0.0033	0.00022	-0.00001	0.00007	0.94	1.74
Central	84.69	-3.44	0.442	-0.0107	-0.0099	-0.0043	0.00030	-0.00001	0.00008	0.97	1.91

1) 1= coarse sand, 2=loamy sand, 3=loam, 4=clay/silt

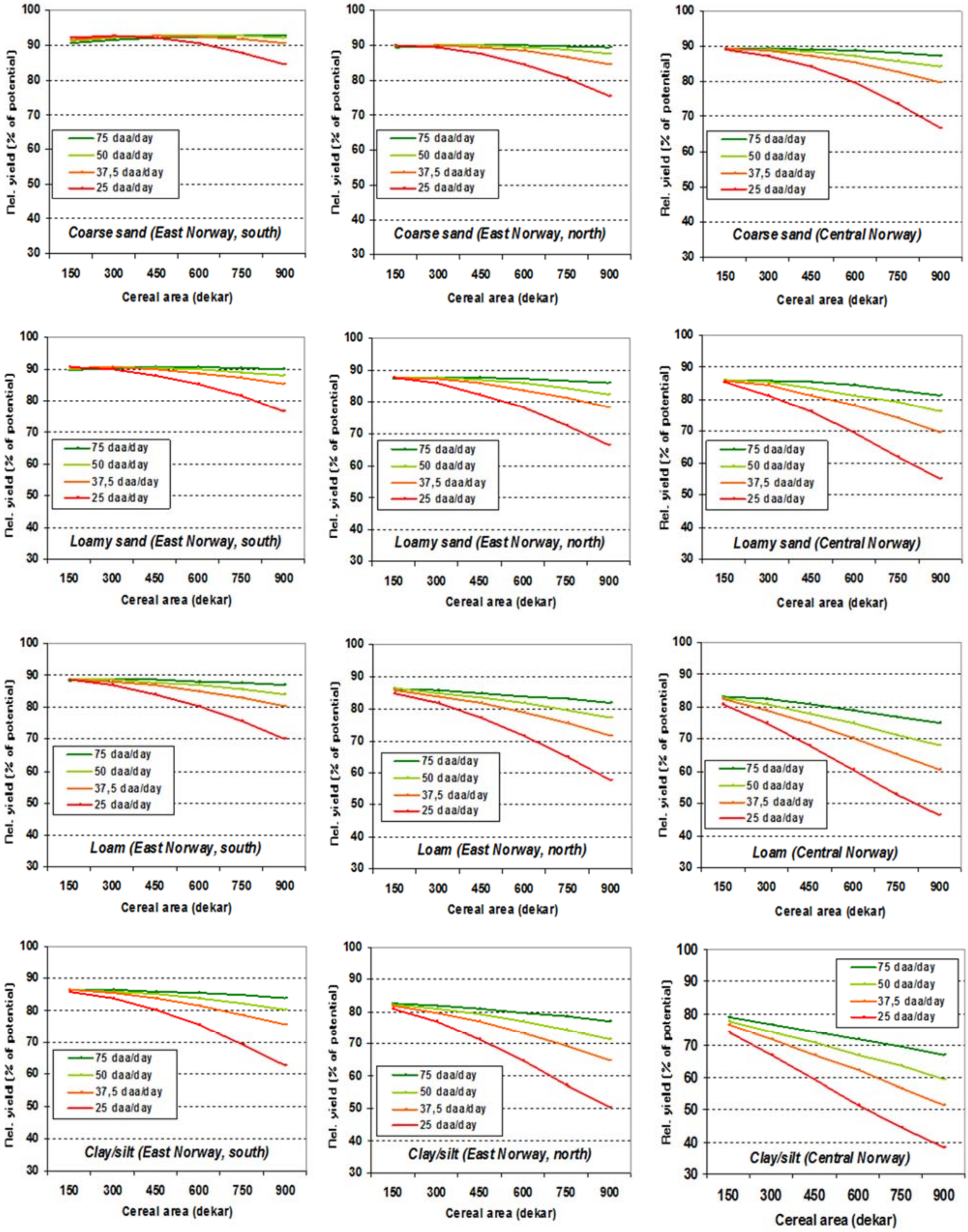


Fig. 4.14. Mean (1937-2012) yield levels (% of potential) for different soil types within the three cereal regions, calculated with increasing work rates using 90% of FC as trafficability criterion.

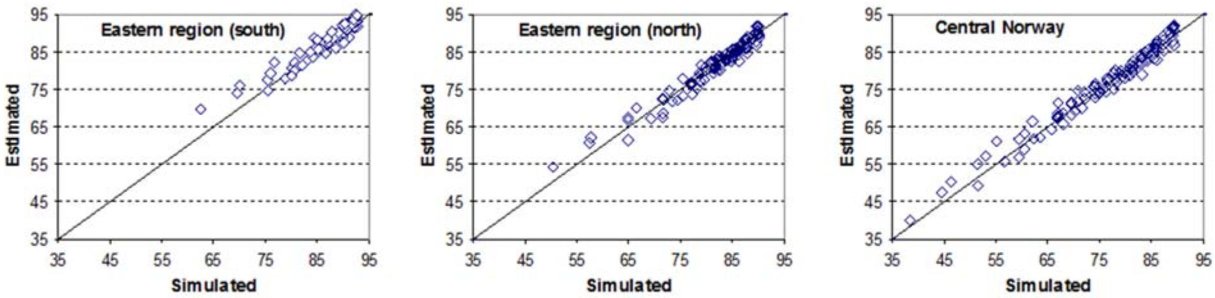


Fig. 4.15. Relative yields estimated using regression equations in table 4.9 versus simulations.

4.7 Estimation of actual yields from relative yields expressed as % of potential yield

The concept of 'potential yield' is of prime importance if the results presented in the previous section are to be used in calculations of the economic gains that may be obtained by increasing the work capacity for particular soils and/or regions. In addition to crop species and variety (genetic factors), potential yields are likely to be governed mostly by climatic factors such as temperature throughout the growing season and the incidence of drought. Four temperature zones in Norway were classified by Strand (1964) in relation to the suitability of spring cereal varieties (Table 4.10). The first three of these zones correspond roughly with the regions considered in this report, whilst the fourth corresponds with Northern Norway and upland areas in south Norway. Average cereal yield levels for the four temperature zones were suggested by Måge & Skjelvåg (1990). These are shown in Table 4.10, expressed in relative terms, averaged over all three spring cereals (wheat, barley, oats).

Table 4.10. Temperature zones for spring cereals (after Strand 1964), with corresponding mean temperatures (May-Sept.), day degree sums, suitable types of variety and relative yield levels (adapted from Måge & Skjelvåg 1990)

Zone	Region	Mean temp.	Day degrees	Barley cv.	Oats/wheat cv.	Rel. yield
1	East (S)	>13.1 °C	> 2000	Late	Late	100
2	East (N)	12.1 - 13.0 °C	1850-2000	Late	Semi-late	92.5
3	Central	11.1 - 12.0 °C	1700-1850	Semi-late	Semi-early	85
4	Upland/North	10.1-11.0 °C	1550-1700	Semi-early	Early	73.5

The effect of drought incidence on cereal crops is governed by both precipitation amounts and the soil's proneness to drought. This was studied by Riley (1989, 1994) under the climatic conditions of the Eastern region (north of Oslo) for soils with contrasting levels of moisture-holding capacity. Simulations performed with weather data for a large number of years suggested that the mean loss of yield due to water shortage varied from 8% on very drought-resistant soil to around 25% on very drought-prone soil. The region in that study has somewhat lower rainfall during the growing season than other regions. As an approximation, it is suggested that, for the soil groups used in this report, suitable average figures over all regions for the loss of yield potential due to drought are 25% for coarse sand, 15% for loamy sand, 7.5% for loam and 0% for clay/silt soils.

The combined effects of temperature zone and drought proneness on different soils on the relative level of potential yield under different conditions are shown in Table 4.11, in which the maximum level is set to 100 under the most favourable conditions (Zone 1, with clay/silt soils). This means that when the potential yield under such conditions is 700 kg daa^{-1}, the potential yield under the least favourable conditions (Zone 4, with coarse sand) is 385 kg daa^{-1}.

Table 4.11. The relative levels of potential yield assumed for temperature zones and soil types

Zone	Region	Clay/silt	Loam	Loamy sand	Coarse sand
1	East (S)	100.0	92.5	85.0	75.0
2	East (N)	92.5	85.6	78.6	69.4
3	Central	85.0	78.6	72.3	63.8
4	Upland/North	73.5	68.0	62.5	55.1

Under the best climatic conditions, it is realistic to expect average potential yields of spring cereals up to ca. 900 kg daa^{-1} in Norway. However, besides climatic factors (temperature, drought), yield levels are affected by management regime (fertilization, weed and pest control etc.). With regard to modelling the effects of sowing time and trafficability, as in this report, overestimating potential yields would lead to an overoptimistic estimation of the possible benefits of increasing the work capacity in spring. A likely range of potential yield under the best climatic conditions is from 500 kg daa^{-1} under extensive management (low levels of fertilizer input and weed and pest control) to 900 kg daa^{-1} with intensive management (high levels of inputs). For the purpose of modelling trafficability effects, the maximum yields obtainable in different areas are dependent upon both the potential yield for the temperature zone and soil type, and on the highest level of relative yield obtainable when work capacity is not limiting (viz. Fig. 4.14).

Table 4.12. Maximum obtainable yields (potential yield x max. factor from Fig. 4.14) for different temperature zones and soil types at five potential yields levels under the best climate conditions

Temp. Zone	Soil type	Max.factor in Fig. 4.14	Potential yield (kg daa^{-1}) under best conditions				
			500	600	700	800	900
1	Clay/silt	0.864	432	518	605	691	778
	Loam	0.888	411	493	575	657	739
	Loamy sand	0.906	385	462	539	616	693
	Coarse sand	0.922	346	415	484	553	622
2	Clay/silt	0.826	382	458	535	611	688
	Loam	0.864	370	444	517	591	665
	Loamy sand	0.879	346	415	484	553	622
	Coarse sand	0.900	312	375	437	500	562
3	Clay/silt	0.789	335	402	469	537	604
	Loam	0.832	327	392	458	523	589
	Loamy sand	0.860	311	373	435	497	559
	Coarse sand	0.894	285	342	399	456	513
4	Clay/silt	0.789	290	348	406	464	522
	Loam	0.832	283	339	396	453	509
	Loamy sand	0.860	269	322	376	430	484
	Coarse sand	0.894	246	296	345	394	444

Table 4.12 illustrates the average maximum yields obtainable when work capacity is not limiting, but when the effects of low trafficability and consequent sowing delay are taken into consideration. These data illustrate what may be expected with the use of different levels of potential yield. The choice of which level to use in an individual case is dependent upon the level of management and past experience. Whilst the highest levels of yield shown are probably obtained by the best farmers, they are nevertheless considerably higher than the average levels achieved. The data shown for a medium level of potential yield are probably appropriate for many conventionally managed cereal farms, whilst those shown for the lowest level of potential yield may be representative for stockless organic cereal farms.

4.8 Yields and grain value obtainable with increasing levels of mechanisation

Some examples are given in Tables 4.13-4.15 of the yield levels obtainable with various levels of spring work capacities on different soils in the three regions. The calculations are made assuming a maximum potential yield of 700 kg/daa in the most favourable region (East Norway south of Oslo), with adjustments for region and soil type as shown in Table 4.11. This choice of potential yield is lower than the genetic potential, but is probably realistic for many farmers in practice, especially considering the fact that national statistics show average grain yields of around only 400 kg/daa. As all the factors in the model are multiplicative, results for other levels of potential yield may be obtained simply by multiplying with the appropriate ratio (e.g. 840/700 for a 20 % increase).

Table 4.13. Mean yields obtainable (kg/daa) in Eastern Norway, south of Oslo, with increasing spring work capacities on different cereal areas (potential yield for region set at 700 kg/daa)

Soil type	Capacity	150 daa	300 daa	450 daa	600 daa	750 daa	900 daa
Coarse sand	25	484	487	484	475	462	443
	37.5	481	486	487	486	481	475
	50	479	484	486	487	486	484
	75	476	481	484	486	486	487
	100		479		484		486
Loamy Sand	25	539	535	524	507	485	457
	37.5	537	539	535	528	519	507
	50	535	539	538	535	530	524
	75	534	537	539	539	537	535
	100		535		539		538
Loam	25	574	563	545	521	491	454
	37.5	575	571	563	552	538	521
	50	574	574	569	563	555	545
	75	573	575	574	571	567	563
	100		574		574		569
Clay/ silt	25	601	586	560	528	486	439
	37.5	604	598	586	570	551	528
	50	605	601	595	586	574	560
	75	604	604	601	598	593	586
	100		605		601		595

Table 4.14. Mean yields obtainable (kg/daa) in Eastern Norway, north of Oslo, with increasing spring work capacities on different cereal areas (potential yield for region set at 650 kg/daa)

Soil type	Capacity	150 daa	300 daa	450 daa	600 daa	750 daa	900 daa
Coarse	25	437	435	425	411	392	366
Sand	37.5	436	437	435	429	421	411
	50	435	437	437	435	431	425
	75	434	436	437	437	436	435
	100		435		437		437
Loamy	25	483	473	454	431	400	366
Sand	37.5	484	480	473	461	447	431
	50	483	483	479	473	464	454
	75	481	484	483	480	477	473
	100		483		483		479
Loam	25	508	489	463	428	389	346
	37.5	514	503	489	472	452	428
	50	517	508	500	489	477	463
	75	517	514	508	503	497	489
	100		517		508		500
Clay/	25	524	498	463	420	372	326
Silt	37.5	530	517	498	475	449	420
	50	533	524	512	498	482	463
	75	535	530	524	517	508	498
	100		533		524		512

Table 4.15. Mean yields obtainable in Central Norway (kg/daa) with increasing spring work capacities on different cereal areas (potential yield for region set at 600 kg/daa)

Soil type	Capacity	150 daa	300 daa	450 daa	600 daa	750 daa	900 daa
Coarse	25	398	390	376	356	330	298
sand	37.5	399	396	390	381	370	356
	50	398	398	395	390	383	376
	75	397	399	398	396	393	390
	100		398		398		395
Loamy	25	432	411	386	352	314	278
Sand	37.5	434	427	411	395	375	352
	50	435	432	423	411	400	386
	75	435	434	432	427	419	411
	100		435		432		423
Loam	25	445	413	375	333	292	255
	37.5	455	435	413	387	361	333
	50	457	445	429	413	393	375
	75	458	455	445	435	424	413
	100		457		445		429
Clay/	25	442	399	354	307	265	228
silt	37.5	455	428	399	370	337	307
	50	462	442	422	399	378	354
	75	469	455	442	428	414	399
	100		462		442		422

Tables 4.16-4.18 show the changes in mean obtainable yield following changes from lower to higher spring work capacities and their cash value, assuming a price of NOK 2.77 per kilo grain, which represents the mean target price for 2016 (bread wheat 3.17, barley 2.70, oats 2.45). Negative figures imply a yield decline due to 'too early' completion of sowing, i.e. in excessively moist soil.

Table 4.16. Changes in mean obtainable yield and grain value following changes from lower to higher spring work capacities in Eastern Norway, south of Oslo, based on the data in Table 4.13

Soil type	Capacity change	150 daa	300 daa	450 daa	600 daa	750 daa	900 daa
Increase/decrease in grain yield (kg/daa)							
Coarse sand	From 25 t0 37.5	-3	-1	3	11	20	32
Loamy sand	daa/day	-2	4	11	21	34	50
Loam		1	8	18	30	47	68
Clay/silt		3	12	26	41	65	90
Coarse sand	From 37.5 to 50	-2	-1	0	1	5	9
Loamy sand	daa/day	-2	0	3	7	11	17
Loam		-1	3	6	11	17	24
Clay/silt		1	4	9	16	23	32
Coarse sand	From 50 to 75	-3	-3	-2	-1	0	3
Loamy sand	daa/day	-2	-2	1	4	7	11
Loam		-2	1	5	8	12	18
Clay/silt		-1	3	6	12	19	26
Coarse sand	From 75 to 100		-2		-1		0
Loamy sand	daa/day		-2		0		3
Loam			-1		3		6
Clay/silt			1		4		9
Increase/decrease in grain value *(NOK/daa)*							
Coarse sand	From 25 t0 37.5	-9	-3	8	30	54	88
Loamy sand	daa/day	-6	11	30	58	93	138
Loam		3	21	49	84	128	186
Clay/silt		7	33	70	114	179	246
Coarse sand	From 37.5 to 50	-6	-4	-1	3	13	25
Loamy sand	daa/day	-4	1	9	18	30	46
Loam		-3	9	16	31	47	66
Clay/silt		2	10	26	45	64	88
Coarse sand	From 50 to 75	-7	-9	-6	-3	1	8
Loamy sand	daa/day	-5	-6	3	11	20	30
Loam		-5	3	14	21	34	49
Clay/silt		-2	7	17	33	51	70
Coarse sand	From 75 to 100		-6		-4		-1
Loamy sand	daa/day		-4		1		9
Loam			-3		9		16
Clay/silt			2		10		26

Table 4.17. Changes in mean obtainable yield and grain value following changes from lower to higher spring work capacities in Eastern Norway, north of Oslo, based on the data in Table 4.14

Soil type	Capacity change	150 daa	300 daa	450 daa	600 daa	750 daa	900 daa
Increase/decrease in grain yield (kg/daa)							
Coarse sand	From 25 t0 37.5	-1	2	9	18	29	45
Loamy sand	daa/day	0	7	19	30	47	65
Loam		6	14	27	44	64	82
Clay/silt		6	18	35	56	78	94
Coarse sand	From 37.5 to 50	-1	0	2	5	10	14
Loamy sand	daa/day	-1	3	5	13	17	23
Loam		3	5	11	17	25	35
Clay/silt		4	7	14	23	32	43
Coarse sand	From 50 to 75	-2	-1	0	2	5	9
Loamy sand	daa/day	-2	0	5	7	13	19
Loam		-1	6	8	14	21	27
Clay/silt		2	6	11	18	27	35
Coarse sand	From 75 to 100		-1		0		2
Loamy sand	daa/day		-1		3		5
Loam			3		5		11
Clay/silt			4		7		14
Increase/decrease in grain value (NOK/daa)							
Coarse sand	From 25 t0 37.5	-2	6	26	50	80	123
Loamy sand	daa/day	0	19	53	82	129	180
Loam		16	38	73	122	175	226
Clay/silt		16	50	97	153	213	258
Coarse sand	From 37.5 to 50	-2	0	6	15	28	40
Loamy sand	daa/day	-2	8	15	34	46	63
Loam		9	15	31	47	68	95
Clay/silt		10	20	39	63	89	118
Coarse sand	From 50 to 75	-4	-2	0	6	15	26
Loamy sand	daa/day	-4	0	13	19	36	53
Loam		-2	16	21	38	57	73
Clay/silt		5	16	31	50	74	97
Coarse sand	From 75 to 100		-2		0		6
Loamy sand	daa/day		-2		8		15
Loam			9		15		31
Clay/silt			10		20		39

Table 4.18. Changes in mean obtainable yield and grain value following changes from lower to higher spring work capacities in Central Norway, based on the data in Table 4.15

Soil type	Capacity change	150 daa	300 daa	450 daa	600 daa	750 daa	900 daa
Increase/decrease in grain yield (kg/daa)							
Coarse sand	From 25 t0 37.5	1	6	14	25	40	57
Loamy sand	daa/day	2	16	26	44	61	73
Loam		10	22	38	54	69	78
Clay/silt		14	29	45	64	73	79
Coarse sand	From 37.5 to 50	-1	2	5	9	14	20
Loamy sand	daa/day	1	5	12	16	25	34
Loam		2	10	17	26	32	42
Clay/silt		7	13	23	29	41	48
Coarse sand	From 50 to 75	-1	1	3	6	10	14
Loamy sand	daa/day	0	2	9	16	19	26
Loam		1	10	16	22	31	38
Clay/silt		7	14	20	29	36	45
Coarse sand	From 75 to 100		-1		2		5
Loamy sand	daa/day		1		5		12
Loam			2		10		17
Clay/silt			7		13		23
Increase/decrease in grain value *(NOK/daa)*							
Coarse sand	From 25 t0 37.5	3	17	38	70	110	158
Loamy sand	daa/day	7	43	71	121	169	201
Loam		28	61	104	148	191	215
Clay/silt		38	81	123	175	200	217
Coarse sand	From 37.5 to 50	-1	4	14	24	38	55
Loamy sand	daa/day	2	14	32	43	68	93
Loam		5	28	46	70	89	114
Clay/silt		18	36	63	78	112	131
Coarse sand	From 50 to 75	-2	3	8	17	28	38
Loamy sand	daa/day	0	7	24	43	53	71
Loam		3	28	43	61	85	104
Clay/silt		21	38	55	81	100	123
Coarse sand	From 75 to 100		-1		4		14
Loamy sand	daa/day		2		14		32
Loam			5		28		46
Clay/silt			18		36		63

In the eastern region south of Oslo there appears for cereal areas up to 300 daa to be relatively little yield increase on any soil type when the work capacity is increased beyond 37.5 daa/day. For larger areas a capacity of 50-75 daa/day gives yield increase, especially on heavier soil, but there appears to be little to gain by increasing the capacity even further.

Generally greater yield benefits may be achieved by increasing capacity as one moves northwards from the southernmost region, and from lighter to heavier soils. In the eastern region north of Oslo, the yield increases on the loam soils which dominate in this area, are of roughly the same magnitude as those indicated for clay soils in the region south of Oslo, in which clays predominate. Relatively large yield increases may be achieved by increasing the work capacity up to 75 daa/day with a cereal area of 600 daa. A further increase in work capacity up to 100 daa/day increases the grain value by kr 15/daa for a cereal area of 750 daa, and by twice as much for an area of 900 daa.

In the central region, around Trondheim, the importance of having an adequate work capacity is even greater. Many soil types are found in this region, but those used for cereals are mostly clays. On such soil an average increase in grain value of kr 38/daa may be obtained by increasing work capacity from 50 to 75 daa/day for cereal areas of 300 daa, whilst for an area of 600 daa, almost as much again may be achieved by increasing it still further to 100 daa/day.

5 OPTIMALISATION OF SPRING TILLAGE

5.1 Examples of tillage mechanisation capacities

Little information is available concerning the time requirement for tillage operations under Norwegian conditions. Norm data given in NIBIO's 'Handbook for farm management planning' (Ellevold 2016) is taken from Danish and Swedish publications. Such data may be representative for Norway, but it is also possible that slope, field size and more demanding topography may lead to greater time requirement under Norwegian conditions. Some Norwegian data was presented by Riley (1988), based on observations made at Kise Research Station on sloping loam soil with a field size of around 30 daa. Some more data was collected at Apelsvoll Research Station in 2015, using more modern equipment on a variety of field sizes from 25 to 110 daa. Both sets of data are presented in Table 5.1. Ploughing is normally the most time-consuming tillage operation, depending on both the size of the plough and the size of the field.

Table 5.1. Time requirement (hours/daa) for a range of field operations, measured on loam soil at Kise and Apelsvoll Research Stations on fields with varying size

Field operation	Field size	Implement type	Maker	Working width	Working depth	Time reqd. hours/daa
Ploughing	28 daa	2 x 16" revers.	Kverneland	0.8 m	25 cm	0.25
	35 daa	4 x 16.5" revers.	Kverneland	1.65 m	25 cm	0.20
	73 daa	4 x 16.5" revers.	Kverneland	1.65 m	25 cm	0.15
	29 daa	4 x 16.5" revers.	Kverneland	1.65 m	25 cm	0.12
	80 daa	4 x 16.5" revers.	Kverneland	1.65 m	25 cm	0.16
	110 daa	4 x 16.5" revers.	Kverneland	1.65 m	25 cm	0.11
	41 daa	4 x 16.5" revers.	Kverneland	1.65 m	25 cm	0.19
	45 daa	4 x 16.5" revers.	Kverneland	1.65 m	25 cm	0.17
					Mean	*0.17±0.04*
	36 daa	3 x 14" revers.	Kverneland	1.05 m	25 cm	0.28
	30 daa	3 x 14" revers.	Kverneland	1.05 m	25 cm	0.28
	25 daa	3 x 14" revers.	Kverneland	1.05 m	25 cm	0.32
	34 daa	3 x 14" revers.	Kverneland	1.05 m	25 cm	0.28
					Mean	*0.29±0.02*
Furrow levelling	28 daa	Ov./und. plank	Nn	3.0 m	5 cm	0.09
	15 daa	Ov./und. plank	Væderstad	5.0 m	5 cm	0.13
	15 daa	Ov./und. plank	Væderstad	5.0 m	5 cm	0.18
					Mean	*0.13±0.05*
Seedbed harrowing	28 daa	C-tine	Nn	3.0 m	10 cm	0.06
	45 daa	Disc-tine	Carrier	5.2 m	10 cm	0.09
	52 daa	Disc-tine	Carrier	5.2 m	10 cm	0.05
	31 daa	Disc-tine	Carrier	5.2 m	10 cm	0.06
					Mean	*0.07+0.02*
Fertilizer harrowing	28 daa	S-tine	Tume	3.3 m	7 cm	0.09
	50 daa	S-tine	Tume	2.5 m	7 cm	0.12
Seed drilling	28 daa	Drag coulter	Nordsten	2.0 m	4 cm	0.13
	28 daa	Triple-disc DD	Mass.-Ferg.	2.5 m	4 cm	0.14
Rolling	28 daa	Cambridge	nn	3.0 m	2 cm	0.07
Subsoiling	28 daa	Winged tines	Kverneland	2.0 m	30 cm	0.17
Spraying	28 daa	Nozzle boom	Hardi	6.0 m	--	0.06

With the use of a 4-furrow reversible plough, the speed of ploughing was almost 30% faster on a field of 100 daa than on one with 50 daa (7.6 and 11.6 mins/daa, respectively, as seen in Fig. 5.1).

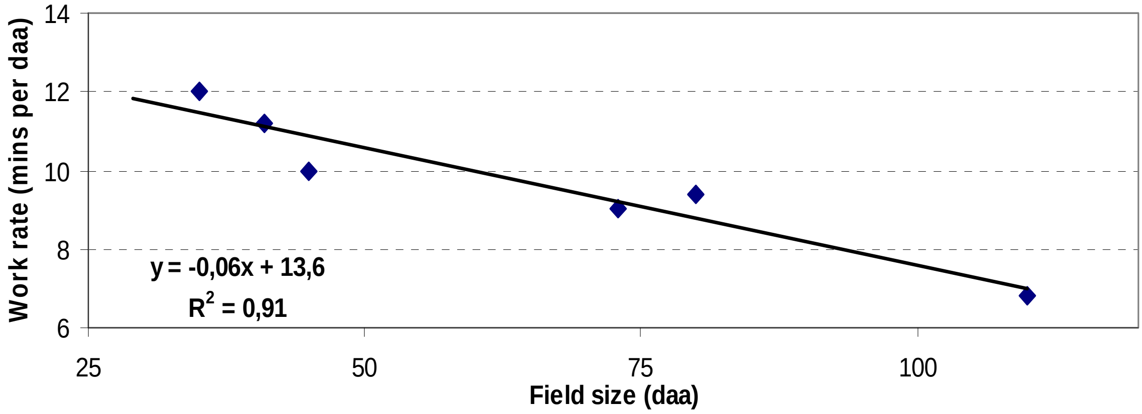


Fig. 5.1. The effect of field size in the ploughing time required, using a 4-furrow reversible plough.

A Danish on-line computer application developed by Danmarks JordbrugsForskning, Bygholm, is available at: https://www.landbrugsinfo.dk/Itvaerktoejer/Maskiner-og-arbejde/Sider/Beregn_arbejdsbehovet_ved_markarbejde_me.aspx

This model allows the user to calculate the time requirement for a large number of tillage and sowing operations, taking into account such factors as field size and shape, implement width and driving speed. A comparison of the values predicted by this model was made with the Norwegian data mentioned above. This comparison is shown in Fig. 5.2.

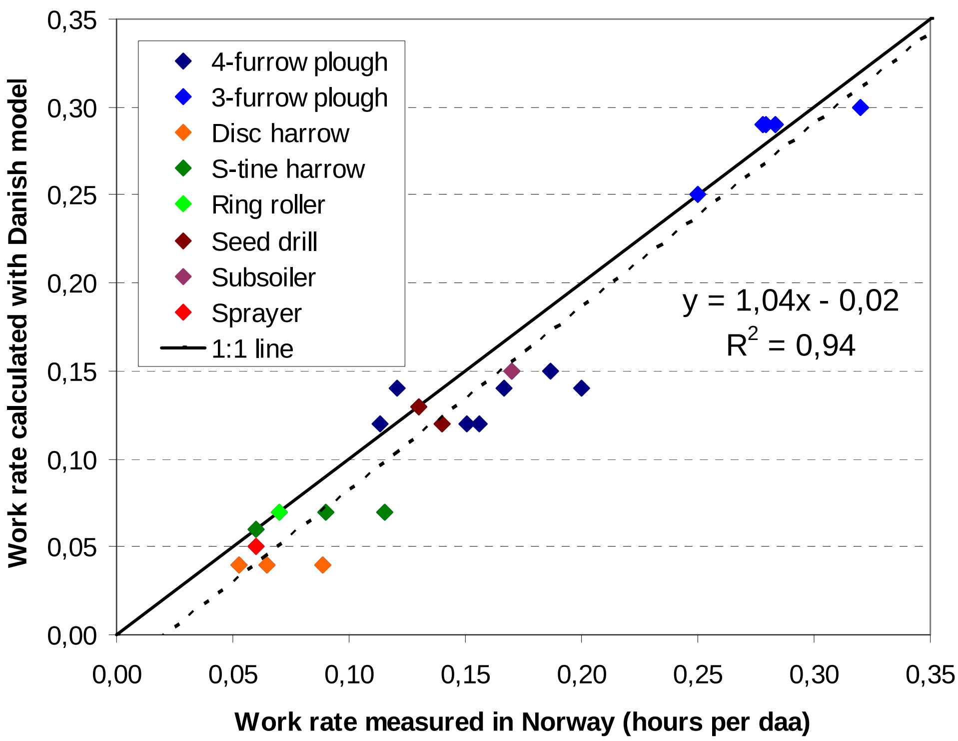


Fig. 5.2. Comparison of time requirement (hours/daa) calculated using the Danish on-line model for a range of field operations with values measured under Norwegian conditions.

The Danish model reflected broadly the time required for the various operations, but the measured values were on average slightly higher than those predicted by the model (by on average 4%). This may be due to more demanding topography in Norway. One tillage operation that the model lacks is furrow levelling (slodding), which is practiced almost everywhere on ploughed land in Norway, but which is little-known elsewhere. Nevertheless, it may be concluded that the Danish model is a useful tool also under our conditions. Table 5.2 contains time requirements calculated for various tillage and sowing operations, illustrating the effects of field size, field shape and driving speed. The examples are considered representative for the range of conditions on Norwegian cereal farms.

These examples show that most operations take around 10% longer to perform on small fields than on large ones, and 5-10% longer in irregular shaped ones (e.g. triangles) than on rectangular ones. The driving speed obviously has a large effect on time required for tillage operations, although the time saving is not quite proportional with the increase in speed, depending on field size and shape. Driving speeds on sloping land, as is common in many regions in Norway, are likely to be slower than on flat land. Increasing the width of implements obviously also reduces the time requirement, but as above, it does not always reduce it proportionally to the increase in implement size. This appears to be especially the case on smaller fields.

Table 5.2. Effects of field size, field shape and driving speed on time requirement (minutes/daa) for various tillage and sowing operations. Values calculated with Danish on-line application

	Working	Effect of field size			Effect of field shape		Effect of speed	
	width	20 daa	50 daa	80 daa	Rectangle	Triangle	(50 daa square field)	
Ploughing		(square field at 6 km/hour)			(50 daa at 6 km/hour)		5 km/hr	7 km/hr
3-furrow 1-way	105 cm	16.5	14.9	14.2	13.7	16.6	17.2	13.3
3-furrow reversible	105 cm	15.6	14.0	13.5	12.9	15.1	16.3	12.5
4-furrow 1-way	160 cm	11.4	10.3	9.7	9.5	11.6	11.7	9.2
4-furrow reversible	160 cm	10.6	9.4	9.1	8.6	10.1	10.9	8.4
6-furrow reversible	240 cm	8.2	7.3	6.9	6.8	8.6	8.3	6.7
Harrowing		(square field at 7 km/hour)			(50 daa at 7 km/hour)		6 km/hr	8 km/hr
Stubble cultivator	2.5 m	4.9	4.7	4.6	4.5	4.7	5.3	4.1
Stubble cultivator	4.0 m	3.2	3.1	3.0	2.9	3.1	4.0	3.3
Stubble cultivator	6.0 m	2.2	2.1	2.0	2.0	2.1	2.3	1.9
Seedbed harrow	3.3 m	3.5	3.4	3.3	3.2	3.4	3.9	3.0
Seedbed harrow	4.5 m	2.6	2.5	2.5	2.5	2.6	2.9	2.2
Seedbed harrow	5.6 m	2.2	2.0	2.0	2.0	2.0	2.3	1.8
Disc harrow	2.3 m	5.6	5.3	5.1	5.0	5.5	6.0	4.7
Disc harrow	3.1 m	4.3	3.9	3.8	3.7	4.1	4.4	3.5
Rotary harrow	3.0 m	4.7	4.3	4.2	4.1	4.4	4.9	3.7
Sowing		(square field at 7 km/hour)			(50 daa at 7 km/hr)		6 km/hr	8 km/hr
Drag coulter (sack)	3.0 m	5.3	4.9	4.8	4.7	5.1	5.5	4.5
Drag coulter (bulk)	4.0 m	4.0	3.7	3.7	3.6	3.8	4.1	3.4
Tine seeder (sack)	3.0 m	5.3	4.9	4.8	4.7	5.1	5.5	4.5
Rotaseeder (sack)	3.0 m	5.7	5.4	5.3	5.2	5.5	5.9	5.0
Direct drill (sack)	4.0 m	3.7	3.4	3.4	3.3	3.5	3.8	3.1
Combi-drill (sack)	3.0 m	6.8	6.4	6.3	6.2	6.6	7.0	6.0
Combi-drill (bulk)	4.0 m	5.2	5.0	4.8	4.7	4.7	5.3	4.6
Cambridge roller	3.6 m	3.4	3.3	3.2	3.2	3.4	3.8	2.9
Cambridge roller	6.0 m	2.2	2.0	2.0	1.9	2.1	2.3	1.8

There are many alternative ways of increasing the work capacity level, including implement choice, implement and tractor size, the number of operators/tractors and the number of hours worked per day. The probable work time requirement for spring tillage and sowing on previously autumn-tilled land is, on the basis of the data presented in tables 5.1 and 5.2, in the region of 20-30 minutes per daa. If one assumes an average working day length (effective time working in the field) of 10 hours per day, this implies a possible work capacity of 20-30 daa/day.

If the soil is to be ploughed in spring, instead of in autumn, this obviously increases the spring work requirement. However, spring ploughing can normally be performed at slightly higher soil moisture contents than secondary tillage. A starting point of 95% of FC, rather than 90 %, may be appropriate. The amount of topsoil moisture contained between 90 and 95% of FC varies from 1.5 mm on coarse sand to 4.5 mm on clay/silt soils. Likely evaporation in spring is around 1-1.5 mm per day. Spring ploughing can thus normally start 1-3 days earlier than secondary tillage. For any given area, the capacity for spring ploughing should roughly equal the capacity for other spring work, in order not to cause delay in sowing. However, further study of this aspect is required.

5.2 Examples of tillage costs

A major part (ca. 50%) of the investment in tillage equipment is due to the cost of the tractor used. On the basis of key price data for >450 tractors published in Norwegian agricultural journals in 2015, Kjell Mangerud (Assoc. prof. emer. at Hedmark University of Applied Sciences) found a close linear relationship between tractor price and tractor power (Fig. 5.3, upper left). Similarly, he found the increases in the capital cost of machinery with implement size (Fig. 5.3, upper right, shows the relationship with seed drill width). Further, using mean data provided by manufacturers for the power requirement of various tillage implements, he found relationships between the width of implements and their tractor power requirements (Fig. 5.3, below, showing relationships for harrows and seed drills).

Using such considerations, Kjell Mangerud made three proposals of the implements and tractors required for secondary tillage and sowing in spring (i.e. after ploughing) in order to achieve various levels of work capacity, together with their associated capital costs (Table 5.3). Using the smallest equipment currently available on the market, he found the spring-work capacity to be 30 daa/day, and this is assumed here to also represent a work rate of 25 daa/day. The example with medium-sized machinery is common on many farms today, whilst that with a powerful tractor and very large implements represents the upper level of mechanisation that may be found on some farms. Linear regression of the these three examples suggest that a capital investment of ca. NOK 66.000 is required in order to increase the work capacity by 25 daa/day (r^2=0.97).

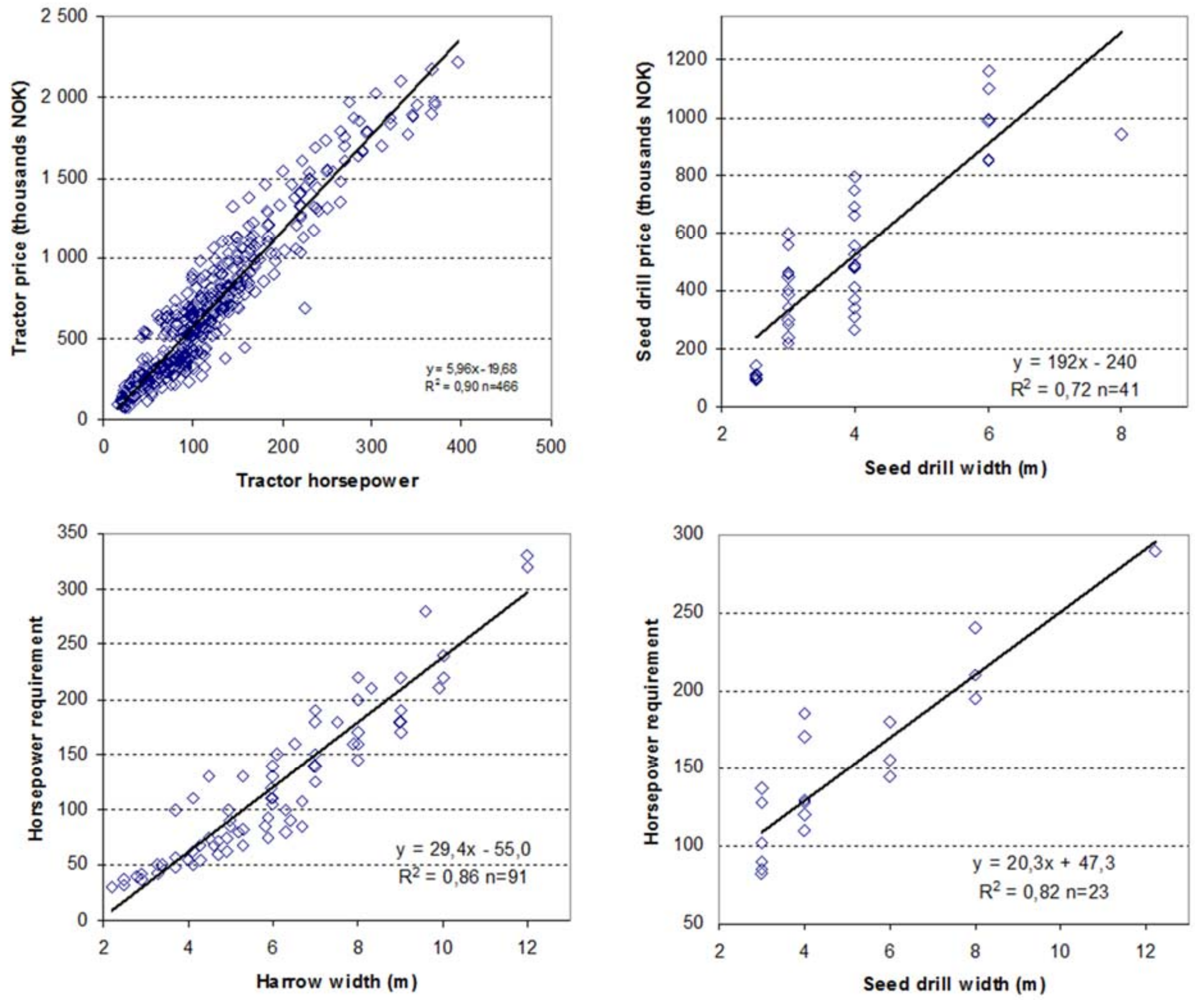


Fig. 5.3. Price increases with tractor horsepower and seed drill width (above) and increases in horsepower requirements (below) with harrow and seed drill widths. (Source: Kjell Mangerud).

Table 5.3. Examples of tractor and implement size, and associated capital costs, required in order to achieve three levels of spring-work capacity (secondary tillage, sowing and rolling)

		Machinery size			Capital cost (thousands NOK)		
Work capacity:		30 daa/day	50 daa/day	100 daa/day	30 daa/day	50 daa/day	100 daa/day
Tractor size		60 hp	100 hp	210 hp	338	577	1232
Soil leveller	8 km/h	2.5 m	4 m	-	20	50	0
Harrow	9 km/h	3 m	7 m	12 m	60	214	408
Seed drill	7 km/h	2.5 m	4 m	6 m	120	551	888
Roller	5 km/h	4 m	10 m	10 m	40	80	120
			Cost of implements		240	895	1415
			Total cost (incl. tractor)		578	1472	2648

The total annual costs of these three proposals were calculated, including costs associated with capital investment and depreciation, maintenance, labour and fuel consumption. The calculations were performed using an excel spreadsheet program devised by Kjell Mangerud. The program allows calculations to be made for different cereal areas, with adjustments for the lifespan of tractors and implements in relation to the length of time they are used (depending on the area):

Tractor lifespan (years) = 10.000 / no. of hours in use (incl. ploughing)
Implement lifespan (years) = 3.000 / no. of hours in use (both with a maximum life of 30 years). The no. of hours in use for each implement = area/speed/width * efficiency factor (set at 0.6).
The annual capital costs = (purchase price/lifespan + purchase price/2) * interest rate/ 100
An interest rate of 2% was assumed.

Maintenance costs were calculated as: Factor * purchase price/1000 * no. of hours in use, with the use of the following factors: tractor 0.091, leveller 0.46, harrow 0.77, seed drill 0.52, roller 0.076.

Fuel costs were calculated as follows:

The number of tractor hours in spring-work * diesel price * 0.12*tractor horsepower. A diesel price of NOK 7.50/liter was assumed.

The cost of labour was set at NOK 250 per hour, which is approximately equivalent to the sum of the tariff wage for agricultural workers plus social expenses and holiday payment. A working time of 10 hours per day was assumed. For each of the proposed sets of implements, calculations were made both with the use of one tractor and one driver, and with the use of two tractors and drivers.

The sums of annual costs per daa for these alternatives are shown in Fig. 5.4 for various cereal areas. The costs per daa rise sharply for cereal areas less than 300 daa, and become more even above 600 daa. The high cost of tractors is reflected in the fact that all alternatives with two tractors are more expensive than those with only one, even though the tractor life is extended considerably using two. Costs per daa of small and medium-sized machinery options differ relatively little for large cereal areas, whilst the cost of the large-sized machinery option remains high even with large areas.

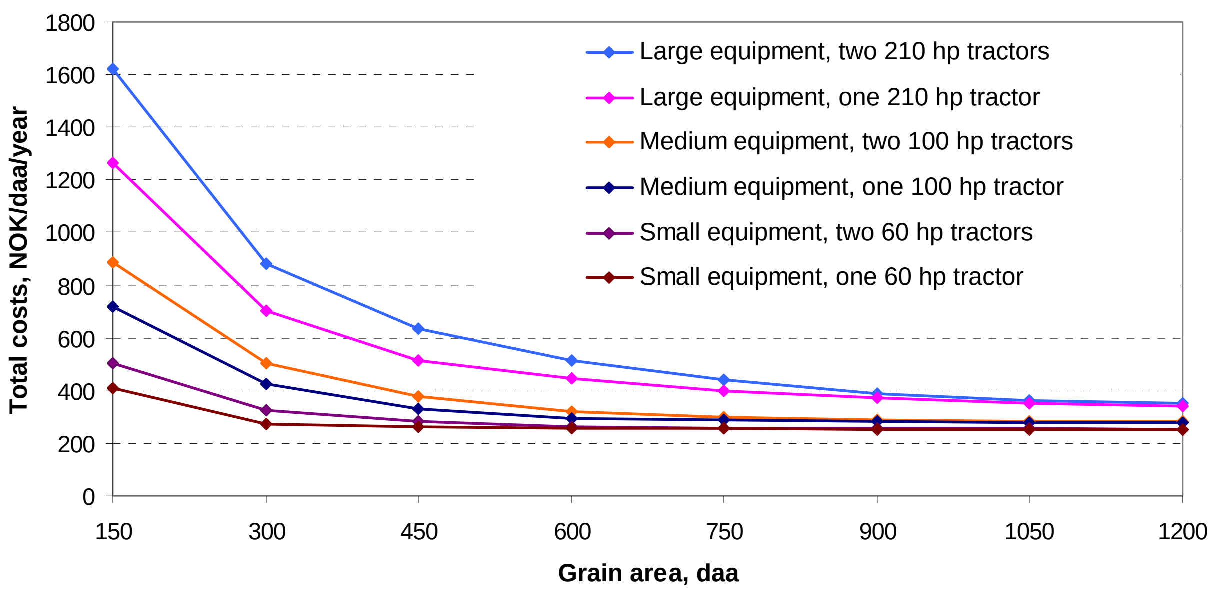


Fig. 5.4. Total costs per daa and year of three tillage mechanisation alternatives, each with either one or two tractors, including costs of tractors and implements, maintenance, labour and fuel.

Fig. 5.5 shows the percentage distribution between capital costs of tractors and implements, and the costs of maintenance, labour and fuel (with one tractor in each case). Capital costs represent the largest proportion of total costs, and increase with increasing machinery size. Labour costs a large proportion of total costs with the use of small machinery, but become much less important with large machinery. The proportion of costs due to maintenance increase both with the size of machinery used and with the grain area. Fuel represents the smallest proportion of total costs.

There are many ways of increasing work capacity, by changes in either the size of machinery used, the number of tractors and drivers or the length of time worked per day. Two alternative ways of increasing from low to medium capacity and from medium to high capacity, are examined here. These involve either increasing the number of tractors whilst keeping the same machinery size, or investing in larger machinery with one tractor suited to the new machinery size. The associated increases in annual costs per daa are given in Table 5.4 for three sizes of grain area. Increasing machinery size appears to be more expensive than increasing the number of tractors and drivers.

Table 5.4. Increases in annual costs of spring tillage with alternative ways of increasing work capacity, by increasing either the number of tractors/drivers or the machinery size (calculated from data presented in Fig. 5.4)

Increase in capacity (from->to, daa/day)		300 daa	600 daa	900 daa
25 -> 50	From 1 to 2 small tractors with small implements (alt. 1)	48	6	4
25 -> 50	From small to medium implements w. 1 medium tractor (alt. 2)	147	37	31
50->100	From 1 to 2 medium tractors with medium implements (alt. 1)	83	24	6
50->100	From medium to large implements w. 1 large tractor (alt. 2)	281	149	89

In order to evaluate whether such changes are justified in relation to the possible increases in grain value that may be obtained due to earlier completion of spring tillage and sowing, Table 5.5 shows the balances between grain value data presented in Ch.4 and the cost increase data in Table 5.4.

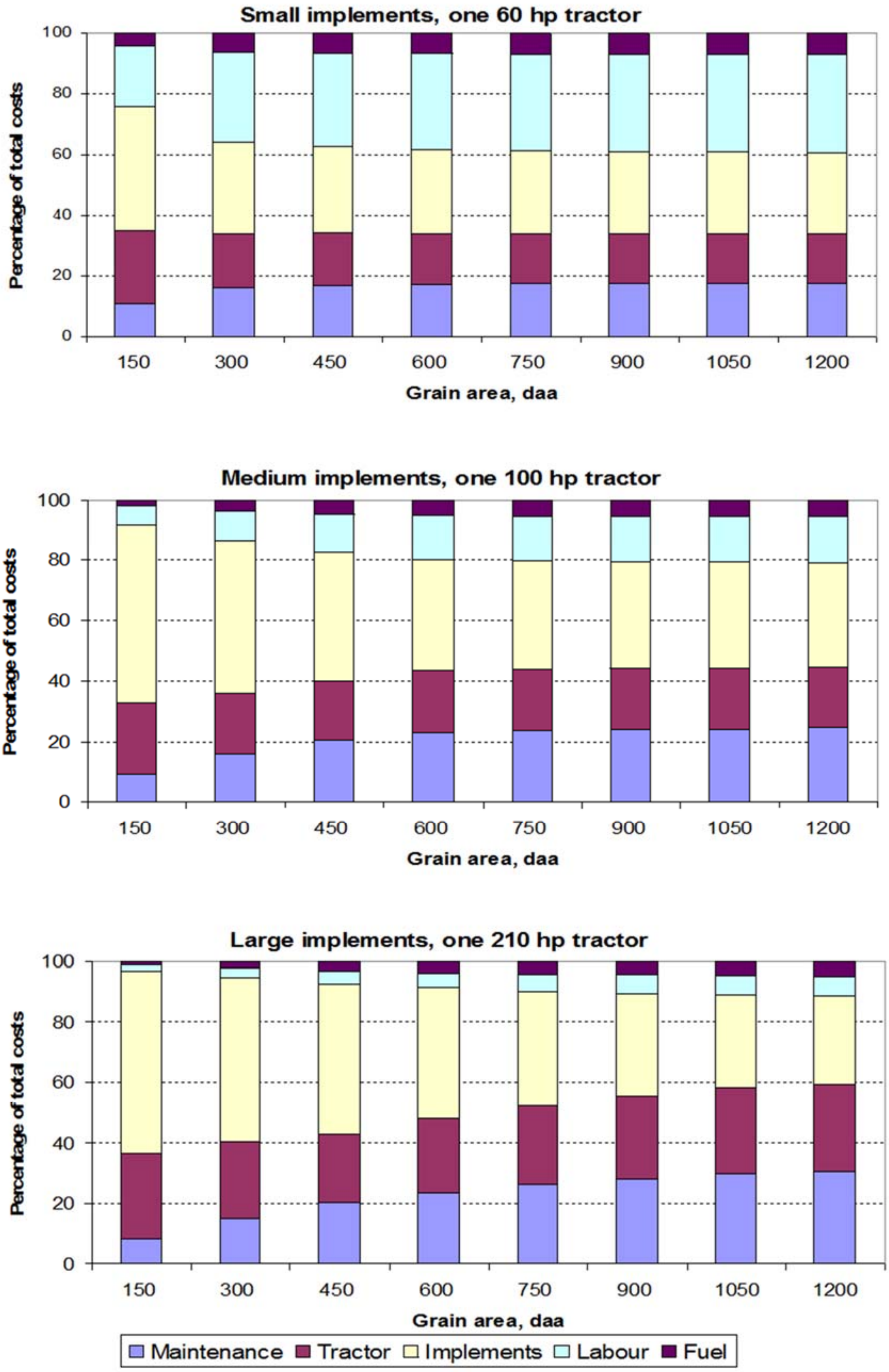


Fig. 5.5. The percentage distribution between capital costs of tractors and implements and the costs of maintenance, labour and fuel (with one tractor in each case), with increasing grain area.

Table 5.5. The balance between changes in mean grain value following changes from lower to higher spring work capacities (Tables 4.16-4.18) and corresponding increases in costs. The alternative ways of increasing capacity are given in Table 5.4. Negative values = loss in income

		Eastern region, south			Eastern region, north			Central Norway		
Soil type	Area, daa:	300	600	900	300	600	900	300	600	900
C. sand	From 25	-55	27	109	-42	60	159	-27	88	209
L. sand	to 50 daa	-37	71	181	-21	110	239	8	158	291
Loam	per day	-18	109	248	4	163	318	40	213	326
Clay/silt	(alt. 1)	-6	153	331	22	210	373	69	248	344
C. sand	From 25	-154	-4	82	-141	28	132	-126	57	183
L. sand	to 50 daa	-136	39	154	-119	79	213	-91	127	264
Loam	per day	-117	77	221	-95	131	291	-58	182	299
Clay/silt	(alt. 2)	-105	122	304	-77	179	346	-30	216	317
C. sand	From 50	-99	-30	1	-88	-17	25	-82	-2	46
L. sand	to 100 daa	-93	-12	33	-85	4	61	-75	33	96
Loam	per day	-83	7	58	-58	29	97	-50	65	143
Clay/silt	(alt. 1)	-74	19	90	-58	47	130	-27	94	179
C. sand	From 50	-296	-155	-82	-286	-142	-58	-280	-127	-37
L. sand	to 100 daa	-291	-137	-50	-282	-121	-22	-272	-92	13
Loam	per day	-280	-118	-25	-256	-96	14	-248	-60	61
Clay/silt	(alt. 2)	-272	-106	7	-255	-78	47	-225	-31	96

The table includes a wide range in possible outcomes, with large negative figures when increasing from a medium to a high capacity on a small grain area, and large positive figures when increasing from a low to a medium capacity on a very large grain area. Such extremes are seldom encountered in practice today. The table also shows the differences in outcome between soil types and between regions. It is clearly more profitable to increase the work capacity on soils with high moisture-holding capacity than on less moist soils, and the same applies when moving from more southerly to more northerly locations when the same soil type is compared between locations.

In the eastern region south of Oslo, none of the alternatives considered appear to be profitable with a grain area of only 300 daa. The use of two tractors/drivers with small machinery appears to be profitable on moister soils in the eastern region north of Oslo even with a small grain area, and even more so in Central Norway. Moving from small to medium-sized machinery with a single tractor appears to be almost as profitable as the latter option when the grain area is >600 daa. Investment in an extra medium-sized tractor (plus driver) may also be profitable on such farms, whilst the move from medium-sized to heavy machinery and a very powerful tractor and very large implements is more doubtful in nearly all cases, except on farms with a large grain area on the heaviest soil types.

6 DISCUSSION AND FUTURE RESEARCH

Several previous models have included the effect of sowing delay on yields, e.g. that of Toro & Hansen (2004) in Sweden. The use of such empirically derived relationships with sowing time is valid provided that climatic conditions, in either spring or autumn, remain constant. This provision may be altered by climatic change. A novel aspect of the work in this report is that the negative effect of soil compaction is combined with that of sowing delay. This is thought to give a more balanced picture of the real-life situation in which farmers are faced with choosing between risking some yield loss due to compaction in order to avoid possibly greater losses due to sowing delay.

The current model assumes that, on a particular 'trafficable' day, all tillage and sowing operations are completed for a given area. This simplification does not take into consideration possible non-completion of work on individual fields. Toro & Hansson (2004) found such 'chain effects' to increase timeliness costs. This may be of particular importance in future studies if effects of spring ploughing operations are also to be addressed. Logistical factors such as the distance to individual fields and effects of having fields of different shape, size and topography should also be included.

Little mention has been made in the current work of possible long-term yield reductions that may be associated with increasing spring-work capacity by the use of heavier tractors and machinery. The risk of subsoil compaction is highlighted in other studies within the same Work Package as this, and ways of incorporating such information in future models of soil trafficability should be sought. There is also a considerable need for more information about the efficiency and time requirements, relative to their cost, of the vast variety and number of new tillage implements that are available on the market today.

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NOTATER

Norsk institutt for bioøkonomi (NIBIO) ble opprettet 1. juli 2015 som en fusjon av Bioforsk, Norsk institutt for landbruksøkonomisk forskning (NILF) og Norsk institutt for skog og landskap.

Bioøkonomi baserer seg på utnyttelse og forvaltning av biologiske ressurser fra jord og hav, fremfor en fossil økonomi som er basert på kull, olje og gass. NIBIO skal være nasjonalt ledende for utvikling av kunnskap om bioøkonomi.

Gjennom forskning og kunnskapsproduksjon skal instituttet bidra til matsikkerhet, bærekraftig ressursforvaltning, innovasjon og verdiskaping innenfor verdikjedene for mat, skog og andre biobaserte næringer. Instituttet skal levere forskning, forvaltningsstøtte og kunnskap til anvendelse i nasjonal beredskap, forvaltning, næringsliv og samfunnet for øvrig.

NIBIO er eid av Landbruks- og matdepartementet som et forvaltningsorgan med særskilte fullmakter og eget styre. Hovedkontoret er på Ås. Instituttet har flere regionale enheter og et avdelingskontor i Oslo.

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