Predicting effects of soil compaction on crop yield and nitrogen dynamics

By:
Carsten T. Petersen and Per Abrahamsen
Department of Plant and Environmental Sciences
University of Copenhagen

Miljø- og Fødevareministeriet
gudp

Title

Predicting effects of soil compaction on crop yield and nitrogen dynamics

Authors

Carsten T. Petersen and Per Abrahamsen
Department of Plant and Environmental Sciences, University of Copenhagen

Publisher and year

University of Copenhagen, Department of Plant and Environmental Sciences

2021

Preface

This report has been prepared as part of the relatively broadly focused project Soil compaction mitigation for productivity and sustainability (COMMIT) with many participants. The project has been funded by the Ministry of Environment and Food of Denmark under the GUDP program, and the overall project management has been handled by Lars J. Munkholm at Aarhus University.

Field trials with different compaction treatments are included. Many have contributed measurements in these experiments, which has been a prerequisite for carrying out the simulation work and making the predictions. This applies not least to the Department of Agroecology at Aarhus University and the Department of Fertilizer and Environment at the national advisory service SEGES.

Copenhagen, January 21, 2021
Carsten Petersen

Table of contents

Summary

Results from a 10-year field trial with studies of the effects of soil compaction on a loamy soil, in which spring barley was grown for eight years and winter wheat for two years, have been used to parameterize the soil-plant-atmosphere model Daisy, and the model has then been used to simulate expected long-term effects of traffic with heavy machinery on yields in spring barley (with and without a cover crop) and winter wheat, on nitrogen balances, and on the environment.

The measurements showed clear and long-lasting effects on the soil, and, thereby, they provide a basis for the simulation work. Thus, driving wheel-by-wheel with 6 Mg wheel load in the spring of the years 2010-2013 gave significantly increased bulk density and reduced air permeability in the subsoil down to 70 cm depth in 2014. These effects remained without measurable changes in 2017, also in subplots where fodder radish was used as a cover crop (2013-2016). Compaction changed the hydraulic properties and resulted in inferior drainage of both the annually loosened topsoil and the still compacted subsoil being measured in the years 2017-2019. Yields tended to be lower on compacted soil in the years after compaction but the effects were generally not statistically significant in the individual years.

It was possible to use the many measurements from the field trial to parameterize the soil and the spring barley crop and on that basis achieve good agreement between measured yields and yields simulated based on the years' management activities and weather records. The same was not the case for winter wheat, probably because the measured data was too sparse and special. The long-term calculations for spring barley are therefore based on a specific crop calibration, while for winter wheat a general calibration from the Daisy library has been used.

The long-term effects are calculated for a 100-year period driven by two different weather patterns that are representative of resp. the “current” East Danish climate (registrations completed in the period 1983-2012) and for an expected future climate in the years 2030-2059. The average simulated effects of compaction with 6 Mg wheel load on the dry matter yield in grains were always negative, albeit relatively small on an annual basis (0.1-0.2 Mg dry matter/ha/year in the current climate or up to 3%). This is in good agreement with measurement results from the much shorter number of years in the experiment and depends solely on the impact of the compaction on the soil. Nor was a very large yield decrease simulated due to compaction in the 10% of years where the yield was lowest due to adverse weather conditions, although the range was larger than average (0.0-0.3 Mg dry matter/ha/year or up to 5%). The loss of dry matter yield on poorly drained soil due to compaction was greater in the expected future climate than in the current one (on average up to 5%).

The simulated compaction effects were sensitive to how the root distribution in the subsoil was parameterized. They became significantly more negative with a change from homogeneous to heterogeneous root distribution, primarily due to more frequent occurrence of water stress. It is well known that soil compaction can lead to more uneven root distribution, where the plant roots to a greater extent accumulate in the macropores and thereby become less efficient in taking up water and nutrients from the soil, but such effects is not well investigated over longer time.

The simulations show that on average less nitrogen (protein) is harvested when the soil is compacted (up to 11 kg N/ha/year corresponding to 9%). Subsoil compaction is thus expected to result in a long-term and stable loss of grain quality, greatest in spring barley. This decrease in the amount of harvested nitrogen on compacted soil ends elsewhere, mainly as increased gaseous losses to the atmosphere (up to an average of 11 kg N/ha/year corresponding to increases of up to 50%). The calculations do not show the extent to which these additional losses occur in the form of harmless N_2 or as the very potent greenhouse gas N_2O, because such model calculations are very uncertain due to lack of experimental field studies.

The long-term effects of subsoil compaction should be calculated over a number of years rather than on an annual basis. The effects on dry matter yield in grains, on grain quality and on the discharge of gaseous nitrogen into the atmosphere are considered to deserve the most attention. There were only minor effects on nitrogen leaching to drains (increased losses of on average up to 4 kg N/ha/year) and on storage of N in the soil (increased storage of on average up to 2 kg N/ha/year).

The simulations indicate that the drainage condition of the soil and the distribution of plant roots in compacted subsoil can have a significant impact on the effects of heavy traffic. The effects of heavy traffic on poorly drained and therefore compact sensitive soil can be relatively small because the soil has already been compacted in connection with ordinary traffic before the treatment. It is suggested that the interaction between drainage condition and soil compaction as well as more extensive root investigations should be included in future compaction studies. Furthermore, it should be investigated to what extent the losses of nitrous oxide to the atmosphere are affected by compaction.

Sammendrag

Resultater fra et 10-årigt markforsøg med studier af eftervirkningsskader af jordpakning på lerjord, hvor der i otte år blev dyrket vårbyg og i to år vinterhvede, er anvendt til at parametrisere jord-plante-atmosfære-modellen Daisy, og modellen er derpå brugt til at simulere forventede langtidseffekter af færdsel med tunge maskiner på høstudbytter i vårbyg (med og uden efterafgrøde) samt vinterhvede, på kvælstofhusholdningen og på miljøet.

Målingerne viste tydelige og langvarige pakningseffekter på jorden, og de giver derved grundlag for simuleringsarbejdet. Overkørsel hjul ved hjul med 6 Mg hjullast om foråret i årene 2010-2013 gav således ved målinger i 2014 signifikant forøget volumenvægt samt reduceret luftpermeabilitet i underjorden ned til 70 cm dybde, og der var ikke sket nogen målbar ændring af dette i 2017, heller ikke i forsøgsled, hvor der blev anvendt olieræddike som efterafgrøde (2013-2016). Pakningen ændrede de hydrauliske egenskaber og resulterede i, at der i årene 2017-2019 blev målt ringere afdræning af såvel den årligt løsnede overjord som af den fortsat pakkede underjord. Der var tendens til fortsat, om end lille udbyttenedgang som følge af pakning i årene efter pakningens ophør, men effekten var generelt ikke statistisk signifikant i de enkelte år.

Det var muligt at anvende de mange målinger fra forsøget til at parametrisere jorden og vårbygafgrøden og på det grundlag opnå god overensstemmelse mellem målte udbytter og udbytter simuleret ud fra årenes dyrkningsaktiviteter og vejrregistreringer. Det samme var ikke tilfældet for vinterhvede, formentlig fordi datagrundlaget var for sparsomt og specielt. Langtidsberegningerne for vårbyg bygger derfor på en specifik afgrødekalibrering, mens der for vinterhvede er anvendt en erfaringsmæssigt god og relativt ny afgrødekalibrering fra Daisy-biblioteket.

Langtidseffekterne er beregnet for en 100-års periode drevet af to forskellige vejrmønstre, der er repræsentative for hhv. det ”nugældende” østdanske klima (registreringer gennemført i perioden 1983-2012) og for et forventet fremtidigt klima i årene 2030-2059. De gennemsnitligt simulerede effekter af pakning med 6 Mg hjullast på tørstofudbyttet i kerner var altid negative, om end relativt små på årsbasis (0,1-0,2 Mg tørstof/ha/år i det nugældende klima eller op til 3 %). Dette er i god overensstemmelse med måleresultater fra den meget kortere årrække i forsøget og beror alene på pakningens påvirkning af jorden. Der blev heller ikke simuleret meget stor udbyttenedgang som følge af pakning i de 10 % af årene, hvor udbyttet var lavest pga. uheldige vejrforhold, om end spændet var større end i gennemsnit (0,0-0,3 Mg tørstof/ha/år eller op til 5 %). Tabet af tørstofudbytte på dårligt drænet jord som følge af pakning var større i det forventede fremtidige klima end i det nugældende (i gennemsnit op til 5 %).

De simulerede pakningseffekter var følsomme over for, hvordan rodfordelingen i underjorden blev parametriseret. De blev markant mere negative ved en ændring fra homogen til heterogen rodfordeling, primært pga. hyppigere forekomst af vandstress. Det er velkendt at jordpakning kan føre til mere uensartet rodfordeling, hvor planterødderne i højere grad samles i makroporerne og derved bliver mindre effektive til at optage vand og næring, men omfanget er ikke velbelyst.

Simuleringerne viser, at der i gennemsnit høstes mindre kvælstof (protein) når jorden er pakket (op til 11 kg N/ha/år svarende til 9 %). Pakning af underjorden forventes dermed at resultere i et langvarigt og stabilt tab af kernekvalitet, størst i vårbyg. Denne nedgang i mængden af høstet kvælstof på pakket jord ender et andet sted, hovedparten som øgede gasformige tab til atmosfæren (op til gennemsnitligt 11 kg N/ha/år svarende til forøgelser på op til 50 %). Beregningerne viser ikke i hvilket omfang disse ekstra tab sker i form af uskadeligt N_2 eller som den meget potente drivhusgas N_2O, fordi sådanne modelberegninger er meget usikre som følge af mangel på eksperimentelle feltundersøgelser.

Langvarige effekter af underjordspakning bør snarere opgøres over en årrække end på årsbasis. Effekterne på tørstofudbytte i kerner, på kernekvalitet samt på udledningen af gasformigt kvælstof til atmosfæren vurderes at fortjene størst opmærksomhed. Der var kun mindre effekter på kvælstofudvaskningen til dræn (øgede tab på gennemsnitligt op til 4 kg N/ha/år) og på oplagring af N i jorden (øget oplagring på gennemsnitligt op til 2 kg N/ha/år).

Simuleringerne indikerer, at jordens dræningstilstand og planterødders fordeling i pakket underjord kan have væsentlig betydning for effekterne af færdsel med tung trafik. Effekterne af tung trafik på dårligt drænet og derfor pakningsfølsom jord kan være relativt små fordi jorden allerede inden behandlingen er blevet pakket i forbindelse med den almindelige trafik. Det foreslås at samspillet mellem dræningstilstand og jordpakning samt mere omfattende rodundersøgelser bør indgå i fremtidige pakningsstudier. Endvidere bør det undersøges i hvor stort et omfang tabene af lattergas til atmosfæren påvirkes af pakningen.

Predicting effects of soil compaction on crop yield and nitrogen dynamics

1. Introduction

Soil compaction caused by traffic with heavy machinery is considered to be a serious threat to sustainable plant production due to negative effects on crop yield, crop and soil quality, as well as the environment (Nawaz et al., 2013; Schjønning et al. 2009; Beare et al., 2009; Lipiec et al., 2003; Soane and Van Ouwerkerk (1995); Håkansson and Reeder, 1994). In particular, compaction of the soil below cultivation depth is considered a major problem, as the damage here is long-lasting and very difficult to repair. Studies have shown that subsoil compaction is widespread in Denmark (Schjønning et al. 2016a, 2009, 2002, 2000).

New compaction trials with heavy machinery were initiated at three localities in Denmark in 2010 (Taastrup, Flakkebjerg, and Aarslev) in collaboration between SEGES, Aarhus University and the University of Copenhagen. The main purpose was to shed light on any long-term effects of subsoil compaction on harvest yields in important agricultural crops. These trials are still ongoing, and it has been part of the COMMIT project to intensify both data collection (during the years 2017-2019) and data analysis in these experiments.

The agro-ecosystem model Daisy is a powerful tool for analyzing experimental data in agriculture, not least when it comes to being able to generalize and extrapolate from incomplete data sets obtained in specific years. In this report, ten years of measurements on soil and crops from the compaction trials are used in connection with the calibration of Daisy, and the model is then used to simulate expected long-term effects of subsoil compaction on plant production, nitrogen turnover and the environment. Specific questions that are sought to be answered are: How are yield levels, yield stability, nitrogen losses, and the environment affected in the long term?

The most complete measurement program offering the best conditions for the modeling work has been carried out at Taastrup, and the present report will therefore focus on this site.

2. Measured effects in field trial

2.1 Description of the compaction experiment at Taastrup

The experimental site, treatments and sampling have been described in details by Schjønning et al. (2011), Schjønning et al. (2016b), Nielsen (2014), Munkholm et al. (2014), and Petersen et al. (2018). Briefly, compaction was performed wheel-by-wheel (covering the whole area) in the spring at assumed field capacity in the topsoil in a randomized, four block design using vehicles with high wheel load (3, 6, or 8 Mg). Eight Mg wheel load was applied only once (in 2010) and will therefore not be considered much here whereas 3 and 6 Mg were applied every year from 2010 to 2013. Evaluated by all means, the repeated 6 Mg wheel load treatment represents the most severe compaction. An un-compacted reference was included as the fourth treatment. In the years 2013-2016, all plots were split in two, respectively with and without a cover crop (fodder radish) seeded right after harvest and supplied (at that time) with extra 30 kg N ha^{-1} to assure good establishment. Plots without the cover crop did not receive extra N. The fodder radish was grown in an attempt to mitigate soil compaction effects. The soil has been ploughed every year to about 25 cm depth. A sketch of the experimental layout is shown in Figure 2.1.

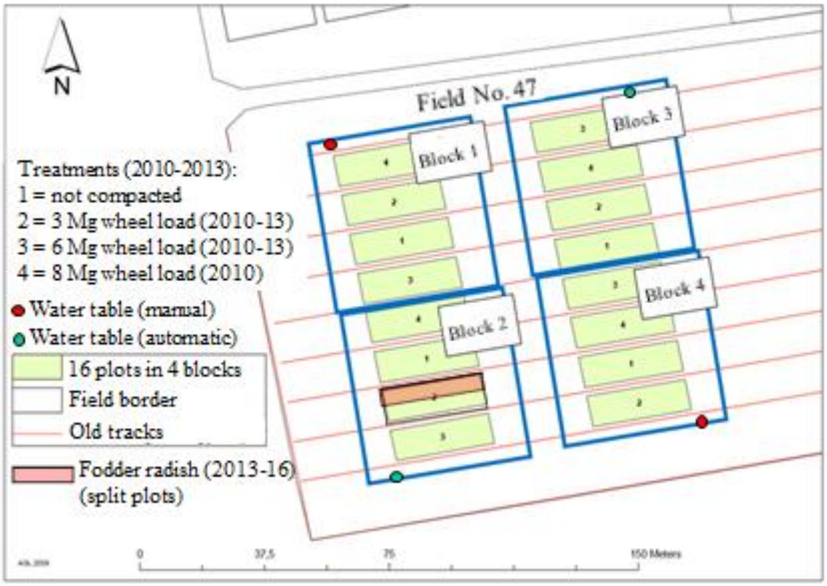

Figure 2.1. Sketch of the experimental layout for the compaction experiment at Taastrup. Compaction treatments (1-4) were conducted in the years 2010-2013. The plots were then split into two with a cover crop (fodder radish) established in the northern part only right after harvest of the main crop in the years 2013-2016. Extra 30 kg N ha^{-1} was applied to the cover crop at sowing. Also shown are locations for logging of the water table (automatic and manual logging).

2.2 Soil structure and hydraulic properties

Effects of heavy wheel loads and cover crops on soil structure and air permeability have been described in details by Munkholm et al. (2014), Munkholm and Schjønning (2015), Schjønning et al.

(2017), and Petersen et al. (2018), and the effects will only be summarized here to the extent necessary for modelling. Bulk density and air permeability were measured by Aarhus University.

2.2.1 Bulk density

Soil compaction is the increase of bulk density or decrease in porosity of soil due to externally or internally applied loads. Bulk density measured in 2014 after the last application of heavy wheel loads was clearly affected by the treatments (Figure 2.2). It increased significantly at all depths with increasing wheel load. Furthermore, it was highest right under the plough layer at 30-35 cm depth and lowest at 50-55 cm depth. The maximum average bulk density (1.77 g cm^{-3}) was measured at 30-35 cm depth after compaction with 6 Mg wheel load. The fact that higher bulk density was measured for the un-compacted treatment at 30-35 cm depth than at 50-55 cm depth indicates that the soil had been somewhat compacted already before initiating the experiments.

So, the applied heavy wheel loads compacted the subsoil clearly measurably to at least 70-75 cm depth. This will have affected both hydraulic and mechanical soil properties and should be considered in the modelling.

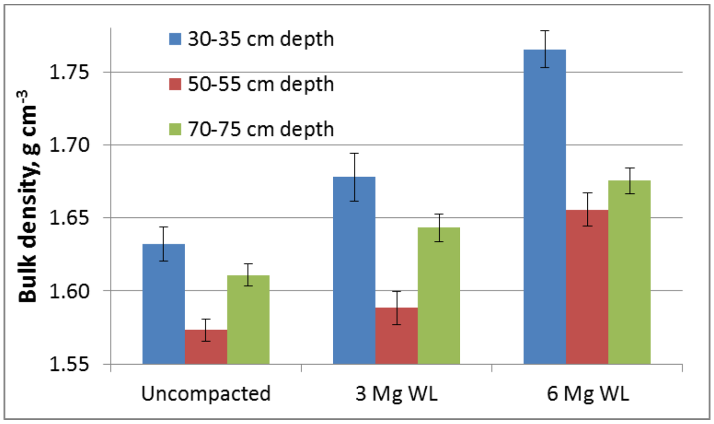

Figure 2.2. Bulk density measured at 3 depths (30-35, 50-55 and 70-75 cm) in the spring 2014 after the final compaction treatment (average ± standard error, n=36). Data for three treatments: un-compacted and compacted at field capacity in the spring every year from 2010 to 2013 with 3 resp. 6 Mg wheel load (WL) (Munkholm, L.J., personal communication; Vestergaard 2018b).

Bulk density after the different treatments varied considerably between the experimental blocks (Figure 2.3). Block 3 generally had lower bulk density than the other blocks, except for un-compacted soil at 70 cm depth. This may be related to higher resistance to soil compaction caused e.g. by a deeper A-horizon extending to > 50 cm depth (supported by data in Schjønning et al., 2011) or to better drainage (see Figure 2.4). It is necessary to consider this spatial variation when parameterizing the soil for modelling because it overlays the variation caused by compaction.

New sampling was performed in 2017 four years after the last compaction treatment (in 2013) and right after the last of four years with a cover crop (fodder radish). Sampling was this time performed at 30-35 and 50-55 cm depth in all split plots (with and without cover crop) within the un-compacted and 6 Mg wheel load treatments. There was no significant change from 2014 to 2017 in the bulk density at these two depths, not even a tendency, and the cover crop had no significant effect on the bulk density measured in 2017 (Pulido-Moncada et al., 2020).

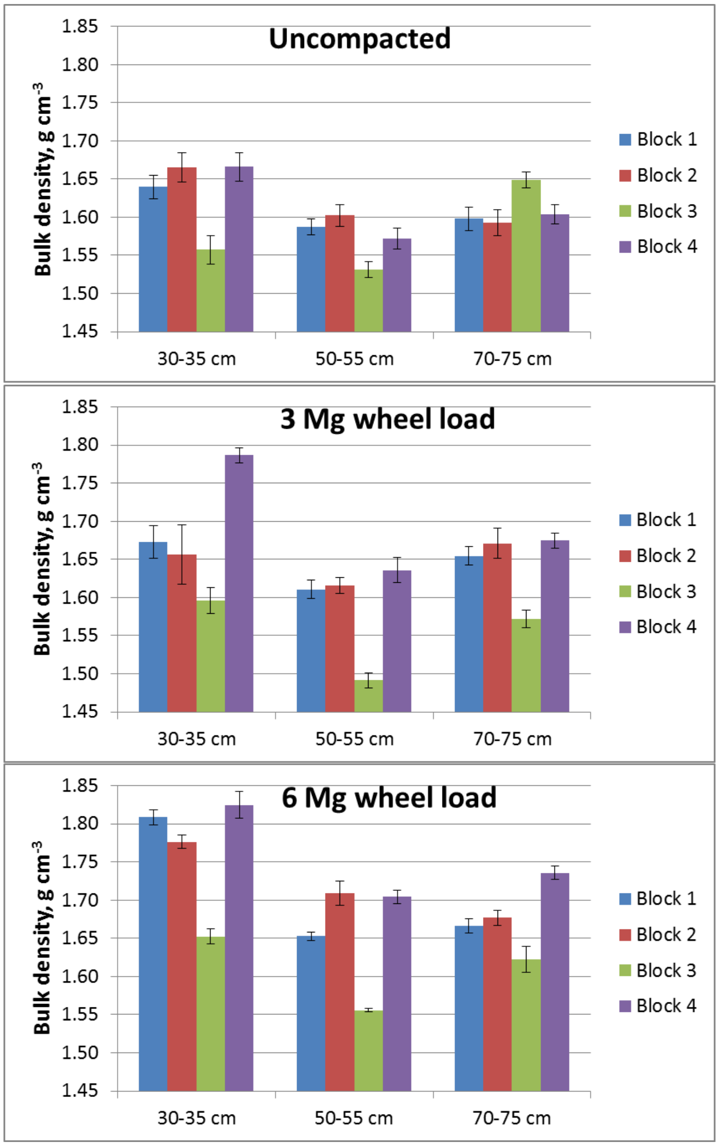

Figure 2.3. Bulk density measured at 3 depths (30-35, 50-55 and 70-75 cm) in 2014 after the final compaction treatment (average ± standard error, n=9). Data for the four blocks and three treatments: uncompacted and compacted at field capacity in the spring every year from 2010 to 2013 with 3 resp. 6 Mg wheel load (Munkholm, L.J., personal communication; Vestergaard, 2018b).

2.2.2 Air permeability

Air permeability plays a direct role for gas exchange in soil. Indirectly when measured in drained soil, it also expresses the maximum hydraulic conductivity which is obtained when the soil is fully saturated with water (e.g. Loll et al., 1999). Transport in continuous macropores (if present in a sample) will generally dominate over the matrix permeability. To represent permeability of the matrix outside macropores, samples with continuous macropores should therefore be discarded from the dataset.

Air permeability was measured in drained 100 cm^3 soil samples taken at 30-35 cm depth in the spring of 2012 before the last compaction treatments (Schjønning et al., 2017). It tended to be smallest for the treatment with 6 Mg wheel load but compaction effects were not statistically significant due to large variability observed (mainly) for this treatment. Saturated hydraulic conductivity estimated from measured air permeability using the general method of Loll et al. (1999) showed a lower ninety percent fractile of about 0.001 mm hour^{-1}, indicating that about 10% of the small samples from this treatment were in practice impervious to water, even when saturated. The median value was about 1 mm hour^{-1}. Air permeability measured in many small (manageable) soil samples, and derived saturated hydraulic conductivity, cannot be transformed directly to the field as absolute values due to scale effects. Permeability most likely increases with sample size until the minimum representative size for effects of continuous macropores is reached (Bouma, 1991). However, they can most likely express relative differences and thus to some extent effects of soil compaction on air permeability and saturated hydraulic conductivity.

Samples from 2014 used for bulk density determinations (see above) were used also for air permeability measurements (Table 2.1). Air permeability (k_a) was significantly larger at 50-55 and 70-75 cm depth than at 30-35 cm depth, and it was significantly smaller at 6 Mg wheel load than for treatments with smaller wheel loads. Similar conclusions were drawn when analyses were conducted with k_a^* (samples representing the soil matrix only). It is noticed that k_a^* is considerably smaller than k_a.

Table 2.1. Air permeability k_a (geometric mean values; n=36) measured at 100 hPa water suction. Data for three wheel loads (WL) and soil depths. The k_a^* values are for the soil matrix outside earthworm channels and are measured with a higher air pressure gradient in the soil similar to the one used by Loll et al. (1999) to facilitate the calculation of saturated hydraulic conductivity (Munkholm, L.J., personal communication; Vestergaard 2018b).

	k_a, µm^2			k_a^*, µm^2		
Depth, cm	0 Mg WL	3 Mg WL	6 Mg WL	0 Mg WL	3 Mg WL	6 Mg WL
30-35	24	21	5	9	9	2
50-55	124	83	42	26	18	5
70-75	103	49	39	18	19	8

[*] Measured to represent the soil matrix with a pressure gradient of 1.4 hPa cm^{-1}; samples with a high risk of dominance by macropore flow (at least one earthworm channel appearing at one end; 53% of all samples) have been discarded based on visual inspection during the measuring procedure.

Samples from the 30-35 and 50-55 cm soil layers in 2017 used for bulk density determinations (uncompacted and 6 Mg wheel load treatments; see above) were also used for measuring air permeability (k_a). The results were not significantly different from those obtained in 2014 (Table 2.1), and there were no significant effects of the cover crop although the permeability for the un-compacted treatment at 30-35 cm tended to be higher with the cover crop than without (Paludo-Moncada et al., 2020; Petersen et al., 2018).

Taken together, the measurements show that soil compaction with 6 Mg wheel load strongly reduces the permeability of the soil at 30-35, 50-55, and 70-75 cm depth. No change (increase) in permeability of the strongly compacted soil was observed between 2014 and 2017, and there was also no significant mitigating effect of fodder radish used as cover crop in the years 2013-2016. Compaction with 3 Mg wheel load tended to reduce the permeability measured in 2014 but the effect was not statistically significant.

2.2.3 Depth to the water table

Depth to the water table was measured at four locations that frame the experimental field and are close to each of the four blocks (Figure 2.1) during the wet autumn of 2017, and in the spring and summer of 2018 and 2019 (Figure 2.4). It appears that depth to the water table differs systematically between the different sites. Block 2 always has shallower water table than the other sites. Compared with Block 3 during the wet seasons, Block 2 has a much more dynamic water table extending at several dates in 2017-2018 all the way to the soil surface. Such events in Block 2 were confirmed both by manual loggings (Figure 2.4) and by visual inspection. Also soil mechanical differences (loadability) felt when walking in the field during wet periods seem to confirm the measured differences between Blocks.

Hence, the water table is generally shallower in Block 2 than in the other Blocks, and drainable porosity is smaller, most evident when comparing with Block 3. This is in good agreement with the lower bulk densities generally measured in Block 3 (Figure 2.3). The significantly lower bulk density in Block 3 than in Block 2 in 30-35 and 50-55 cm depth without a compaction treatment indicates that more compaction had taken place in the poorly drained Block 2 before the onset of the compaction experiment.

It is noticed that in the spring around April 1 (both years), the water table is located at about 60 cm depth in Block 2 whereas it is at about 100 cm depth in the other Blocks. At hydraulic equilibrium, the surface layer will therefore be close to field capacity in these other Blocks, whereas the water content will exceed field capacity in Block 2. Evaporation may reduce water content of the surface layer and thereby make this layer workable. However, a smaller suction will be maintained in the subsoil above the water table in Block 2 thereby increasing its water content and reducing its content of air and mechanical strength. Hence it is likely that Block 2 has been more prone to subsoil compaction than the other blocks when the compaction treatments were conducted in 2010-2013. This, however, is not clearly reflected in the measured bulk densities (Figure 2.3).

Since depth to the water table when being smaller than about 100 cm affects drainage and water content of the subsoil, and because simulated water contents need to be validated against measurements, it is needed to make the simulations separately for Block 2 and for other Blocks.

The experimental layout does not consider the drain system, and (average) distance to the tile drains may therefore differ between blocks, plots, and sites for soil water content measurements.

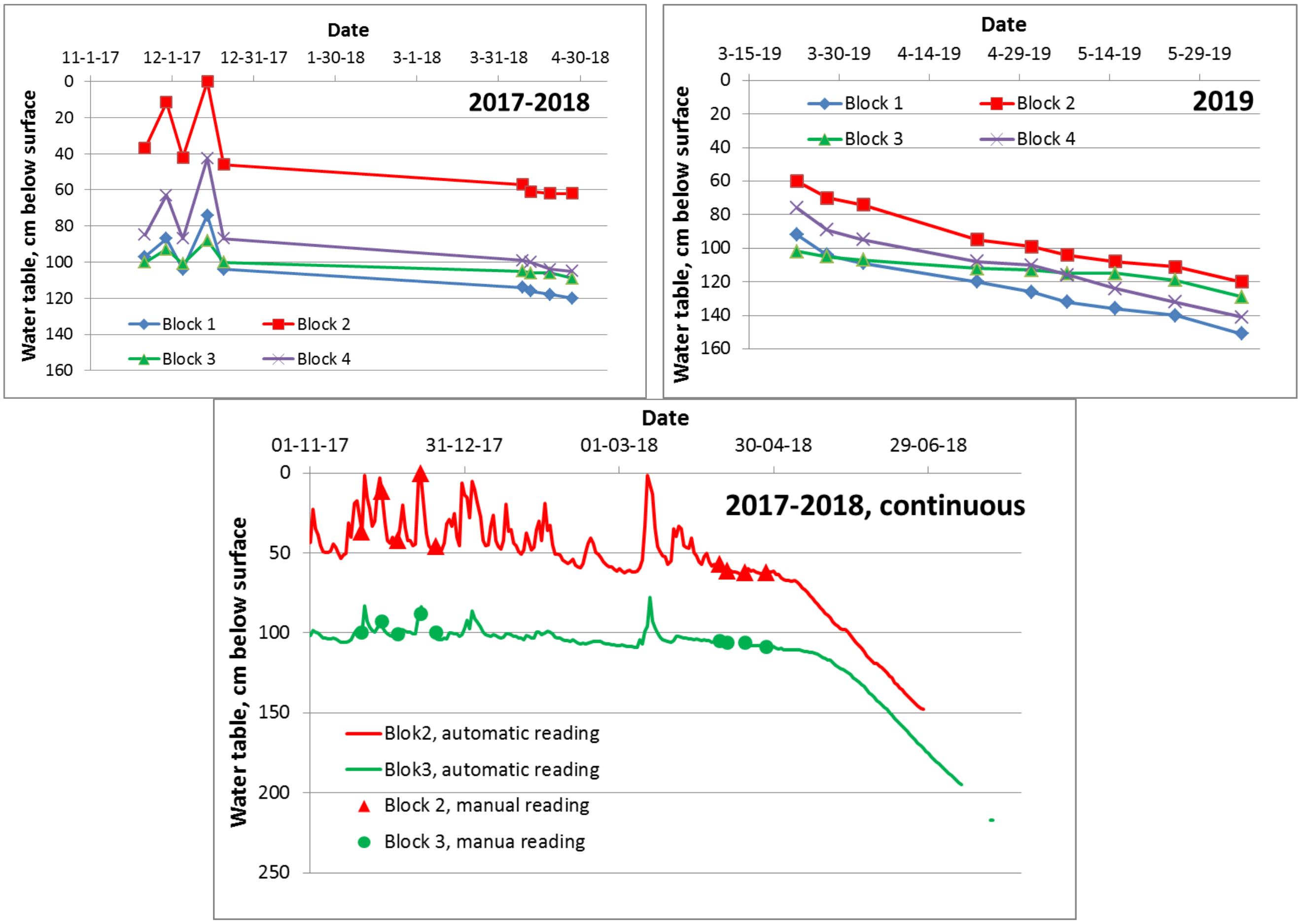

Figure 2.4. Depth to the water table measured manually and automatically in the 2017-2018 season and in the 2019 growth season. Data for the four experimental Blocks.

2.3 Canopy development and crop yield

Effects on canopy development and crop yield have been reported annually in "Oversigt over Landsforsøgene". Results are included here because canopy development and crop yield are important for calibrating/validating the crop module in Daisy. Daisy must be able to simulate crop growth and yield in order to simulate nitrogen balances.

Canopy development has been characterized by measuring Relative Vegetation Index (RVI) during the growth season in all years from 2010-2019, using methods (including equipment) described by Petersen et al. (2002). RVI expresses the amount of green vegetation (canopy). It reaches saturation when the amount becomes large (Green Leaf Area Index (GLAI) in cereal crops > about 3.0, or RVI > about 12), and is therefore most sensitive during early and late growth stages. RVI can be transformed into GLAI (Petersen et al. 2002) which is used in Daisy.

No statistically significant repercussion of the compaction treatments on RVI have been found at any time during the 3-year period from 2017-2019. By contrast, small, but statistically significant, positive effects of the previous cover crop (which is supplied 30 kg N per ha at sowing) on RVI are measured in all three seasons (Figure 2.5). In 2017, this positive effect was significant at all measuring dates from June 1, in 2018 from May 17, and in 2019 at all measuring dates. No significant interaction with respect to RVI was measured between compaction treatments and cover crop in 2017 or 2018. In 2019, there was a significant interaction with larger positive effects of the cover crop for the un-compacted reference treatment than for the compaction treatments (particularly 6 Mg wheel load).

Differences in canopy development expressed by RVI (Figure 2.5) could not be observed visually in the field, except in one case (last measuring date in June 2019). It is noticed that RVI peaks at a much smaller value (about 8.5) in the extremely dry year 2018 compared with 2017 and 2019. A RVI of 8.5 can be transformed into a GLAI value of about 1.7 which means that the amount of green canopy was too small, even at the peak value, to take full advantage of the sunlight in photosynthesis (requires GLAI > about 3).

The RVI measurements were to some extent reflected in the yields of dry matter in grains (Table 2.2). There were no significant effects of any compaction treatment in any of the years (Bennetzen, 2017; Vestergaard, 2018a; Vestergaard, 2019). There were significant positive effects of the cover crop in 2017 and 2018. This was not the case in 2019 although yields tended to be higher with the cover crop. In terms of grain yield, there were no statistically significant interactions between compaction treatment and cover crop. The effect of the cover crop + extra 30 kg N ha^{-1} on the main crop yield during the years 2013-2016 determined as the average for 2017-2019 was 0.28 Mg ha^{-1} of dry matter and 5.8 kg of N per ha.

Table 2.2. Harvested dry matter (DM) and nitrogen (N) in grains in the years 2017, 2018, and 2019. Average values (n=4) for the different compaction treatments (Comp. trt; see detailed explanations in Figure 2.1) with (+) and without (-) a previous cover crop.

		2017 (spring barley)		2018 (winter wheat)		2019 (winter wheat)	
Comp. trt.	Cover crop	DM in grains, Mg ha^{-1}	N in grains, Kg ha^{-1}	DM in grains, Mg ha^{-1}	N in grains, Kg ha^{-1}	DM in grains, Mg ha^{-1}	N in grains, Kg ha^{-1}
0 Mg	-	6.42	96.6	5.98	92.4	7.77	123.6
	+	6.73	98.0	6.21	98.0	8.73	139.2
3 Mg	-	6.74	101.4	5.89	92.9	7.64	123.2
	+	7.21	109.5	6.18	97.5	8.29	135.5
6 Mg	-	6.61	99.4	5.76	89.0	8.11	128.9
	+	6.78	103.1	5.87	93.6	7.71	130.8
8 Mg (2010)	-	6.72	96.8	5.77	90.1	8.3	132.3
	+	7.21	107.3	5.92	91.4	8.22	131.8

So, there has been no statistical significant effect of soil compaction in the years 2017-2019, neither on the amount of green canopy (RVI), nor on harvested grain yield. However, there was significant positive legacy of the previous cover crop in the years 2013-2016 (including 30 kg ha^{-1} year^{-1} of extra N) on RVI in all the years 2017-2019, and on grain yield in the years 2017 and 2018.

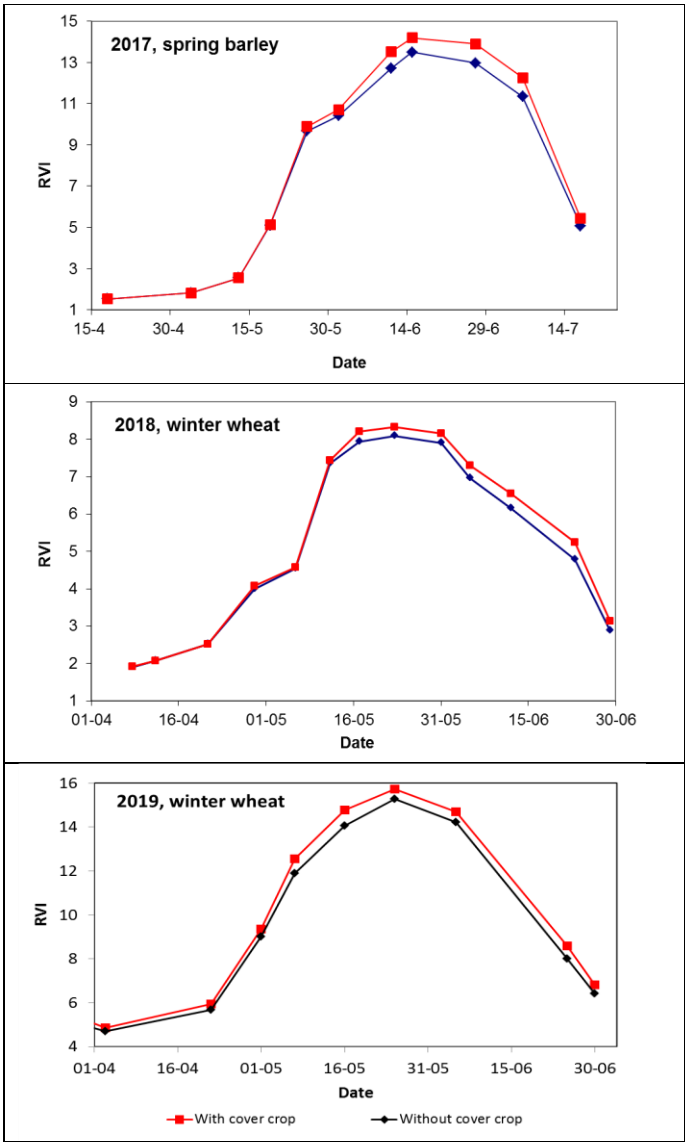

Figure 2.5. Relative Vegetation Index (RVI) measured during the growth seasons of 2017-2019 in plots with and without a previous cover crop, respectively. Each marker represents the average of n=128 observations covering each about 1.0 m^2 (eight randomly distributed samples per plot). Standard errors cannot be shown because they are (generally) hidden behind the markers. With the measuring equipment used, RVI is approx. 1.52 for a bare and dry soil surface after seedbed harrowing and approx. 2.4 for a fully ripe (wilted without green weeds) and dense cereal crop. Notice the different scaling of the y-axes.

Some clear trends with respect to soil compaction can be seen in the yield data even though statistical significance is hard to obtain. When averaged over the years 2014-2017 (years with spring barley in the ploughed system in Taastrup after the annual compaction treatments had stopped), severe compaction (6 Mg wheel load in the years 2010-2013) tends to decrease both dry matter yield and nitrogen yield in grains (Table 2.3). These effects seem to be mitigated or removed by the inclusion of the cover crop.

Table 2.3. Harvested grain yield (dry matter with 15 % moisture and nitrogen) in spring barley. Average values in 2014-2017 for the different compaction treatments (0-8 Mg wheel load; see detailed explanations in Figure 2.1) with (+) and without (-) a cover crop in 2013-2016. Source: Nielsen (2014) and Bennetzen (2017).

Compaction	*0 Mg*		*3 Mg*		*6 Mg*		*8 Mg (2010)*	
Cover crop	-	+	-	+	-	+	-	+
Average yields 2014-17	*Grain yield, hkg/ha (standard quality, i.e. 15 % moisture in dry matter)*							
	75.8	***78.4***	*76.8*	*79.3*	***73.4***	***76.5***	*75.9*	*78.9*
	Nitrogen yield in grains, kg/ha							
	95.2	***97.9***	*100.1*	*103.3*	***93.9***	***98.2***	*94.0*	*99.1*

2.4 *In-situ* soil water content

Water content was measured at different soil depths from 0.1 to 1.0 m and at different dates from 2017 to 2019 with a multi-sensor capacitance PR2 Profile Probe (Delta-T Devices Ltd, Cambridge, UK). The measurements were conducted for treatments with 0 and 6 Mg wheel load. These measurements have earlier been presented in some details (Petersen et al., 2017; Petersen et al., 2018; Petersen et al., 2019; Pulido-Moncada et al., 2020). Here, results that focus on treatment effects will be summarized to support model calibration.

In 2017, volumetric water content was measured 13 times in plots without a previous cover crop distributed over the whole growing season. Compaction with 6 Mg wheel load in the years 2010-13 clearly affected the measured water content and the water distribution (

Figure 2.6). When the soil was wet in and just below the plow layer (0-25 cm depth), the water content was generally highest in the compacted plots. This may be because drainage was inhibited in and by the compacted soil under the plough layer (Figure 2.2 and Table 2.1). The air content will be low in compacted soil at 30 and 40 cm depth which add to the general increase in volumetric water content measured at these depths. This effect of compaction on air space will be taken into account during the simulations. At 30 cm depth in the plough pan, up to on average 8.6% higher water content was measured in compacted plots than in un-compacted plots.

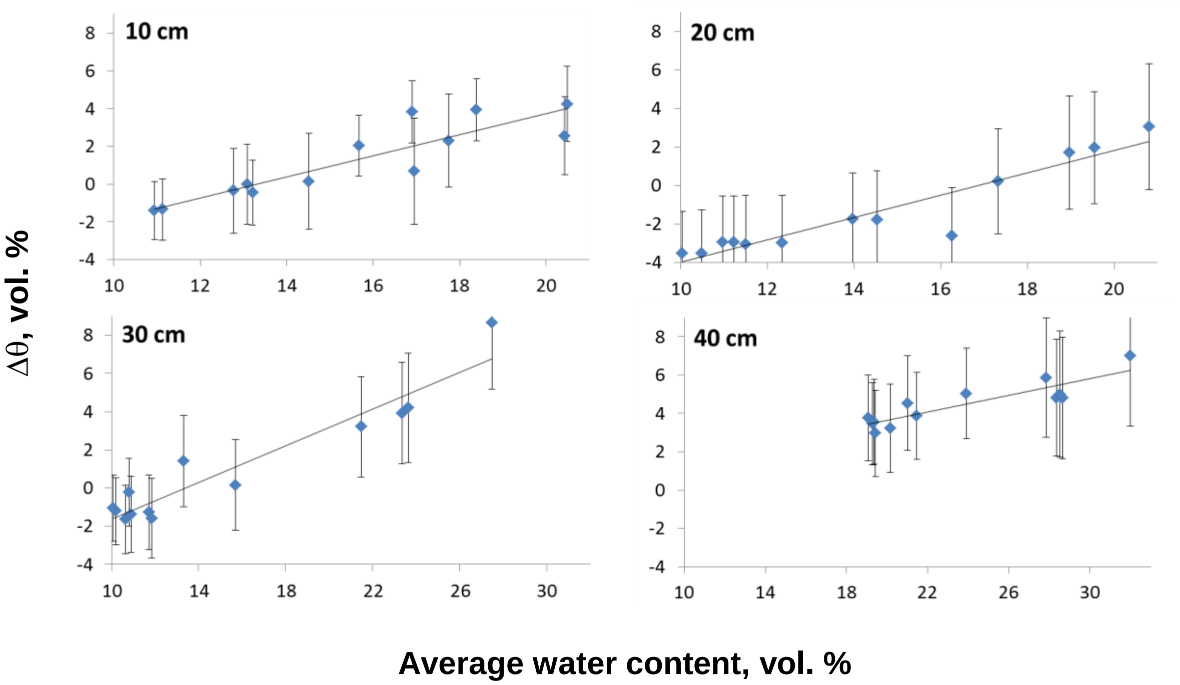

Figure 2.6. Difference between average volumetric water content measured in plots compacted with 6 Mg wheel load and in un-compacted plots ($\Delta\theta$; n = 8) as a function of overall average water content. Data for four depths (10, 20, 30 and 40 cm) and 13 dates distributed on the whole growing season in 2017 (crop: spring barley). Significant regression lines as well as 95% confidence intervals are included.

Water contents at 10 and 20 cm depth in the plough layer was also systematically affected. The soil was wetter in compacted plots during wet periods, particularly at 10 cm depth, even though it has been ploughed annually and not been exposed to heavy traffic since 2013. But the plough layer also gets drier in dry periods, especially near the bottom at 20 cm depth. Roughly the same pattern is seen at 30 cm depth immediately below the plough layer. This tendency for stronger drying out of the bottom region of the furrow layer in compacted plots may be due to higher root activity caused by difficulties in penetrating the subsoil.

At a depth of 40 cm, the average water content does not fall below 19.1%, and thus neither compacted nor un-compacted plots get close to the wilting point (about 10 vol.%). This may be due to a combination of low root activity, uneven root distribution and abundant rainfall in 2017. The water content is in all cases significantly higher in compacted plots than in unpacked plots.

Significantly higher moisture contents in the subsoil of compacted plots as well as in the topsoil of compacted plots under wet soil conditions (poorer drainage) were also measured in 2018. Measurements at 15 cm depth in the middle of the subsoil and in the plough sole at 35 cm depth are shown as examples in Figure 2.7. The shown overall tendencies are clear even though also the spatial variability is high as indicated by large standard errors. Much of this spatial variability can be removed due to the experimental design (not shown). It is noticed that in late June after a prolonged hot and dry period, moisture content of the topsoil gradually drops to about 6 vol. % which is well below the wilting point.

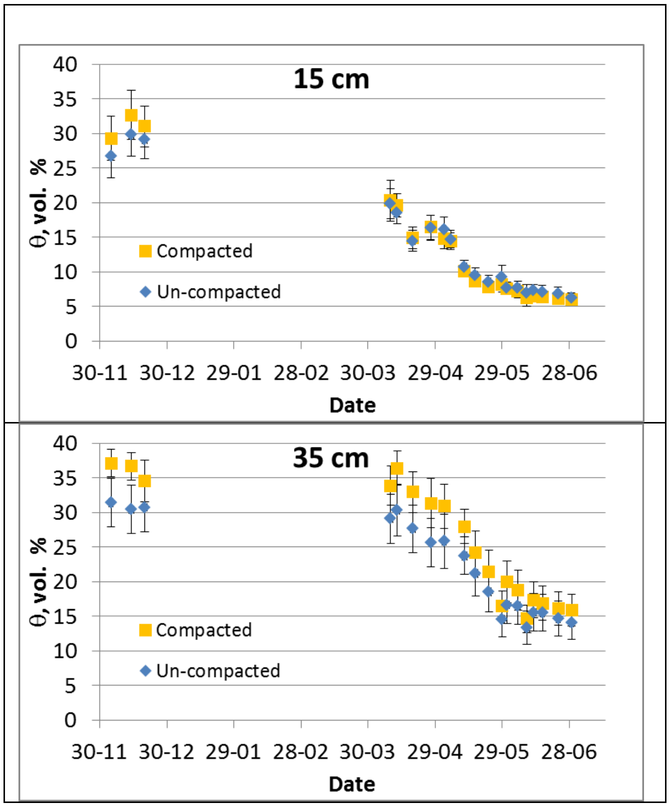

Figure 2.7. Moisture content in December 2017 and in the growing season of 2018 (crop: winter wheat) measured in plots compacted with 6 Mg wheel load and in un-compacted plots at 15 cm depth and at 35 cm depth (overall average for plots with and without a previous cover crop (n=16) and with standard errors shown as bars).

Much less rainfall was received in the extremely dry 2018 growing season than in 2017, and water extraction by evapotranspiration from the soil reservoir was therefore higher. We assume that volumetric water content measurements conducted at 10, 20, 30, 40, 50, 60, 90 and 100 cm depth can be used to calculate the total amount of water stored in the soil profile to 110 cm depth, and not least to calculate changes of this quantity. Water content in the profile is subject to spatial variability as affected not least by drainage conditions which differ considerably between Blocks (Figure 2.4). Measured water content in the poorly drained Block 2 and the well-drained Block 3 are shown in Figure 2.8. It appears that the water content is about 50 mm higher in poorly drained block. Water contents of Block 1 and 4 are generally between these two extremes. So, it is necessary to consider water table depth when simulating soil water contents. In late June in 2018 when the crop is in the ripening phase and water consumption ceases, there is still between 200 and 250 mm of water left in the profile meaning that the soil is far from being at the wilting point.

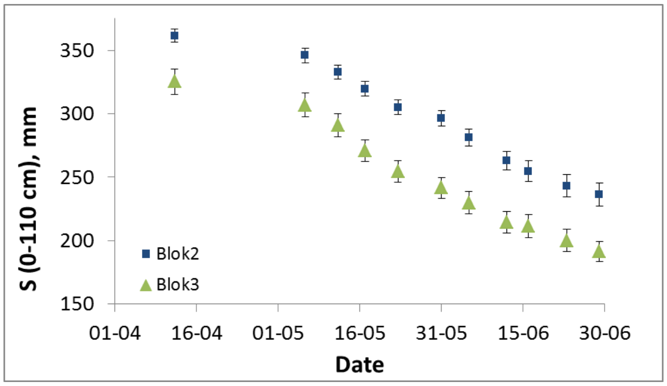

Figure 2.8. Total water content in the soil profile (S (0-110 cm); mean values with standard errors shown as bars; n = 8) measured in Block 2 and 3, respectively, during the period 1 April - 30 June 2018.

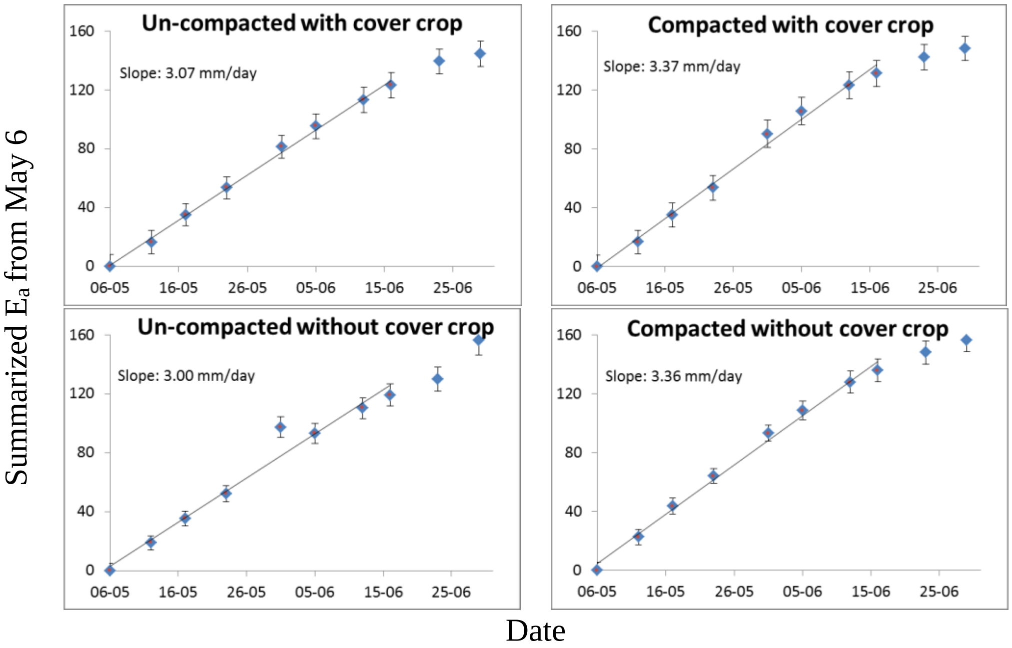

Figure 2.9. Summarized evapotranspiration (E_a) for the period May 6 to June 29 2018 calculated as rainfall plus decrease in root zone water content (0-110 cm depth). The results are for un-compacted plots and plots subjected to 6 Mg wheel load with and without a previous cover crop, respectively (average values with standard errors shown as bars; n = 8). Calculated evapotranspiration from the 0-110 cm layer is fairly constant during the period 6 May - 16 June and is shown as slopes on the figure.

In early May, the groundwater level is beginning to decline (Figure 2.4). If water movements at the bottom of the root zone (110 cm depth) are initially disregarded, the water consumption for evapotranspiration can be calculated according to the water balance method as precipitation plus decrease in the measured water content. Average values for evapotranspiration thus summarized from May 6 can be seen in Figure 2.9. The slopes express the evapotranspiration in mm per day. These are fairly constant until approx. mid-June and thereafter decreasing in accordance with a rapidly decreasing green leaf area of the wheat crop (Figure 2.5). As an average for the period up to 16 June, the evapotranspiration is determined to be between 3.0 and 3.4 mm day^{-1}, with a tendency for slightly higher values in the compacted plots (not statistically significant). The use of fodder radish as cover crop in the years 2013-2016 also did not affect the calculated water consumption. The soil compaction treatment did not significantly affect wheat grain yields in 2018 which is remarkable because the crop clearly suffered from water stress (Vestergaard, 2018a). Similar results were obtained in similar field experiments at Flakkebjerg and Aarslev.

The estimated evapotranspiration rates (Figure 2.9) are small compared to the period's exceptionally high reference evapotranspiration (on average 4.2 mm day^{-1}) calculated from weather observations according to Penman's method. It is likely that some unknown amount of water has been extracted also from below 110 cm depth. And it is possible that the tendency of smaller water extraction from 0-110 cm depth in un-compacted plots was offset by higher water extraction below 110 cm made possible by deeper root development (see also 2.6).

Measurements of soil water in 2019 overall confirm results from 2017 and 2018: soil compaction hampered drainage in the compacted subsoil and (somewhat less evident though in 2019) in the un-compacted topsoil (Petersen et al., 2019). Water extraction from the 0-110 cm soil layer (on average 2.9 mm day^{-1} during the 69 days period with maximum green canopy or slightly less than in 2018) was very similar for the different treatments ($\pm$ 6 Mg wheel load and $\pm$ cover crop). This figure can be compared with an average reference evapotranspiration of 3.4 mm day^{-1}. There were no significant treatment effects on crop yield (crop: winter wheat), neither from compaction nor from the cover crop (Vestergaard, 2019). The average dry matter grain yield considered as “normal” for the site was 8.10 Mg ha^{-1}, 35% higher than in the very dry year 2018 (Table 2.2). In late June, the water content of the soil profile (0-110 cm) was on average 63 mm higher than in 2018.

Taken together, measured *in-situ* soil water content shows reduced and/or delayed drainage in compacted plots, both in the compacted subsoil layers and in the loosened (ploughed) topsoil. Poor drainage (a shallow water table) also reduces drainage and may overlay the effect of soil compaction. Poor drainage and soil compaction may interact and reinforce each other. So, possible water table effects need to be considered when simulating effects of soil compaction on drainage and soil water content. Measured soil water content in combination with canopy development and final crop yield did not indicate or show better root development, more efficient water uptake or less water stress in severely compacted plots than in un-compacted plots. There was also no clear effect of the cover crop on water extraction from the profile, not even in the extremely dry year 2018. Yields were significantly higher though in 2017 and 2018 in plots with a previous cover crop, and it tended to be higher also in 2019 (Bennetzen, 2017; Vestergaard, 2018a; Vestergaard, 2019). This effect may be closer related to better access to soil nitrogen than soil water.

2.5 Mineral nitrogen in the soil

Mineral nitrogen content in the soil profile (0-50 cm depth and 50-100 cm depth) was measured by Aarhus University in December 2017 and 2018 (Table 2.4). Significantly more mineral nitrogen was left in the soil after the very dry growth season in 2018 than in 2017. There were no significant treatment effects, neither from the most severe compaction with 6 Mg wheel load, nor from the cover crop (including 30 kg N ha^{-1} at sowing).

Table 2.4. Amount of mineral nitrogen (ammonium and nitrate) measured in the soil in December 2017 and 2018. Averages based on sampling in all plots (n=4) with standard errors in brackets (Munkholm, L.J., personal communication).

		Mineral N in soil (N_{min}), kg ha^{-1}			
		December 12, 2017		December 12, 2018	
Depth, cm	Cover crop	Un-compacted	6 Mg wheel load	Un-compacted	6 Mg wheel load
0-50	+	15.0 (1.0)	12.8 (0.6)	60.6 (2.9)	69.2 (7.8)
	-	14.1 (2.5)	12.0 (1.5)	51.9 (1.7)	50.1 (3.0)
50-100	+	7.9 (1.9)	7.5 (1.9)	52.3 (5.5)	50.5 (2.9)
	-	10.2 (3.1)	10.0 (2.9)	38.1 (1.7)	45.0 (2.3)

2.6 Root growth

No direct measurements of roots were conducted at Taastrup. Results measured by Aarhus University in very similar experimental set-ups at Flakkebjerg and at Aarslev are mentioned here as a reference.

Root growth was measured in the cover crop (fodder radish) on October 18, 2013 and in the following main crop (spring barley) on July 22, 2014 at Aarslev in a compaction experiment very similar to the one at Taastrup (Munkholm et al., 2014). Root growth of the cover crop (sown right after harvest) extending below 70 cm depth was unaffected by the compaction treatments. In the barley crop at 30 cm depth, however, root intensity was significantly larger in un-compacted plots than in plots compacted repeatedly with 3 or 8 Mg wheel load. At 50 cm depth, root intensity was smaller in plots compacted with 8 Mg wheel load than in plots subjected to less or no heavy wheel loads, whereas there were no significant compaction effects at 70 cm depth.

Root growth was also measured at Aarslev in 2015(Munkholm et al., 2016). These measurements were conducted in spring barley close to the time for flowering in June. The root density was significantly smaller at 30 and 50 cm depth in plots subjected to the largest wheel load (8 Mg as compared with 3 and 0 Mg). There were no measurable compaction effects on root density at 10, 70 or 90 cm depth.

3. Daisy modelling

A mechanistic model of a system (like Daisy) is an expression of the modelers understanding of the system, and as such the model simulations can help to highlight where this understanding is lacking when held up against measurements. Furthermore, the model simulations can be used for extrapolation beyond what has been measured. In the present project we do both. In section 3.1 we describe how the model is calibrated from soil and groundwater data, and RVI measurements. In section 3.2 we compare the yields predicted by the model with measurements. Finally, in section 3.3 we use the model to make educated guesses about how different cropping systems would react to compaction under different soil, weather and climatic conditions, as well as with different assumptions about how root development is affected.

As the most notable and consistent measured data is from the Tåstrup site, we have focused on that site for the modelling. The Tåstrup site is divided into 4 blocks that differ with respect to soil conditions and treatment effects (section 2.1). The modelling focuses on two blocks: Block 2, which is poorly drained, and Block 3, which is well drained (see section 2.2.3). Within each block, there are four different levels of compaction treatments (section 2.1). However, only the extreme treatments, i.e. the 0 Mg (un-compacted) and the repeated 6 Mg wheel load treatment, have been simulated.

The same crop rotation has been applied on the whole field, with spring barley from 2010 to 2017, and winter wheat in 2018 and 2019. However, each plot was split in two in 2013. A cover crop (fodder radish) was sown in half of the plots after harvest of the spring barley in the years 2013-2016 together with the addition of extra 30 kg N/ha. This extra nitrogen was not applied to plots without the cover crop. To see the long-term effect, this split was maintained in in all years after 2013. We have simulated both with and without the cover crop.

3.1 Calibration

The soil calibration was based mostly on direct measurements (e.g. section 0 and 2.4). Groundwater measurements were used for the lower boundary. RVI measurements were used in calibrating the spring barley (section 3.1.2). Usually the last calibration step is the soil organic nitrogen system; however, the best data we have are from 2019, which was problematic to model, and the remaining observations did not point in a specific direction. In the end, we used the default values for the soil organic nitrogen system, without any calibration.

3.1.1 Soil

3.1.1.1 Soil hydraulics

The soil calibration was performed based on direct measurements of soil properties, including soil water and groundwater (section 2). Texture data is from the initial characterization of the experimental site (Schjønning et al., 2011), while dry bulk density (ρ_b) for the topsoil and for the deep bottom horizons are obtained from Christensen (2011). Hydraulic effects of compaction are also documented in Vestergaard (2018b). Hydraulic properties were estimated with the HYPRES pedotransfer function (Wösten et al., 1999), except in three cases:

1. K_{sat} below the plough layer in the compacted soil was adjusted based on measured air permeability.
2. An anisotropy factor of 10 (water prefers to move laterally in wet soil) was applied to the top soil.
3. An anisotropy factor of 40 was applied in Block 3 in the layer containing drains.

For simplicity, we have focused the simulations on two blocks (2 and 3) and two treatments (no compaction and 6 Mg wheel load), giving us four soil columns for the simulations. An overview of the data can be found in Table 3.1.

Table 3.1. Soil data for the four columns used in the simulations: bulk density (ρ_b), saturated hydraulic conductivity (K_{sat}; vertical direction), organic matter contentment (OM), and textural distribution on classes (Clay, Fine silt, Coarse silt, Fine sand, and Coarse sand). Also given is the ratio between saturated hydraulic conductivity in the horizontal and the vertical directions (Anisotropy).

Depth	ρ_b	K_{sat}	**OM**	**Clay** < 2 µm	**Fine silt** < 20 µm	**Coarse silt** < 63 µm	**Fine sand** < 200 µm	**Coarse sand** < 2000 µm	**An-isotropy**
cm	g cm^{-3}	mm h^{-1}	(g g-1)*100						
Block 2, no compaction									
0-25	1.57		2.5	20.0	18.7	9.0	26.0	23.8	10
25-35	*1.67*		1.1	25.1	17.4	10.1	24.0	22.2	1
35-55	*1.60*		1.1	25.1	17.4	10.1	24.0	22.2	1
55-115	*1.59*		0.5	23.0	18.0	12.2	20.9	19.6	1
115-200	1.86		0.5	23.0	18.0	12.2	20.9	19.6	1
Block 2, 6 Mg compaction									
0-25	1.57		2.5	20.0	18.7	9.0	26.0	23.8	10
25-35	*1.78*	*0.31*	1.1	25.1	17.4	10.1	24.0	22.2	1
35-55	*1.71*	*0.40*	1.1	25.1	17.4	10.1	24.0	22.2	1
55-115	*1.68*		0.5	23.0	18.0	12.2	20.9	19.6	1
115-200	1.86		0.5	23.0	18.0	12.2	20.9	19.6	1
Block 3, no compaction									
0-25	1.57		2.6	17.6	17.5	11.0	27.1	24.4	10
25-35	*1.56*		1.6	17.8	16.9	11.9	24.6	27.3	1
35-55	*1.53*		1.6	17.8	16.9	11.9	24.6	27.3	1
55-115	*1.65*		0.6	22.4	17.6	12.7	24.6	22.2	*40*
115-200	1.86		0.6	22.4	17.6	12.7	24.6	22.2	1
Block 3, 6 Mg compaction									
0-25	1.57		2.6	17.6	17.5	11.0	27.1	24.4	10
25-35	*1.65*	*0.56*	1.6	17.8	16.9	11.9	24.6	27.3	1
35-55	*1.56*	*0.62*	1.6	17.8	16.9	11.9	24.6	27.3	1
55-115	*1.62*		0.6	22.4	17.6	12.7	24.6	22.2	*40*
115-200	1.86		0.6	22.4	17.6	12.7	24.6	22.2	1

3.1.1.2 Lower boundary

Below 2-meter depth, Daisy assumes the presence of an aquitard defined by a depth and a conductivity and below the aquitard the presence of an aquifer defined by a pressure. None of these three numbers has been measured directly; instead, they are calibrated based on the measured groundwater level. The depth of the aquitard was set to 2 meters, and the conductivity then calibrated to 0.015 mm h^{-1}. The pressure of the aquifer was set divided into a dry season from July 1 to October 1, and a wet season from October 1 to May 1. Between May 1 and July 1, the aquifer pressure is assumed to decrease linearly. In the dry season, the aquifer pressure corresponds to a hydrostatic water level at the top of the aquitard (2 meter) which is the default value in Daisy. In the wet season, the aquifer pressure corresponds to a hydrostatic water level at the effective drain depth. The effective drain depth in block 2 is 110 cm under terrain, which is a common depth for drainpipes in Denmark. However, in the poorly drained block 3 the effective drain depth is set to 80 cm under terrain.

Using this information, Daisy can calculate a dynamic groundwater level, which is shown in Figure 3.1.

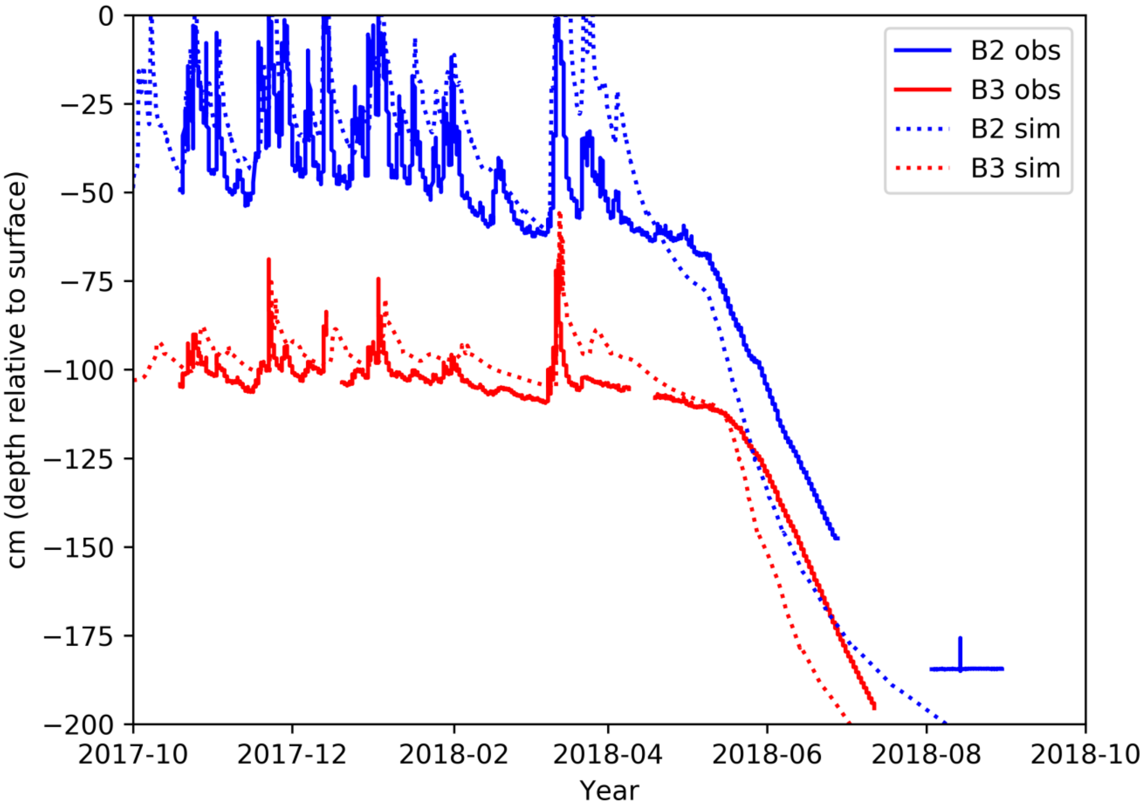

Figure 3.1. Measured and simulated groundwater table for Block 2 (B2) and Block 3 (B3). The elevation of the water table ("depth") is given relative to the soil surface. The simulated data is for the 0 Mg treatment with no cover crop.

3.1.2 Crop

The spring barley was initially calibrated using RVI data and yield for the non-compacted treatment on block 2 with no cover crop, then generalized together with general harvest data from SEGES with special focus on N response. This latter process is documented in Styczen et al. (2020) and Styczen and Abrahamsen (2017). See Figure 3.2. The winter wheat was calibrated with data from other fields (and literature), documented in Gyldengren et al. (2020). The cover crop was not calibrated.

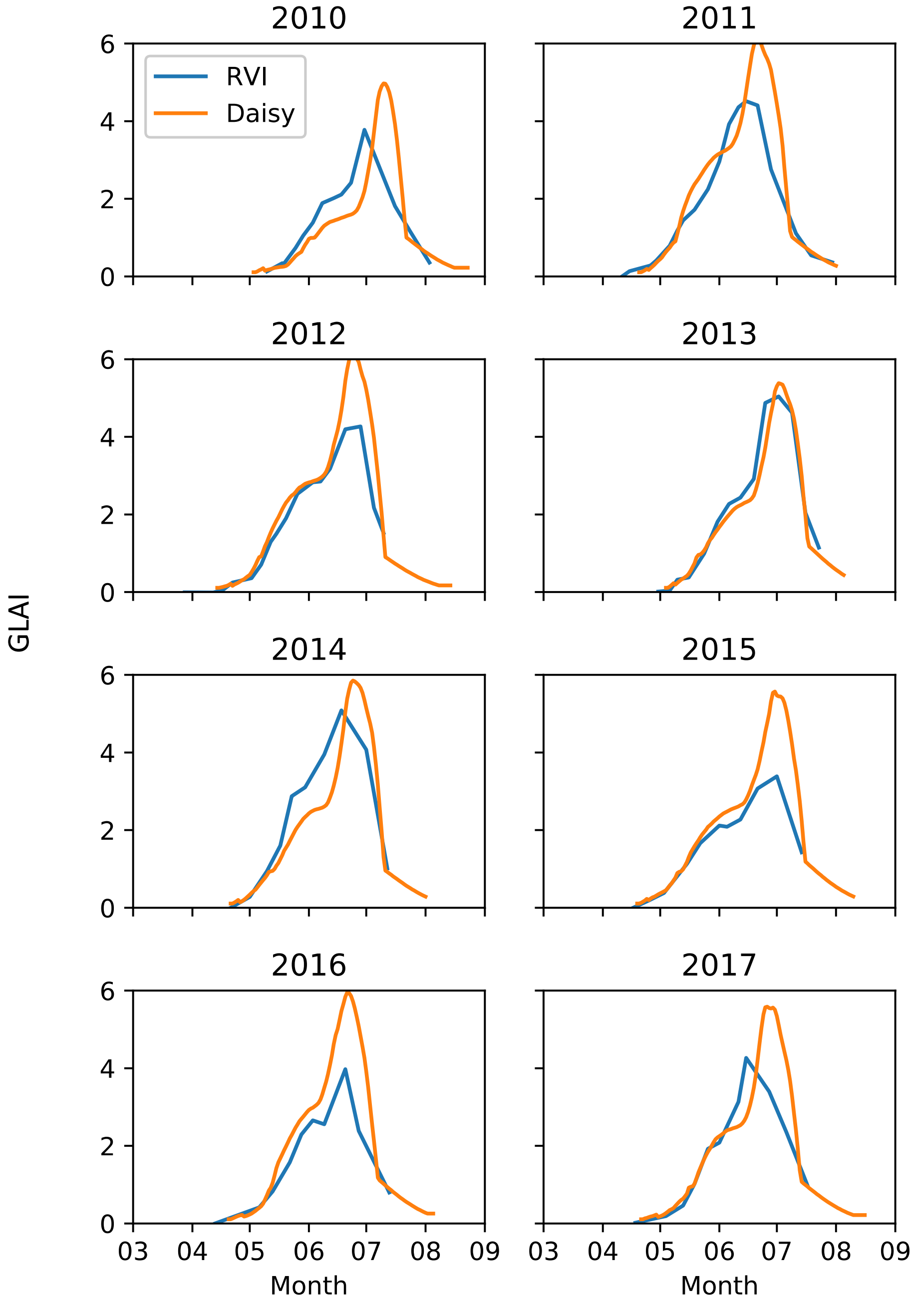

Figure 3.2. Green Leaf area index (GLAI) of spring barley in uncompacted plots without cover crop based on relative vegetation index (RVI) measurements conducted during 8 years at the Taastrup field site (blue curves) compared to simulated GLAI (red curves). Simulated values are from Block 3.

3.2 Comparison of measured and simulated yield

There were three different sets of yield measured. Harvest grain “wet” weight (standard quality, i.e. 15% moisture in grain dry matter) was measured in all years and for all blocks. The measurements can be seen in section 3.2.1 together with simulated data when available. There were also field scale measurements of grain dry matter and nitrogen all years (average values for all blocks), as well as straw dry matter for the winter wheat. We don’t have a field scale simulation, but the measured numbers for the field are presented together with simulated values for Block 2 and Block 3 (section 3.2.2).

3.2.1 Dry matter in grains at the block level

Grain wet weight (15 % moisture in dry matter, i.e. standard quality) was observed separately for each block and treatment, but only two blocks (2 and 3) and two treatments (0 Mg and 6 Mg) have been simulated. The simulated grain yield is shown together with observed yield for all blocks on Figure 3.3 and together with all treatments on Figure 3.4. Finally, protein content in grains measured for all blocks and all treatments in 2019, is presented together with simulated values in section 3.2.3.

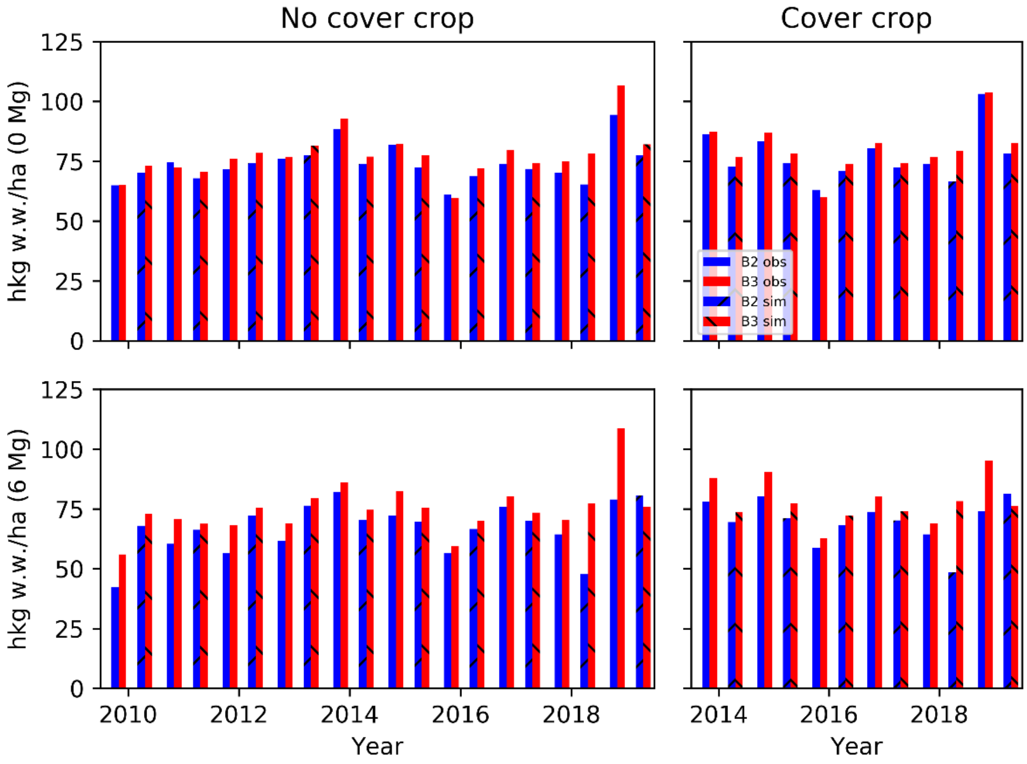

Figure 3.3. Observed (average) and simulated grain yield (wet weight (w.w), i.e. dry matter with 15 % of moisture) in Block 2 (B2; poorly drained) and Block 3 (B3; well drained) for uncompacted soil (0 Mg) and compacted soil (6 Mg). From 2010 to 2017 the crop is in spring barley, for 2018 and 2019 it is winter wheat. In 2013 the plots where split in two, with one half getting a cover crop after harvest of the spring barley.

On Figure 3.3 we see that simulations and observations agree to the general trend that poor drainage (comparing Block 2 and Block 3) leads to lower yield, and the cover crop to higher yield. For the simulation, the latter is due to the extra 30 kg N/ha of nitrogen, as the soil physical properties were not altered.

On Figure 3.4 we see that the compacted soil in general have lower yield than the uncompacted soil. However, measured differences are small or absent after the last compaction treatment in 2013. For the simulation, 2019 on poorly drained soil is the only exception. We have not analyzed why, and this effect is not observed. The difference in simulated values for the dry year 2018 is mostly due to water stress. All four 2018 simulations have approximately two weeks of production lost due to nitrogen stress. The well-drained soil (Block 3) has additionally 4-5 days of production lost due to water stress. The poorly drained soil (Block 2) has 19 days of production lost due to water stress in the uncompacted soil, and 31 days in the compacted soil.

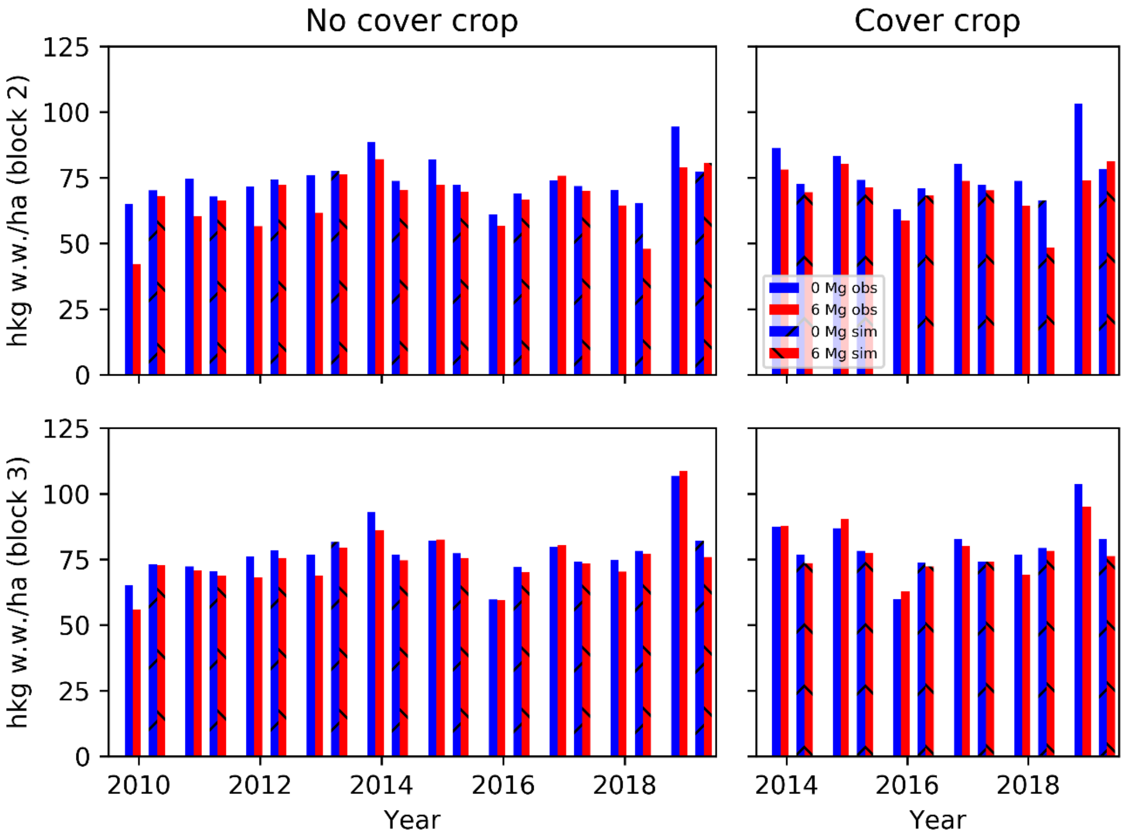

Figure 3.4. Observed and simulated grain yield in Block 2 (poorly drained; upper figures) and Block 3 (well drained; lower figures) for the 0 Mg and 6 Mg treatments. From 2010 to 2017 the crop was spring barley, in 2018 and 2019 it was winter wheat. In 2013 the plots were split in two, with one half getting a cover crop (fodder radish).Yield is given as "wet weight" (w.w), i.e. dry matter with 15 % of moisture (standard quality).

In **Error! Reference source not found.**, Table 3.3, Table 3.4, and Table 3.5 we compare the simulated effects of block, treatment, cover crop, and year with the observed effects. We have restricted the comparison to the years 2014 to 2017, because the significant first year effects of compaction we see from 2010 to 2013 are not included in the simulations. In 2018 and 2019, we have a different crop, and we were not able to simulate the effect of the extreme weather of 2018. For all four years, we have spring barley sown after spring barley without or with a catch crop, enabling a comparison of cover crop effects. Observed data from block 1 and 4 are only included in **Error! Reference source not found.**, and observed data from the 3 Mg and 8 Mg treatments are only included in Table 3.3.

In general the simulated yield is a bit lower than the observed however isolated effects of block, treatment, and cover crop on harvested yield (wet weight (w.w.) , i.e. with 15 % moisture in dry matter) are all within one hkg of the observed values. Yields (observed and simulated) in the poorly drained Block 2 are lower than in the well-drained Block 3 (**Error! Reference source not found.**). And yields for the 6 Mg treatment are (marginally) lower than for the 0 Mg treatment (Table 3.3). Furthermore, the cover crop provides a slight yield improvement (Table 3.4).

The largest divergence is between years (Table 3.5), but even there we see the right trend. The conformity between simulated and observed yield is best in 2014 and 2015, while it is worst in 2016. It appears that the simulation does not catch the magnitude of the variance, with 2016 being overestimated and the other years being underestimated. This should be kept in mind when evaluating the scenarios (section 3.3) where the trends are more trustworthy than the absolute numbers.

Table 3.2. Average observed (obs) and simulated (sim) dry matter yield in grains (wet weight (w.w.), i.e. including 15% moisture) for each block from 2014 to 2017. Only the 0 Mg and 6 Mg treatments are included. Both plots with and without cover crops are included. Block 3 is used as reference when calculating the block effect.

hkg w.w./ha/year	Block 1	Block 2	Block 3	Block 4
Average (obs)	76	75	79	75
Block effect (obs)	-3	**-4**	0	-4
Average (sim)		71	75	
Block effect (sim)		**-4**	0	

Table 3.3. Average observed (obs) and simulated (sim) dry matter yield in grains (wet weight (w.w.), i.e. including 15% moisture) for each treatment from 2014 to 2017. Only the 0 Mg and 6 Mg treatments are included. Both plots with and without cover crops are included. The 0 Mg treatment is used as reference when calculating the treatment effect.

hkg w.w./ha/year	Compaction treatment			
	0 Mg (uncompacted)	3 Mg (2010-2013)	6 Mg (2010-2013)	8 Mg (2010)
Average (obs)	78	78	77	79
Treatment effect (obs)	0	1	**-1**	1
Average (sim)	74		72	
Treatment effect (sim)	0		**-2**	

Table 3.4. Average observed (obs) and simulated (sim) dry matter yield in grains (wet weight (w.w.), i.e. including 15% moisture) without and with the cover crop (fodder radish) from 2014 to 2017. Only the 0 Mg and 6 Mg treatments and Block 2 and Block 3 are included. Yield without the cover crop is used as reference when calculating cover crop effects.

hkg w.w./ha/year	No cover crop	Cover crop
Average (obs)	76	78
Cover crop effect (obs)	0	**2**
Average (sim)	72	73
Cover crop effect (sim)	0	**1**

Table 3.5. Average observed (obs) and simulated (sim) dry matter yield in grains (wet weight (w.w.), i.e. including 15% moisture) in the single years from 2014 to 2017. Only the 0 Mg and 6 Mg treatments and Block 2 and Block 3 are included. The average yield over the four years is used as reference when calculating the year effects.

hkg w.w./ha	Year			
	2014	2015	2016	2017
Average (obs)	86	83	60	78
Year effect (obs)	**9**	**6**	**-17**	**2**
Average (sim)	74	75	70	73
Year effect (sim)	**1**	**2**	**-2**	**0**

3.2.2 Field scale harvest measurements and simulation results

Grain nitrogen content and dry matter yield has been derived for all treatments at field scale, ignoring the block effects. For the winter wheat, we additionally measured straw removed at harvest. See Figure 3.5 where measured values are compared to simulated values for the 0 Mg and 6 Mg treatments on Block 2 and 3.

The most notable discrepancy is the lower simulated nitrogen content in grains in winter wheat (2018 and 2019), which in 2019 but not 2018 is also fully reflected in an underestimation of the dry matter harvest of both grain and straw. We do not have an explanation for this, but can speculate that it is related to the unusually dry and hot summer in 2018.

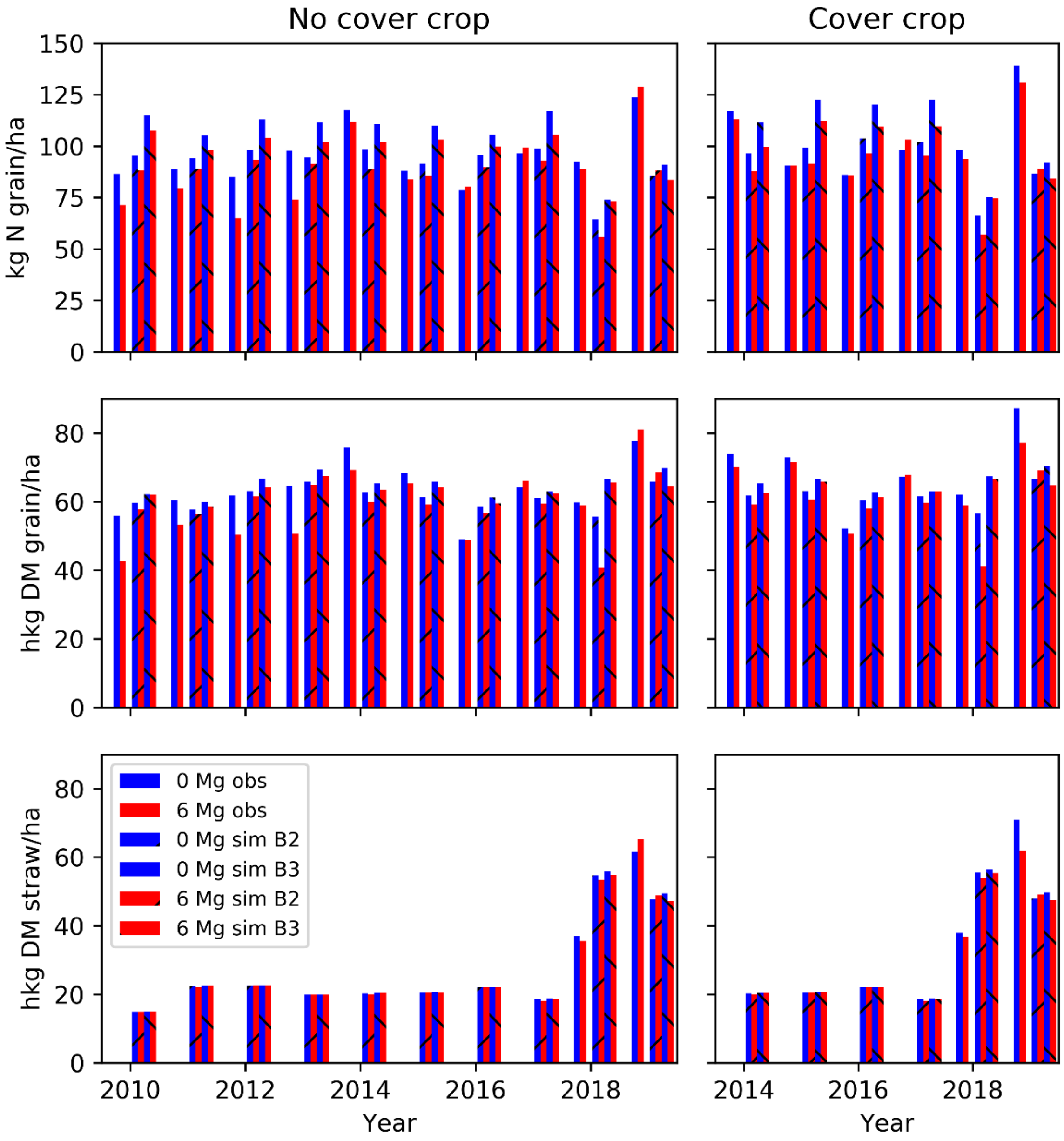

Figure 3.5. Observed and simulated yields in grain and straw at harvest (nitrogen (N) and dry matter (DM) in grains; DM in straw) for different treatments (0 and 8 Mg wheel load with and without cover crop; see section 2.1). The observed (obs; unshaded columns) yields are for the whole field, while the simulated (sim; shaded columns) yields are for Block 2 (B2; poorly drained) and Block 3 (B3; well drained). The cover crop was first introduced in 2013. Only the winter wheat had straw DM measured but simulated values are available also for spring barley.

3.2.3 Protein concentration in grains in 2019

Measured and simulated protein concentration in grains is shown on Figure 3.6 and Figure 3.7, organized by treatment and block respectively. Unfortunately, no matter the organization, all they show is that same as Figure 3.5: the 2019 nitrogen uptake in grains were severely underestimated by the simulation.

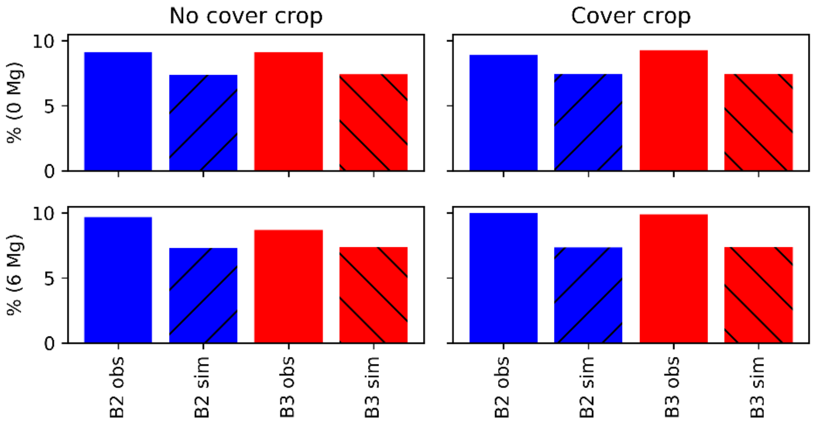

Figure 3.6. Observed (obs) and simulated (sim) protein concentration (% of dry matter) in wheat grains in 2019 in poorly drained soil (Block 2, B2) and in well drained soil (Block 3, B3). The results are organized by treatment (0 and 6 Mg wheel load without and with a cover crop in 2013-2016; see section 1). A conversion rate of 5.7 from N to protein has been assumed for the simulated values.

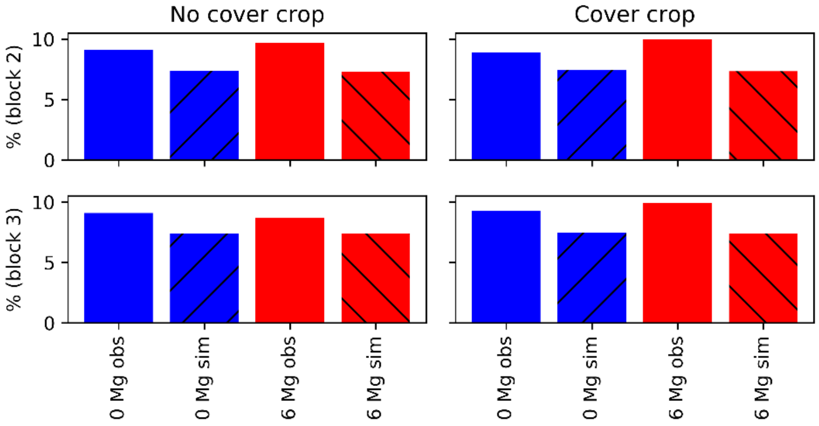

Figure 3.7. Observed (obs) and simulated (sim) protein concentration (% of dry matter) in grains in Block 2 (poorly drained) and Block 3 (well drained) in 2019 organized by treatment (0 and 6 Mg wheel load without and with cover crop in 2013-2016; see section 1). A conversion rate of 5.7 from N to protein has been assumed for the simulated values.

3.2.4 Summary

For dry matter, we in general see similar effects of drainage conditions and compaction in the simulations, as we observe in the field experiment. Except during the first years when compaction took place, differences between Blocks (effects of drainage conditions) are generally larger than differences caused by compaction. We generally simulate slightly smaller yields with compaction than without compaction, and slightly larger yields with a cover crop than without. Observations generally show the same trend. The yield levels for spring barley are also comparable, with some years being overestimated, and others underestimated. This is not surprising, as the spring barley parameterization was partly based on this dataset. The amount of nitrogen harvested in grains is, as a trend, slightly overestimated. However, the winter wheat yields are a poor match; in particular, the nitrogen harvested in grains is severely underestimated. It is difficult to fix this discrepancy as the spring barley data points in the direction of too much nitrogen, and because 2018 was an unusually warm and dry year, which likely also has had affects in 2019.

3.3 Scenario simulations

The idea behind the scenario simulations is to expand and quantify the impact of compaction on yield and environment. We simulated 3600 years, divided into 2 climates with 100 years of weather each, 3 cropping systems, and 6 soil columns. The results are analyzed with regard to both yield and environmental impact.

3.3.1 Factors investigated

3.3.1.1 Weather variability and climate change

It is obvious from both measurements and simulations that weather plays a key role in yields, both in general and specifically on the COMMIT field trials. Weather varies from year to year, but there is also a long-term trend with global warming and changing precipitation patterns. It is relevant to examine the effect of compaction not just for the current climate but also for an expected future climate. We have chosen to build the scenario simulations on 100 years of weather data picked from two generated, long-term weather series given by Rasmussen et al. (2018). One (the control weather series) is based on observed data from eastern Zealand in the years 1983 to 2012. Hence, the control series reflect recent but still historical weather observations from the Taastrup region. The other representing an expected near-future (2030-2059) climate is the so-called ECHAM–Racmo series. Several other expectations for the climate of the near-future exist corresponding to different models for climate change. The ECHAM–Racmo series is in the middle of the spectrum with an increase in average air temperature of 1.3 °C, and with no change in annual rainfall but a modest increase in winter rainfall (Rasmussen et al., 2018).

3.3.1.2 Soils

We look at Block 2 (poorly drained) and Block 3 (well drained), both in combination with the no compaction and the 6 Mg compaction treatments. For the 6 Mg compaction treatment, we look at two variations. One where only the hydraulic properties of the soil is allowed to affect the simulation results, and one where the roots of the crops (due to soil compaction) are assumed to be less homogeneously distributed for a given depth and therefore less efficient when it comes to water and nutrient uptake. The latter effect (more heterogeneous root distribution in compacted soil) is documented in e.g. Tardieu (1994). We do not have enough experimental data from the present study or elsewhere to parameterize this compaction effect but we can still make a sensitivity analysis. In Daisy by default, a root homogeneity of 100 % is assumed which means that all roots in a layer have the same distance to each other. Here we also set this parameter to 10 % below the plough layer representing a very heterogeneous root distribution in the subsoil with most roots being present in few, penetrating macropores. Apart from this, the soils are as described in Table 3.1, with the lower boundary as described in section 3.1.1.2.

3.3.1.3 Crop management

We examine three different cropping systems, spring barley without a cover crop (or catch crop; fodder radish), spring barley with the cover crop, and winter wheat. For practical reasons, we do this by running the same crop 100 years in a row; however, we are *not* simulatingthe long-term effect of such a system.

For simplicity, sowing, fertilizing, and tillage are always performed on the same calendar dates every year. Harvest is done when the crop is ripe, but no later than a given date. The dates and actions for the three systems can be seen in Table 3.6.

Table 3.6: Crop management specified by actions taken at different dates. Harvest is done when the crop is ripe but no later than the specified date (in grey).

Spring barley

Month	Day	Action
3	5	115 kg N/ha Ploughing
4	5	Sowing
8	29	Harvest

Spring barley with cover crop

Month	Day	Action
3	5	115 kg N/ha Ploughing
4	5	Sowing
8	29	Harvest
4 days later		Cover crop 30 kg N/ha
12	1	Ploughing

Winter wheat

Month	Day	Action
9	8	Ploughing
9	10	Sowing
4	9	41 kg N/ha
4	12	20 kg N/ha
4	20	86 kg N/ha
9	7	Harvest

3.3.2 Yield

In Table 3.7 we present the mean grain yield over the 100 years of weather, with each combination of cropping system, climate, and soil. Yields for compacted soils are shown as changes relative to the uncompacted soils, directly illustrating the effect of the compaction. For the mean yield we show both nitrogen and dry matter, furthermore we show the median yield, representing a typical year, and the 10th percentile, representing a bad year (with poor yield). Besides lack of photosynthesis, reasons for a poor yield will either be nitrogen or water stress (see Table 3.8).

Daisy will calculate potential production (based on light interception) first, then adjust for nitrogen and water stress. The adjustment for the two factors are independent, if there are 50 % water stress and 50 % nitrogen stress, production will be adjusted to 25 % of the potential. When production is reduced, nitrogen demand is also reduced correspondingly. So high water stress will tend to reduce nitrogen stress, there is simply produced less dry matter, and thus a reduced need for nitrogen. The opposite is also true, but to a much smaller degree. While less dry matter production will affect the leaf area and thereby reduce the need for transpiration, the weather is usually the dominating factor for calculating the potential transpiration, and thus nitrogen stress will have less of an impact in water stress.

If we integrate stress over time, we get a measure of the total amount of stress the crop has experienced (as "stress days"). In Table 3.8 we summarize the stress days for the various simulations.

The first thing we note is that while the level of our spring barley grain yields is satisfactory compared with observations, the level for winter wheat is not. The explanation can be found in Table 3.8, the winter wheat is in general severely limited by lack of nitrogen. We also see that compaction only have a limited effect on dry matter yield if we assume roots are still homogenously distributed but some effect (around 5 hkg/ha) if we assume, they are not. Heterogeneous root distribution in particular affect yields in the bad years (the 10th percentile). For spring barley, the nitrogen yield is negatively impacted in both compaction scenarios, so we expect lower protein content in grains from severely compacted soil. The poorly drained part of the field has lower yields, which can be explained by increased nitrogen stress.

In spring barley (SB and SB+CC), the primary cause of stress in compacted soil switches from nitrogen deficiency to water deficiency when we move from a homogeneous root profile to a heterogeneous root profile (Table 3.8). This is particularly but not exclusively the case in poorly drained soil indicating that uneven root distribution in the subsoil is more severe when shallow ground water prevents the normal root depth. Nitrogen deficiency is still the dominating cause of stress in winter wheat with a heterogeneous root distribution in the subsoil, particularly in well-drained soil with less water stress.

The future climate does not have much effect on the spring barley but gives about 5 hkg/ha higher mean and median grain yield for winter wheat. The 10th percentiles indicate that bad years will be just as bad or even worse with soil compaction. Compaction will have a considerably higher impact if we assume that the compaction causes poor root homogeneity (10 % root homogeneity).

Table 3.7: Yield in grains for two soils (well drained Block 3 and poorly drained Block 2), two climates (current and near future), without and with 6 Mg compaction, and (for compacted soil) with a homogeneous (100 %) and a heterogeneous (10 %) root distribution. Data for three cropping systems, i.e. spring barley (SB) with and without a cover crop (CC), and winter wheat (WW). The mean of 100 years is shown for both nitrogen (N) and dry matter (DM), and the median and 10th percentile (50 % and 10 %, respectively) are shown for dry matter. Values for compacted soils are shown relative to uncompacted soils (i.e. compacted – uncompacted).

Crop	**No compaction**				**6 Mg, 100 % root homogeneity**				**6 Mg, 10 % root homogeneity**			
	Absolute yield				Relative yield to no compaction				Relative yield to no compaction			
	Mean	Mean	50 %	10 %	Mean	Mean	50 %	10 %	Mean	Mean	50 %	10 %
	kg N/ha	Mg DM/ha			kg N/ha	Mg DM/ha			kg N/ha	Mg DM/ha		
Block 3 (well drained), current climate												
SB	126	6.7	6.8	6.4	-10	-0.1	-0.1	0.0	-16	-0.4	-0.4	-0.6
SB+CC	130	6.7	6.8	6.4	-10	-0.1	-0.1	0.0	-14	-0.4	-0.3	-0.6
WW	99	7.0	7.0	6.2	-2	-0.1	-0.1	-0.1	-4	-0.3	-0.2	-0.3
Block 2 (poorly drained), current climate												
SB	105	6.4	6.5	6.1	-9	-0.2	-0.2	-0.3	-11	-0.6	-0.5	-0.9
SB+CC	109	6.4	6.5	6.0	-7	-0.2	-0.1	-0.2	-11	-0.5	-0.4	-0.9
WW	94	6.7	6.8	6.0	-1	-0.1	-0.1	-0.2	-6	-0.6	-0.6	-0.9
Block 3 (well drained), near future climate												
SB	129	6.7	6.8	6.3	-11	0.0	-0.1	0.0	-15	-0.6	-0.5	-0.9
SB+CC	127	6.7	6.7	6.2	-11	-0.1	-0.1	-0.1	-14	-0.6	-0.4	-0.9
WW	107	7.4	7.5	6.2	-2	-0.2	-0.2	-0.2	-6	-0.5	-0.5	-0.6
Block 2 (poorly drained), near future climate												
SB	108	6.5	6.5	6.1	-10	-0.3	-0.3	-0.3	-11	-0.8	-0.7	-1.2
SB/CC	107	6.4	6.4	5.9	-8	-0.3	-0.2	-0.3	-11	-0.7	-0.7	-1.0
WW	101	7.1	7.2	5.8	-2	-0.2	-0.3	-0.1	-8	-0.8	-0.8	-1.2

Table 3.8: Days of production lost due to water and/or nitrogen stress. The numbers are averages over 100 years of weather, for two soils (Block2 and Block 3), two climates (current and near future), three cropping systems (spring barley (SB) with and without a cover crop (CC), and winter wheat (WW)) with and without compaction, and (for compacted soil) with a homogeneous (100 %) and a heterogeneous (10 %) root distribution. Values for the compacted soils are presented as extra stress days compared to the uncompacted soils.

Crop	No compaction		6 Mg, 100 % root homogeneity		6 Mg, 10 % root homogeneity	
	Water	Nitrogen	Water	Nitrogen	Water	Nitrogen
	Stress days		Extra stress days relative to no compaction			
Block 3, current climate						
SB	0	0	0	1	3	2
SB+CC	0	0	0	1	3	1
WW	0	40	0	7	1	13
Block 2, current climate						
SB	0	3	1	2	5	2
SB+CC	0	3	1	1	5	1
WW	1	62	1	3	5	7
Block 3, near future climate						
SB	1	0	0	1	6	1
SB+CC	1	1	0	1	6	1
WW	0	43	0	7	2	10
Block 2, near future climate						
SB	0	3	2	2	9	0
SB+CC	1	3	2	1	9	0
WW	1	63	1	3	6	6

3.3.3 Environmental impact

3.3.3.1 Effect on soil

The column named 'Soil' in Table 3.9 shows the amount of organic nitrogen lost from the soil. A numerically large number indicate that the system is in imbalance, if it is positive the soil is being depleted for nitrogen, and we can expect yield to decrease over time. If it is negative, there is a build-up of nitrogen in the soil, with potential for increased yield as well as increased leaching in the future. As can be seen, the spring barley is rapidly depleting the soil, which can be alleviated with a cover crop. The winter wheat has a modest buildup of nitrogen in the soil. In general, the compaction will reduce this buildup.

In the future climate simulations, all three cropping systems deplete the soil even faster than before. This is a consequence of the warmer climate leading to faster turnover of organic matter.

3.3.3.2 Effect on the aquatic environment

Daisy will calculate both deep leaching, in these simulations defined as leaching below 2 m depth, and leaching to drain pipes. These are denoted 'Deep' and 'Drain' respectively (Table 3.9). First, a note about the 'Deep' values being all zero: The values are averaged over 100 years. Because the groundwater table on the experimental field is close to the surface, the deep percolation will be negative during the summer, where nitrogen will be carried upwards due to capillary rise and positive in winter where the net percolation is high. Still, for some years the value will be positive, for other negative. For most years the values will be small though, since the system is generally N starved (as seen in Table 3.8). The loss through drainpipes is always positive though, we assume that no water flows the other way through the pipes on this particular field.

We see than the winter wheat leaves the water mostly free of nitrogen for all soils and both climates. A cover crop removes some of the nitrogen, but not all. Compaction increases leaching when growing spring barley, especially if we assume poor root homogeneity. The leaching does not become worse with future climate, possibly because we investigated two scenarios with similar total amount of precipitation.

3.3.3.3 Effect on climate

Most of the nitrogen loss in gasses to the atmosphere (the 'Air' column in Table 3.9) is likely in the form of harmless N_2; however, a fraction of the loss is N_2O, which is a potent climate gas, 298 times stronger than CO_2 (Solomon et al., 2007). The fraction lost as N_2O varies with soil, climate, and cropping system. (Vinther, 1984) got a ratio of $N_2 + N_2O$ to N_2 varying between 1.0 and 7.2 for denitrification in spring barley under Danish conditions, that is variations in the composition from pure N_2 to mostly N_2O.

The nitrogen loss for the soil (the 'Soil' column in Table 3.9; negative values represent increments) is accompanied by a similar loss of carbon in the form of CO_2 to the atmosphere. Daisy calculates this directly. While it is not listed explicitly in the table, the carbon loss can be found by multiplying the nitrogen loss with 11, as all the columns are assumed to have a C/N ratio of 11.

Table 3.9: Nitrogen (N) loss for two soils (Block 2 and Block 3), two climates (current and near future), with and without 6 Mg compaction, and (for compacted soil) with homogeneous (100 %) and heterogeneous (10 %) root distribution. Data for three cropping systems, i.e. spring barley (SB) with and without a cover crop (CC), and winter wheat (WW). The mean of 100 years is shown for each combination. Values for compacted soils are shown relative to the uncompacted soils. 'Air' denotes loss to the atmosphere in the form of N_2 *and* N_2O*. 'Drain' is loss of* NO_3^- *through drainpipes. 'Deep' is loss of* NO_3^- *with deep percolation. 'Soil' is the decrease of organically bound nitrogen in soil.*

Crop	**No compaction**				**6 Mg, 100 % root homogeneity**				**6 Mg, 10 % root homogeneity**			
	Nitrogen loss [kg N/ha/y]				Extra loss [kg N/ha/y] compared to no compaction							
	Air	Drain	Deep	Soil	Air	Drain	Deep	Soil	Air	Drain	Deep	Soil
Block 3, current climate												
SB	21	8	0	37	10	1	0	-2	10	6	0	-3
SB+CC	28	3	0	12	10	2	0	0	12	3	0	-1
WW	23	0	0	-5	5	0	0	2	8	1	0	3
Block 2, current climate												
SB	33	12	0	29	4	3	0	-2	5	5	0	-2
SB+CC	41	9	0	6	3	4	0	-1	7	5	0	0
WW	29	1	0	-6	1	0	0	0	7	1	0	1
Block 3, near future climate												
SB	22	9	0	43	11	0	0	-2	11	6	0	-2
SB+CC	32	3	0	12	11	1	0	0	14	3	0	1
WW	26	0	0	6	6	0	0	2	10	1	0	3
Block 2, near future climate												
SB	34	12	0	34	5	3	0	-2	6	5	0	0
SB+CC	44	7	0	6	5	4	0	0	9	5	0	2
WW	33	1	0	5	2	0	0	0	9	1	0	1

3.3.4 Summary on the effects on crop yield, nitrogen turnover and the environment

Compaction is expected to decrease the protein content of the grains, and if the root system is damaged (roots heterogeneously distributed in the subsoil), the dry matter yield will be considerably reduced as well. The main environmental risk is a potential increase in the release of greenhouse gases, in particular N_2O. Everything bad about compaction is expected to get worse in the future; compaction affects poorly drained soil more than well-drained soils, and more in bad years than in typical years (Table 3.7).

4 Discussion

4.1 Yields

Repeated traffic with heavy machinery in the spring (6 Mg wheel load) in the Taastrup trial in 2010-2013 has caused significant and prolonged compaction of the subsoil down to a depth of at least 70 cm, documented by e.g. increased bulk density and decreased air permeability. This compaction has affected the hydraulic properties of the soil, which is expressed e.g. by inferior or delayed drainage in winter and spring of both plough layer and subsoil.

With increased bulk density in compacted soil, the mechanical strength of the soil also increases. One could therefore expect that compaction would hamper deep root development of the plants under dry conditions and thereby in particular reduce the yields in dry years, when the need for water uptake from deep soil layers is greatest. The trial period included a year with exceptionally dry conditions during the growth period, namely 2018. In this year, intensive measurements of the soil profile's water content in uncompacted and heavily compacted soil were carried out in winter wheat at Taastrup but these measurements did not show clear difference on the plants' water uptake from the soil layer down to 110 cm depth. Water extraction was also not improved by the fodder radish cover crop, which had been grown on half of the plots in the years 2013-2016. There was even a tendency for slightly higher water uptake in compacted soil than in uncompacted soil (Figure 2.9). These results are supported by the fact that, contrary to expectations, no significant yield reduction could be measured in 2018 as a result of compaction, neither in Taastrup (winter wheat), Aarslev (winter wheat), nor in Flakkebjerg (spring barley) (Vestergaard, 2018a). This was the case even though all crops were clearly water stressed, and yields were low. The measurements thus show that the compaction carried out in the years 2010-2013 did not have a significant effect on the harvest yields in the drought year 2018. As a consequence of these measurements, Daisy has been parameterized with the same maximum root depth regardless of compaction treatment and catch crop.

The simulation results indicate that the long-term effect of subsoil compaction on grain yields in spring barley and winter wheat is generally negative, albeit relatively small. This is in line with measured results from the Taastrup trial (and from the other two trial sites), where it has generally been difficult to detect statistical significant yield losses already a few years after ending the compaction treatments (section 2.3). However, the fact that yield losses are small and difficult to measure in single or few years do not imply that such losses are not important as they expectedly will last for many years.

The specific simulation results for the dry year 2018 to some extent confirm the expectation (although not the measurements), as a significant yield loss on poorly drained soil due to compaction is calculated. The loss is mainly due to the fact that the high groundwater level on poorly drained soil model-wise prevents the crop from achieving full root depth. The crop thereby becomes more water stressed. This effect of a shallow water table on root systems and on crop water uptake is well known from textbooks, and we have therefore chosen to maintain the effect in the Daisy calculations. On well-drained soil, no yield loss due to compaction is simulated in 2018 in accordance with the measurements.

Thus, the average and usually simulated yield effects of soil compaction (mean and median values, respectively) were relatively small. There were also (with homogeneous root distribution) no large effects in years with low yields due to poor weather, although the compaction effects were generally slightly larger (10th percentiles in Table 3.7). This is particularly the case in spring barley on poorly drained soil. It is therefore not meaningful to analyze the simulation results in more details to see what goes wrong in these bad years. With heterogeneous root distribution, yield losses increased markedly, primarily due to water shortage (Table 3.8). The effect of soil compaction on yields is therefore expected to depend on the extent to which the distribution of the roots in the subsoil is affected. Plant roots are never able to utilize all water resources in the subsoil, so real water availability in the subsoil will always be affected by root distribution and soil hydraulic properties. This can be illustrated also by measured data obtained in the present project. The winter wheat in Taastrup left even under extremely hot and dry conditions in 2018 significant amounts of so-called plant available water (water retained between field capacity (about 30 % (v/v)) and the wilting point (about 10-15 % (v/v)) in the profile down to 110 cm depth when evaporation almost ceased at the end of the growing season (Figure 2.8 and Figure 2.9).

With the current climate and homogeneous root distribution, nitrogen deficiency generally causes more stress (expressed as loss of production days) than water scarcity. With heterogeneous root distribution, this picture changes for spring barley (Table 3.8). Water shortages continue to play a smaller role than nitrogen shortage in winter wheat, which generally suffers from a severe lack of nitrogen. It is again noted that the simulation results in winter wheat were obtained with a standard crop calibration and not from a calibration based on measurements in the present compaction experiment (see section 3.1.2). The low yield level in winter wheat due to N deficiency must therefore be regarded as somewhat uncertain.

4.2 Environmental effects

For spring barley, the simulated nitrogen yield was negatively impacted by compaction in all scenarios (homogeneous and heterogeneous root distribution with current and future climate and on well-drained and poorly drained soil; Table 3.7), so we expect lower protein content in grains from severely compacted soil. This is confirmed by clear tendencies in measured values from 2014-2017 (Table 2.3). In winter wheat, the simulated compaction effects on N-yield are smaller but still significant. Hence, the harvested grains remove less nitrogen from the compacted field implying that more nitrogen needs to end up somewhere else. This could be in gaseous losses to the atmosphere originating from denitrification (as N_2O or N_2), as leaching losses to drains or to deep soil layers (as NO_3^-), or the nitrogen could be incorporated into organic matter in the soil.

Daisy keeps track on these losses in compacted and uncompacted soil making sure that no mass is lost (Table 3.9). By far the most of the simulated extra nitrogen loss in compacted soil ends up in the atmosphere (4-14 kg N/ha/year in barley and 1-10 kg N/ha/year in winter wheat), making up a very significant contribution to the total atmospheric losses (up to 50 %). The effect appears to be smaller on poorly drained soil than on well-drained soil but it should be born in mind that the losses are greater on poorly drained soil even without compaction. In an excellent, albeit somewhat old, review of the long-term effects of soil compaction on the environment, Soane and Van Ouwerkerk (1995) reported that soil compaction under certain conditions can cause an increase in the denitrification rate of 400–500%. The proportion of nitrogen lost as N_20 is generally small. On average 1.25% of the N input (as fertilizer, manure or through biological N_2 fixation) is emitted from the field as N_2O, but the observed range of emission factors is large: 0.25 to 2.25% (IPCC, 1996). Compaction slows down N_20 transport through the soil, and the longer N_20 stays in the soil, the greater the chances that it will be reduced to the harmless N_2 gas. Thers et al. (2020) recently measured losses of 2-3 kg N_2O-N ha^{-1} day^{-1} in oilseed rape on a Danish sandy loam soil.

In barley, soil compaction also increases leaching losses to drains, particularly on poorly drained soil and when roots are heterogeneously distributed in the subsoil (0-6 kg N/ha/year) whereas the leaching to deep subsoil is unaffected (still very small). There is virtually no nitrogen leaching in the nitrogen starving winter wheat crop.

In the spring barley systems, nitrogen – and thereby also soil organic carbon - is clearly being depleted from the soil (by rates up to 43 kg N/ha/year without cover crop and up to 12 kg N/ha/year with the cover crop; Table 3.9). In general, soil compaction slightly reduces this imbalance by up to 3 kg N/ha/year. Effects on the carbon balance of the soil can be found from effects on the nitrogen balance by multiplying with a factor of 11 (assuming a constant C/N ratio of 11).

The most pronounced environmental concern of soil compaction appears to be that it increases N-losses to the atmosphere. From an environmental point of view, it is important to know the extent to which atmospheric losses are as N_2 or as N_2O. Daisy calculates both but the distribution is highly uncertain due to lack of experimental data from the field to validate calculations. Therefore, only sums of atmospheric losses are reported here.

4.3 Final remarks

Treatments representing compaction from the heaviest machinery applied in Denmark during the spring were included as worst cases in 2010 when the compaction trials were initiated. Today even heavier machinery is seen in Denmark, although not very often (Landskonsulent Henning S. Lyngvig, personal communication, 18. August 2020). Simulated (and measured) effects of soil compaction should therefore not necessarily be taken to represent worst-case scenarios. On the other hand compacting the subsoil by driving heavy equipment wheel-by-wheel, as in this study, likely causes accelerated effects which in practice may be seen only after several years.

We have simulated yield losses in spring barley and winter wheat associated with subsoil compaction. Other crops may show a different sensitivity. Root crops, as an example, are generally regarded as particular sensitive to soil compaction (Lipiec et al., 2009). Likewise, our simulations for the chosen future climate scenario will not be accurate if it turns out that the scenario is incorrect. This applies, for example, if the winter precipitation becomes greater and the summer precipitation less than expected, in which case the compaction effects expectedly should be greater.

Soil compaction causes poorer/slower drainage which means that it negatively affects both trafficability and loadability. However, effects on management opportunities are not included in this study. All field operations (whether in the simulations or in reality) are conducted simultaneously which means that the timing is adapted to the poorest (i.e. compacted) soil conditions and that days with crop growth are lost at the well-drained sites.

At Taastrup, the soil is loamy with about 20% of clay in the plough layer (Table 3.1). It is therefore classified as a “lerjord” or JB7 which means that it is a heavy soil for Danish conditions. The clay content increases somewhat below the plough layer. Many compaction effects are likely relatively large on heavy soil types (Soane and Van Ouwerkerk, 1995). However, poor drainage caused by traffic with water accumulating on and near the surface can be observed in the Danish landscape in wet seasons, even on sandy soil.

5 Conclusions

The Daisy model was successfully calibrated based on results obtained in spring barley in the years 2010-2017 whereas results in winter wheat (2018 and 2019) were too few and too special for a proper, site-specific calibration. The scenario simulations are therefore more uncertain in winter wheat than in spring barley.

The long-term scenario calculations generally showed small negative effects of soil compaction with 6 Mg wheel load on dry matter (DM) and nitrogen (N) yield in grains in barley and wheat (on average up to 0.3 Mg DM and 11 kg N per ha and year). This is consistent with the measurements. The use of a cover crop was not assumed to mitigate compaction effects on soil hydraulics but nitrogen yields were nonetheless increased. Compaction effects on DM yield was larger on poorly drained soil than on well-drained soil. Yield-losses were increased dramatically when assuming that soil compaction leads to a very heterogeneous root distribution in the subsoil (on average up to 0.8 Mg DM and 16 kg N per ha and year). Further studies are needed on how compaction affects root distribution in the subsoil.

With less nitrogen being harvested from the field, more nitrogen must go somewhere else. The scenario simulations showed increased losses of gaseous nitrogen to the atmosphere with compaction (on average 1-14 kg N/ha/year or up to 50 %). Future field studies should uncover the extent to which such losses occur as climate-damaging N_2O. They should also investigate the interaction between compaction and poor drainage conditions, as the losses of gaseous nitrogen are already greater on poorly drained soil. Compaction also increased leaching losses to drain lines but to a lesser extent (on average 0-6 kg N/ha/year).

Bibliography

Beare, M.H., Gregorich, E.G., St-Georges, P. (2009). Compaction effects on CO_2 and N_2O production during drying and rewetting of soil. Soil Biology & Biochemistry 41, 611–621.

Bennetzen, E.H. (2017). Jordpakning. I: Oversigt over Landsforsøgene 2017 (ed. Jon Birger Pedersen), pp. 255-257.

Bouma, J. (1991). Influence of Soil Macroporosity on Environmental Quality. Advances in Agronomy, 46, 1-37.

Christensen, L. (2011). Soil hydraulic properties and macropore transport to field drains [Master thesis]. University of Copenhagen.

Gyldengren, J. G., Abrahamsen, P., Olesen, J. E., Styczen, M., Hansen, S., & Gislum, R. (2020). Effects of winter wheat N status on assimilate and N partitioning in the mechanistic agroecosystem model DAISY. Journal of Agronomy and Crop Science.

Håkansson, I., Reeder, R. (1994). Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. Soil & Tillage Research 29, 277-304.

IPCC (1996). IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual, pp 4:83–4:89. IPCC Secretariat, Geneva.

Lipiec, J., Medvedev, V.V., Birkas, M., Dumitru, E., Lyndina, T.E., Rousseva, S., Fulajtár, E. (2003). Effect of soil compaction on root growth and crop yield in Central and Eastern Europe. International Agrophysics, 17, 61–69.

Munkholm, L.J., Schjønning, P., Wahlström, E.M., Nicolleau, M. (2014). Pakningsskader til mindst 70 cm dybde. I: Oversigt over Landsforsøgene 2014 (ed. Jon Birger Pedersen), pp. 271-274.

Munkholm, L.J., Schjønning, P. (2015). Effekt af trafik på jordens struktur. I: Oversigt over Landsforsøgene 2015 (ed. Jon Birger Pedersen), pp. 251-253.

Munkholm, L.J., Schjønning, P., Wahlström, E.M. (2016). Effekt af trafik på jordens struktur. I: Oversigt over Landsforsøgene 2016 (ed. Jon Birger Pedersen), pp. 260-262.

Nawaz, M.F., Bourrié, G., Trolard, F. (2013). Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33, 291–309.

Nielsen, J.A. (2014). Jordbearbejdning. I: Oversigt over Landsforsøgene 2014 (ed. Jon Birger Pedersen), pp. 269-271.

Petersen, C., Munkholm, L. (2017). Effekter på jord og afgrøder i Taastrup. I: Oversigt over Landsforsøgene 2017 (ed. Jon Birger Pedersen), pp. 257-259.

Petersen, C., Vestergaard, R.K., Munkholm, L., Pulido-Moncada, M. (2018). Effekter på jord og afgrøder i Taastrup. I: Oversigt over Landsforsøgene 2018 (ed. Jon Birger Pedersen), pp. 247-251.

Petersen, C., Munkholm, L., Pulido-Moncada, M. (2019). Effekter på jord og afgrøder i Taastrup. I: Oversigt over Landsforsøgene 2019 (ed. Jon Birger Pedersen), pp. 238-241.

Petersen, C.T., Jensen, C.R., Mogensen, V.O. (2002). Analysis of variation of spectral vegetation index measured in differently fertilized field barley. Communications in Soil Science and Plant Analysis, 33, 1485-1506.

Pulido-Moncada, M., Petersen, C.T., Munkholm, L.J. (2021). Limiting Water Range: Crop Responses related to In-Season Soil Water Dynamics, Weather Conditions and Subsoil Compaction. Soil Sci. Soc. Am J. (in print).

Pulido-Moncada, M., Schjønning, P., Labouriau, R., Munkholm, L.J. (2020). Residual effects of compaction on the subsoil pore system—A functional perspective. Soil Sci. Soc. Am. J. 84:717–730.

Rasmussen, S. B., Blenkinsop, S., Burton, A., Abrahamsen, P., Holm, P. E., & Hansen, S. (2018). Climate change impacts on agro-climatic indices derived from downscaled weather generator scenarios for eastern Denmark. European Journal of Agronomy, 101, 222–238. https://doi.org/10.1016/j.eja.2018.04.004

Schjønning , P., Lamandé, M., Crétin, V., Nielsen, J.A. (2017): Upper subsoil pore characteristics and functions as affected by field traffic and freeze–thaw and dry–wet treatments. Soil Research, 55, 234–244.

Schjønning, P., van den Akker, J.J.H., Keller, T., Greve, M.H., Lamandé, M., Simojoki, A., Stettler, M., Arvidsson, J., Breuning-Madsen, H. 2016a. Soil Compaction. Chapter 6 in: Stolte, J. et al. (Eds) Soil Threats in Europe; EUR 27607 EN; doi:10.2788/488054 (print); doi:10.2788/828742 (online).

Schjønning, P., Lamandé, M., Munkholm, L.J., Lyngvig, H.S., Nielsen, J.A. (2016b). Soil precompression stress, penetration resistance and crop yields in relation to differently-trafficked, temperate-region sandy loam soils. Soil Tillage Res. 163, 298–308.

Schjønning, P., Rasmussen, S. T., Lamandé, M., Nielsen, J. M., Christensen, B. B., Nørgaard, H., Bak, H., Nielsen, J. A. (2011). Startkarakterisering af arealer til jordpakningsforsøg. Aarhus Universitet.

Schjønning, P., Heckrath, G., Christensen, B.T. (2009): Threats to soil quality in Denmark - A review of existing knowledge in the context of the EU Soil Thematic Strategy. Report Plant Science, No. 143. Aarhus University, Denmark. 121 pp.

Schjønning, P., Elmholt, S., Munkholm, L.J., Debosz, K. (2002): Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. Agriculture, Ecosystems & Environment 88, 195-214.

Schjønning, P., Munkholm, L.J., Elmholt, S., Debosz, K., Mikkelsen, G.H., Trautner, A. (2000): Den danske dyrkningsjords tilstand og kvalitet – konsekvenser af trafik og jordbearbejdning. Tidsskrift for Landøkonomi 4, 293-300.

Soane B., Van Ouwerkerk C. (1995). Implications of soil compaction in crop production for the quality of the environment. Soil & Tillage Research 35, 5–22.

Solomon, S., Intergovernmental Panel on Climate Change, & Intergovernmental Panel on Climate Change (Eds.). (2007). Climate change 2007: The physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Styczen, Merete E., Abrahamsen, P., Hansen, S., Knudsen, L. (2020). Model analysis of the significant drop in protein content in Danish grain crops from 1990-2015. European Journal of Agronomy, 118, 126068.

Styczen, M., Abrahamsen, P. (2017). Årsager til faldende proteinindhold i kerne fra ca. 1990 til 2015: Modelanalyse og resultater. Projektrapport, Københavns Universitet. 128 sider. https://daisy.ku.dk/pdfs/NYield_final_report.pdf

Tardieu, F. (1994). Growth and functioning of roots and of root systems subjected to soil compaction. Towards a system with multiple signalling? Soil and Tillage Research, 30, 217–243.

Thers H., Abalos, D., Dorsch, P., Elsgaard, L. (2020). Nitrous oxide emissions from oilseed rape cultivation were unaffected by flash pyrolysis biochar of different type, rate and field ageing Science of the Total Environment 724, 138140.

Vestergaard, A.V. (2018a): Jordpakning. I: Oversigt over Landsforsøgene 2018 (ed. Jon Birger Pedersen), pp. 244-247.

Vestergaard, R. K. (2018b). Long term effects of heavy field traffic on soil hydraulic properties and processes [Master thesis]. University of Copenhagen.

Vestergaard, A.V. (2019): Jordpakning. I: Oversigt over Landsforsøgene 2019 (ed. Jon Birger Pedersen), pp. 235-238.

Vinther, F. P. (1984). Total denitrification and the ratio between N_2O and N_2 during the growth of spring barley. In J. Tinsley & J. F. Darbyshire (Eds.), Biological Processes and Soil Fertility (pp. 227–232). Springer Netherlands. https://doi.org/10.1007/978-94-009-6101-2_20

Wösten, J. H. M., Lilly, A., Nemes, A., & Le Bas, C. (1999). Development and use of a database of hydraulic properties of European soils. Geoderma, 90, 169–185.