KØBENHAVNS UNIVERSITET
DEPARTMENT OF PLANT AND ENVIRONMENTAL SCIENCE

AGROHYDROLOGY

PhD thesis

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Drainage and Plant Production

Growth, resource utilization and yields of cereal crops, under different and fluctuating groundwater depths

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Preface

This PhD project was facilitated and supervised at University of Copenhagen, Department of Plant and Environmental Science, Section of Environmental Chemistry and Physics, Agrohydrology research group. The work was substanstially co-funded by Carlsen-Langes Legat stiftelse, Stiftelsen Hofmansgave, Foreningen Plan Danmark, Innovationsfonden, DLF Trifolium, DLG, Landbrugets hudefond, Promilleafgiftsfonden for landbrug, SEGES og Østlige øres landboforening. The project wouldn't have been possible without these larger contributions.

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Summery

The interest in drainage and disposal of surplus precipitation as an essential part of agriculture goes back to the beginning of civilisation. Many regions not least in Northern Europe experience an increase in surplus precipitation with more extremely wet periods, and this trend is expected to continue according to climate scenarios.
This challenges the capability of the old drainage systems (tiles and streams) to maintain drainage conditions at the level required to support production on large agricultural areas.

The adverse effects of waterlogging have been demonstrated in numerous trials. However, the majority of newer trials are conducted as lysimeter or greenhouse setups focusing on process description. The reported drainage field trials are mostly with constant or unquantified water levels over few growing seasons. This complicates the quantitative interpretation of the yield response considering the implications of climate, crop management and soil type. The interaction between these factors can be substantial and encourage the examination of the drainage response under drainage conditions representative for artificially drained agricultural fields in Denmark.
Considering the large proportion of tile drained areas in the temperate humid climate of Northern Europe, there are few field studies to support the implication of drainage on agricultural production and environmental impact under modern agricultural conditions. For this reason, multilocational trials were conducted over several years in fields with old drainage systems. Yield response to drainage conditions and its variation were quantified. Drainage conditions were characterized on the basis of continuous measurements of water table depths. These measurements were each year transformed into a single drainage index, which was used as the explanatory variable for the grain- and N-yield.
Significant yield reductions of 25% in winter wheat and spring barley were found due to poor drainage conditions representing common field conditions found in Denmark and without visually observed symptoms during the growing season. The yield results from 11 site years were strongly correlated to the SEW_{60} drainage index for both dry matter and N yield. The treatment of three N levels applied did not interact with drainage but was an additive factor, indicating limited possibilities to compensate yield depressions by application of extra N fertilisation.
Soil surface temperature is a fundamental physical variable influenced by drainage. Low temperatures in the spring can reduce plant growth and thus the yield potential. Therefore, soil temperature was measured and modelled at field scale by simulations on the basis of soil texture,

groundwater and weather data. Both measurements and modelling showed that the average daily maximum soil surface temperature was approximately 1^{O}C higher in the spring months (March, April and May) on well drained plots compared to the poorly drained plots. The modelling showed higher soil heat flux during the daytime derived from less energy used on evapotranspiration under well drained conditions. The detailed level of process description in the modelling of the system in this scale can serve as basis for further investigations of drainage process description. This enable us to generalise effects on basis of soil properties, water measurements in the system and weather.

There are limitations to the interpretation of the results regarding the specific crop management, weather and soil and interaction in between these factors.

The clearly observed yield response to drainage conditions as specified in a drainage index quantifies the significant impact on production and nitrogen use efficiency in a modern agricultural system under humid temperate conditions and is believed to have the potential to be a contribution in future water management decisions.

Resume (Danish)

Dræning er en essentiel del af kulturteknikken i jordbrug og beskrivelserne af dræning går tilbage til civilisationens vugge. Øget nedbør og mere ekstreme vejrforhold i form af våde perioder opleves i tiltagende grad i mange regioner ikke mindst i Nordeuropa. Fremtidige klima scenarier forudser en forværrelse af denne trend.
Dette udfordrer kapaciteten af et aldrende dræningssystem bestående af rørbaseret detailafvanding på markerne og hovedafvandingen i åer og kanaler, under en forudsætning om opretholdelse af en fortsat høj produktion på landbrugsarealerne.
En række forsøg af primært af ældre dato reporterer de negative effekter af dårlig afvanding. Mange nyere forsøg er primært basseret på lysimeter eller potte forsøg og i markskala er de rapporterede dræningsforsøg typisk udført med konstant kontrolleret vandstand eller uden kvantificering af vandstanden. Dette vanskeliggør den kvantitative fortolkning af resultaterne under markforhold hvilket forværres af implikationerne af klima, afgrøde management og jordtype. Interaktionen mellem disse faktorer kan være væsentlige, hvilket er en væsentlig motivationsfaktor til udførelse af nye afvandingsforsøg der belyser udbytteeffekterne af dårlig dræning på drænede arealer i Danmark. Der er meget få markforsøg der undersøger de produktions- og miljømæssige aspekter af dræning i betragtning af den store andel af drænede arealer i Nordeuropa. På denne baggrund blev der i dette arbejde udført dræningsforsøg over en årrække på tre marker i Danmark med ældre drænsystemer. Udbytte responsen blev kvantificeret. Afvandingstilstand blev estimeret på baggrund af kontinuerte målinger af grundvandsstand og omregnet til et dræningsindeks, hvilket blev sammenholdt med de målte udbyttetab af kerne og kvælstof.
Der blev målt betragtelige udbyttetab på op til 25% i vinter hvede og vårbyg i marker med dræningsforhold repræsentative for Danmark. Effekterne var til stede uden visuelle observationer af afgrødepåvirkning i dyrkningssæsonen. Der blev fundet en stærk sammenhæng mellem udbytteresultaterne fra 11 forsøgs år fordelt på de tre lokaliteter og det fundne dræningsindeks (SEW_{60}) både for kerne- og kvælstof udbyttet i kernerne. Forskellige kvælstof tildelingsniveauer blev fundet værende en additiv faktor, hvilket betyder at der er begrænsede muligheder for at kompensere for den negative faktor af dræning på udbyttet ved ekstra tildeling af kvælstof.
Dræningens indflydelse på overfaldetemperaturen er en fundamental jord fysisk effekt. Planteväksten begrænses af lave temperaturer i foråret under danske forhold, hvilket kan reducere udbyttepotentialet. Dræningens påvirkning på jordtemperaturen blev derfor undersøgt og analyseret ved modellering på baggrund af målinger af tekstur, grundvand og detaljerede

vejrdata. Den gennemsnitlige maksimale dagsværdi af overfladetemperaturen var ca. 1 grad varmere som funktion af bedre dræning i forårsmånederne. Det er derfor sandsynligt at plantevæksten er reduceres som følge af dræningseffekten på jordtemperaturen. Udbytteresultaterne fra dette arbejde understreger den betydningsfulde virkning af afvanding på dyrkningen af afgrøde og ressourceudnyttelsen af kvælstof i et moderne jordbrug under tempererede klimaforhold. Det er forhåbningen at dette arbejde kan være et bidrage til beslutningsgrundlaget i fremtidig vandforvaltning.

Contents

Rationale for research

The benefit of drainage on arable land are well-recognized (Aslyng 1980; Williamson & Kriz 1970; Cannel et al. 1984). This might be the reason why very few new studies have been conducted in modern plant production schemes with technologically improved new crops, new varieties, and heavier machinery in a changing climate. Therefore, it is assumed that drainage trials conducted under field conditions in a modern, highly efficient agricultural system in temperate climate can contribute to future drainage strategies.

Raise of agricultural productivity and simultaneous improvement of the water quality in streams have essential roles in modern water management in large agricultural areas, including the implementation of the EU Water Framework Directive (EU, 2000). Simultaneous achievement of these interdependent goals, requires focus on resource effectivity and detailed process-based knowledge about the soil-water-plant system on arable land. This was supported in a comprehensive report by the Nature and Agriculture Commission regarding the future of Danish agriculture (Natur og Landbrugskommisionen, 2013), who stressed the goals of improving agricultural productivity and - at the same time - the quality of the streams which, in turn, play an important role in draining the agricultural land.

Lack of scientific arguments in the recent debate about the Danish water action plans as national implementation of the EU Water Framework Directive have clearly displayed the lack of recent up to date knowledge about plant response to water logging and insufficient drainage. This both concern the yield reductions described in old literature and changes in nitrogen dynamics in the system under different drainage conditions. The newest Danish drainage field trials, relevant to the major areas of tile drained sandy loam soils on arable land in Denmark, have been carried out in the years 1927-34 (Aslyng, 1980).

In the internationally broader perspective the most applicable drainage studies for Northern European climates and crops were done in Britain more than 30 years ago (Belford et al., 1985; Cannell et al., 1986, 1984, 1980). Most of these trials were studies of the processes conducted in lysimeters or greenhouses, which are also common approaches in most other studies of drainage. Such systems may not mirror the groundwater dynamics or the chemical and physical alterations to which a drained/poorly drained soil is subject before and during the measurements. This can lead to issues in the interpretation and quantification of the drainage effects under undisturbed conditions in the field.

The significant effects of drainage have also been described in studies of crops other than cereals and in different climates. However, the effects of drainage in these trials might be very different since the crop sensitivity to waterlogging and the interaction with the climate could result in other quantitative effects.

Climate changes are described as generally increasing the precipitation and the intensity of precipitation events. The latest large drainage campaign in Denmark took place more than 50 years ago, and the drainage systems are therefore often of older origin and dimensioned to former precipitation levels and intensities. This imposes an increased risk of capacity issues in an under-dimensioned drainage system in the future of increased precipitation, as described by Rasmussen et al. (2018).

This is not only relevant in Denmark but also internationally since other regions with comparable climate and soil type have similar issues of the changing climate.

The importance of drainage in plant production relates mainly to the maintenance and extent of gas exchange, that has major effects on a number of chemical/physical/ biological states and processes in the soil. These states and processes have fundamental influence on the crop growth and ultimately effects on the yield potential.

One of the most important and well described factors is nitrogen availability as promoter for plant growth and sensitivity to redox state in the soil. This can lead to reduced growth in poorly drained soils as a result of water logging (Aslyng 1980; Belford et al. 1985). Reduced soil temperature and impaired plant growth in the spring as a function of this is also a well-established perception.

Objectives

The main objective of this study was to quantify the harvest yield effects of shallow groundwater tables in modern cereal varieties due to insufficient drainage conditions under Danish field conditions.

Yield effect hypotheses:

- There is a yield effect in cereals of varying waterlogging conditions across growing seasons and localities.
- Dynamic measurements of the water table depth can be the foundation of a drainage index that can be used as basis for the yield function.
- There is an interaction between N application rate and drainage conditions on cereal yield, and extra N application can thereby reduce the effect of poor drainage on yield.

Temperature effect hypotheses:

- There are significant drainage effects on soil temperature, which can be measured in field trial with different drainage conditions.
- Temperature observations in well drained and poorly drained fields can be modelled and described by energy fluxes on the basis of measured soil properties and available, hourly meteorological data.

In order to investigate the hypotheses field trials were conducted at three locations with diverse drainage conditions over several growing seasons.

This thesis consists of five chapters:

Chapter 1. An introduction consisting of a basic literature review of relationships between drainage and yield that serves as background for the project and the methods used in this study.

Chapter 2. The basic trial design and measurements are described under "Methods".

Chapter 3. *Yield and development of winter wheat (Triticum aestivum L.) and spring barley (Hordeum vulgare) in long-term experiments with variable drainage conditions*

This article aims at describing the yield response of poor drainage across different locations and growing seasons in a modern North European growing system of cereals.

[Submitted to European Journal of Agronomy]

Chapter 4. *Drainage effects on soil surface temperature, a field trial on loamy sand in Denmark*

This manuscript aims at quantifying the effect of poor drainage on the top soil temperature under spring fields conditions in a growing crop and describing the derivative basic energy fluxes by modelling.

[Manuscript draft]

Chapter 5 Conclusion and Perspectives

Chapter 1 Introduction

This introduction serves as background for the objectives with references to the most recent state of the art scientific publications and achievements within the topic in this study of drainage and plant production. In addition, it serves as the theoretical basis for the chosen experimental methods used in this study.

Definitions and basic drainage system

Definition of drainage used in this thesis is:

"The removal of excess surface and subsurface water from
the agricultural land to enhance crop growth"

This is inspired by the definition of the International Commission of Irrigation and Drainage (ICID) (1979) and demonstrates the close connection between the purpose of the huge efforts put into drainage in agriculture.

In the global scale, drainage as a mean of salinity control is also important, but has not been included in this work.

The basis features and nomenclature of a drainage system is shown as a schematic version in Figure 1, showing the main drain at the ending out in the recipient at the drainage outlet. The field drains are connected to the main drain through the "collectors".
The drains are typically placed in the soil with a gradient, depending on the diameter of the pipe, from the outlet to the end of the field drains in order to facilitate the required water flow rate in the system.

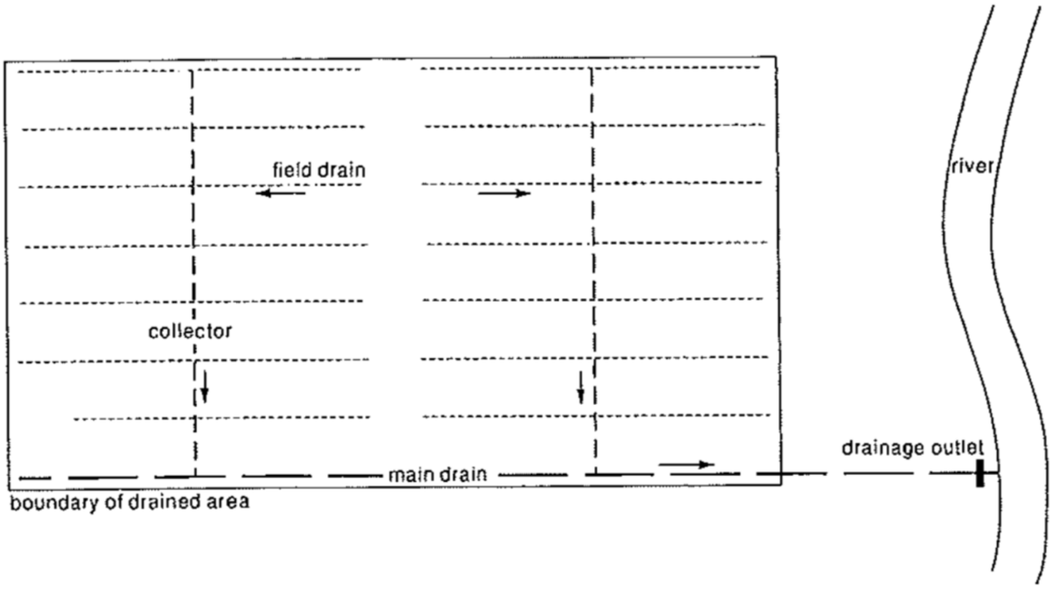

Figure 1 Basic simplified schematic drainage system (Ritzema, 2006). The drainage outlet is the key point, letting the water into the recipient, at the end of the main drain. The field drains (also called side drain) are connected to the main drain through a "collector".

The terms of waterlogging and flooding used in this thesis is defined as:

- Waterlogging is defined as shallow groundwater table affecting the root system of plants.
- Flooding is defined as water levels higher than the soil surface.

History and extent of drainage

The development of agriculture goes hand in hand with the control of water and the development of drainage in substantial areas of the world.

The first recordings go back to Mesopotamia kingdom 3000 B.C. (Jacobsen and Adams, 1958), and the Indus valley 2500 B.C. (Snelgrove 1967 cited by Ritzema, (2006)).

Some of the first written Danish history, Saxo Grammaticus (1160-1208) describes the famine under king Oluf Hunger (translated: Oluf Famine) to be caused by extreme rainfall and water on the fields at harvest, farmer had to harvest the ears in the standing water. In the middle ages Danish historians write about "evil water" as a farmer plague.

These very early records of drainage issues show the significance of drainage from the first days of agriculture.

Technological development of drainage

The first drainage systems consisted of ditches dug by hand to help water out of the field, and in the 17th century trenches were filled with bushes or stone (Ritzema et al., 2006) as some of the first subsurface drainage measures. The extent of drainage was intensified with the invention of the tile drain in England 1810 (Ritzema, 2006) and mechanisation of the manufacturing process in the mid 19th century. The tiles where dug down by hand in the beginning and the extent was accelerated by the mechanisation of the installation after the 1940s.

The mechanisation involved the use of excavators to lower the cost of installation and later other machinery like ditchers and drain ploughs were able to drain large areas more effectively. But drainage is still an expensive operation in terms of materials and installation, and requires a solid cost-benefit analysis as foundation for the work.

The development of the drained area in Denmark is shown in Figure 2 (from Aslyng, 1980). It shows how fast the extent of drainage evolved in some regions. In 1900 over one fourth of the area was drained in Denmark. This emphasises that a substantial part of the activities took place before mechanisation and according to Ritzema et al. (2006) before a solid empirical knowledge was established, including well-founded recommendations of the design in terms of depth, spacing, dimensions and estimations of capacity. This indicates that parts of the drainage system are not optimally installed leading to suboptimal drainage depth and conditions, due to the burdensome manual installation. This is supported by observations of tile drains at shallow depth in part of this work by a drainage depth of 55cm in parts of a field. There are few publications on the quality and maintenance state of the drainage system. Under Danish conditions the state of the drainage systems was estimated by Skriver and Hedegård (1973) and referred by Aslyng, (1980). They found the maintenance to be inadequate under a presumption of an 80 years average effective lifespan of the systems. They estimated a large need for new investments in the drainage system for maintenance and renewal. Hence, there is a risk of large areas of poor drainage condition due to insufficient maintenance.

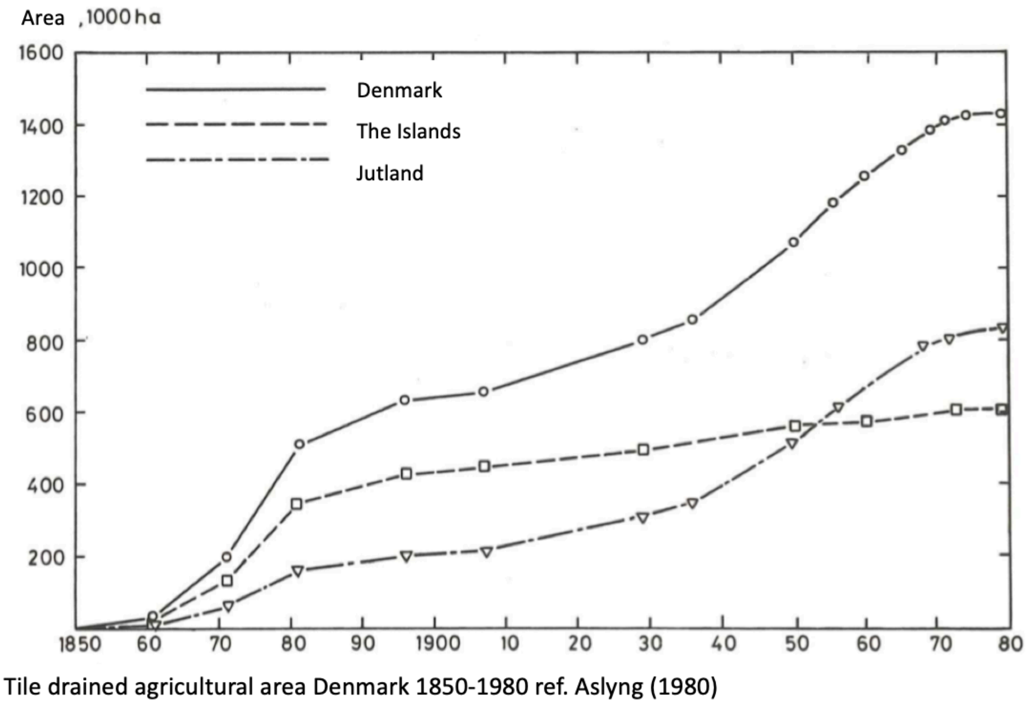

Figure 2 Development in drained area in Denmark 1850-1980, 1850-1929 based on production of tile drain and 1937-1979 on the statistics of paid subsidies to drainage (Aslyng, 1980). The total agricultural area is in the period close to 2.500.000 ha.

The technical solutions and theory behind the design of drainage systems have reached a high level today, but Ritzema et al. (2006) stated the implementation to be a considerable part of the installation process, that can lead to suboptimal drainage conditions even in newly installed systems. Even though we have the knowledge to construct the systems, this knowledge is not always optimally implemented in the drainage design and have been experienced to be more empirically founded by the contractors experiences. Van Schilfgaarde (1979) describes this issue as “not much will be gained from the further development of new solutions to abstractly posed problems. The challenge is to imaginatively apply the existing catalogue of tricks to the development of design producers that are convenient and readily adapted by practicing engineers”.
If this is the case, many areas can be affected by poor drainage without our knowledge due to insufficient use of knowledge in the implementation of the systems.

This means that there is a risk of poor drainage even in drained fields resulting in yield losses, because the old or newer drainage systems potentially have not been installed according to the most recent recommendations and there is a risk that the systems have suffered from insufficient maintenance.

Drained area

The importance of drainage as agrotechnical practice can be illustrated by the major extent, however a study of Powell et al. (2012) estimates 15-20% of the worlds wheat crops are prone to periodic flooding every year.

Global extent

In the global scale Ritzema et al. (2006) estimated 150 million ha to be artificially drained. However, it's also estimated that another 300 million ha need drainage, particularly in developing countries. This tendency can also be identified in Figure 3 showing highest densities of drainage in the developed countries The artificially drain area was estimated by Feick et al. (2005) to be 168 mill ha. The estimate and global distribution were based on national data of the proportion of drained area from different databases as well as estimates of agricultural area.

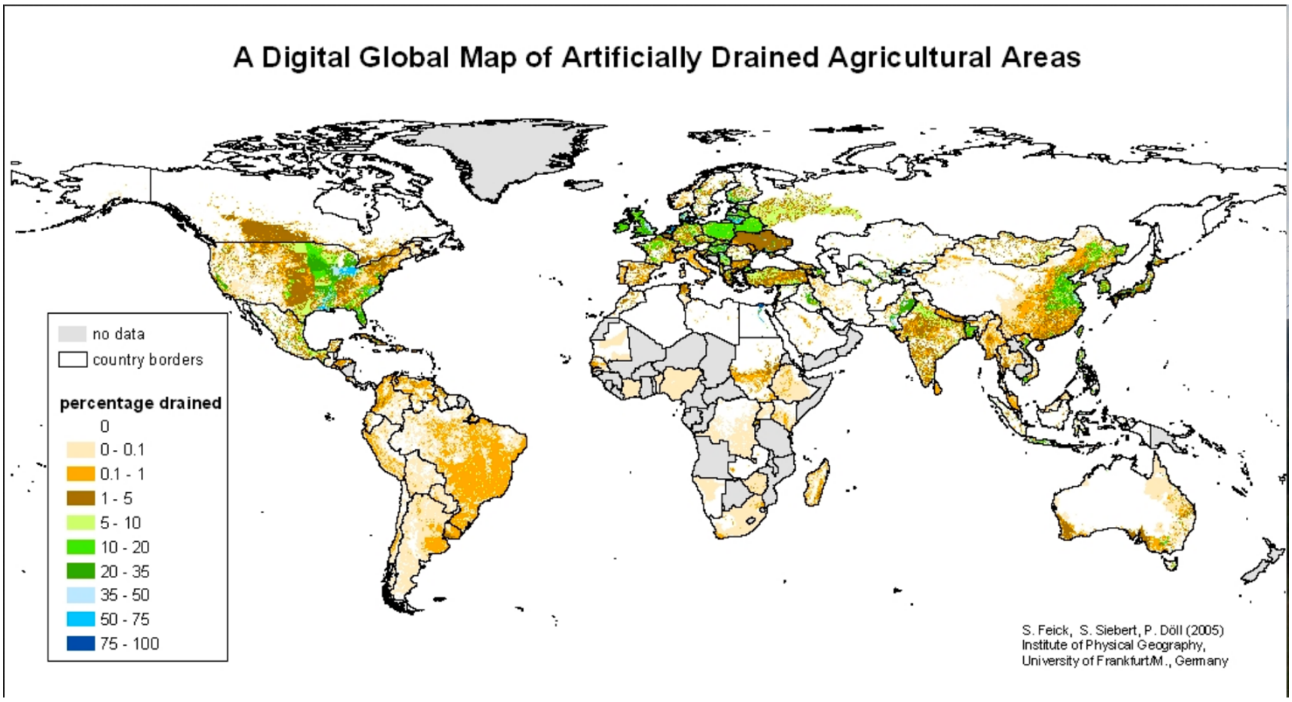

Figure 3 A digital global maps of artificially drained agricultural areas (168 mil ha in total), from (Feick et al., 2005).

Northern Europe

When zooming in on Europe in Figure 4, it is clear that the agricultural area in north Europe have a considerable proportion of drained area.

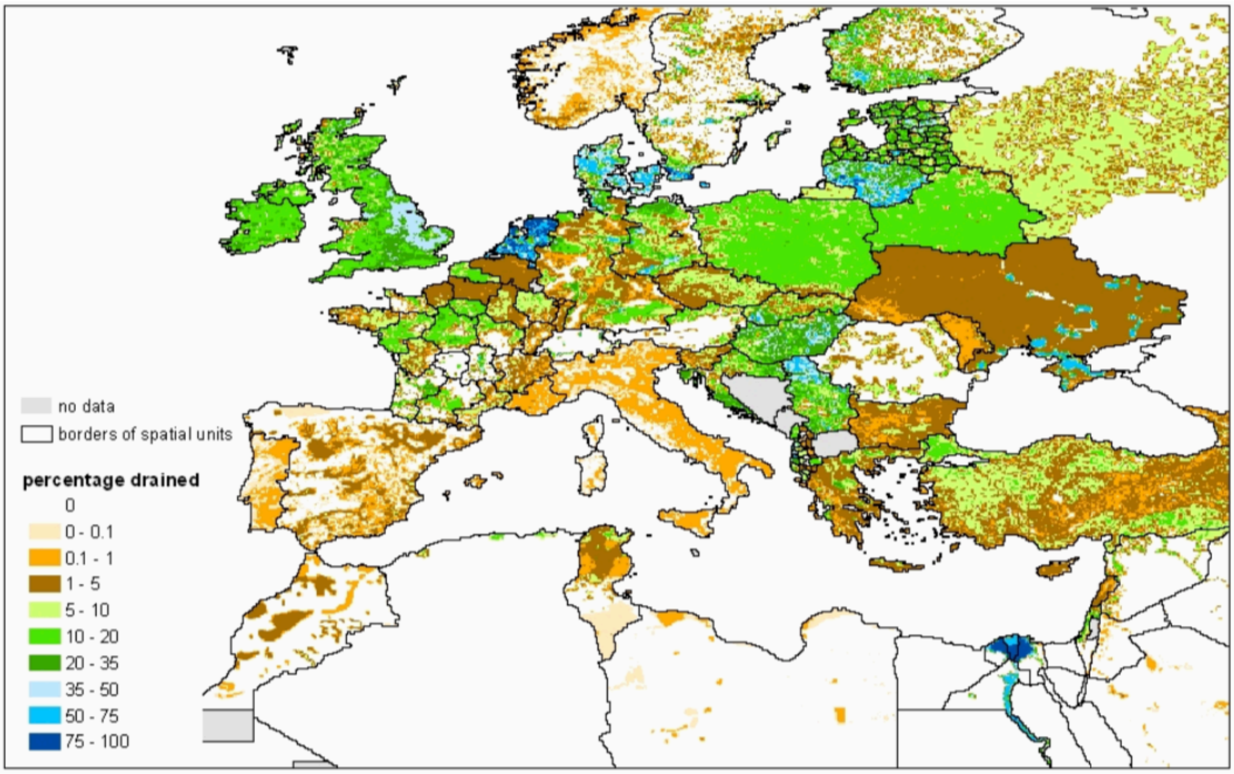

Figure 4 Artifical drained agricultural areas in Europe (Feick et al., 2005)

Recently, a more detailed Danish GIS-study of the drained area based on 46 covariate layers was carried out by (Møller et al. 2018). They estimated 49% of the area to be drained, as shown in Figure 5. The estimates by Feick et al. (2005) are at a rough global scale, which can be seen by the divergence when comparing the more detailed map in Figure 4 with the map in Figure 5, but still the total estimated area of 168 million ha is close to 150 million ha estimated by Ritzema et al. (2006).

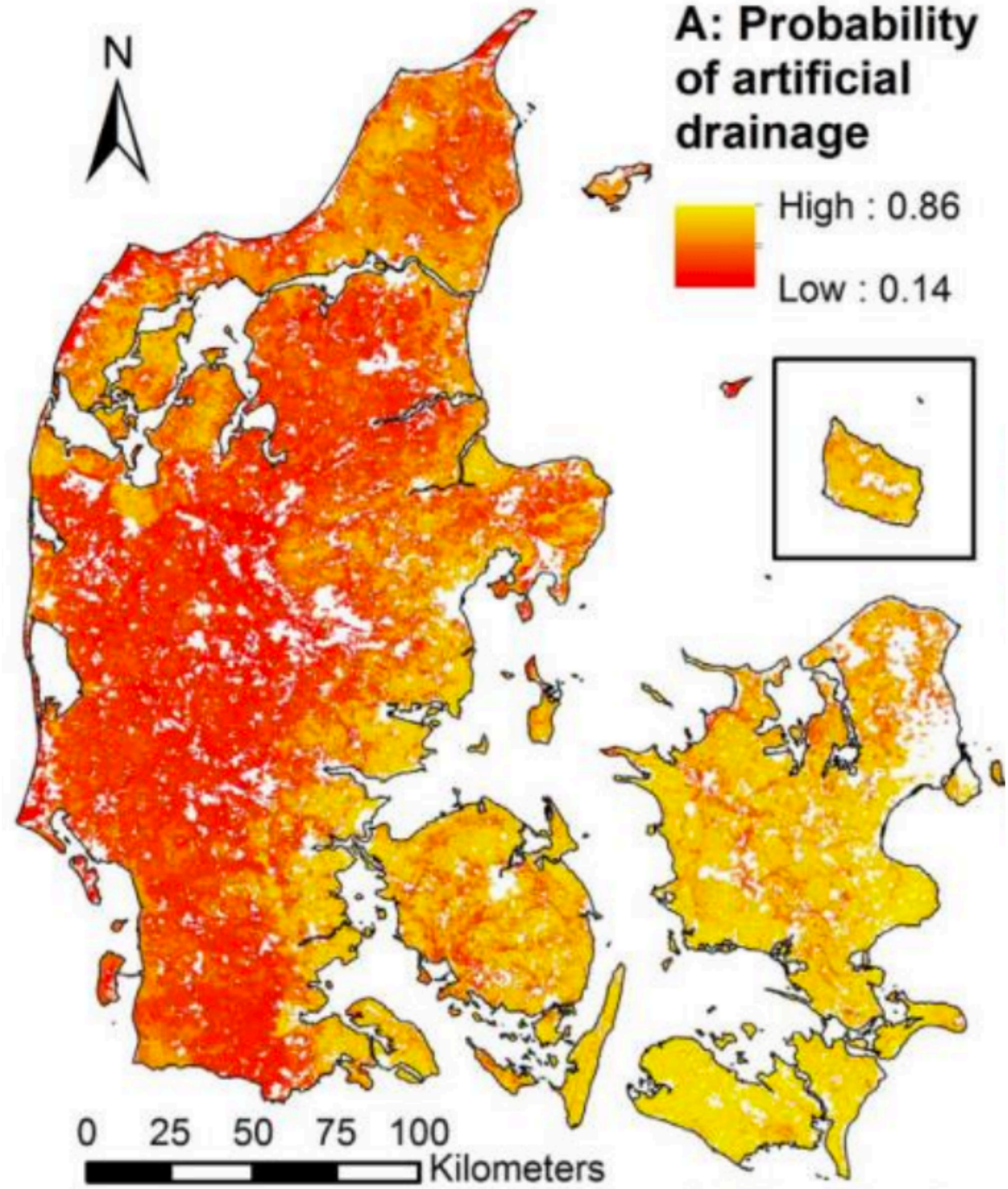

Figure 5 Map of the probability of artificial drainage in Denmark from (Møller et al., 2018)

The drainage need is mostly related to the topography and soil hydraulic properties, which determine the capability of the area to drain of naturally (Møller et al. 2018).

Generally, the extent of drained area shows the relevance of examining the magnitude of yield losses due to deficient drainage since the knowledge can be applied on a significant area, particularly in Northern Europe.

Drainage yield response

The empirical interest in the yield response of drainage has to some degree followed the described historic development in drainage activities and has served as basis for the major investments in subsurface drainage systems (tile drainage). Therefore, many of the studies are of older origin, at least with respect to field trials under north European conditions, since a large proportion of the agricultural land in this area was drained early. This was due to the invention of the tile drain and more effective mechanised installation methods afterwards. The scientific development within the area of drainage is summed up by Ritzema et al. (2006) who writes that “In the first half of the 20th century, the prevailing empirical knowledge of drainage and salinity control gained a solid theoretical footing”.

In 1970 Williamson and Kriz, (1970) summarized a number of field trials published from 1952-1966 and illustrated basic importance of managing the water table and the large differences in crop specific sensibility in between crops. The results of Hoorn, (1958) was part of this publication and are illustrative for the basic yield conception and correlation to constant water table in “Wheat”, “Oats” and “Barley”. These results is shown in Figure 6 as referred by Aslyng, (1980).

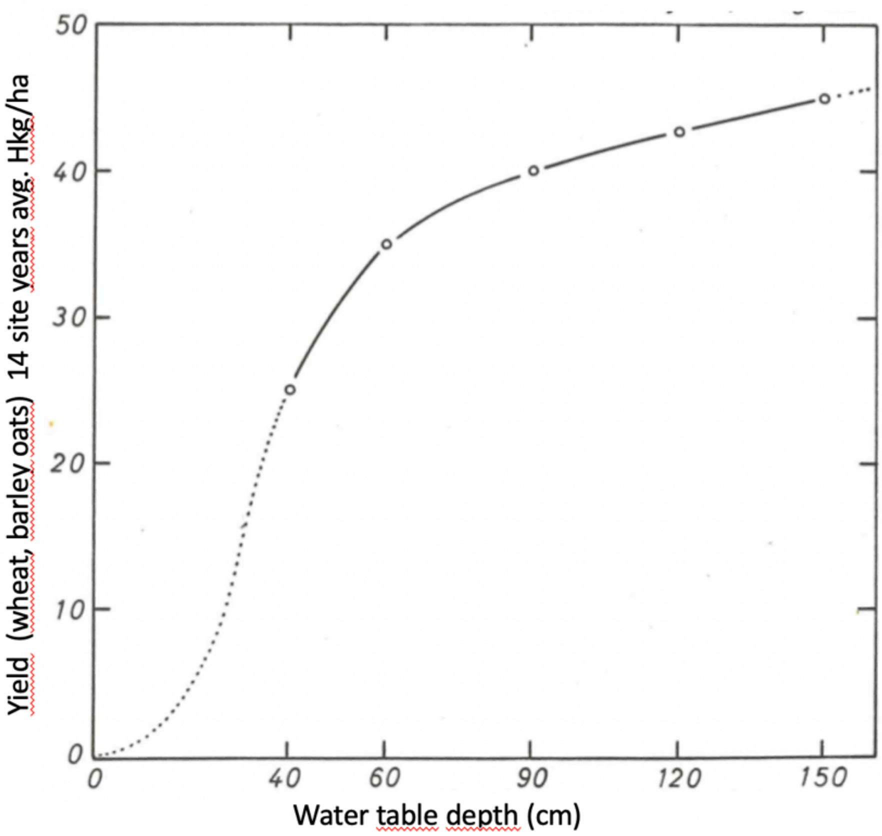

Figure 6 Grain yields under different water tables, average of 14 site years on clay in Holland (illustration from Aslyng, 1980).

Williamson and Kriz, (1970) also described the difficulties of transferring the results due to differences in climatic conditions, soil type and "watering procedure". The last refers also to the issue of comparing different "treatments" or drainage conditions, since a constant water table were used in the referred trials. Fluctuating groundwater are more prevalent and therefore the drainage yield functions derived from trial of a constant water level can be fundamentally different and difficult to compare quantitively. This was addressed by Sieben, (1964) by the introduction of the Soil Excess Water (SEW) concept to describe the effect of high water levels over time on yield. The concept of SEW is presented in equation 1.

Equation 1 $$\mathbf{SEW_{threshold\ depth}} = \sum_{i=1}^{N}\left(\mathbf{threshold\ depth} - \mathbf{WTD_i}\right)$$

Where WTD_i is the daily average groundwater table depth (cm) for day i and N is the number of days in a selected period. Negative contributions are ignored. In the SEW index both groundwater depth and duration of the waterlogging events are included in the calculation of the index value. This is intended to reflect the influence of waterlogging on the crop response, and is in line with the linear relationships between yield and durations of the waterlogging treatments described by Collaku and Harrison, (2002) in wheat in Louisiana USA and by Masoni et al, (2016) in barley in Italy both in pot trials.

The significant impact of waterlogging on plant growth and yield was overall described by (Herzog et al., 2016) in a comprehensive review. The results consist of a metanalysis of the yield effects of different waterlogging treatments including both pot and field experiments. The median yield was reduced to 57% as a result of waterlogging in different trials. The most prevailing studies are more process oriented in the sense of being conducted under more controlled conditions in lysimeters or greenhouses. This imposes a risk of leaving out the soil environmental factors that can be significant due to effects in a longer perspective, including N interactions.

The impact of the climatic conditions, crop management and soil type narrow down the direct quantitative application and relevance of drainage trial results to cereals grown in Europe.
This confines the trials to be located in the area of focus in this study on more comparable soil types and climate in Northern Europa. In addition, the differences in crop response is described by Williamson and Kriz, (1970) who emphasises the need to study representative crops in the right management system. In the area of Northern Europe, the number of publications on

drainage field trials and scientific recent interest in drainage yield effects have been moderate, taking the immense development of science in general in consideration.

However, Dickin et al. (2009) conducted a field trial in two subsequent years in the UK as part of an examination of differences in tolerance between cultivars. An average yields loss of 9% was found as the effect of a waterlogging treatment of approximately 3 months during winter. The treatment was done by irrigation in the winter on a field which is not described as poorly drained. This will normally lead to "unnatural" water movement out of plots into the "control" treatments and the drainage state was not quantified. It can therefore be problematic to directly compare the found yield effect to areas of waterlogging and poor drainage.

In order to show the magnitude of drainage yield effects under conditions more relevant to the aim of this study, the following significant results have been reported in wheat grown in north Europe.

- In the late 70´s a three years trial was conducted on clay and loamy sand monoliths in lysimeters by Cannell et al., (1980). The yield response to waterlogging was 0-15% in the treatments of constant high groundwater level in the treatment period. But the effect was strongly correlated to the yield level, with highest response in the high yielding trials.
- A higher yield response of 21-24% in winter wheat was described by Cannell et al. (1984) in a very comparable lysimeter trial. Water logging was described to cause more variation in yields (depression) than drought in this study.
- Yield depression of 32% after three waterlogging treatments of constant high groundwater level during pre-emergence (5 days in October), tillering (42 days mid-winter) and stem elongation (21days from mid-April) was found in clay monoliths lysimeters in UK by Belford et al., (1985). Single waterlogging lowered the effect to 4-12%, and two waterlogging gave 20% yield loss.
- Earlier on, Belford (1981) conducted a two year outdoor trial in soil columns with waterlogging at the same development stages. A 19% yield loss was found.
- The installation of a combination of mole drains (0.6m depth) and tile drains (0.9m depth) resulted in average 13% yield depression in a four year field trial on heavy clays (Cannell et al., 1986).
- In a two year lysimeter trial done by Dickin and Wright (2008) waterlogging from January to primo March resulted in 20-24% yield decrease.

In a recently conducted spring barley field trial in Finland, severe logging decreased the yield by 68% on P deficient soil. The effect could be compensated by very high P applications of Super Phosphate (Ylivainio et al., 2018).

Essentially, these trials all show a significant response even though the yield response differs from trial to trial. This essentially points back on the point from Williamson and Kriz (1970) that the interaction between yearly weather, soil conditions and management result in variation in yield response. However, it also illustrates some of the challenges related to drainage trials, since none of the trials were conducted on established drainage conditions in the field with dynamic quantified water tables. Also, the interaction with the management factor of N application and related risk of denitrification under dynamic conditions can be important and have not been examined. The soil physics and chemistry were therefore disturbed, and the long-term effects of drainage were not included. In the few trials done under field conditions the water levels were not quantified and can therefore not be compared to measurements of groundwater elsewhere. Sieben, (1964) solved this problem by using the SEW index in order make it possible to comparing drainage conditions between years and locations. This was adopted by Hardjoamidjojo et al. (1982) who developed a yield model based on the SEW_{30} index and tested it successfully against three datasets of long term drainage trials. However, this work was carried out for corn in three different states in the USA. This leaves us with a proof of the concept of a general model of a yield function related to the dynamic groundwater, but without a sound quantitative relation for cereals in Northern Europe, that according to Williamson and Kriz, (1970) differs from the effects in corn.

The yearly variation in yield

The yield function of Hardjoamidjojo et al. (1982) showed a strong relationship between yield and drainage conditions across location and year. However, the interaction between crop management and weather lead to yield variation that is not captured in the relatively simple SEW drainage index. The complexity of comparing yield and a simple measure of drainage state (index) is also illustrated by the variation in yield response over a five year period of different average groundwater levels during winter and corresponding yield in winter wheat in Figure 7 by Ritzema (2006).

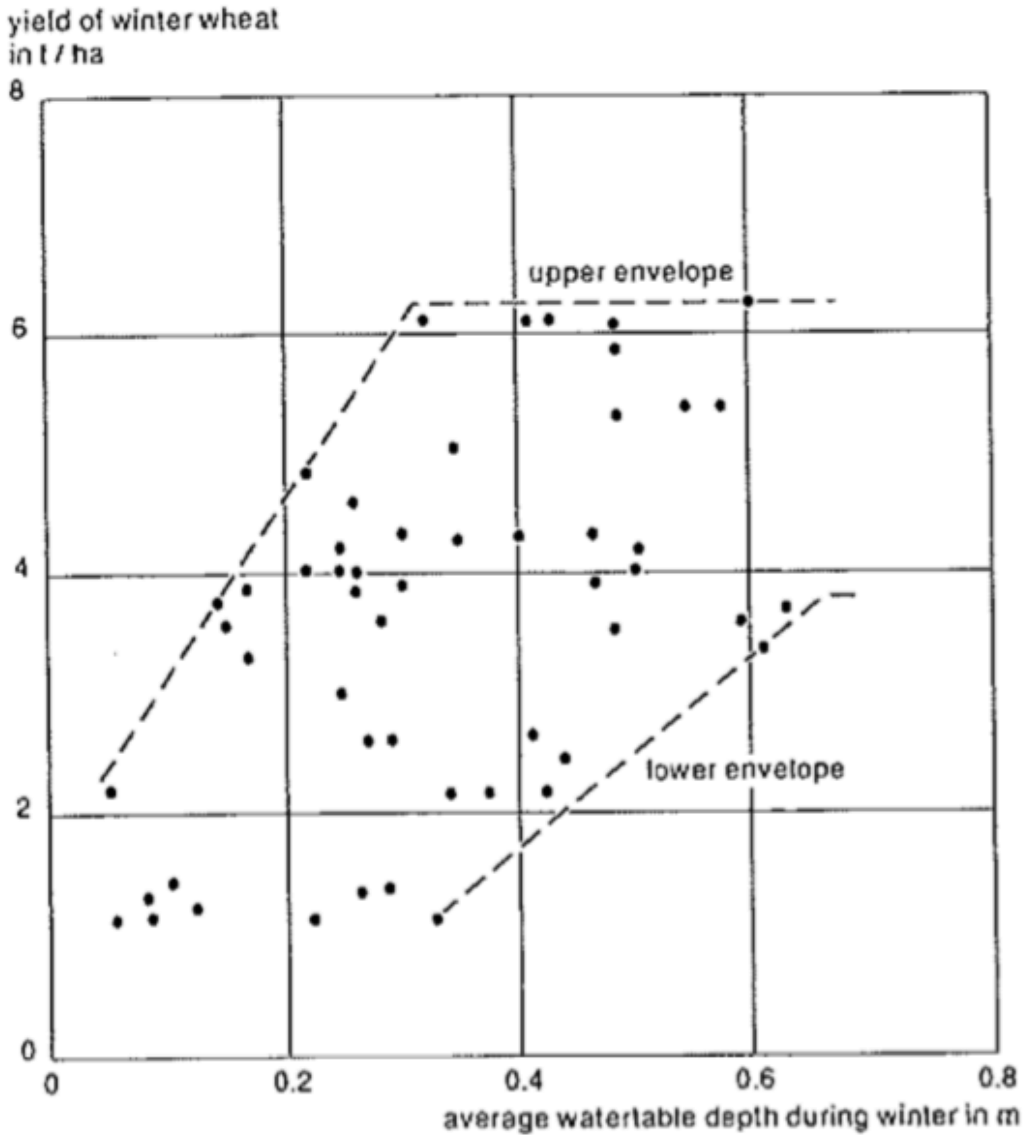

Figure 7 Illustration of the 5 years observations of yield in winter wheat versus average groundwater depth in winter on a heavy clay soil (Ritzema, 2006)

Multi-year trials and the estimation of variation can therefore of interest, and can also finally contribute to a better understanding of the underlying processes. In a field trial of dynamic groundwater, the current weather conditions in the trial year is affecting the drainage index values. Different weather years therefore impose the need to have several site years, in order to get a wider range of index values. The yearly variation in yield response to drainage conditions can also be an essential measure in estimating the need for drainage management solutions and other consequences of poor drainage, since this is a description of the potential yield loss risk.

The factors leading to yield losses are described in more detail under “Drainage effects on soil” and “Drainage effects on plants”

Old drainage systems in a changing climate.

Potential capacity decreases in the drainage system

The increasing concern of environmental impacts in the streams and disturbance caused by maintenance of the streams by cutting of vegetation and removal of sediments have led to reduced maintenance. This can shrink the cross section of the stream and increase the roughness of the stream banks. Both factors can lessen the conductivity of the streams and increase the water pressure and propagate though the drainage system in the catchment. This factor is therefore related to the drainage conditions in the fields. Similarly, the capacity of the drainage system can be under pressure since the tile drains have a limited life expectancy, that imposes a need for maintenance in the old tile drain systems. Some studies have shown that this might be lacking behind in Denmark (Skriver and Hedegård, 1973).

Climate change and drainage needs

The future climate change in Northern Europe is predicted to result in increased winter precipitation and more extreme precipitation events together with increasing temperature (van der Linden and Michell, 2019). The impact of the higher precipitation on drainage discharge were examined by Rasmussen et al. (2018) under Danish conditions. The discharge was estimated to increase with 10% in the “near future” (2030-2059) and 16% in the “far future” (2070-2099) primarily due to increased precipitation in the autumn and winter. This will lead to a higher demand for drainage in regards to the area that needs drainage, which will increase, but also the capacity of the system. The old drainage systems are dimensioned after the historic precipitation at the time of installation which has increased compared to the reference period (1983-2012) used by Rasmussen et al. (2018). Figure 8 shows the development in yearly precipitation in Denmark 1874-2013. In this perspective the risk of poor drainage now and the future is apparent.

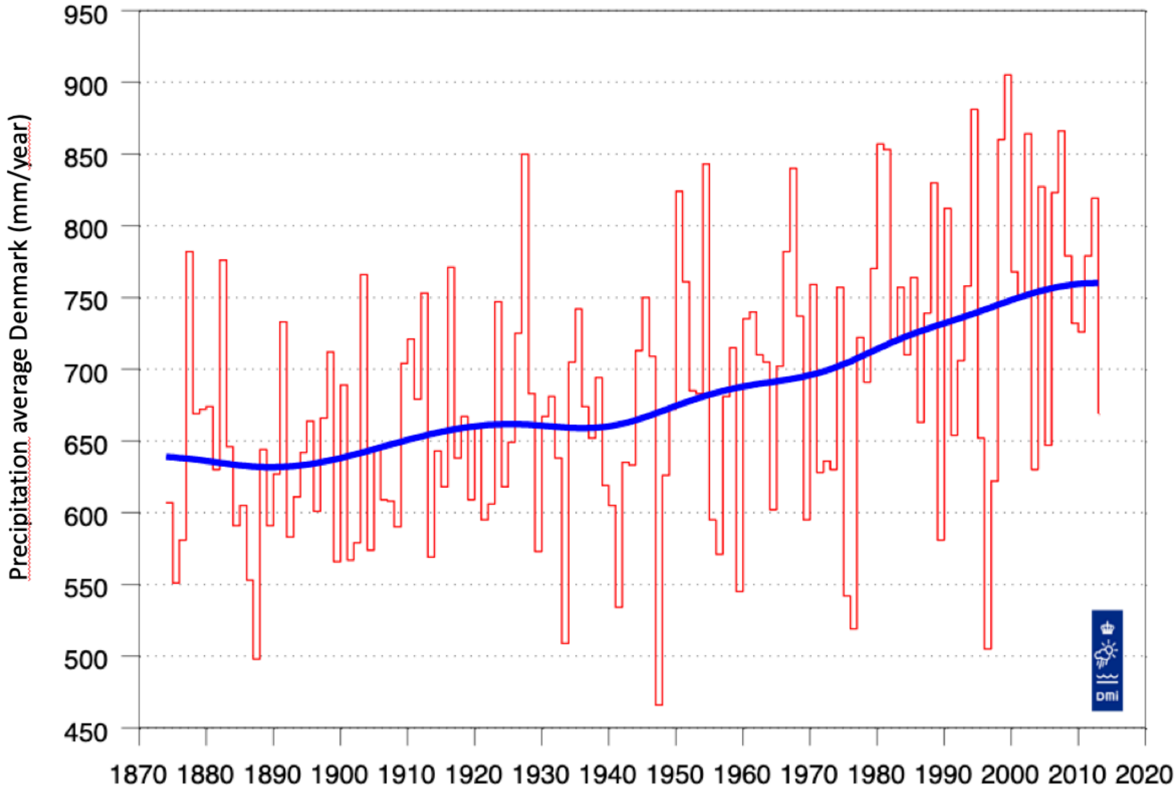

Figure 8 Yearly precipitation in Denmark 1874-2013, blue line average over nine years. Cappelen (DMI), (2014)

Future heavier rainfall events is also a factor that will lead to higher demands to drainage, since drainage systems provide more stable growing conditions and reduces the weather-induced risks of flooding and periods of waterlogging during the growing season. This higher stability in yields and food security can be an important matter in a world of increasing world population.

Environmental impact of poor drainage / modern intensive plant production

The environmental impact of the agricultural production is a growing concern that needs to be addressed. The drainage intensity can impact the leaching potential of N, which was illustrated by Kladivko et al. (2004) by an negative correlation between drainage spacing and leaching in a 11 year corn trial in Indiana (USA) at fertiliser levels of 200-300kgN/ha/year. However, the yield effect was reported to be low in this trial, compared to the previously mentioned yield losses and harmed plant growth due to poor drainage in winter wheat. This raises a question of the nutrient use efficiency and derivative nutrient losses in poorly drained systems, which to the authors knowledge have not been quantified in a field trial of winter wheat in Northern Europe. Denitrification risk is increased by poor drainage, which can lead to increases in the nitrous oxide concentration in the soil atmosphere as a result of oxygen depletion during waterlogging which was shown in a lysimeter trial with winter wheat by Belford et al. (1985).

The N uptake of the crop is a significant component of the N-balance and thus important in the understanding of N losses to denitrification, leaching and changes in the organic N pool. With the knowledge of yield response to drainage, we will be able to make better decisions in future drainage management giving higher productivity with less environmental impact. Kladivko et al. (2004) thus states that long term trials are needed in order to develop appropriate managements strategies to the right climate and soil type.

Drainage effects on soil

Drainage as a measure for removal of excess water have fundamental effects on the soil physic, chemistry. Tile drains helps controlling (lowering) the groundwater. This affects the soil water content in the topsoil by lowering the soil water pressure in the soil column. An example of this relationship is illustrated in Figure 9 as soil moisture in the topsoil (0.15m depth) as negatively related to the depth of the water table by Young and Ligon, (1972) modified by Ritzema, (2006).

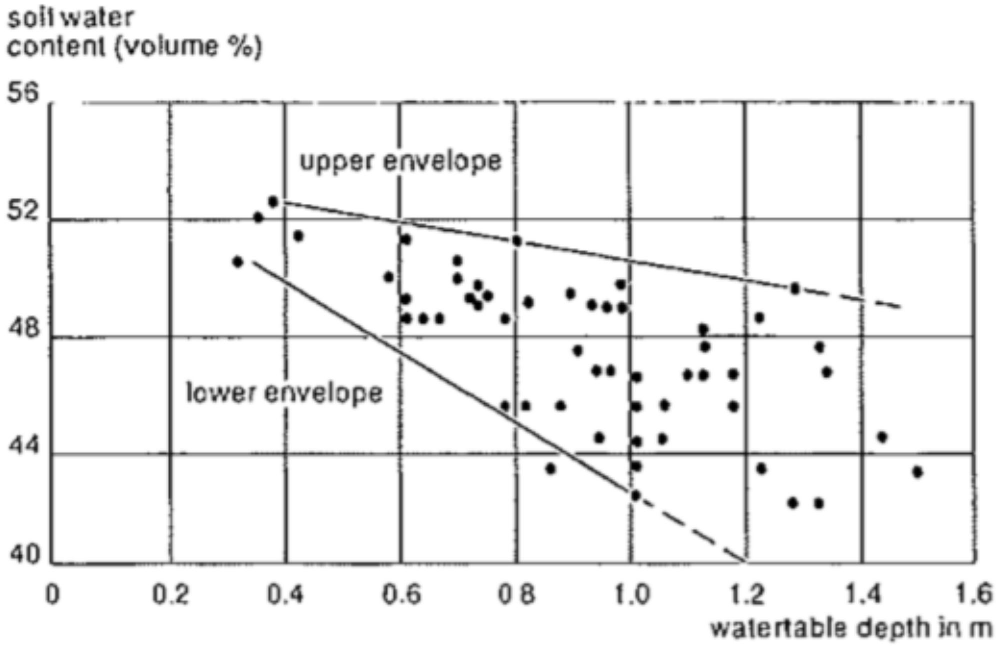

Figure 9 Relationship between soil water content at 0.15m depth and water table depth in a silt loam soil in S. Carolina USA from January through May 1970 Young and Ligon, (1972) modified by Ritzema, (2006)

Similar correlation between groundwater level and soil water content in the top soil (0-12cm depth) was found by Elsborg and Rasmussen (unpublished) in collaboration with the author and is shown in Figure 10. The observation was done during spring on sandy loam in winter wheat. The soil water content affects the gas exchange, soil chemistry, thermal- and mechanistic soil properties.

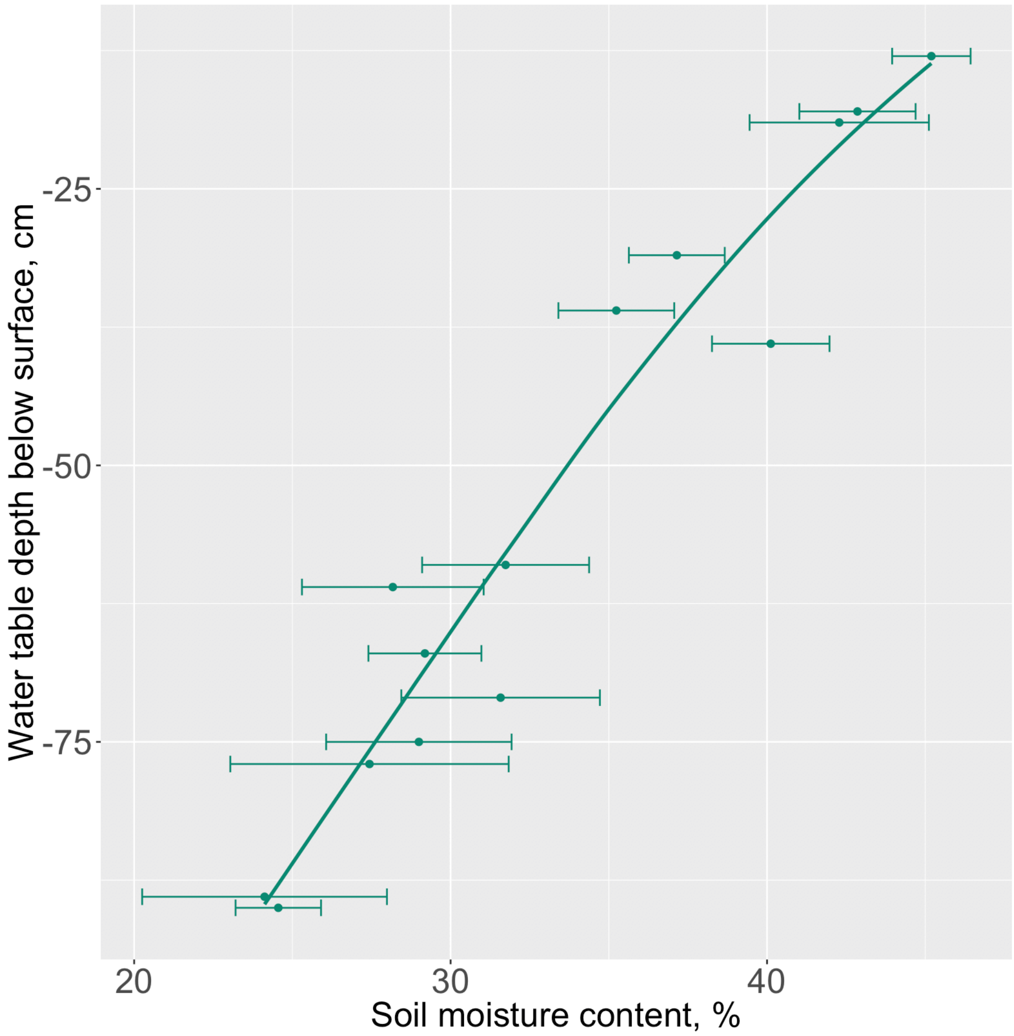

Figure 10 Correlation between soil water content and groundwater level measured on sandy loam 28/2 to 25/4–2019 in winter wheat.

Gas exchange

At high soil water content, the largest pores in the soil are water filled, hindering a sufficient gas exchange. Drainage reduces the water potential in the soil by drainage of water from the largest pores resulting in higher air permeability and better gas exchange. Poor gas exchange under consumption of oxygen in the soil can lead to severe reductions in oxygen concentration in the soil atmosphere due to waterlogging. This was measured by Belford et al. (1985); Cannell et al. (1984, 1980) in a lysimeter trial. Brisson et al. (2002) illustrated the rapid decrease in oxygen concentration after waterlogging resulting in concentrations lower than 0.12 mol m^{-3} O_2 after 48h (16-18^{0}C) (Figure 11 (b)) as well as the correlation between soil water pressure and oxygen concentration shown in Figure 11 (a).

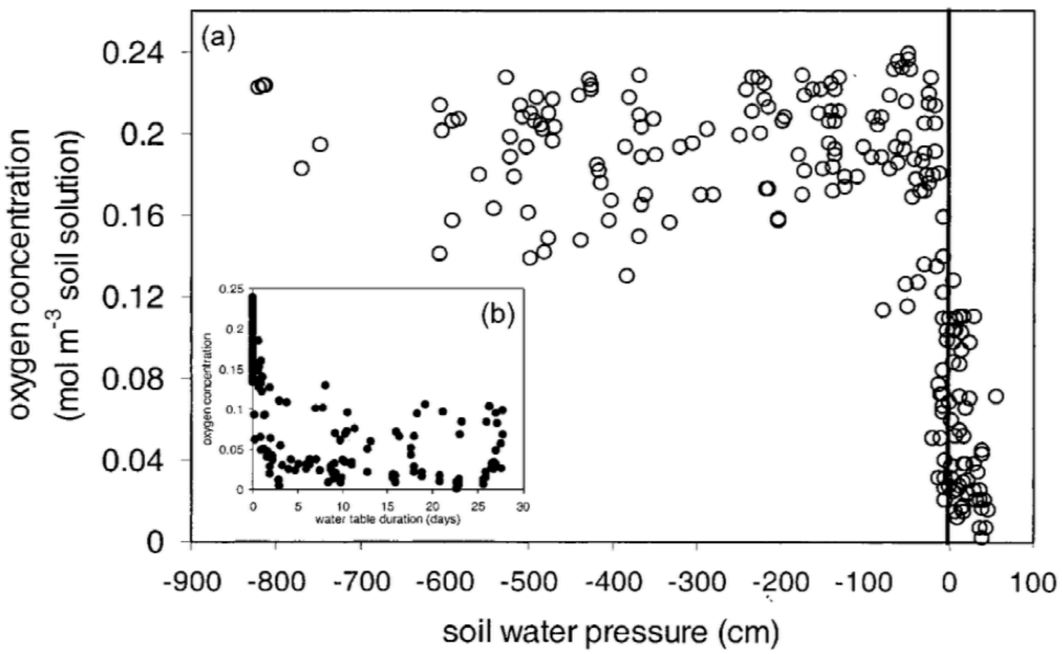

Figure 11 Relationship between soil pressure (a) or water table duration (b) on oxygen concentration (Brisson et al., 2002).

Increased risk of soil compaction due to lower trafficability on poorly drained soils is a factor that can worsen the issue of reduced permeability and thereby reduced gas exchange. Lower air permeability as a consequence of soil compaction is a common feature (Batey, 2009). This is also described by Berisso et al. (2013) for a sandy clay loam in Sweden.

The air permeability at field capacity was measured in one of the trial locations in this work (Tokkerup) by Holbak, (2017). Permeability measurements were done in 50cm depth over the tile drains at a depth of 60cm and under at a depth of 100cm. The texture and bulk density were close to identical in these two depths, however the permeability was significantly lower in the samples under drainage depth. This could indicate that permeability had increased in the horizon over drainage depth. This is comparable to the findings of (Jafari-Talukolaee et al., 2016), who found improved hydraulic conductivity after four years by installation of subsurface drainage tiles.

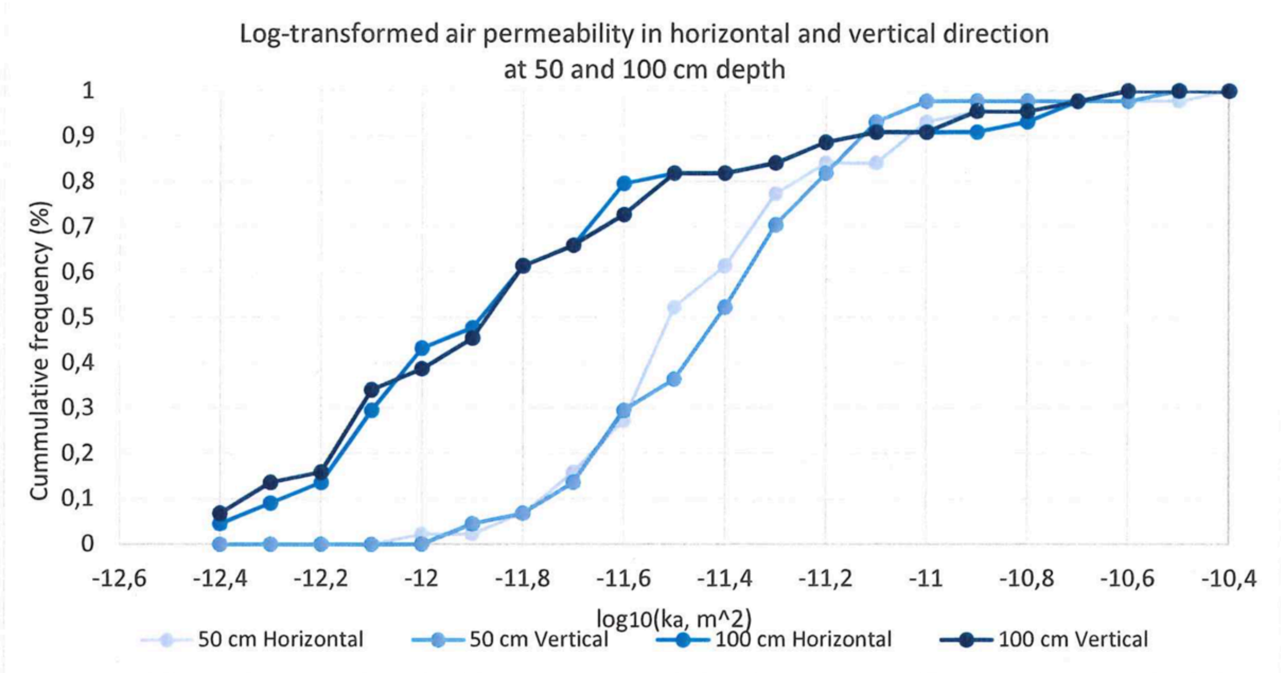

Figure 12 Cumulative frequency of air permeability measurements smaller than the corresponding $\log_{10}(k_a,m^2)$ Data is shown from each measuring direction at 50cm and 100cm respectively (Holbak, 2017).

Soil chemistry

When gas exchange is restricted, the redox state is reduced due to oxygen consumption in the soil. In a pot experiment by Malik et al. (2001), the redox potential dropped from 600 mV to 200 mV after the first days of waterlogging and then further to 40 mV at the end of the treatment. Similar redox reductions are described by Musgrave, (1994) as indicator of absence of free oxygen in the rootzone.

The redox potential can potentially recover rapidly in the topsoil layers, but in deeper soil layers the redox potential recovery can be delayed after waterlogging (Malik et al., 2001), which indicates that waterlogging effects are not only restricted to the period of the treatment, but can last longer due to the changes in the soil chemistry.

The redox reduction is not only caused by plant induced root respiration but is also due to microbial activity. The rate of oxygen depletion is therefore temperature dependent Brisson et al. (2002). The effect of temperature was measured by Cannell et al. (1980). In three waterlogging treatments the fastest oxygen depletion was found in warmest periods of 5-6 days in May, and 8-9 days in December. The slowest rate was found in the coldest month of January of 10-15 days. The trials were done in lysimeters of clay and sandy loam under winter wheat in Britain and therefore comparable to the conditions in this study.

The reduction in redox state introduces an increased risk of reduced N availability of the crop, since the denitrification and nitrification in the soil are redox state dependant. The denitrification process is strongly correlated to the redox state in the affected soil horizons and causes nitrate to be reduced to N_2 or nitrous oxides. The correlation between denitrification rate and oxygen concentration in the soil was described by increased nitrous oxide development measured as increased concentrations in the soil atmosphere under waterlogged conditions by Cannell et al. (1980). Decrease in soil nitrate concentration accompanied by increase in nitrous oxide evolution was found by Belford et al. (1985) as oxygen concentrations decreased.

Soil temperature and microclimate effects of drainage

A physically based positive effect of drainage in temperate humid climate is that lower soil water content in the topsoil in well drained soils can raise soil temperature in critical periods for plant growth (Aslyng, 1980; Feddes, 1971; Ritzema, 2006) . This is because the water potential is lowered to a level were evaporation is restricted from the soil surface, but also because the thermal conductivity and capacity in reduced by drainage. This can result in a lower loss of energy in the topsoil resulting in higher soil heat flux, particularly in periods of low soil temperature in the subsoil, which is typically happening in spring. Hence, higher temperatures due to drainage have the potential to lead to increase biological activity. In the spring period, plants are typically limited by temperature in germination- and growth rate (Feddes, 1971). Hence, the length of the growing season can thereby be prolonged by drainage, resulting in higher yield potential.

Some of the negative temperature effect of poor drainage can partly be compensated by breaking the capillary forces in a tillage operation. But this presumes that the soil is trafficable, allowing tillage in spring sown crops. It still does not fully compensate the effect of drainage since there will be a hydraulic conductivity with the potential to transport water to the surface. Spring tillage of autumn sown crops is not an option and therefore the temperature effect can be higher.

Management and timing.

Management operations in the field are restrained to the periods where the workability and trafficability criteria are sufficiently met. Removal of excess water as a fundamental criteria to increase trafficability and workability of the soil is described by Müller et al. (1990), who also writes that an average spring time water table depth of 90-110cm should be reached by deep land drainage as a requirement for arable farming on the examined location of clay soil in Germany. Similarly Skaggs (1980) found that trafficability was heavily affected by different subsurface drainage intensities during seedbed preparation in North Carolina, USA. Figure 13 show the correlation between drainage intensity (termed drawdown time) and workable days in spring found by Skaggs (1980). Hence, the right timing of management operations is promoted under well drained conditions.

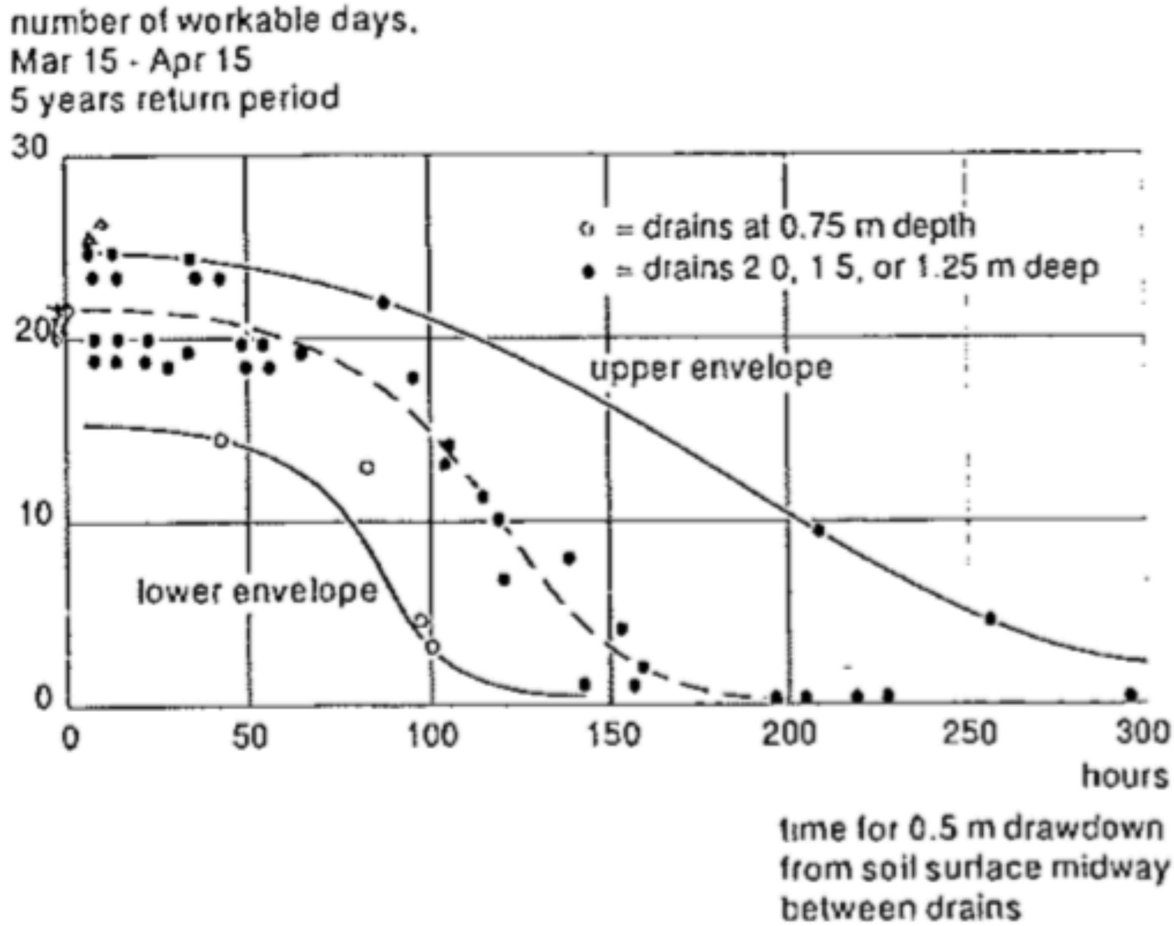

Figure 13 Number of workable days for different drainage intensities versus drawdown time of the watertable in North Carolina USA (Ritzema, 2006 modified from Skaggs, 1980)

Cannell et al. (1984) described that reduced trafficability as a result of poor drainage can lead to additional yield reduction due to limitations in the ability to do crop management such as application of fungicides, herbicides and fertilisation at the correct time. Cannell et al. (1986) reported a direct implication of the management in a drainage trial, as a significant interaction between drainage and tillage method in one year out of four trial years. This shows that good drainage can lead to higher resilience to different weather conditions and thereby increase management possibilities.

Drainage effects on plants

Physiological response

The yield effects of drainage are based on adverse physiological responses of crops exposed to waterlogging. First, anoxic conditions in the soil created by poor gas exchange leads to oxygen deficiency in the root system. Even though wheat root systems have aerenchyma to facilitate some gas exchange of oxygen and carbon dioxide in the root system, severe hypoxia will occur in the root tissue during waterlogging (Herzog et al., 2016). Belford, (1981) also found a higher proportion of aerenchym tissue in the roots and increased nodal root production as a function of winter water logging, along with reduced tillering, chlorosis and premature senescence of leaves.

The lack of respiration leads to a shift of metabolic pathways to a lower ATP yielding ethanolic fermentation in the roots. This results in impaired functioning of the basic root functions such as water and nutrient transport (Herzog et al., 2016). Consequently, growth of the roots is first reduced dramatically and finally the growth stops. Hence, a reduction of the root shoot ratio from 0.4 to 0.2 is reported (Herzog et al., 2016). The shoot growth of the plant is affected by hampered root function by decline in the photosynthesis due to feedback mechanisms from accumulation of sugars in the tissue. Additionally, restricted nutrient uptake and reduced translocation of nutrients to the shoot tissue results in N deficiency Herzog et al. (2016). Reductions of 70-80% in net photosynthesis and reduced N concentrations in the leaves were observed by Malik et al. (2001) in winter wheat grown in pots .

The crop susceptibility is growth stages dependent and crops are therefore more sensitive to waterlogging stress in some periods of the growing season. Waterlogging at the pre-emergence growth stage was reported to reduce the plant population dramatically from 338m^2 to 35m^2 by Belford et al. (1985) and water logging at the pre-emergence stage had the most severe effect on yield of treatments at three different growth stages (pre-emergence, tillering and anthesis) in a study by Cannell et al. (1980). The most susceptible period to waterlogging in wheat and barley was identified to be around anthesis by de San Celedonio et al. (2014), whereas water logging in the grain filling period had less effect. This shows that timing of waterlogging influences the magnitude of the yield response. Reduced tillering and fewer ears was found by Belford, (1981) and Cannell et al. (1984) as morphological traits of waterlogging. This reduces the yield potential of the crop.
Lower temperatures decrease the biological activity and thereby also oxygen consumption, hence high groundwater during winter have less impact compared to the spring and summer

waterlogging. In accordance with this, Luxmoore et al. (1973) found no significant effect of 30 days of flooding in winter wheat at 5^0C but a reduction of the stem dry weight per tiller of 95% at an increase of soil temperature to 25^0C.

Root growth

Anoxic conditions and reductions in winter wheat root growth was examined by Brisson et al. (2002) in lysimeters and plots in a field near Paris, France. The close correlation between oxygen concentration and indexed changes in root density ($\mathbf{\Delta}d_{10}(h)$) and root growth ($Id_{10}(h)$) is shown in Figure 14. Positive values indicate root growth and negative values a decline in root growth, and a threshold value of 0.12mol oxygen m^{-3} water separates the two. This led to the conclusion that the water table topped with a capillary zone of 6cm was the lower boundary of favorable root growth conditions (Brisson et al., 2002). In the same study, root growth stopped within 3 days after waterlogging (16-18ºC) due to low oxygen concentrations, which is illustrated in Figure 11 (b).

The negative effect of waterlogging on roots growth was also found in the first vegetative growth phases in a pot trial in the UK winter wheat by Dickin et al. (2009) who also found that the potential water logging tolerance was not significantly affected by cultivar.

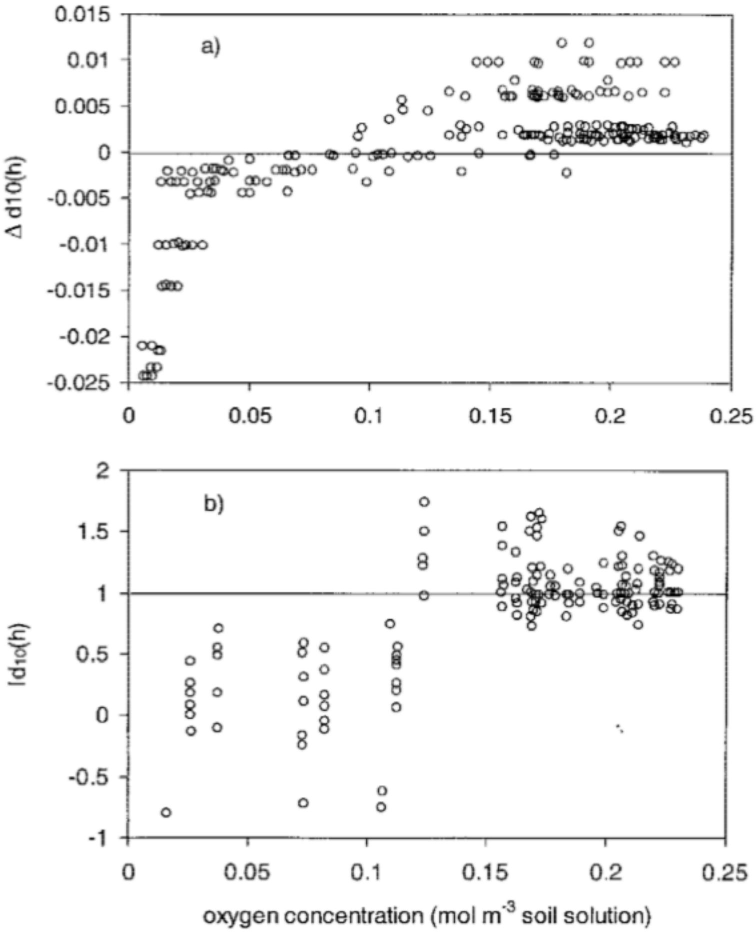

Figure 14 Relationship between oxygen concentration and (a) increase in root density in the corresponding layer $\Delta d_{10}(h)$ and (b) root growth index $Id_{10}(h)$ by (Brisson et al., 2002).

Root development was examined under dynamic groundwater conditions in the trial in this study at the Taastrup location over two growing seasons. 24 minirhizotrons were drilled in the drainage trial (Taastrup) to a depth of 2.3m. Approximately 24.000 photos were taken in the minirhizotrons and the root density were estimated using a line intersect methods described by Rasmussen, (2015) placing a grid on the photos. A detailed description of the rest of the trial can be found in Jensen et al. (submitted). The influence of drainage on root distribution has not yet been analyzed, but the root depth was found to be closely related to groundwater depth (Jensen and Svane, in prep.). Measurements from poorly and better drained plots of groundwater and maximum rooting depth is seen in Figure 15.

Contrary to these results, Dickin and Wright (2008) did not find an effect on the root depth but only an effect on the total root length in a lysimeter trial also using minirhizotrons. This indicates that a temporary waterlogging treatment as used by Dickin and Wright, (2008) can lead to higher recovery compared to field data.

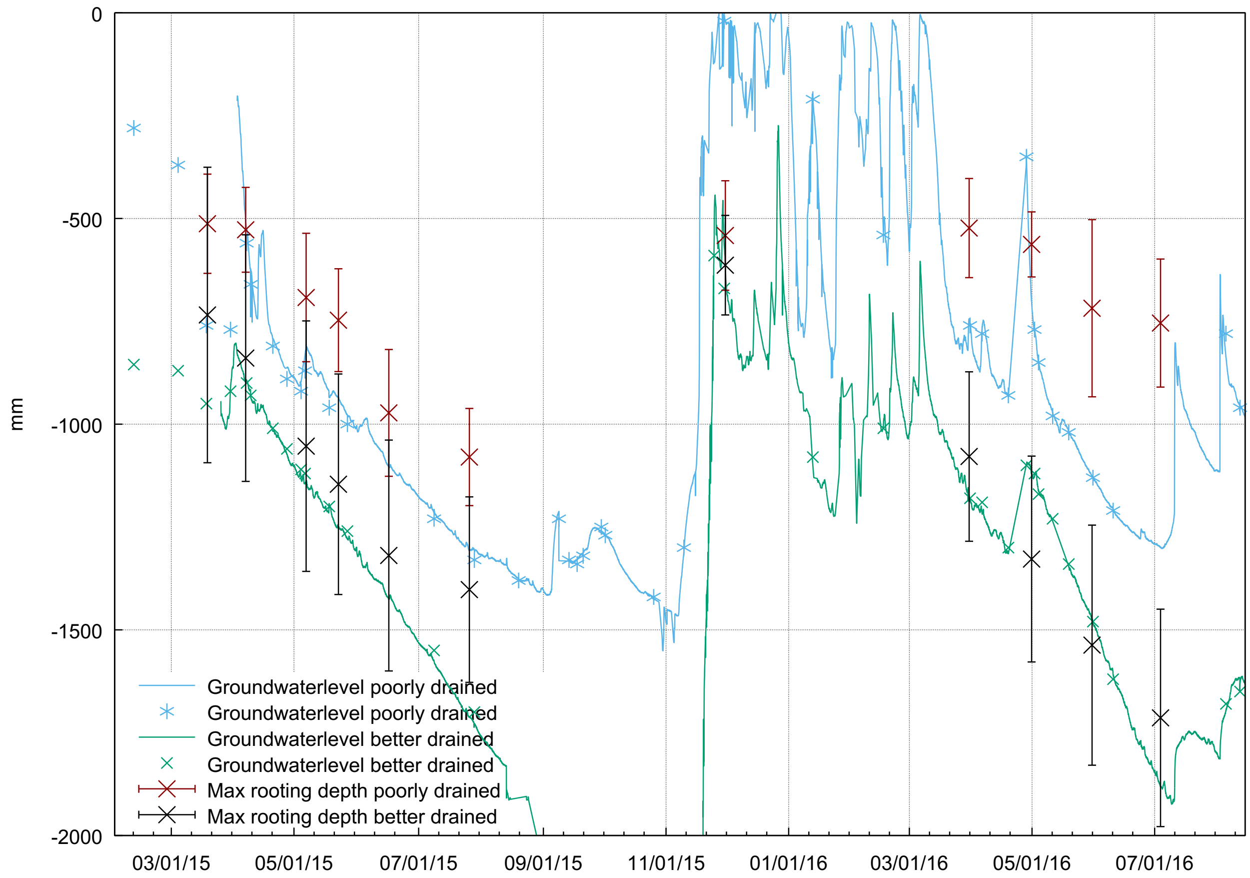

Figure 15 Measured maximum rooting depth (average and SE) and groundwater level at better drained and poorly drained plots in Taastrup 2015 and 2016. Measurements are from the trial referred by Jensen et al. (submitted)

Despite reduced root growth and an expected higher susceptibility to drought, Dickin and Wright (2008) reported the effect of waterlogging and drought to be additive. Similarly, Cannell et al. (1984) could not support a hypothesis of interaction between drainage conditions and drought tolerance.

Nutrient uptake

Reduced root growth and root functionality under waterlogged conditions reduces the ability of crops to take up nutrients, which can lead to yield depression due to nutrient deficiency. Reductions in the vegetative growth of corn and reduced uptake of both N, P and K was shown by N. Ahmad et al. (1992) under different waterlogging treatments 21 days after emergence. The drainage-imposed risk of denitrification and the significance of N as plant growth promoter leads to special focus on the availability of this nutrient in relation to drainage and the interaction with drainage. The interaction between N application rate and intensity of drainage in different drainage systems (subsurface drainage being the most intensive) was examined by Schwab et al.

(1966) in maize over a three years period and is shown in Figure 16. The strongest interaction between the factors (drainage and N application) was found in the application of the first 100 kgN/ha. This shows that the N level can be a matter of importance in the understanding of the interaction between growth factors of N uptake and drainage.

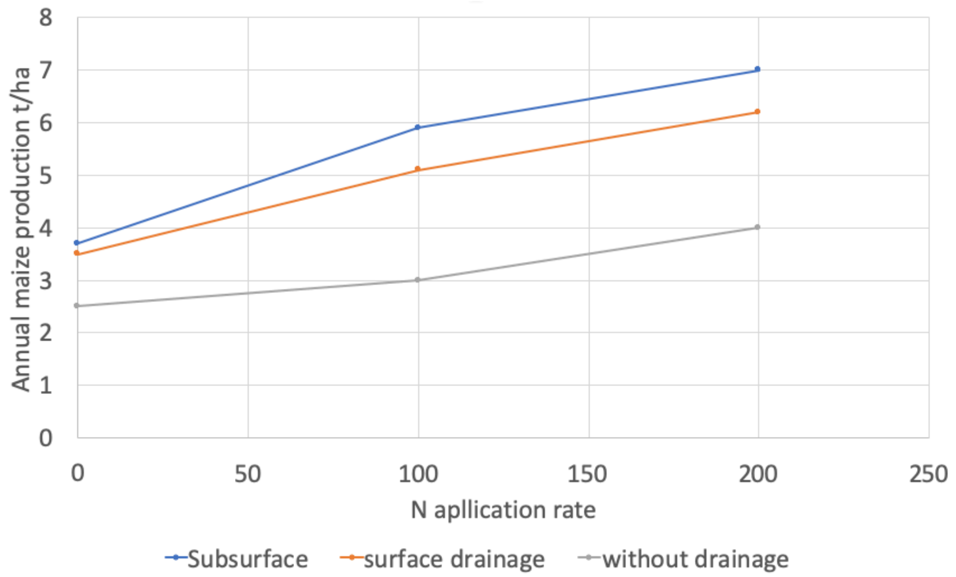

Figure 16 Maize yield as a function of different N application and drainage intensity in drainage systems (subsurface drainage being the most intense, surface drainage and without drainage as control) (Schwab et al., 1966 cited from Ritzema, 2006)

In winter wheat, Dickin et al. (2009) found that the total N uptake was reduced by 50% in the waterlogged plots after treatments measured over two winters (from 17 December 2002 to 4 March 2003 and 3 December 2003 to 28 February 2004). Cannell et al. (1980) also found reduction in both N and K concentrations in the plant material after midwinter waterlogging of winter wheat in the vegetative phase. At harvest the N amount in the winter wheat grains was calculated to be reduced 16% by 44 days of winter waterlogging (Dickin and Wright, 2008). This indicate that the application of fertilizer in spring to some degree can compensate the effect of winter waterlogging on nutrient uptake. This emphasises the importance of the interaction between management (timing of fertilisation) and water logging.

The P availability can also be a significant factor. This is illustrated by the results of Ylivainio et al. (2018) who showed a significant ability of high P application to compensate for the effect of waterlogging. However, the measure to mitigate water logging is described to be improved drainage and not very high application of P fertilizer; “to improve utilization efficiency of P fertilizer in a boreal climate, where rainy summers occur frequently, the most important measure is clearly proper drainage of agricultural soils” (Ylivainio et al., 2018).

Chapter 2 Methods

This chapter describes the basic concepts and chosen experimental design used in this study. The detailed description of measurements in the trials are described in the articles (chapter 3 and 4).

Trial design

The effect of waterlogging on plant production was chosen to be examined under field conditions contrary to many of the reported yield studies conducted as lysimeter or pot trials. The great advantage of lysimeter and pot trials is that the waterlogging treatment and boundary conditions can be meticulously controlled. However, this approach lead to limitations in the quantitative interpretation of the results since the system is disturbed in several ways.
The trials in this study were placed on sandy loam since few trials have been reported on this soil type and because tile drainage is common on this soil type in Denmark. Thus, the field trials were conducted in order to get as close to naturally occurring undisturbed Danish field conditions as possible. Hence, the measurements were done in plots placed on different drainage conditions representing a set of existing well-established environmental conditions in the field. Thus, no new installations of tiles were carried out and the water level in tile wells in the field was not controlled. The fields were selected on basis of farmers' descriptions and/or measured differences in drainage conditions within a field of normal cultivation. This design increases the risk of heterogeneous soil conditions biasing the results. To counteract this risk, the trial was repeated at three sites to increase the number of plots and thereby reduce the risk of soil differences biasing the results. However, the normal strategy to account for the soil factor by conducting randomised block trials cannot be applied. This is because the risk of neighbouring effects of drainage treatments is critical in a drainage trial, since the different treatment-induced water levels and water potentials will lead to water transport between the plots.

The chosen uncontrolled treatment of drainage conditions in the field leaves the groundwater levels in the field to be determined by the soil drainage capability in the plot and net precipitation. Thus, the combination of crop management and weather will lead to different groundwater levels in different years. This increases the need for multiyear trials since weather and interaction with crop management can be significant. Several trial locations increase the possibility of different weather conditions within a year.

Three trial sites with sandy loam as the dominating soil type and different precipitation levels were chosen. The three site locations are: Seggelund (55º19`44N 9º28`56 E), Tokkerup (55º17`35N 12º08`41 E) and Taastrup (55º40`20N 12º17`21 E). The sites are shown in Figure 17 together with the average precipitation in the period 1961-1990.

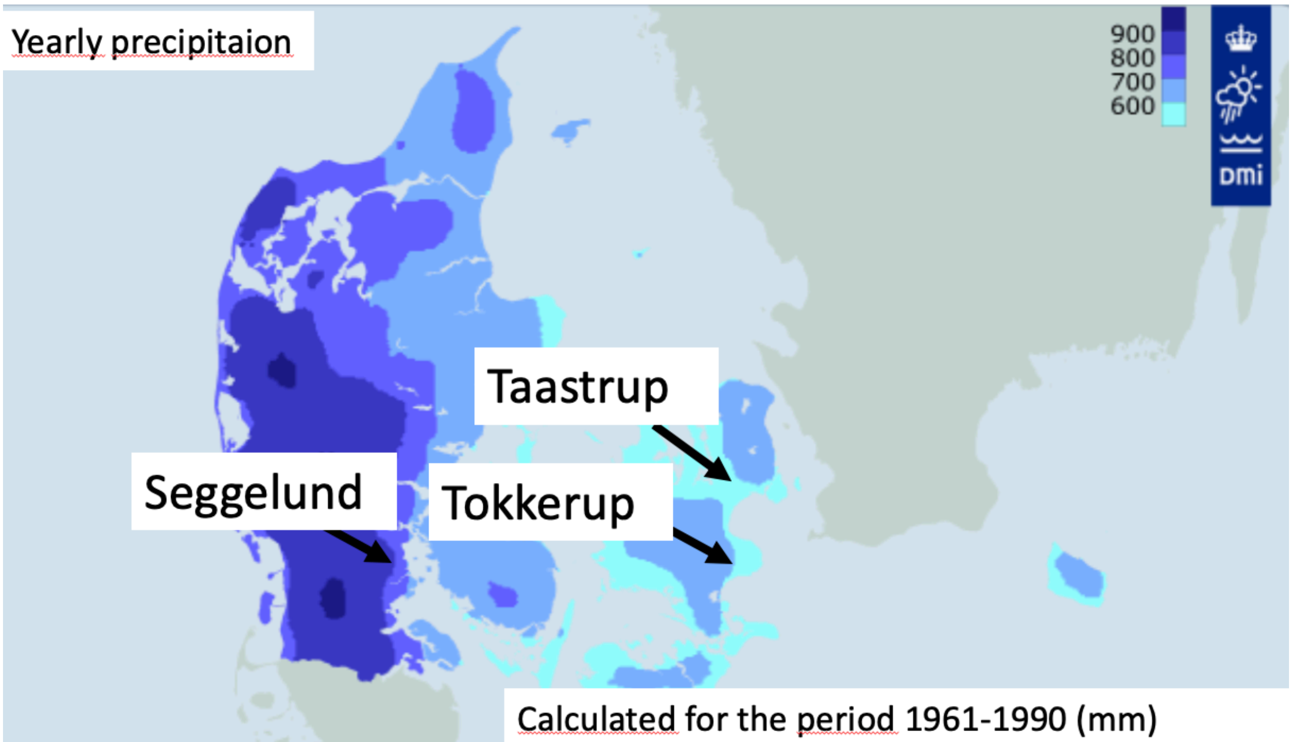

Figure 17 Location of the three field trials under precipitation map from less than 600mm to over 800mm. source dmi.dk

Trial locations

The individual designs of the three trial locations are shown in Figure 18, Figure 19 and Figure 20. The total trial area in a field range from 0.5ha to 3.8ha. The plot distribution is based on differences in drainage conditions and additionally EM38 (Domsch and Giebel, 2004) soil texture maps at the Tokkerup and Seggelund sites to minimize the textural variation between the plots. The drainage conditions were measured by continuously as the groundwater level in a groundwater well in each plot of approximately 100 to 200 m^2, representing the drainage conditions in the sub divided 8-10 subplot in each plot. At the Tokkerup and Taastrup location different N levels were applied in order to examine the interaction between N level and drainage. The temperature measurements used in chapter 4 as well as the root measurements in minirhizotrons were conducted at the Taastrup site.

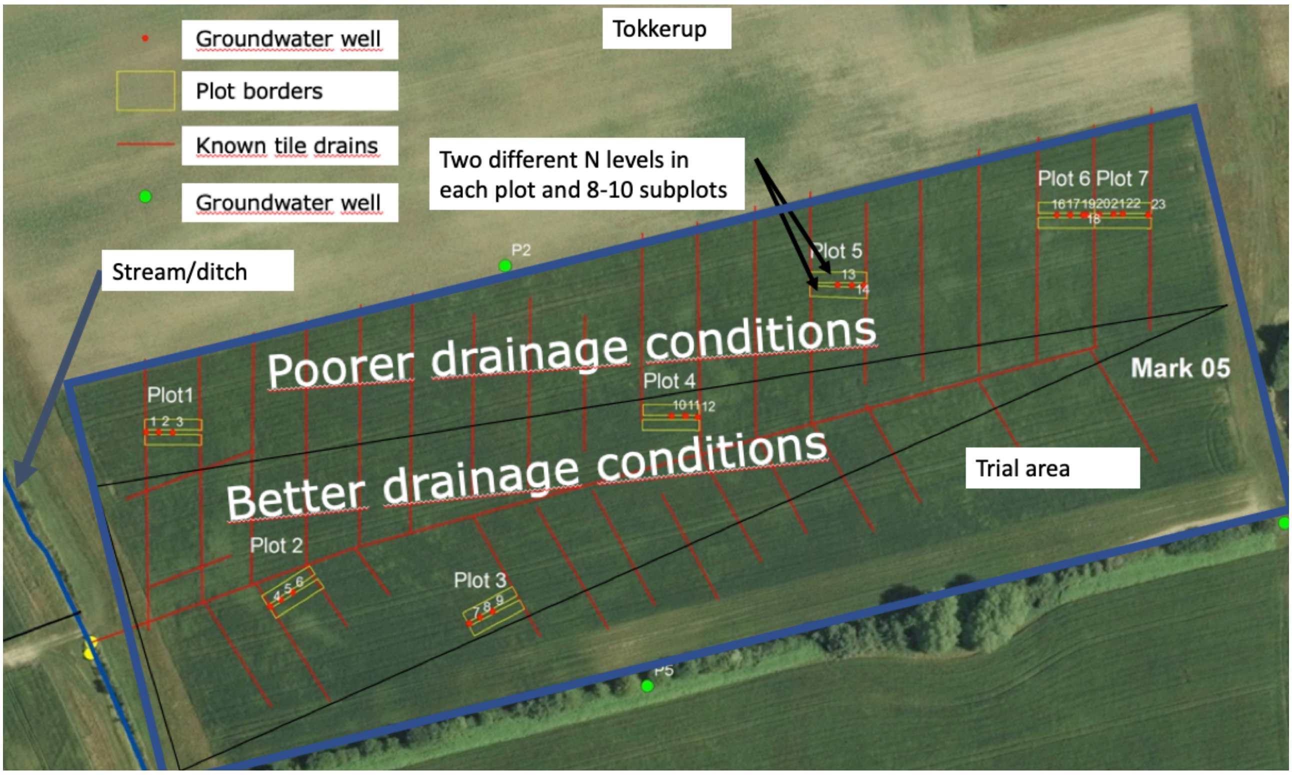

Figure 18 Tokkerup trial setup and plot distribution. 3.8ha field characterized by low topographical difference in surface height. The known parts of the tile drainage system from the 50´s is marked with red lines, showing the main pipe in the middle of the field, the side drains on both sides and the outlet in the left side of the picture going into the stream marked with blue. There is a gradient in drainage depth because the drainage system is sloping towards the stream. The drainage conditions within the black triangle in thereby better due to the deeper tile drains.

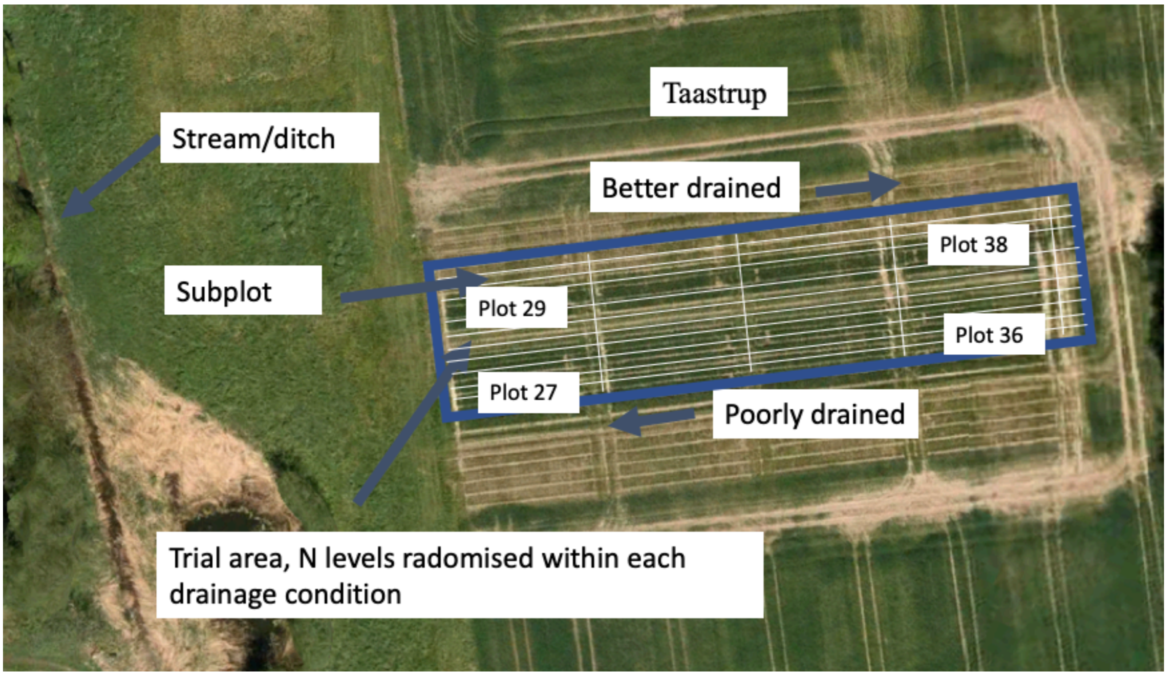

Figure 19 Taastrup trial setup. There is a gradient in groundwater depth from the poorly drained plots closest to the stream in the left side of the map and the better drained plot in the right side. The total area is approximately 0.5ha. Root measurements were conducted in all of the plots.

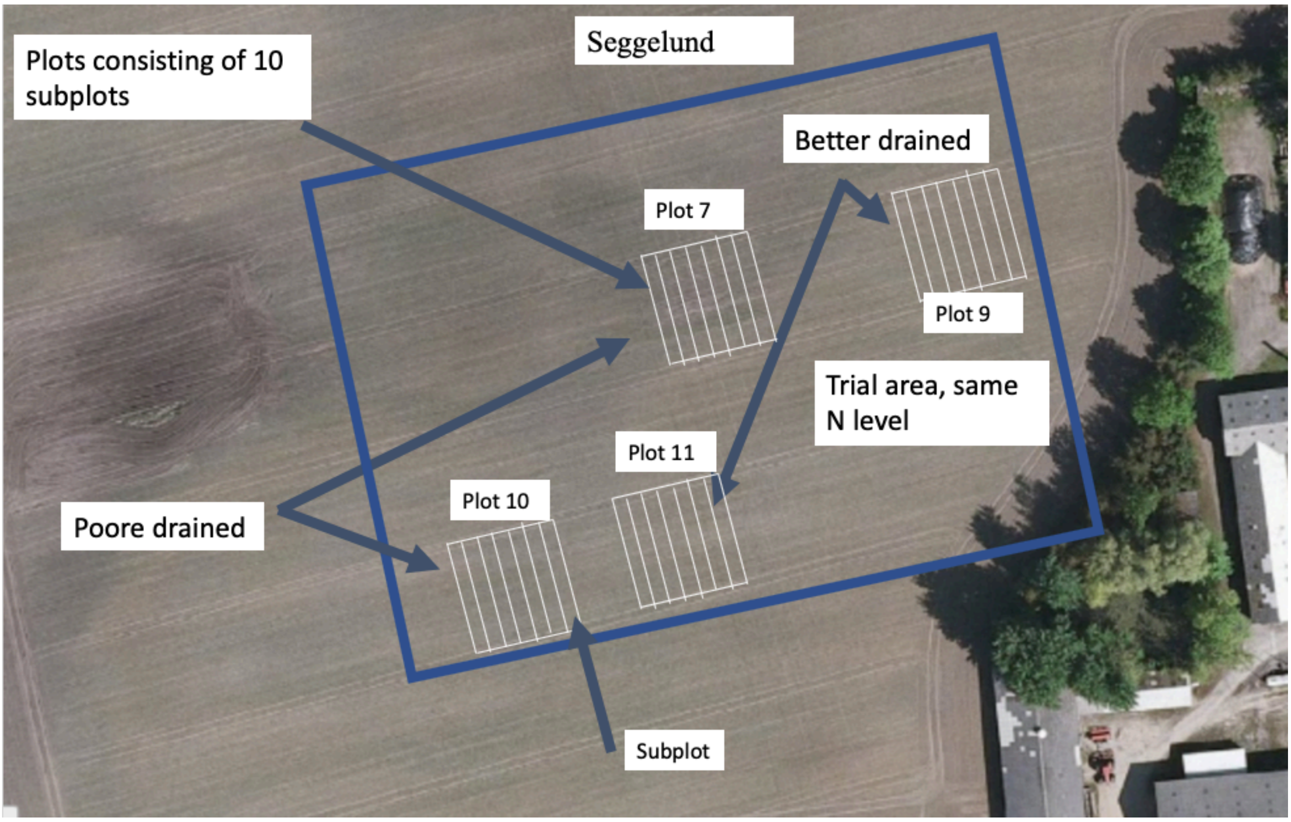

Figure 20 Seggelund trial setup. Four plots (two WD and two PD) consisting of 10 subplots each were distributed on the field. The same N level was applied in all plots. The total area is approximately 1 ha.

Management

The crop rotation in the trials consists of winter wheat and spring barley which together cover a significant proportion of the agricultural area (42-46% in the period 2006-2018 (Danmarks Statistik, 2019)) in Denmark.

Trafficability in the field and workability of the soil are affected by the drainage state. The timing of the management operations in the field is thereby restricted to a shorter period in the poorly drained parts of the trial. This can result in a suboptimal timing compared to well drained conditions of seedbed preparation and sowing, but also of fertilisation and crop protection measures. Ultimately harvest can also be hindered by reduced trafficability. Part of the trial set up is therefore to consider whether the management should be done independently and optimally in each plot or evenly in all plots with the same timing. Independent management of the plots is clearly the most complicated since an extra response factor is included by different management timing. In this trial, uniform management was chosen to leave the management factor out. Thus, field operations were conducted when the whole field is manageable. However, this might lead to an underestimation of the yield loss due to poor drainage and the results should be seen in this perspective.

Soil temperature and Soil-Vegetation-Atmosphere-Transfer modelling

In the spring, crop growth is limited by low temperatures in Denmark. Therefore, the physical effect from drainage and derived top soil water content on soil surface temperature can potentially reduce the growth potential of the crop. However, the significance of drainage on surface temperature at field scale has not been quantified on a loamy sand in a humid temperate climate. This quantification of temperature and process understanding at crop scale is fundamental in order to extrapolate to other soil types and different weather.This issue was therefore included in this study in order to contribute to the process understanding of the yield response.

The characterization of the different drainage conditions by groundwater measurements in the drainage trial in Taastrup was utilized as basis for the temperature description. The effect of drainage on surface- and soil temperature at different depths was continuously measured in the spring months. Since the growing cover of the crop has a significant influence on the energy fluxes, this factor was included by conducting the trial in winter wheat.

The measured temperature dynamics from different drainage conditions and different depths in the field serve as basis for the modelling. In order to improve the process understanding the energy fluxes leading to the temperatures in the system were modelled on the basis of detailed hourly weather data, estimated hydraulic soil properties and crop management. Since the water-content and potential of the soil have major influence on the energy fluxes in the system, detailed measurements of the water potential were conducted and used in the calibration process.

The DAISY model (Hansen et al. 2012) and SVAT module (Plauborg et al. 2010) were used since they offer the possibility to work at field scale by including a description of the plant canopy effect on the energy fluxes between soil and atmosphere.

Further details of the measurements in the trials are presented in chapter 3 and chapter 4.

Chapter 3 *Yield and development of winter wheat (Triticum aestivum L.) and spring barley (Hordeum vulgare) in long-term experiments with variable drainage conditions*

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Abstract

The benefits of drainage to improve yield level and -stability was recognized millennia ago, hence drainage is an old agronomical practice. However, agriculture is under constant change, and few long-term field studies exploring the need for drainage have been conducted in modern north European agricultural systems.

The objective of this study is to describe yield variations in modern cereal crops as a function of the different dynamic drainage conditions that may appear in ordinary agricultural fields with old drainage systems.

Seven years of field experiments were conducted at up to 3 field locations per year and with different N application levels. Drainage conditions were quantified annually in an index (SEW_{60}) accumulating on a daily basis the depth of shallow groundwater (< 60 cm beneath the soil surface).

Yield reductions up to 25% was caused by poor drainage, despite that no visual plant symptoms were observed during the growing season. The yield variation across years, crops, and locations could be explained by SEW_{60}. Yield effects of poor drainage were not significantly different for the investigated N-fertilization levels. This indicates that other factors than N are important for reduction of the yield potential induced by poor field drainage.

The results clearly show the importance of good drainage as basis for agriculture in a region of excess precipitation, and they emphasize the need to focus on drainage conditions in a changing climate with increasing winter precipitation. Additionally, this can be a considerable factor in future water management trying to reconcile environmental and agricultural needs.

Highlights

- Relative yield correlated with drainage conditions across year, crop, and location
- An accumulation of water table levels below 60 cm depth specified drainage conditions
- Negative responses to poor drainage were similar at all N application levels
- Poor drainage conditions hampered early crop development

Key words:

Waterlogging; drainage; yield; nitrogen; sandy loam; groundwater

1 Introduction

Drainage is the basis for agriculture in substantial areas both in Denmark and in the rest of the world. The global estimate of drained area is 167 mio ha (Feick et al., 2005) and in Denmark it is approximately 1.29 mio ha or 49% of the agricultural land (Møller et al., 2018). The benefits of drainage on arable lands are well recognized, and documented in several old trials (Aslyng 1980; Williamson and Kriz, 1970; Belford et al., 1985; Cannell et al., 1980, 1984). The severe effect of waterlogging is emphasised in a comprehensive review of drainage trials by Herzog et al. (2016), who find that dry matter yield on average is reduced by 43% in different crops. The well-established perception of positive effects of drainage on plant production might be the reason why surprisingly few new field studies have been conducted in modern plant production systems. However, the technological improvements and increased yield potentials in plant production over the last decades have most likely raised the demand for optimal drainage. Additionally, the use of heavy machinery in modern agriculture increases the drainage demands of the fields to avoid soil structural damage.

Climate change is expected to generally increase the precipitation excess in northern Europe and thereby increase the need for drainage. For Danish conditions Rasmussen et al. (2018) found an expected 10% increase of drain flow in the near future (2030-2059) and 16% in the far future (2060-2099). This is on top of a continuous increase in annual rainfall observed in Denmark from around 1930 till now from approximately 650 mm to more than 800 mm. In parallel, views on stream maintenance methods have changed, leading to less removal of vegetation and sediment for environmental reasons. Drainage of agricultural fields were primarily done between 1860 and 1890 and from the 1930'es to the 1970'es (Breuning Madsen, 2010). Field drainage systems with clay tiles have a limited lifespan, so the capacity of these old systems may be deteriorating. The increased rainfall adds to the risk that the capacity of the systems is inadequate. Few international studies examine this issue, but a Danish study done by Skriver and Hedegård (1973) clearly indicates a lack of renewal of the drainage systems based on an assumed tile lifespan of 80 years.

At the same time, the debate about water environment versus agricultural production brought about by the implementation of the EU water frame directive under Danish conditions. This have clearly displayed the lack of up to date knowledge about plant response to waterlogging and

insufficient drainage conditions. This may bias cost benefit analyses of certain water management practices, not least stream restoration measures.
Heavily waterlogged or flooded areas are often easy to identify by ponded water or clear plant responses such as chlorosis. However, semi waterlogged areas can be hard to identify, even though yellowing of the leaves or chlorosis as a result of poor drainage have been reported to appear as symptoms in the very early spring prior to fertilisation (Cannell et al., 1980). This can lead to significant "hidden" yield losses. The identification and possible mitigation of such yield losses could help to increase agricultural productivity. This study therefore investigates relationships between yield losses and drainage conditions.

Restricted nitrogen (N) availability and reduced N uptake are important reasons for reduced photosynthesis and plant growth under poorer drainage conditions (Aslyng 1980; Belford et al. 1985; Malik et al. 2001; Dickin and Wright, 2008). This is often linked to impaired root development due to reduced gas exchange and lack of oxygen for root respiration (Belford et. al 1985 Dickin and Wright, 2008). Reduced nitrogen mineralization and/or increased denitrification under poorer drainage conditions and waterlogging, particularly in the carbon enriched A horizon, may also reduce N availability. Hence, N uptake during the growing season could be a significant element in the understanding of the plant response to waterlogging. The interaction between drainage effects on yield and N dynamics is therefore included in this study by investigating the crop response to different N application levels.

Detailed studies of the mechanisms leading to reduced plant growth as a result of waterlogging are most prevalent as greenhouse or lysimeter studies. However, the comprehensive effects of different drainage conditions on physical, chemical and biological properties of the soil, both on a short term within the growing season and on a longer term, are difficult to re-create under greenhouse and lysimeter conditions. The quantitative effects obtained in such systems may be difficult to transfer to field conditions as described by McFarlane et al. (1989). As an example, a waterlogging trial done by Dickin and Wright (2008) in a greenhouse led to maturation one month earlier than under field condition, influencing the results by a significantly shorter growing season.
Field trials are required to include all drainage factors and derivative factors under natural conditions, both on short term within the growing season and on a longer term. The field trials are also advantageous when working with nitrogen turnover and interactions with the environment in the agricultural system.

Varying weather conditions introduce variation in the results in field trials within and between each growing season, leading to differences in groundwater behaviour and thus drainage conditions. This interacts with timing of the crop management and results in varying responses in drainage trials across location and year. A prerequisite to this drainage study was therefore to have multilocational and multiyear field trials representing several combinations of weather and soil conditions.

The need for a general drainage index and the use of relative yields in order to compare drainage effects across years, locations and crops seems obvious since frequency, magnitude and timing of drainage events are unique. The SEW drainage index introduced by Sieben (1964) has the great advantage of making it possible to compare years and locations. It condenses variable drainage conditions occurring during a longer period in the field, e.g. during a growing season, into a single number by summing up daily water table depths above a certain threshold depth (typically 30 cm). A disadvantage of SEW is that specific drainage effects occurring at specific times and/or crop development stages may not be well represented. This includes interaction between temperature and high groundwater, as sensitivity of crop yield to high groundwater is temperature dependent (McFarlane et al., 1989). Oxygen levels in the soil will drop rapidly due to higher biological activity at higher temperatures (Belford et al., 1985). Also, sensitivity to waterlogging differs over the growing season. Setter and Waters (2003) find relative high sensitivity to waterlogging in the pre-emergence, early post-emergence phases on the shoot and in the flowering phase.

In order to improve the correlation Gayle et al. (1987) modified the index by increasing the reference depth of the SEW index to 45 cm in a sugarcane drainage trial to include a larger part of the root zone. Nevertheless, use of a SEW index seems to be the simplest applicable describing variable for the variations in drainage yield response between years, fields and location, and this approach is therefore beneficial in the analyses of yield response to waterlogging.

In order to investigate the effects of drainage conditions in modern agriculture, a study was conducted on three Danish field locations with old drainage systems on sandy loam soils and dynamic groundwater conditions covering areas of poor and good drainage. The study was made over up to seven growing seasons per location to cover different weather conditions. Cereals are the dominating crop species in northern Europe hence, winter wheat (WW) and spring barley

(SB) were chosen as species in this trial. The experiments included different N-application levels in order to investigate interactions between drainage level and N-dynamics.

This paper aims to identify a general yield response to drainage conditions across years, crops, and locations characterized by a SEW drainage index. Thus, the objectives are to:
1) Quantify drainage condition in the field,
2) Quantify the yield response of DM and N due to poor drainage conditions,
3) Examine the effect of drainage conditions under different N application rates – e.g. whether it is possible to compensate for poor drainage conditions by adding more nitrogen fertilizer,
4) Examine effects of poor drainage conditions on crop development in spring.

Yield responses were reported as function of one SEW drainage index. A systematic optimization of the chosen drainage index was not the scope of this paper.

2 Materials and Methods

2.1 Field sites and trial design

2.1.1 Locations and characterization

The experiment was conducted on three locations in Denmark: Seggelund (55°19`44N 9°28`56 E), Tokkerup (55°17`35N 12°08`41 E) and Taastrup (55°40`20N 12°17`21 E). The soil origin is glacial deposits. The sites were selected on basis of long-term well-established differences in drainage conditions within the field and relatively comparable texture (sandy loam). The fields have all been tile drained for at least 50 years. Figures showing the specific design of each experimental site are found in Appendix A. The depth and maintenance of the tile drains was examined at Tokkerup prior to the study by inspection at specific places in the field. The drainage system was installed in 1955 and found to be well-functioning, but due to limitations in depth of the drain outlet, the tiles were not placed at the recommended depth of 1-1.2m in parts of the field. The drainage depth varies from 0.55m to 1.2m with a spacing of 16m. At Taastrup and Seggelund, the exact age of the drainage system and its location and depth are uncertain. The yearly average precipitation (1961-1990) is higher at the Seggelund location (823mm/year), compared to the region of the two other locations (584mm/year), but solar radiation and air temperature are fairly equal at the three locations.

2.1.2 Trial design

The trials were conducted on fields with old (more than 50 years) drain systems of normal agronomical practice and therefore within a span of drainage conditions normally found in Danish agriculture. A classical randomized block design was not possible, among other reasons because the design should also reveal long-term effects of drainage conditions. Initially, well drained (WD) and poorly drained (PD) subareas were identified at each field location (the area of each field range between 0.5 and 3.8 ha) based on visual inspection and farmer experience. Further screening to avoid extreme deviations on texture was done by EM38 screenings (Domsch and Giebel, 2004), which led to the layout of four to seven plots of approximately 120 m^2 within both WD or PD areas, respectively. A broad range of existing drainage conditions developed over many years was thereby represented at each location.
Eight to ten subplots (repetitions) of minimum 12 m^2 were placed within each plot representing equal drainage conditions within the plot measured by one groundwater well. Most of the years the subplots were divided in two groups within each plot to represent two different N levels either 50% and 100% or 100% and 150% of normal application rate.

2.1.3 Soil characterization

Soil horizons were identified in a profile description from core-samples taken out with an "Eijkelkamp soil column cylinder auger" with an intake diameter of 84mm (Eijkelkamp Soil & Water, 2019) to a depth of 1 m in each plot. Bulk density was measured by drying of the soil core in sections representing the horizons. Sub samples for texture determinations were taken out from most of the deep horizons and all A horizons. Texture measurements were done by the pipette method (SSSA, 2002) and organic matter content determination by the Loss-On ignition method (SSSA, 1996). Texture from horizons deeper than 1m was estimated by hand on the basis of samples taken with an auger.

2.1.4 Crop management

Agricultural management including tillage, sowing, selection of crop genotypes, fertilization, weed-, fungi- and insect control, and harvest was generally performed as "best practices". This implies that management varies between fields and years. Field management operations within each field were done at the same time in all plots independently of drainage conditions. Winter wheat (Triticum aestivum L.) (WW) and spring barley (Hordeum vulgare) (SB) were grown in a crop rotation having maximum two consecutive years of the same crop. Dates and methods of soil tillage, sowing, fertilizer application and harvest, are presented in Table 1, including the N levels applied.

Table 1 Crop management on the three trial locations. Soil cultivation, sowing and harvest dates. Fertilization dates, fertilizer type and N amount as kg/ha and % of normal application rate.

Year (Harvest)	Location	Crop	Previous Crop	Plowing	Harrowing	Sowing	1. Fertilization		2. Fertilization		N level of normal	Harvest
				Date	Date	Date	Date	Type and kgN/ha	Date	Type and kgN/ha		Date
2012	Tokkerup	SB	SB	31/3 12	3/4 12	3/4 12	2/4 12	Ammonia 110			100%	16/8 12
2013	Tokkerup	WW	SB	null	15/9 12	15/9 12	18/4 13	NS 90	15/5 13	NS 90 or 180	100% and 150%	9/8 13
2014	Tokkerup	WW	WW	null	16/8 and 16/9	22/9 13	18/4 14	NS 80	15/5 14	NS 100 or 190	100% and 150%	7/8 14
2015	Tokkerup	SB	WW	null	10/8, 8/9 and 17/4	11/4 15	21/4 15	NS 70 or 140			50% and 100%	28/8 15
2015	Seggelund	WW	WW	Medio sep	Medio sep	Medio sep	medio april	180 kgN			100%	21/8 15
2016	Tokkerup	WW	SB	null	31/8 and 29/9	30/9 15	12/4 16	NS 90 or 180			50% and 100%	17/8 16
2016	Seggelund	WW	WW	Medio sep	Medio sep	Medio sep	medio april	180 kgN			100%	24/8 16
2016	Taastrup	WW	WW	10/9 15	11/9 15	11/9 15	22/3 16	NS 80	24/4 16	NS 100	50% and 100%	15/8 16
2017	Tokkerup	WW	WW	null	Ultimo sep	Ultimo sep	30/3 17	NS 90 or 180			50% and 100%	23/8 17
2018	Tokkerup	SB	WW	null	18/4 18	22/4 18	1/5 18	NS 70 or 140			50% and 100%	9/8 18

2.2 Field measurements

2.2.1 Weather

Hourly values of precipitation, net radiation, relative humidity and air temperature (1.5m height) were measured. All measurements were conducted locally (max 200m from the trial) except relative humidity at the Seggelund and Tokkerup locations where data from nearby weather stations were used (approximately 10 km from trial).

2.2.2 Groundwater

Drainage conditions were described by continuous (hourly) measurements of groundwater levels in wells. The wells were installed centrally in each plot to a depth of 2.5m with good hydraulic contact to the soil. This was obtained by repacking with soil from the respective soil horizons. Pressure transducers were placed near the bottom of the wells. The water level was measured and quality controlled by a series of manual measurements. In addition, the water level in the neighboring streams was recorded monthly to assess the hydraulic boundary conditions of the fields at Taastrup and Tokkerup.

Gaps in the data from periods of missing measurements of the groundwater level, were filled with data obtained by simulations with the agrohydrological model "DAISY", based on Richards equation (Hansen et al., 2012). The model was set up on the basis of measured weather data, crop management and hydraulic properties derived from the soil properties using the pedotransfer-function HYPRES (Wösten et al., 1999). Measured groundwater data from the specific plots were used to calibrate the model. The drainage related hydraulic properties; tile drain depth, lower boundary conditions and horizontal conductivity (in few horizons) were adjusted in the calibration process.

2.2.2.1 SEW index and drainage conditions

The dynamic drainage conditions were converted into a single drainage index to facilitate the comparison of different growing seasons and locations. The drainage index used in this study is based on the daily Sum of Excess Water (SEW) in the profile above a threshold depth. The concept of SEW is presented in equation 1.

Equation 1 $SEW_{threshold\ depth} = \sum_{i=1}^{N}\left(threshold\ depth - WTD_i\right)$

Where WTD_i is the daily average groundwater table depth (cm) for day i and N is the number of days in a selected period. Negative contributions are ignored.

The SEW index applied in this study (hereafter "SEW_{60}") was modified by increasing the threshold depth to 60 cm compared to the typically used 30 cm. The period used was the primary part of the growing season from 1/3 to 1/8. The reason for this modification was to improve the sensitivity to drainage related growth factors in deeper parts of the root zone, since also water table depths in the range 30-60 cm beneath the soil surface were expected to have negative effects on important growth factors and crop growth.

2.2.3 Crop development

Crop development were observed by NDVI measurements in seven of the individual trials. This was supplemented by biomass cuts and BBCH stage recordings during the growing season in four of the trials. NDVI measurements (Skye Instruments "Skye light sensor 2 Channel" with center wavelengths at 647nm, 799nm) were performed intensively in the early growth stages in Tokkerup 2012-2016, Seggelund 2016 and Taastrup 2016. NDVI was measured at 7-10 randomly distributed areas (0.66 m^2) within each subplot.

A series of biomass cuts of 0.25 m^2 (n= 6-18) were made in spring and early summer in 2012, 2015 and 2016 at the Tokkerup location and in 2016 at the Taastrup location. The biomass samples were dried right after harvest and homogenised later. N content and thus N uptake was determined in the Tokkerup samples from 2015 and 2016. 250 mg subsamples were analysed by dry combustion in the VARIO Max Cube (Elementar Analysensysteme GmbH).

2.2.4 Yield data

Harvest and weighing of grains from each subplot were obtained by the use of a "Haldrup plot combine harvester" (Haldrup, 2019). Subsamples (approximately 1kg) from each subplot were cleaned for impurities and analysed for water and N content by the Foss infratec NOVA (FOSS, 2019).

2.3 Statistical analysis

Yields of DM and N and NDVI from the poorly drained plots were calculated as relative values with reference to the average values of the better drained plots within same location, date and year.

Association between drainage conditions (SEW_{60}) and relative DM and N yield (Y) was described by a logarithmic model (Equation 2).

Equation 2

$$Y = \log(a * SEW_{60} + b)$$

The model was estimated by fitting a linear model to the exponential-transformed outcome with N level, SEW_{60} and their interaction as explanatory variables. Model choice was based on visual assessment of model fit. Model assumptions were assessed by visual assessment of residuals in residual and QQ plots. Test for equal slopes for all N levels were based on an F-test comparing a model with and without the interaction between SEW_{60} and N level. Pairwise comparisons of intercepts were based on post hoch t-tests. The final models are presented as parameter estimates ± SE.

For each location and year, DM development and N uptake were analysed using a linear mixed model with the combination of date and drainage condition as fixed effect and plot as random effect. DM development and N uptake were log-transformed before the analysis to account for heteroscedasticity in the residual error components and an exponential correlation structure was included to capture the serial correlation in the plot specific growth curves using day of the year as the underlying time line.

Pairwise comparisons between drainage conditions at each observation date were based on post hoch t-tests. Estimates and SE were back-transformed using the delta method and presented as estimate ± SE on the original scale.

NDVI was analyzed using a linear mixed model with the combination of location, year, drainage condition and N level as fixed effect and plot as random effect. An exponential correlation structure was included to capture the serial correlation in the plot specific growth curves using day of the year as the underlying time line. Relative NDVI for the PD condition compared to the WD condition was estimated in an after-fitting step using the delta method and presented with 95% confidence intervals.

All analyses were carried out in the statistical programming environment **R** version 3.4.2 (R Core Team, 2017). In particular, the extension packages *nlme* (Pinheiro et al., 2017) and *car (Fox and Weisberg, 2011)* were used for fitting linear mixed models and the delta method, respectively.

3 Results

3.1 Soil and weather

3.1.1 Soil profiles, texture and bulk density

Based on texture of the A horizon, all the investigated soils were classified as sandy loams (FAO texture classification; clay content 7-19%). The bulk density of the A horizon ranged from 1.3 to 1.6 Mg/m^3. The bulk density increased with depth and was consistently found to be highest in the deepest horizons (up to 2 Mg/m^3), probably due to the occurrence of calcareous material below 1m depth. The organic matter content varied from 2.5% to 4.8% in the A horizon. It decreased with depth, except in one plot (plot 7 at Seggelund) where organic deposits were found in two deeper horizons. Measured and estimated soil properties in all horizons are described in Appendix B (Tables 1,2, and 3).

3.1.2 Weather conditions

Monthly averages of air temperature and global radiation were very similar across locations. The precipitation was found to be within the expected range for the sites and lowest at the Taastrup location. Monthly average values of the measured weather conditions are found in Appendix F (Table 4).

3.2 Drainage conditions

3.2.1 Measured groundwater

The measured groundwater levels supported the division of the plots in two groups, well drained (WD) and poorly drained (PD), respectively. The two groups were characterized by very different groundwater levels, especially during the drainage season with excess water, primarily in the autumn, winter and early spring. The groundwater level in the early spring was therefore higher in the PD plots. Most PD plots also had higher groundwater level in the summer period. The groundwater level changed considerably over time, with rapidly rising groundwater under precipitation events, followed by drain off periods with falling groundwater. Figure 1 shows an example of these dynamics and illustrates the described patterns in groundwater levels and the clear division between PD plots and WD plots at the Taastrup location. The continuous measurements from the groundwater sensors were consistent with the manual measurements. Groundwater measurements from the rest of the plots can be seen in details in Appendix D (figure 6-14).

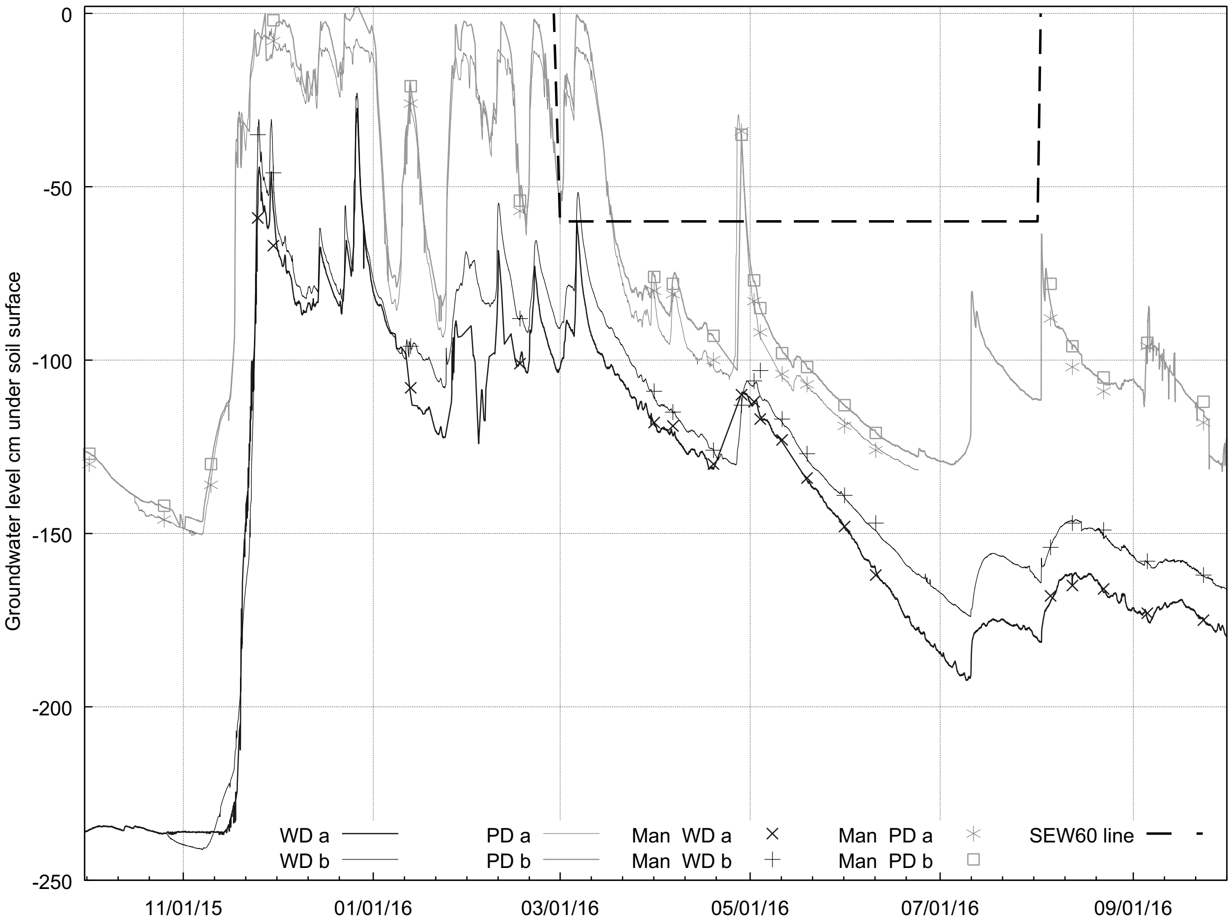

Figure 1 Groundwater level Taastrup 2015-2016, automatic continuous measurements are shown as lines and manual measurements as points for two repetitions (a and b) of poorly drained (PD) and two repetitions (a and b) of well drained (WD) plots. The period and depth defining the SEW_{60} index are shown with hatched lines. SEW_{60} (cm day) corresponds to the area bordered by these lines and (upwards) by the line showing the water table depth.

3.2.2 Simulated groundwater

The measured patterns, groundwater levels and dynamics were retrieved in the modelled data and was used to cover the relatively short periods of missing data in the calculation of SEW_{60}. An example of modelled and measured data is shown in Appendix C (figure 6).

3.2.3 Drainage conditions

Drainage conditions expressed as SEW_{60} (cm day) derived from the groundwater levels are listed in Table 2. The division of the plots in WD and PD is reflected in higher SEW values in the PD plots in all years except the extreme drought season of 2018, where the SEW values are zero in both WD and PD plots. The rest of the years can be divided into three wet years (2015, 2016 and 2017) compared to the three drier years (2012, 2013 and 2014).

Table 2 Drainage conditions at different locations and years divided in well drained (WD) and poorly drained (PD) shown as SEW_{60} (cm day).

		SEW_{60} (cm day)	
Location	Year	WD	PD
Seggelund	2015	80-105	942-1125
Seggelund	2016	0-3	1105-2213
Taastrup	2016	0-6	591-636
Tokkerup	2012	0-231	440-900
Tokkerup	2013	0-3	145-942
Tokkerup	2014	0-11	86-592
Tokkerup	2015	0-631	765-1324
Tokkerup	2016	0-332	707-1160
Tokkerup	2017	0-572	668-1045
Tokkerup	2018	0	0

3.3 Harvest grain yield

3.3.1 DM yield response to different N application rates

Harvest yields of DM and N from WD plots varied between 6-11 Mg/ha DM and 97-163 kg N/ha covering both SB and WW over all the growing seasons, except the drought season of 2018, which had very low yields. WW yields were clearly larger than SB yields making it difficult to find a general relationship between absolute yields and SEW_{60}. Use of relative yields showed more consistent results. PD plots yielded lower than WD-plots and the drainage index (SEW_{60}) was a significant factor (p-value <0.0001) in explaining the relative yield response across different locations, growing seasons and crops (Fig. 2). Equation 3 and Equation 4 describe the DM- and N-yields as a function of SEW_{60} at normal N application rate.

Equation 3 DM Yield response model of relative Y as a function of SEW_{60} (drainage conditions) under normal N application.

$$\text{Relative DM yield} = \log(-5.45\text{e-}04 * SEW_{60} + 2.78)$$

Equation 4 N Yield response model of relative Y as a function of SEW_{60} (drainage conditions) under normal N application.

$$\text{Relative N yield} = \log(-5.75\text{e-}04 * SEW_{60} + 2.79)$$

The correlation of relative yield (DM and N) and drainage index (SEW_{60}) differed between the three N application rates: As expected, DM-yield increased and the marginal effect of extra applied N decreased with increasing N-application rate. Thus, the derived relationship between DM yield and SEW_{60} at 50 % N was significantly different from Eq. 3 (p-value <0.0001), while the relationship at 150 % N was not. Model parameters describing relationships for the three different N levels are found in Table 3.

There was no significant interaction between SEW_{60} and N level (p-value 0.97), and the relative yield response to the drainage index is therefore similar for all N levels. The relative drainage yield response varied between years and locations but the relation was consistent within each year. The relative and absolute yield curves of DM and N related to other SEW indexes and also differentiated by year, location and crop is shown in Appendix E (figure 15-26).

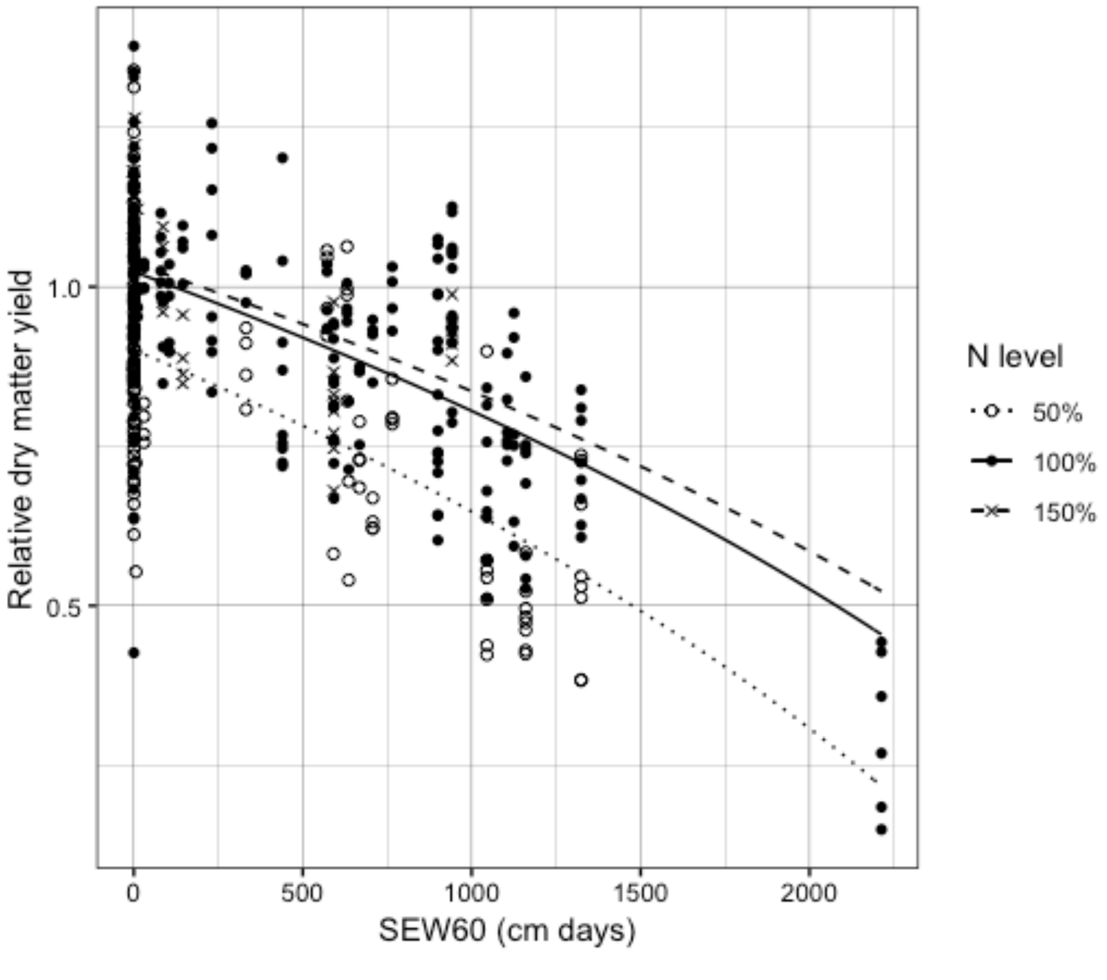

Figure 2 Relative dry matter yield in grains related to SEW_{60}. Data covers winter wheat (WW) and spring barley (SB) for all years and for all test locations. The symbols indicate results for the different N application levels expressed relatively to what is considered to be normal for the crop, i.e. 50% (WW: 90 kg N/ha; SB: 70 kg N/ha), 100% (WW: 180 kg N/ha; SB: 140 kg N/ha), and 150% (WW: 255 kg N/ha). The curves represent the fitted model at each N level.

3.3.2 Nitrogen yield response to different N applications

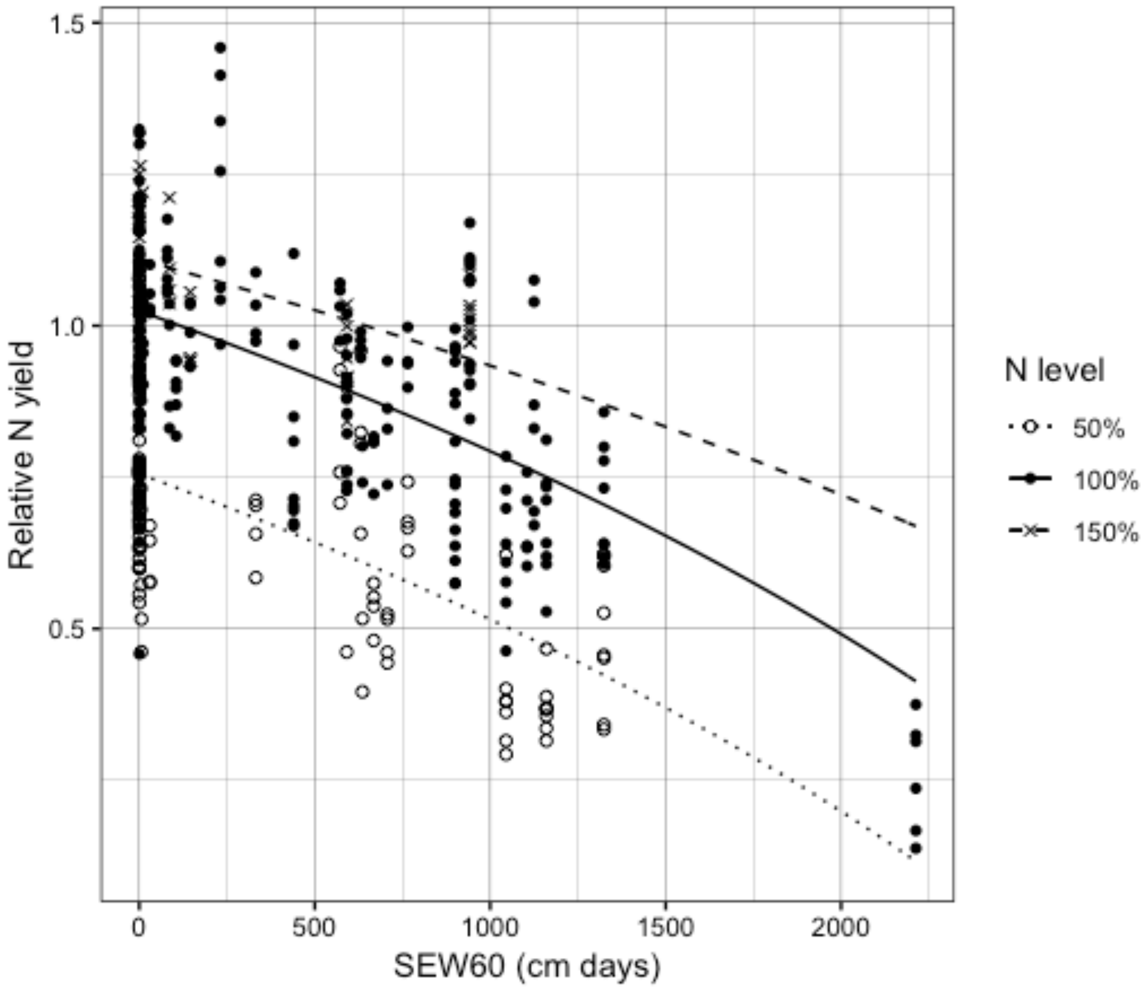

Figure 3 Relative N yield in grains related to SEW_{60}. Data covers winter wheat (WW) and spring barley (SB) for all years and for all test locations. The symbols indicate results for the different N application levels expressed relatively to what is considered to be normal for the crop, i.e. 50% (WW: 90 kg N/ha; SB: 70 kg N/ha), 100% (WW: 180 kg N/ha; SB: 140 kg N/ha), and 150% (WW: 255 kg N/ha). The curves represent the fitted model at each N level.

The N yield response mirrors the DM results and the drainage index was a significant factor explaining the N yields (p-value <0.0001). The three N application levels resulted in three significantly different N yields (p-value <0.0001). There was no significant interaction (p-value 0.33) between the drainage index and N application level.

Table 3 Model parameters to drainage yield response on both relative DM yield and relative N yield divided in treatments of N application rates. Model: DM/N-Yield = log(a *SEW_{60} + b)

Model parameter	a	b
Rel. DM Yield	Est ± SE	Est ± SE
50% N	-5.51e-04 ± 0.70e-04	2.46 ± 0.04
100% N	-5.45e-04 ± 0.82e-04	2.78 ± 0.03
150% N	-5.12e-04 ± 1.64e-04	2.82 ± 0.09
Rel. N Yield		
50% N	-4.54e-04 ± 0.71e-04	2.12 ± 0.05
100% N	-5.75e-04 ± 0.83e-04	2.79 ± 0.03
150% N	-4.88e-04 ± 1.67e-04	3.03 ± 0.07

In the growing season 2014/2015 the most widespread attack of barley yellow dwarf luteovirus in Denmark in modern history was recorded (Nielsen, 2016), causing severe yield depressions in winter wheat in Taastrup. Winter wheat data from the Taastrup location in 2015 have therefore been omitted in the analysis.

3.4 Crop development

3.4.1 Biomass

For all years and locations, there is a consistent tendency to delayed crop biomass development in PD plots compared to WD plots. However, a significantly negative effect of poor drainage on biomass development was found only in SB at Tokkerup in 2012, and at the earliest measuring dates in WW at Taastrup in 2016 (Figure 4).

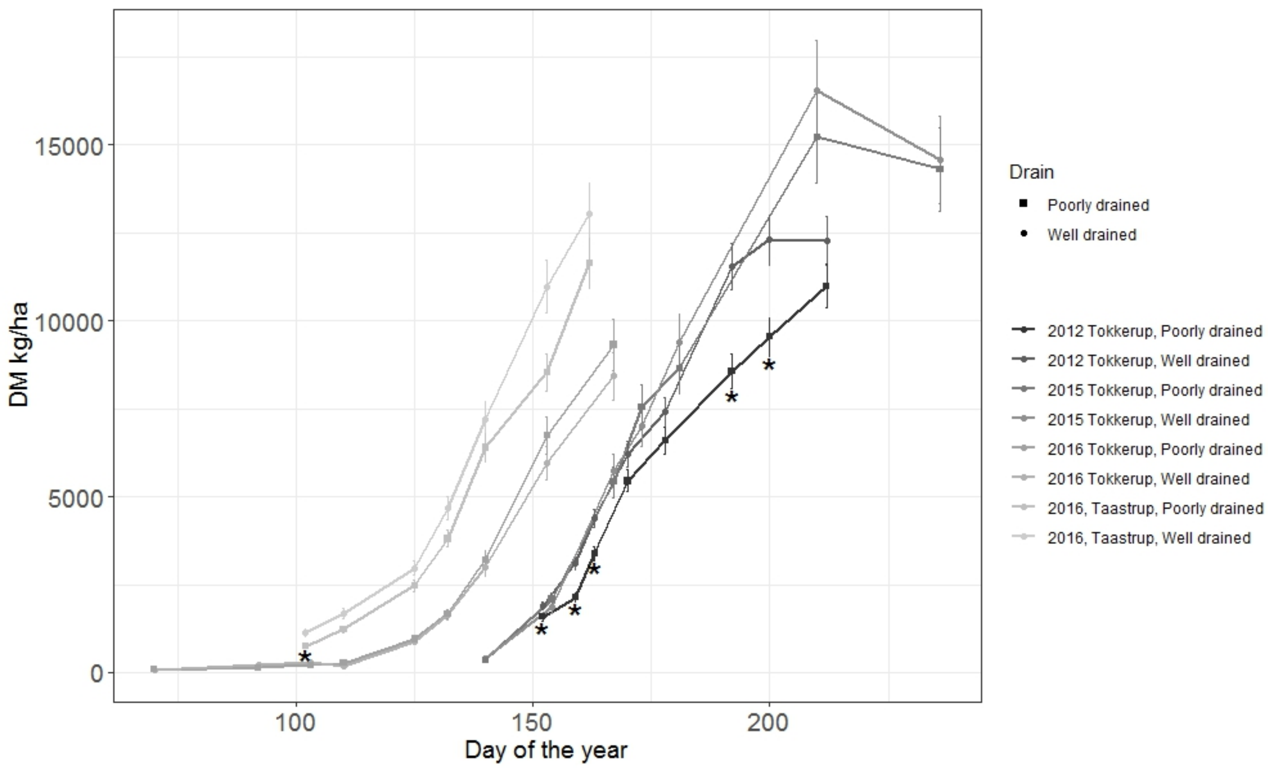

Figure 4 Biomass development in shoots under different drainage conditions (poorly and well drained) at normal N application rate (100%). Mean values with SE (bars) for spring barley in Tokkerup 2012 and 2015, and for winter wheat in Tokkerup and Taastrup 2016. Significant effects of drainage conditions are shown as *.

3.4.2 N uptake

N uptake in shoots tended to be higher in WD plots than in PD plots over the two growing seasons in Tokkerup, in which measurements were available. Significant differences were only found on two dates (Figure 5).

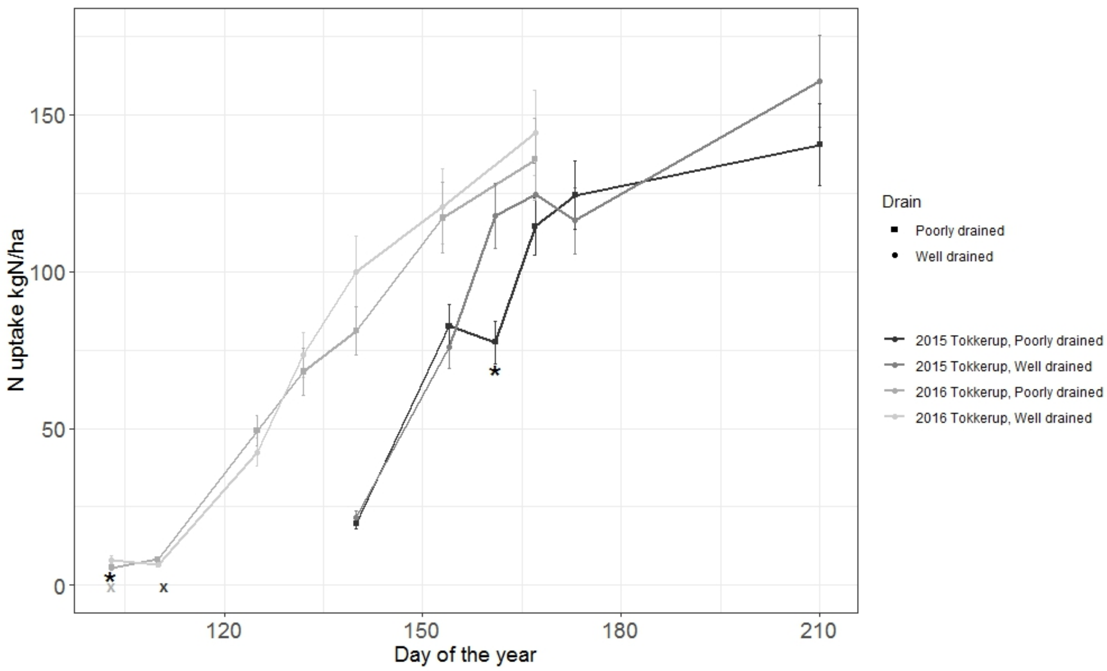

Figure 5 N uptake in shoots under different drainage conditions (poorly and well drained) at normal N application rate (100%). Mean values with SE (bars) for spring barley in Tokkerup 2015, and for winter wheat in Tokkerup 2016. Significant effects of drainage conditions are shown as *. Fertilization time is marked with one X for each respective year.

3.4.3 NDVI

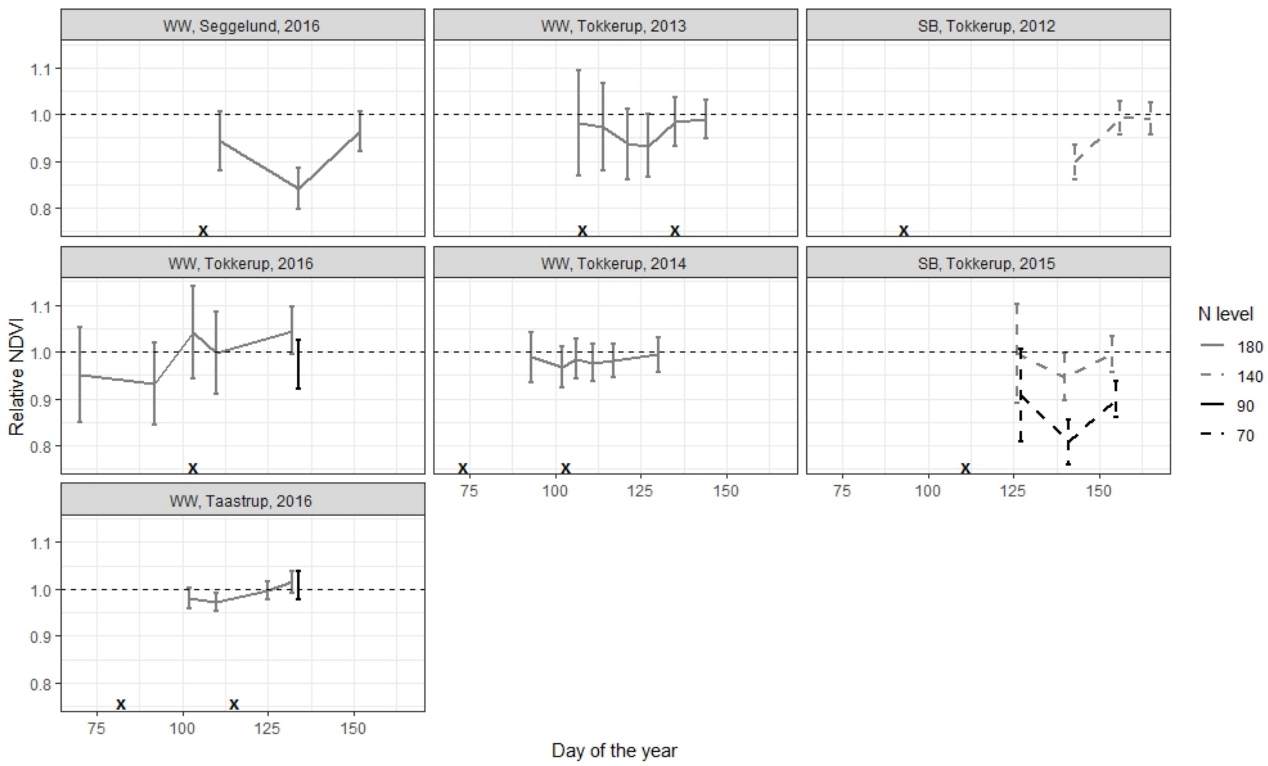

Figure 6 Relative NDVI, i.e. NDVI measured in poorly drained (PD) plots relative to values measured in well drained (WD) plots (mean values with SE shown as bars) determined over the growing seasons 2012-2016 at the three trial locations in spring barley and winter wheat. The different curve symbols represent different N application levels (kg N/ha). Fertilization is marked by X on the X axis.

Relative NDVI of PD compared to WD was significantly lower in five out of seven growing seasons. In the remaining two seasons (Tokkerup 2014 and 2016) there were also a tendency to periods with lower NDVI in the PD plots during spring. The timing of the drainage effect was different between seasons and locations, varying from 11/4 in Taastrup in 2016 to 22/5 in Tokkerup in 2012 (Day of the year in the range from 102 to 143). Crop development stage did not correlate to the effect on NDVI. Examples of the NDVI development in absolute values are shown in Appendix G (Figure 27 and 28).

3.4.4 Crop development stage

At two occasions during heading, crop development was recognized to be delayed in the PD plots relative to the WD plots in Tokkerup. This observation was done by coincidence since the detailed BBCH stages are easy to identify in the "50" stages of heading. On 17/6-2013 in winter wheat, BBCH stages differed from 62 at WD plot to 56 at the PD, and on 30/6-2015 in spring barley, from 59 in WD plots to 56 in PD plots.

4 Discussion

In order to describe the results the design of the trial needs to be considered as a start.
The field trials were not designed as classical block experiments for two main reasons related to the application of different drainage conditions (treatments). First, the risk of neighbouring effects of the different drainage treatments would be high, which would increase the uncertainty of the measured drainage state. Secondly, the drainage treatment has major impact on most physical, chemical and biological states and processes in the soil. Some of these effects develop over several years. The WD and PD plots in this study were therefore placed on different locations with different long-term established drainage conditions. The applied division in PD and WD plots was confirmed by the continuous groundwater measurements.

To minimize soil variation, the placement of subplots was furthermore supported by texture measurements and EM-38 mapping. It was later confirmed, that textural variation between WD and PD plots was very limited (Table of texture data is shown in Appendix B). This trial thereby has the strength of including long-term effects of drainage. Nevertheless, it cannot be completely ruled out that some of the drainage effects presented in this study are caused by soil effects.

This study differs from earlier studies in being conducted over several sites and years under modern field conditions. To our knowledge, multilocational field drainage trials over several growing seasons, revealing the variability of yield response between year and location, have not been reported since Hardjoamidjojo et al. (1982) who described yield responses to drainage in corn grown in the period 1962-1979 in Ohio and Indiana. The results from our study provides updated data from cereals under temperate oceanic climate conditions (Köppen classification) of North Western Europe.

The management operations were carried out when the whole field was workable, and they could thus have had a more optimal timing at WD areas. This could lead to underestimation of the yield effects. The workability and trafficability of the PD soils are affected by a higher soil water content leaving a shorter time span for field operations. Lower soil temperature and later sowing in the spring is reported by Jin et al. (2008) as factors likely to decrease the yield potential as a result of poor drainage.

The trial design, with one crop at each location each year, was not specifically done in order to investigate the crop specific yield response, but as a consequence of requiring a crop rotation in a long-term trial. This hinders a direct analysis of the differences in response between SB and WW. However the results did not indicate a difference which is in line with results described by Hoorn, (1958) and referred by Williamson and Kriz, (1970) on drainage effects in SB and WW.

4.1 Drainage conditions

Describing the impact of drainage conditions on plant growth can be very challenging. Most of the plant stress response to poor drainage is a function of anoxic conditions due to poor gas exchange in (parts of) the root system. The oxygen level decreases rapidly in submerged soil layers following a raise of the water table (Cannell et al., 1984). Groundwater level, above a certain reference level in the root zone, therefore seems potentially to be a good measure for yield reductions due to waterlogging. The great advantage of using the water table to express drainage conditions in the field is that it is easy to measure continuously, and that it is likely to represent the surrounding plot area.

The use of a simple drainage index like SEW_{60} to characterize drainage conditions offers the ability to compare effects of waterlogging over different locations, years and crops. However, this simplification has limitations since the origin of the yield effect can be different factors such as the nutrient availability, soil temperature and crop physiological stress that may occur at different times or growth stages. These factors have mutual interactions and interacts with the major external factor of weather. Exactly the same effects can therefore not be expected in different years.

The most obvious limitation relates to the interaction between waterlogging and soil temperature due to the exclusion of the temperature factor as described by McFarlane et al. (1989). Furthermore, the drainage induced crop stress is not weighted according to variations in the susceptibility at different crop growth stages (Cannell et al., 1980; Robertson et al., 2009).

The period used in the index is restricted to the primary growing season (1th of March to 1th of August) in order to reduce the effect of the interaction between SEW_{60} and temperature. This period demands a higher emphasis since the interaction of temperature on the drainage effect is likely to be higher due to higher biological activity at higher temperatures. Evans et al. (1990) found that the effect of flooding on yield reduction was influenced by temperature. Thus, the sensibility of the index is likely to be improved by exclusion of the winter season with low temperatures and thus lower impact of shallow groundwater. This approach was also used by Hardjoamidjojo et al. (1982) when modelling drainage yield effects in corn based on a stress day index including the SEW index combined with a growth stage dependent susceptibility factor to improve the description in different growth stages. Hence the use of the period 1/3-1/8 is in line with the approach used in other studies.

The reference level is lowered to 60 cm depth in the applied index compared to the original 30 cm introduced by Sieben (1964) to better represent the deep root zone of autumn sown crops in this trial. The inclusion of effects of a water table in deeper horizons in SEW improves its sensitivity in the range of semi poor drainage conditions because effects on deeper parts of the root system are also included. The importance of extracting N from deeper soil layers in autumn sown crops, particularly because N is often a yield limiting factor under Danish conditions, is described by Rasmussen et al. (2015). It is therefore likely that the increased reference depth in this study better captures any utilization of deep available N resources. This is because anaerobic conditions as a function of high groundwater levels impose a risk of denitrification in the affected soil horizons as described by Belford et al. (1985).

Periods of missing groundwater data were covered by simulated data. This was also done by Gayle et al. (1987), who filled in periods of missing measured data with modelled groundwater level, simulated on the basis of weather data, soil hydraulic properties and plant growth to be able to calculate SEW values. The comprehensive data used for modelling in this study, and long period of groundwater data for calibration, resulted in a correlation between modelled and measured data of $R^2 = 0.77$. A figure of the fit is shown in Appendix C. For this reason and since only a small proportion of the data used within the SEW calculation period is over the threshold value, the use of modelled data is not considered a major source of error in the description of the drainage conditions in the drainage index.

Despite the limitations in the use of a drainage index, this approach with the applied calculation period and threshold depth showed a close correlation to the relative yield and the index was an explanatory factor for the yield variations at different groundwater levels.

The amount of data from this study containing several trials gives the possibility to optimize the SEW index in terms of threshold value and period, which could include a temperature threshold value. However, that would be a relatively complicated task which is out of the scope of this paper and a systematic approach to optimize the SEW index was not attempted. Alternatively, mechanistic modelling could be a solution for describing the yield response and achieving a better process understanding. This is, however also outside the scope of this paper. SEW indices based on different depths or other periods are not independent, but give different weight to the groundwater level. The SEW index was developed by Sieben (1964) with a threshold depth of 30 cm and the whole year as calculation period. The used SEW_{60} index with a threshold at 60 cm and restricted to the period 1/3 to 1/8 provided better correlation with the relative yields. Examples of this are shown in Appendix E (figure 15-26) including correlation to absolute yield.

4.2 DM and N yield drainage response

Eleven different field trials distributed on three locations and seven different growing seasons, with a range of drainage conditions that are considered to be normal in Danish agriculture, showed a clear quantitative negative relationship between yields (DM and N) and drainage condition specified as SEW_{60}. This is expressed by Equation 3 and Equation 4. It is remarkable that yield reductions of up to 25% was measured without any observed visual symptoms of poor drainage on either the soil or the crop. This includes yellowing of leaves or chlorosis that have been reported as a symptom of poor drainage in the very early spring prior to spring fertilisation (Cannell et al., 1980). Ahmad et al. (1992) found leaves turning purple as a trait of poor drainage, but this was not observed in any of the PD plots either. The yield losses due to poor drainage can thereby by overlooked or misinterpreted as the result of other growth depressing

factors. This stresses the need to mind the drainage conditions in order to obtain the full yield potential and can support economical quantifications of decisions in the planning phase of the drainage systems.
Furthermore, the results confirm the fundamental agronomical importance of well drained conditions for optimal crop growth also found in older studies under various growing conditions from Australia (McFarlane et al., 1989), USA (Williamson and Kriz, 1970) and Northern Europe (Belford et al., 1985; Cannell et al., 1984; Feddes, 1988). Nevertheless, this updated quantification of the yield response takes us further and improves our understanding of the interaction between poor drainage condition and yield reduction, specifically in cereals in Northern Europe, which is a region with potentially high drainage needs and where cereals are widespread crops.

The climatic conditions, soil textures and crops from this trial are comparable to a series of controlled lysimeter trials conducted in Britain in 1974-1982 (Belford et al., 1985; Cannell et al., 1984, 1980). For these trials, we therefore calculated the SEW_{60} index based on the given information of periodically constant, controlled water table positions. Belford et al. (1985) found an average yield reduction of 18% at a calculated SEW_{60} of 840 cm day compared to a WD SEW_{60} plot value of 0. In similar trials, Cannell et al. (1980) found an average yield decrease of 11-13% at a calculated SEW_{60} value of 1000 cm day, and Cannell et al. (1984) found yield reductions of 16, 21, 24, and 30% in four different years at a SEW_{60} of 1500 cm day. These yield responses are within the range found in this study. However, comparison must be done with caution since the effects of dynamic groundwater levels in the field can be different from those at constant groundwater levels applied in a lysimeter. In a trial closer to field scale and with somewhat more dynamic water table variation, Cannell et al. (1986) found a yield effect of mole drainage of 15%. However, the effect on water table depths was not quantified

The drainage response differed between seasons. This was expected since the interactions between weather factors, soil conditions and crop management (particularly N application rate and timing) result in different crop sensitivity between the years. The yield effect from drainage conditions expressed as the SEW_{60} can therefore not be generalised to concern every specific growing season, but must be considered to have yearly variations according to the specific conditions in each individual year. However, the study clearly showed that functioning drainage systems are required to minimize the risk of yield losses, the need of climate change mitigation strategies emphasises this.

A logarithmic yield response model was chosen because we expected that the marginal effect should increase with increasing SEW_{60}. In that respect, our approach is similar to that used by Feddes (1988), Feddes and Van Wijk (1976) and Sieben (1964) in cereals. Some report the yield penalty of waterlogging to be proportional to the duration of the stress, which is not explicitly addressed by the SEW_{60} index in this study. This is the case for Marti et al. (2015) in wheat and for Feddes (1988) in forage grass under considerably higher N applications rates.
In practice, poor drainage may affect the yield indirectly by having negative impacts on choice or timing of crop management and rotations. Such effects were not included in the present study since all field operations were performed in the same manner and at the same time at WD and PD areas.

More widespread growth of weed at the poorly drained sites is a general observation. Especially annual meadow grass (*Poa annua)* has been found to withstand a degree of waterlogging and temporary flooding (Hutchinson and Seymour, 1982).

4.3 N application rates and drainage effects

N application rate was a significant yield determining factor with decreasing marginal effect of extra N. Hence, there was a larger response of extra N application when going from 50% to 100% of normal application rather than from 100 to 150%. This is in line with the expectations of a normal N response under WD Danish conditions of a cereal crop. It should be noted that the 150% application rate was only used in two years (Tokkerup 2013 and 2014), and we cannot exclude that this effect was specific for those two growing seasons.
The N response was expected since the anoxic conditions in poorly drained soil horizons imposes a risk of more denitrification and less nitrification. This is described by Belford et al. (1985), who measured lower redox potential causing falling nitrate concentrations and nitrous oxide evolution. Also reduced root growth and rooting depth in particular is a common result of waterlogging (Brisson et al., 2002). Both factors reduce the N uptake of the crop, which was also found in this study in SB 2015 and WW 2016 at Tokkerup (Figure 5) as a temporary effect.

The applied N levels did not interact with the drainage treatment but acted as a strongly significant additive factor in the description of the yield. This is unexpected because a higher marginal effect (interaction) could be expected under PD conditions due to a lower mineral N content after a higher denitrification risk during winter. Feddes and Van Wijk (1976) found interaction with N in forage grass yields, but to our knowledge, this has not been shown in cereal field trials over several growing seasons within the last decades. This simple hypothesis would result in a lower offset at the N response curve, resulting in a higher marginal N effect under PD conditions if N availability was the only limiting factor for plant growth.

This hypothesis was rejected by the missing interaction between N and drainage. This could indicate that the effect on marginal yield of lower mineral N availability in the spring is counteracted by poorer utilization of applied N. This could be caused by higher denitrification risk for applied N and poor root development, resulting in severely decreased leaf nitrogen concentrations from waterlogging also found by Malik et al. (2002). In this case timing of the fertilization in relation to drainage events and high groundwater is important since the risk of significant denitrification is particularly high right after fertilization. Robertson et al. (2009) found that application of N after waterlogging increased yield but N application at sowing before the treatment had no effect on the yield. Hence, N dynamics in the system can affect the response and interaction with drainage.

Alternatively, the reason for no interaction between N application and drainage could be that other drainage related factors suppress the yield potential, dominating over the N effect of waterlogging induced as a transient N deficiency (Robertson et al., 2009). Malik et al. (2002) found that short- and long-term waterlogging may severely affect the seminal root system, thereby affecting the balance between root and shoot growth and inducing physiological stress. Reduced root growth is also documented by Dickin and Wright (2008) and Brisson et al. (2002). P and K uptake may also be significantly reduced by waterlogging in corn (Ahmad et al., 1992). Ylivainio et al. (2018) found that very high P application could compensate for the negative effects of waterlogging in spring barley. These factors could have reduced the yield potential in this trial, but wasn´t examined in this study.

Reduced growth in the spring due to lower temperatures in poorly drained soil was reported by Jensen et al. (in prep) and Robertson et al. (2009). Robertson et al. (2009) also found that lower soil temperatures had adverse effects on the growth of tillers and ultimately on yields. These observations are supported by the delayed crop development measured in this study, showing that the crops were in some cases affected early in the spring before fertilization.

The findings from this study can thereby partly support that it is possible to compensate yield decrease due to poor drainage at low N application rates by higher N application. This is described by Belford et al. (1985), who suggest the use of additional nitrogen fertilizer as a procedure to reduce yield loss. But the lack of interaction between drainage also indicates that the yield cannot be compensated at high N levels because the yield potential was found to be lower at the poorly drained plots. This might be different in other crops or at higher N levels in other growing seasons. More detailed process understanding, not least covering implications of different factors such as temperature, crop physiological stress and N response is warranted. A natural next step towards a better understanding of yield responses to poor drainage could be modelling.

4.4 Delayed crop development

Since the yield response to poor drainage could not be fully described by N (no interaction), other yield reducing factors should be of importance. Yield potential can be reduced from the early growth stages, especially in autumn sown crops, which are limited in growth by low temperatures in the early spring. Autumn sown crops also have a higher risk of exposure to high groundwater in poorly drained areas. This is supported by lower NDVI values in the poorly drained plots in the beginning of the growing season in a majority of the trial seasons and by some of the biomass cuts (Figure 6 and Figure 4). NDVI responds to both optical properties of the canopy and to amount of canopy. Hence, the effect of drainage conditions on NDVI can be due to different N concentrations in the leaves and/or different leaf area index (LAI), which both could be due to lower temperatures in the PD. Ahmad et al. (1992) reported delayed growth and a linear relationship between LAI and SEW_{30} in corn subjected to different periods of waterlogging.

Reduced N availability of the poorer drained plots might also lead to an earlier decay of the green leaves in the maturing phase. This was not examined systematically in this study but some observations from the trial could indicate this effect and could be a topic for future research in the explanations of the drainage yield effect.

5 Conclusion

This paper aimed to investigate the quantitative response of poor drainage on yield, N uptake and early development of cereal crops grown under ordinary field drainage conditions on sandy loam soils in Denmark. Detailed measurements of the dynamic groundwater level in the plots could be utilized to describe the drainage conditions by a SEW_{60} index. Both the relative yield of grain and the relative nitrogen content in grain at harvest were correlated to SEW_{60} across crops, seasons and locations and at different N application levels. The results did not indicate any difference in tolerance to waterlogging between spring barley and winter wheat.

The negative effect of poor drainage on DM yield could be compensated at N levels lower than normal rate (50% of normal), but could not be compensated by addition of extra N fertiliser (up to 150% of normal rate). The lack of full compensatory effect at the highest N level indicate that other drainage related factors are important in setting the yield potential. The drainage response on N yield was higher than the response on DM yield, and extra N application could compensate the negative effect of poor drainage on N yield to a higher degree than on DM yield.

There was no interaction between SEW_{60} and N application level, neither with respect to DM yield nor N yield. According to this, the marginal effects of extra N application on yield losses due to poor drainage were independent of the drainage conditions. NDVI measurements during early growth stages in the spring revealed periods of reduced or delayed plant growth in poorly drained plots, both in spring barley and in winter wheat. In future research, it is suggested to include a comprehensive modelling approach to help improving our understanding of the effects of different drainage response factors and their interactions.

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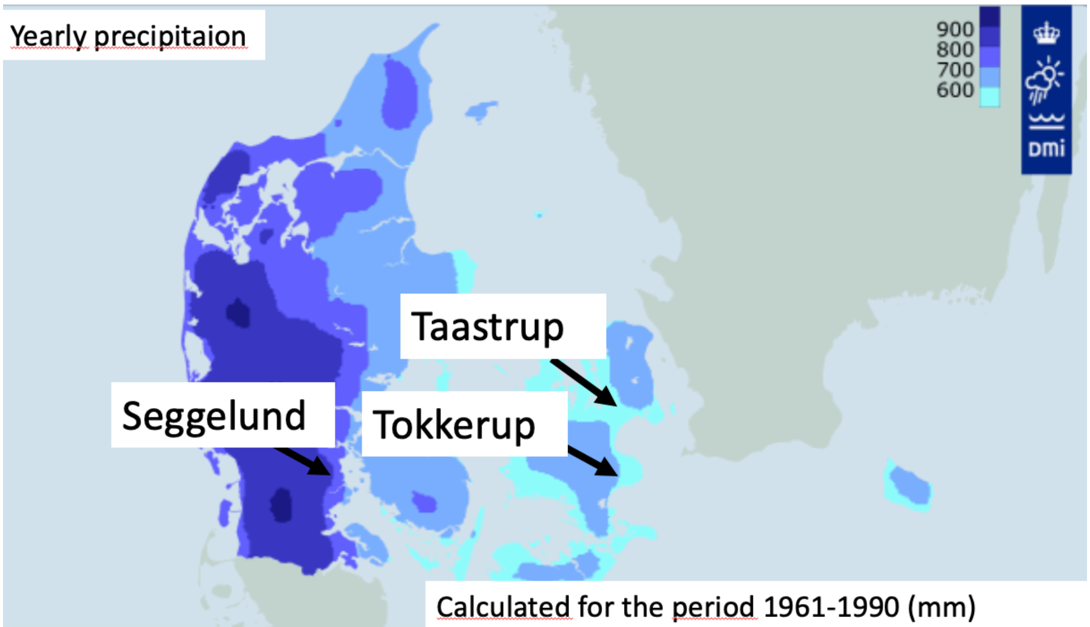
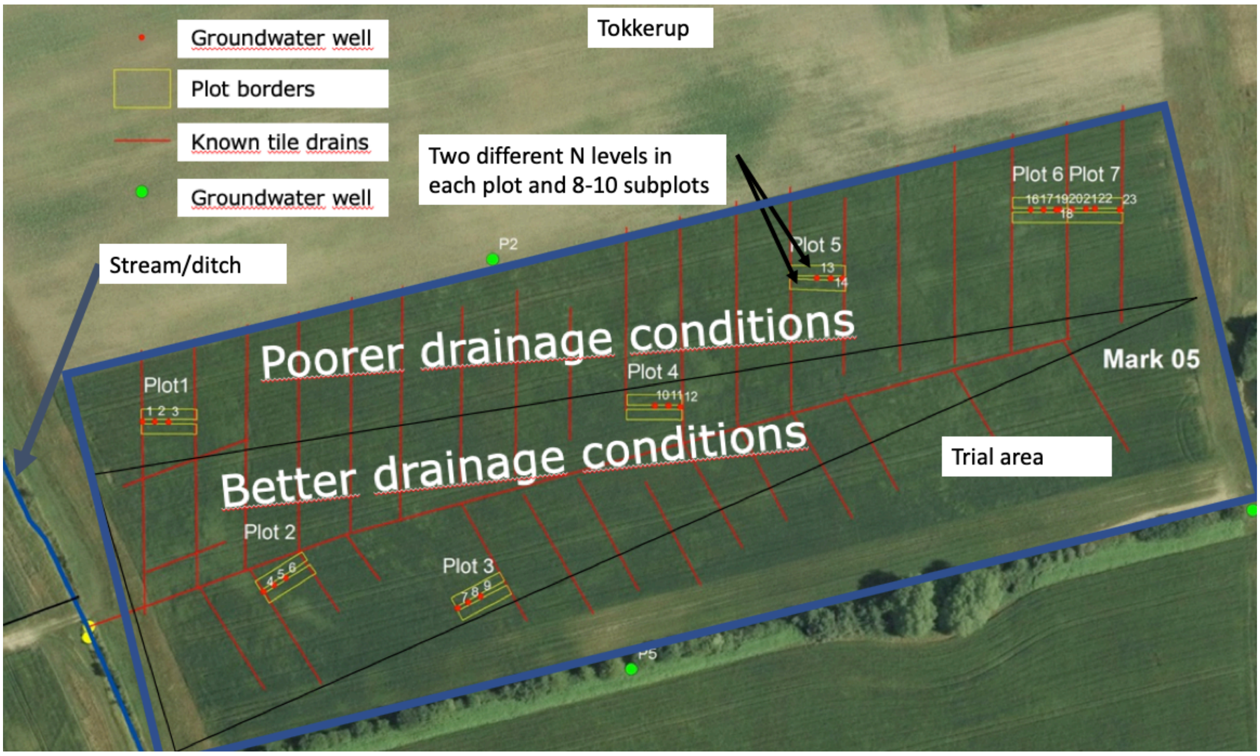
Appendix

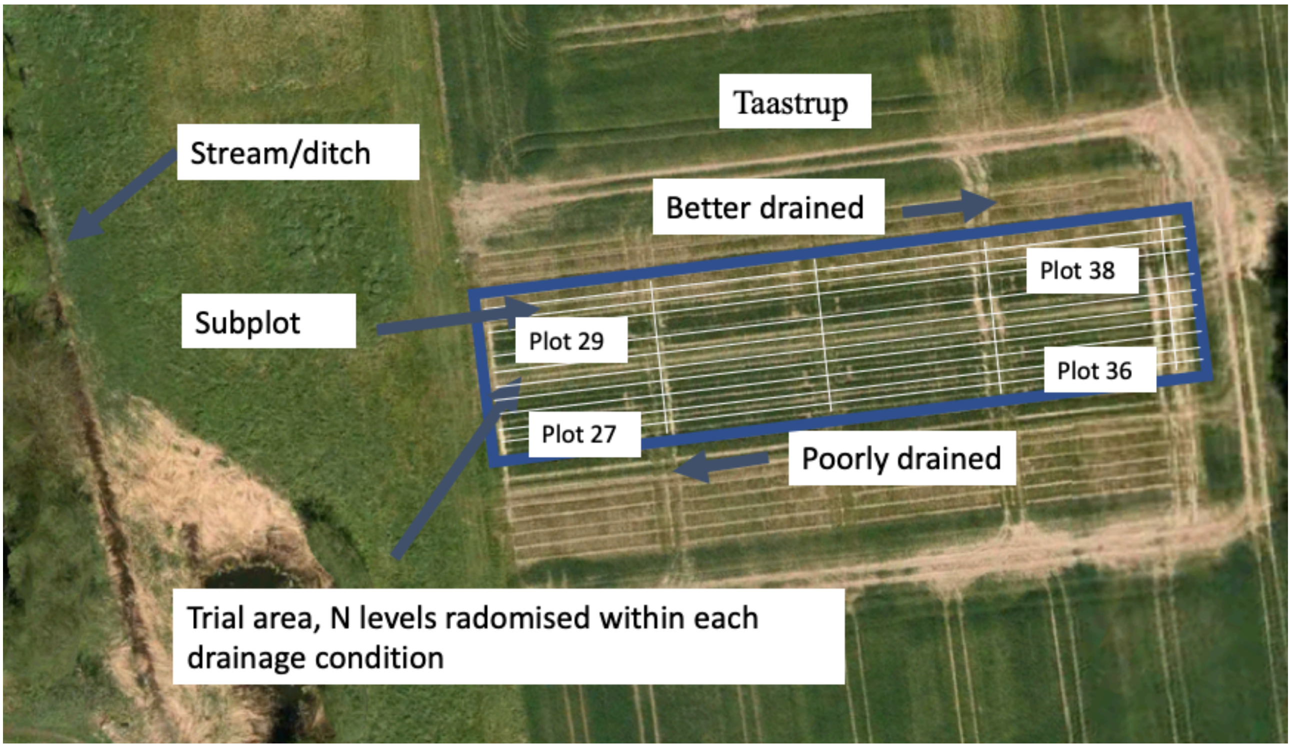
A. Trial locations and design



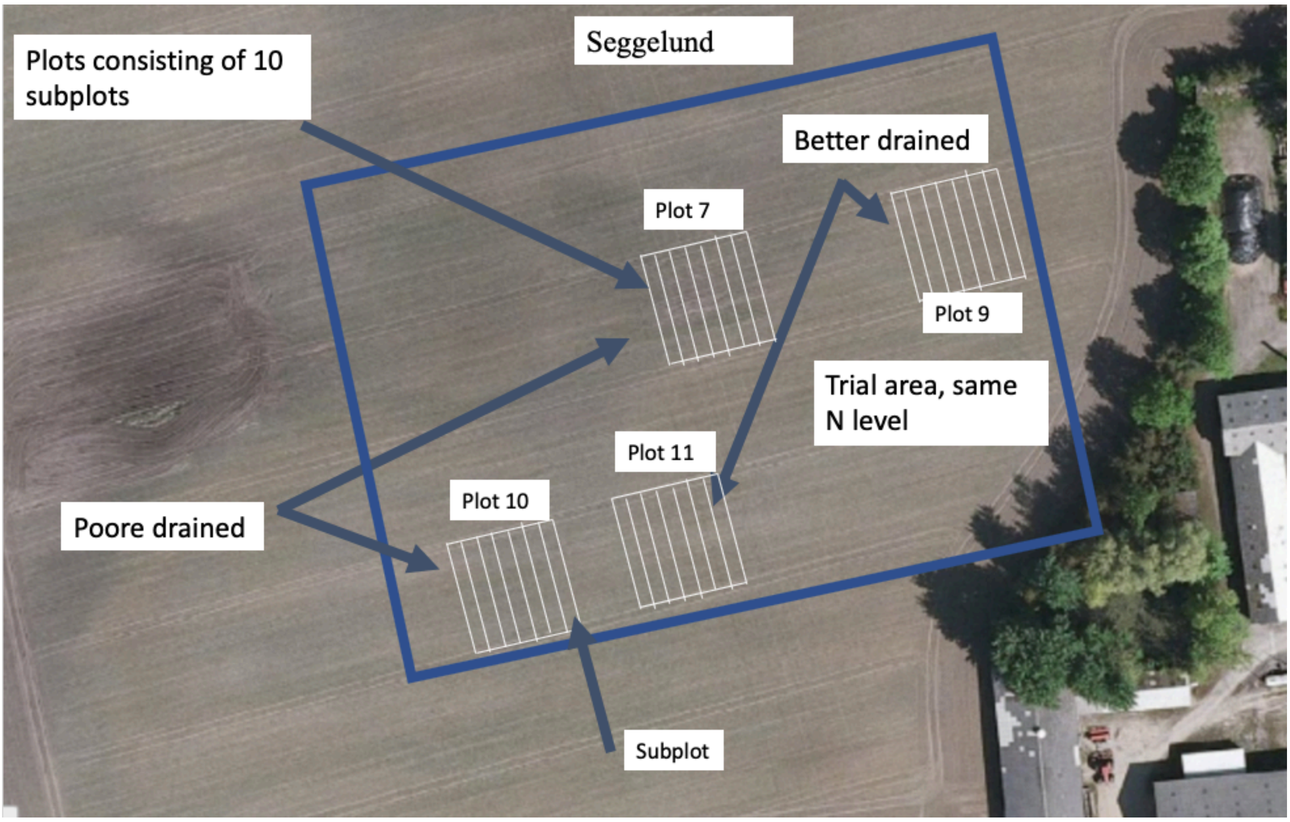
Appendix Figure 1 Trial locations and yearly precipitation calculated for the period 1961-1990 source www.dmi.dk.



Appendix Figure 2 Tokkerup trial setup and plot distribution. 3,8ha field characterized by a low topographical difference in surface height. The known parts of the tile drainage system from the 50´s is marked with red lines, showing the main pipe in the middle of the field, the side drains on both sides and the outlet in the left side of the picture goring into the stream marked with blue. There is a gradient in drainage depth due to the slope in the drainage system is sloping towards the stream. the drainage conditions within the black triangle in thereby better due to the deeper tile drains.



Appendix Figure 3 Taastrup trial setup. There is a gradient in groundwater depth from the poorly drained plots closest to the stream in the left side of the map and the better drained plot in the right side. Root measurements are conducted in all of the plots.



Appendix Figure 4 The Seggelund location, four plots (two well drained and two poorly drained) with 10 subplots in each.

B. Texture and bulk density

Appendix Table 1 Taastrup texture and bulk density

Horizon	Depth	Clay	Silt	Silt	Fine Sand	Coarse sand	Org. Content	Bulk density
Poore draine	cm	< 2um %	2-20um %	20-50um %	50-200um %	200-2000um	%	Mg/m3
Ap	0-32	7.0	14.5	8.5	31.4	34.9	3.7	1.35-1.44
E	32-47	8.1	8.4	6.4	43.2	33.1	0.9	1.68
B	47-81	6.9	6.5	5.0	46.4	34.9	0.4	1.83
C	81-100	2.9	2.9	1.4	22.9	69.8	0.2	1.87
C	100-180	*8*	*3*	*1*	*23*	*65*	*0.2*	*1.87*
C	180-250	*23*	*17*	*10*	*29*	*22*	*0.2*	*1.97*
Better drained								
Ap	0-30	8.0	17.0	9.5	27.3	34.6	3.5	1.44-1.59
E	30-46	11.0	20.2	11.8	27.1	28.9	0.9	1.72
B	46-80	21.8	17.7	8.4	21.7	29.3	1.1	1.83
C	80-106	16.9	18.8	7.6	23.6	32.6	0.5	1.87
C	106-160	*17*	*19*	*8*	*24*	*33*	*0.2*	*1.87*
C	160-250	*17*	*19*	*8*	*24*	*33*	*0.2*	*2.07*

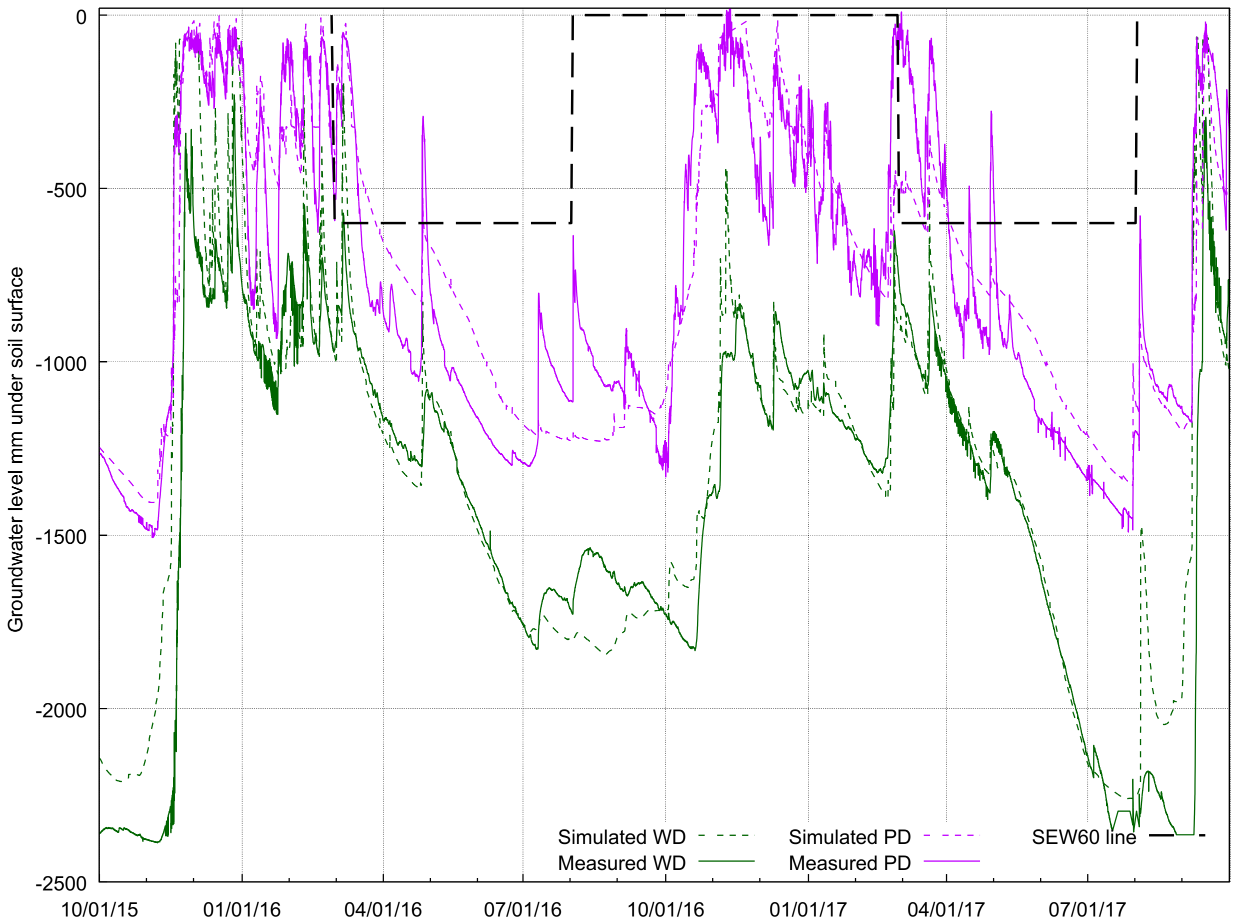
Appendix Table 2 Tokkerup texture and bulkdensity

Horizon	Depth	Clay	Silt	Fine Sand	Coarse sanc	Org. Conte	Bulk density
WD plot 2	cm	<2um %	2-20um %	20-200um	200-2000um	%	Mg/m3
Ap	0-30	18	14	38	27	2.8	1.48-1.6
C	30-60	8	20	52	20	0.5	1.83
C	60-125	13	41	36	10	0.5	1.73
C	125-170	13	41	36	10	0.5	*1.73*
C	170-190	5	9	63	23	0.5	*1.73*
C	190-250	*13*	*41*	*36*	*10*	*0.5*	*1.73*
WD plot 4							
Ap	0-30	15	11	42	28	4.6	1.4-1.6
C	30-60	7	19	45	29	0.5	1.80
C	60-180	11	21	41	27	0.5	1.90
C	180-200	*5*	*9*	*63*	*23*	*0.5*	*2.00*
C	200-250	*12*	*10*	*41*	*34*	*0.5*	*2.00*
WD plot 6							
Ap	0-30	12	10	41	34	2.8	1.4-1.6
C	30-75	18	24	34	23	0.8	1.87
C	75-130	17	22	38	22	0.8	1.93
C	130-250	17	22	38	22	0.8	*2.00*

Appendix Table 3 Seggelund texture and bulkdensity

Horizon	Depth	Clay	Silt	Fine Sand	Coarse sand	Org. Content	Bulk density
PD Plot 7	cm	< 2um %	2-20um %	20-200um %	200-2000um	%	Mg/m3
Ap	0-29	17	11	38	30	4.3	1.47
Ap, plowpan	29-40	*17*	*11*	*38*	*30*	*4.3*	1.24
O	40-46	*17*	*11*	*38*	*14*	*20*	0.91
C	46-73	*17*	*11*	*38*	*30*	*3.7*	1.40
O	73-90	*17*	*11*	*38*	*30*	*20*	0.7
C	90-300	*17*	*11*	*38*	*30*	*0.2*	*1.9*
WD Plot 9							
Ap	0-27	13	9	42	33	2.8	1.37
E, plowpan	27-52	*13*	*9*	*42*	*33*	*1.8*	1.65
B	52-93	*18*	*9*	*42*	*30*	*0.5*	1.70
C	93-300	*18*	*9*	*43*	*30*	*0.2*	*1.87*
PD Plot 10							
Ap	0-27	19	12	32	32	4.8	1.32
B, plowpan	27-45	*19*	*12*	*32*	*32*	*4.8*	1.62
C	45-75	*19*	*12*	*32*	*36*	*0.8*	1.87
C	75-90	*19*	*12*	*32*	*36*	*0.2*	1.87
C	90-300	*19*	*12*	*32*	*37*	*0.2*	*1.87*
WD Plot 11							
Ap	0-25	12	9	41	36	2.5	1.6
B, plowpan	25-30	*12*	*9*	*41*	*36*	*2.5*	1.9
C	30-45	*19*	*9*	*41*	*31*	*0.5*	1.85
C	45-300	*12*	*9*	*41*	*38*	*0.2*	*1.87*

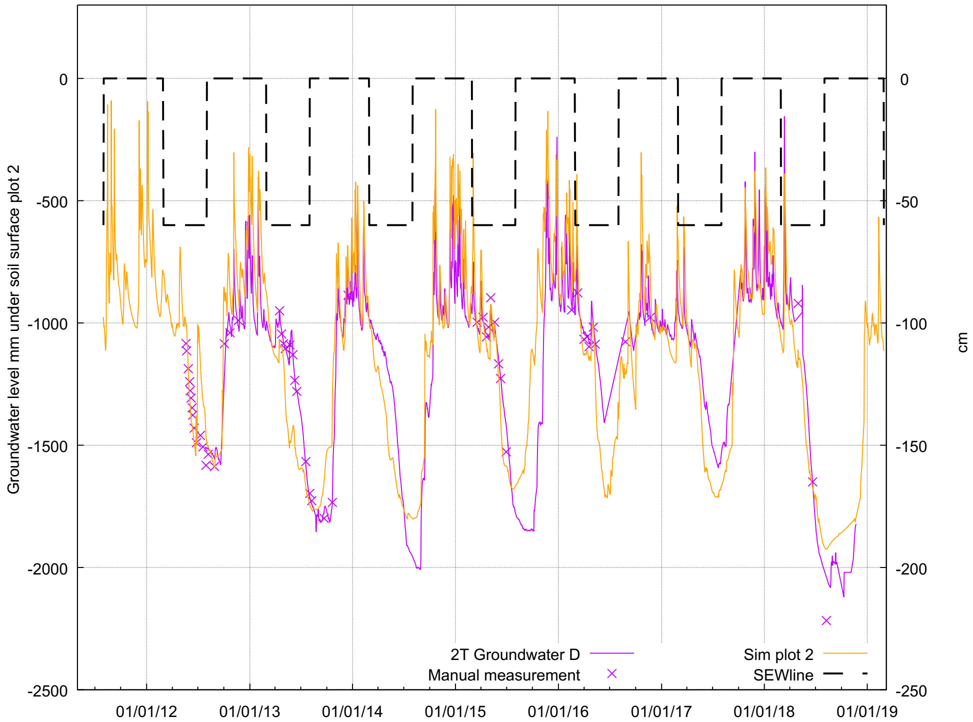
C. Model fit to measured groundwater



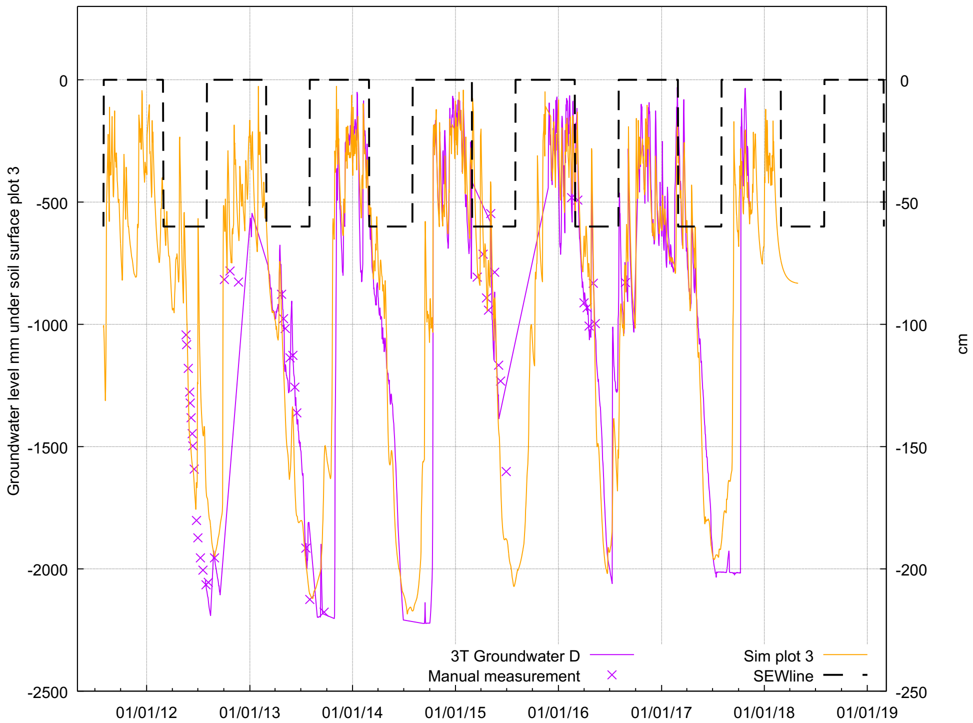
Appendix figure 5 Measured and simulated groundwater at the Taastrup location for well drained WD and poorly drained PD plots.

D. Groundwater Measurements all plots

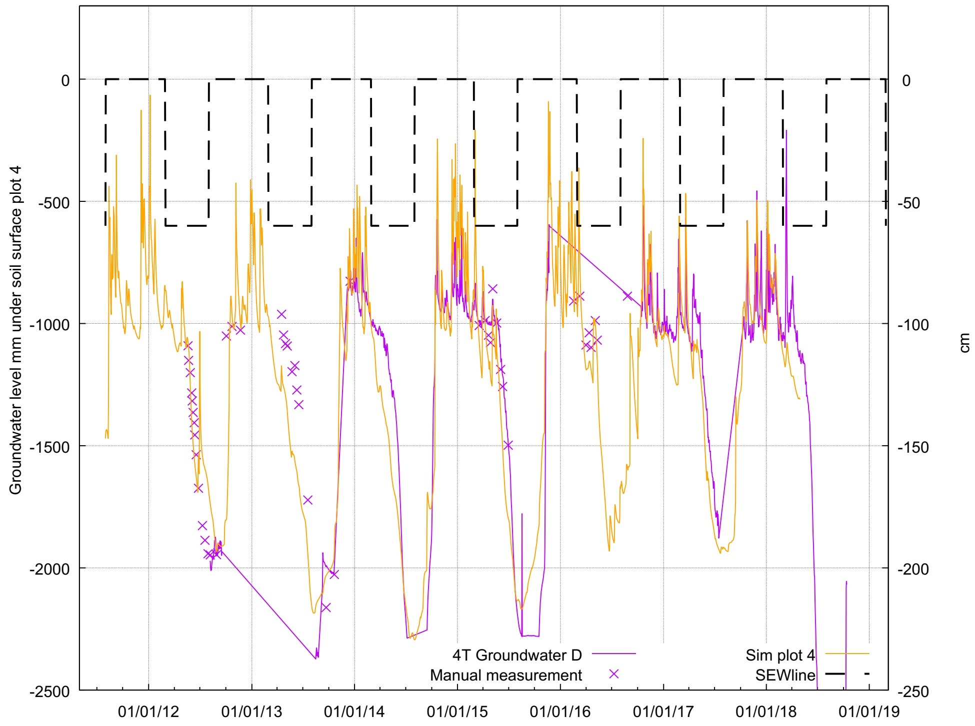
Tokkerup



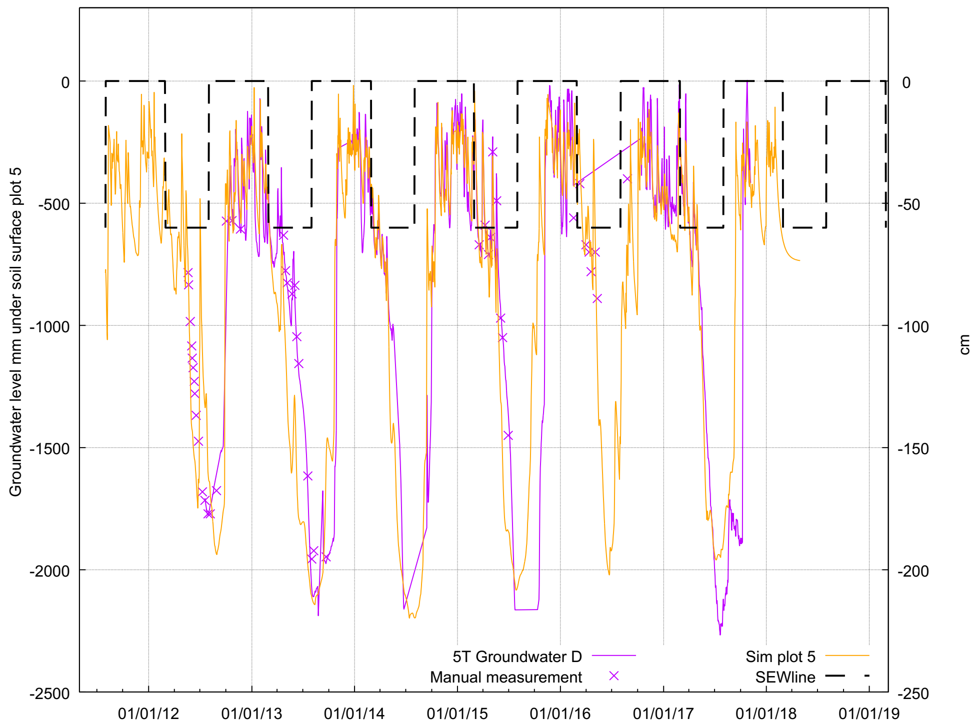
Appendix Figure 6 Measured and simulated groundwater level in plot 2



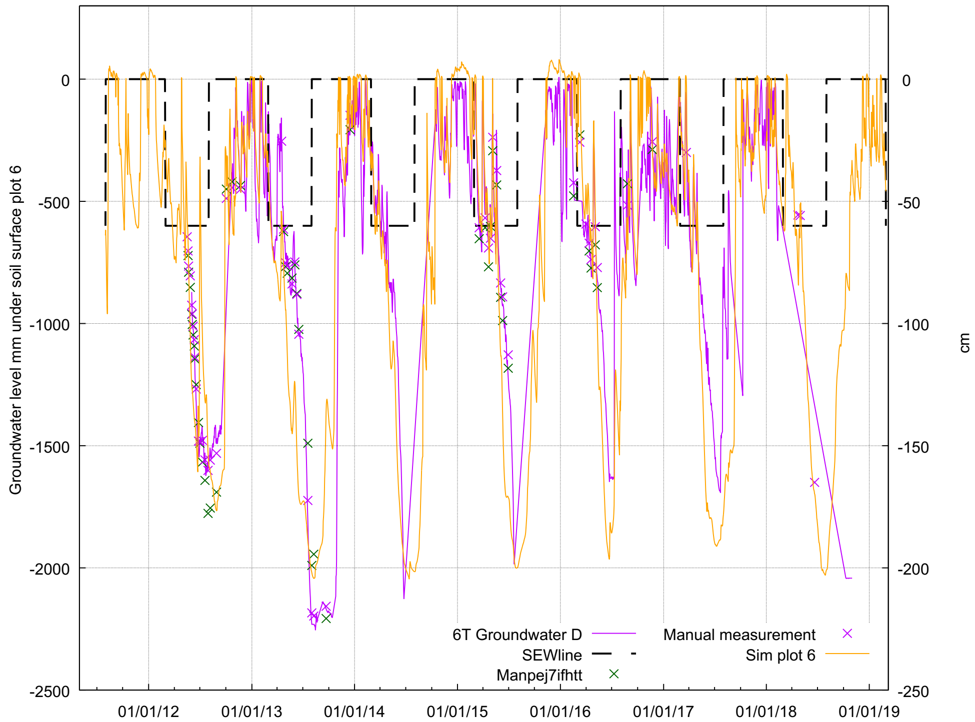
Appendix Figure 7 Measured and simulated groundwater level in plot 3



Appendix Figure 8 Measured and simulated groundwater level in plot 4

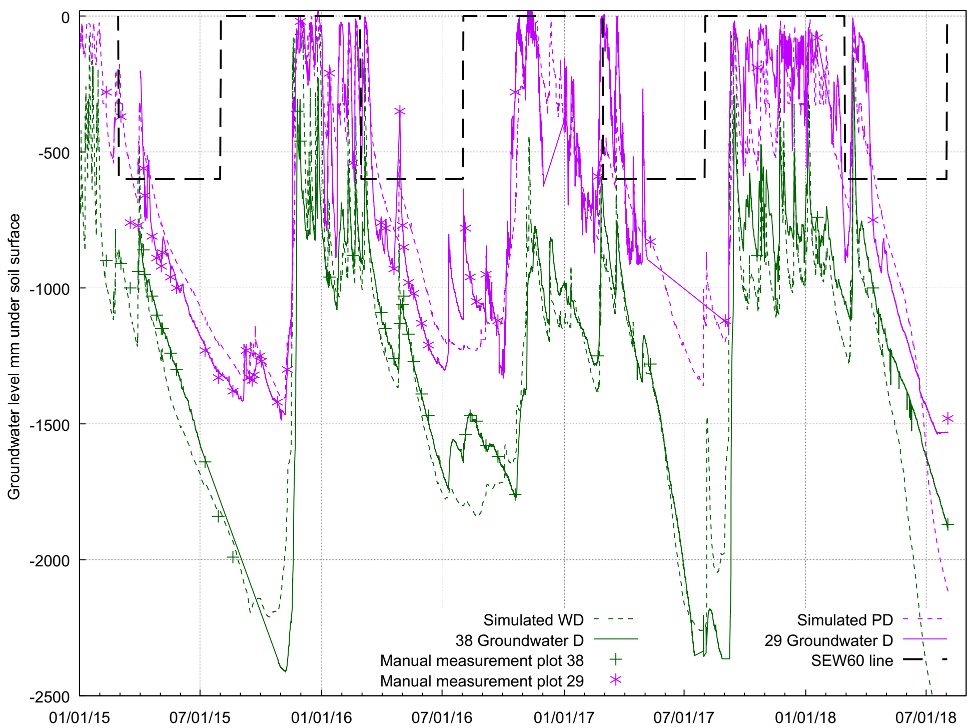


Appendix Figure 9 Measured and simulated groundwater level in plot 5

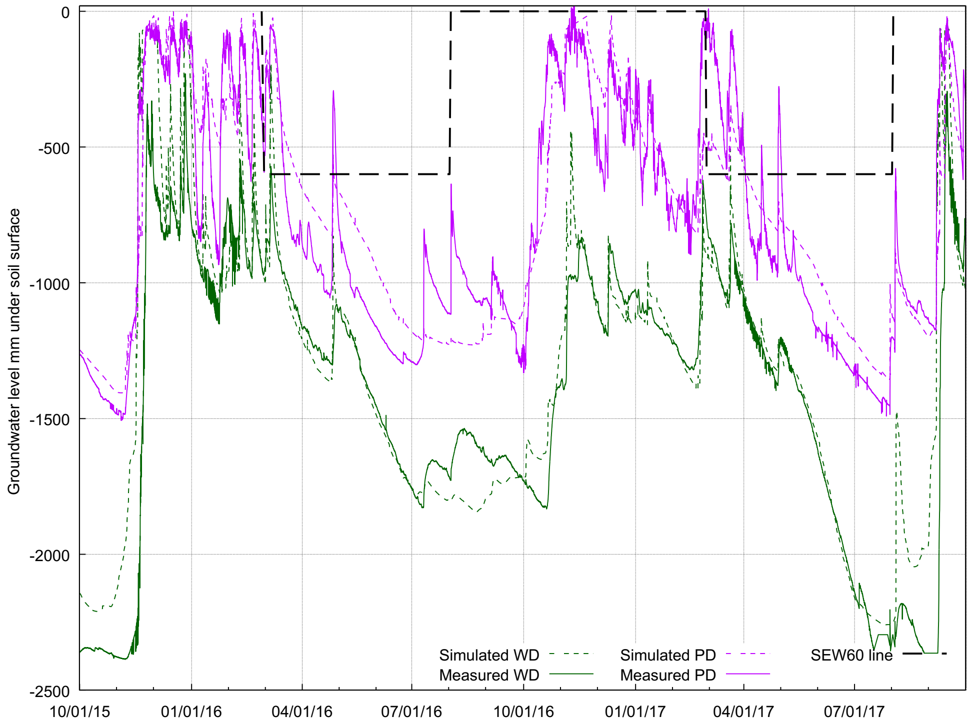


Appendix Figure 10 Measured and simulated groundwater level in plot 6 and 7

Taastrup measured and simulated groundwater

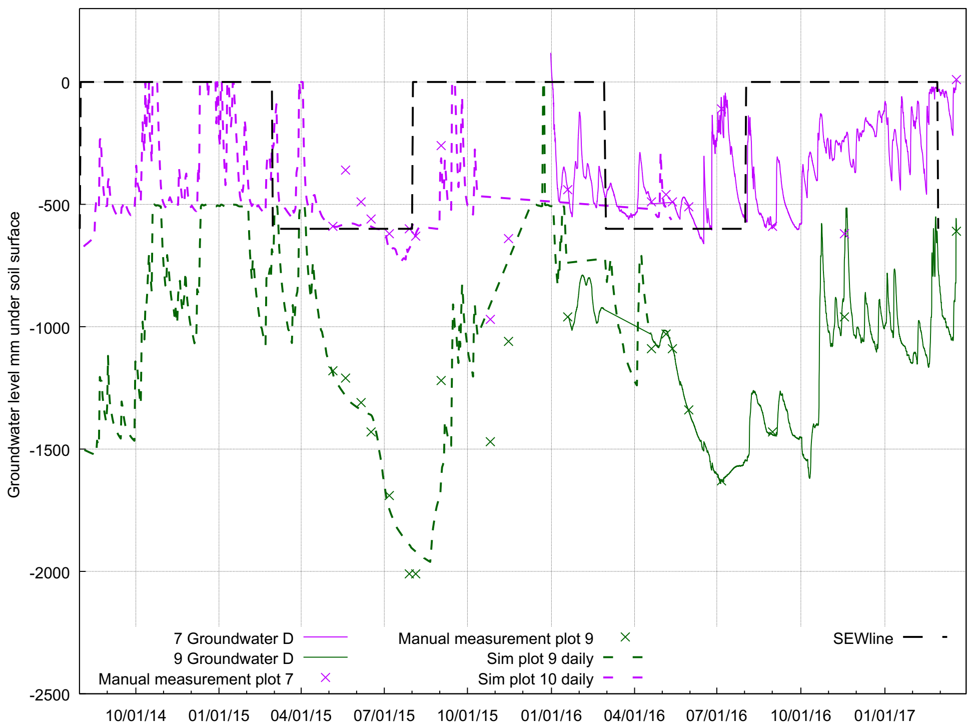


Appendix Figure 11 Measured and simulated groundwater level in plot 38 and 29

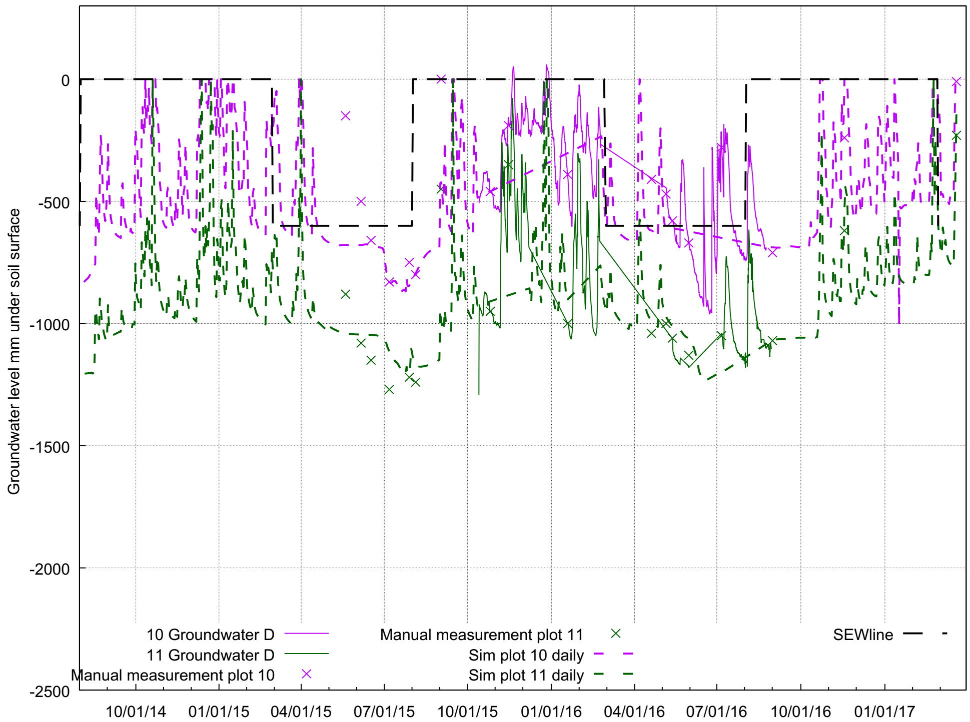


Appendix Figure 12 Measured and simulated groundwater level in plot 36 and 27

Seggelund measured and simulated groundwater



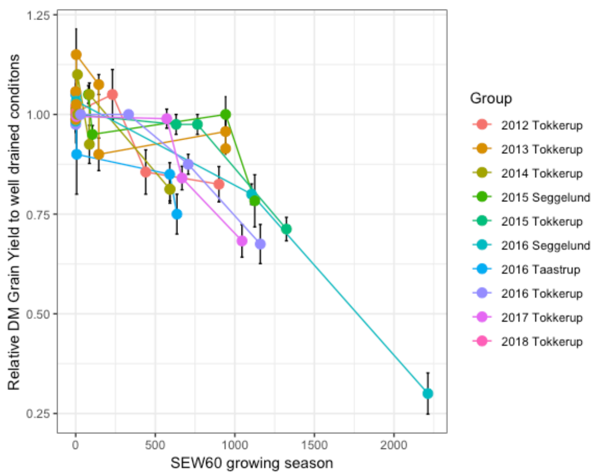
Appendix Figure 13 Measured and simulated groundwater level in plot 7 and 9



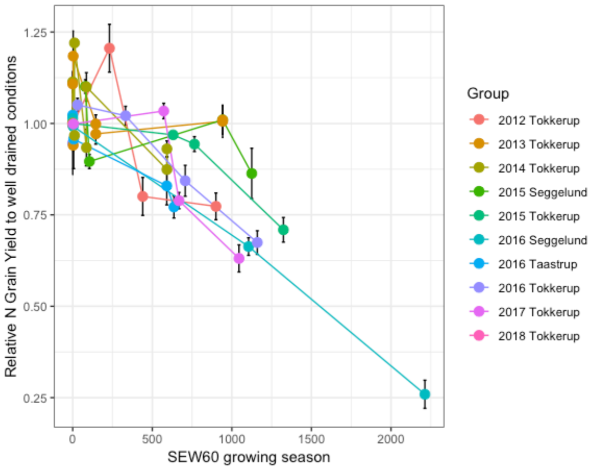
Appendix Figure 14 Measured and simulated groundwater level in plot 10 and 11

E. SEW yield relations using other threshold depths and periods

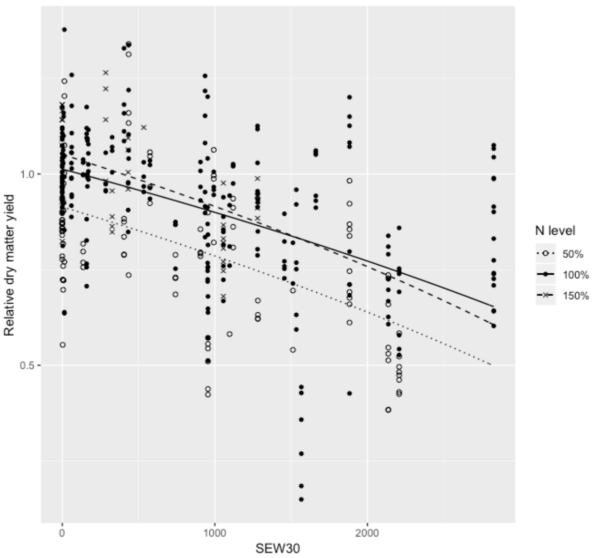
SEW index was calculated at two threshold values (30 and 60cm) and two periods (N) 1/8-1/8 (all year), supplementing the threshold value of 60cm and spring period 1/3-1/8 (the primary part of the growing season, (growing season)). This is referred as $SEW_{30\ all\ year}$, $SEW_{60\ all\ year}$ $SEW_{30\ growing\ season}$ and $SEW_{60,\ growing\ season}$ respectively. The relative and absolute yield correlations to these SEW index are shown below, divided into year and location.



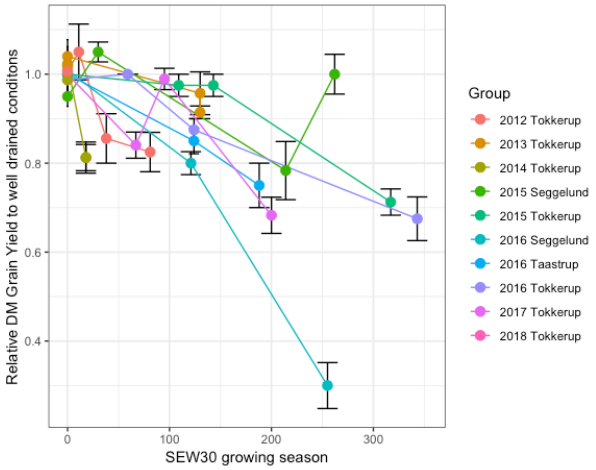
Appendix Figure 15 Relative DM yield to N norm fertilized better drained yield as a function of drainage conditions ($SEW_{60\ growing\ season}$)1/3-1/8, divided in year and location. Standard error for the relative yield at each SEW value is given as SE.



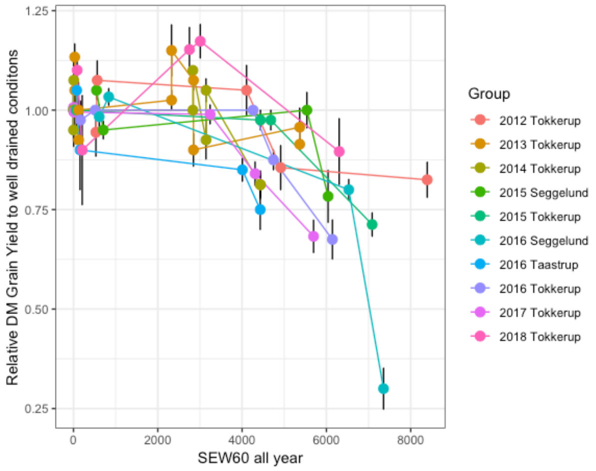
Appendix Figure 16 Relative N yield to N norm fertilized better drained yield as a function of drainage conditions ($SEW_{60\ growing\ season}$)1/3-1/8, divided in year and location. Standard error for the relative yield at each SEW value is given as SE.



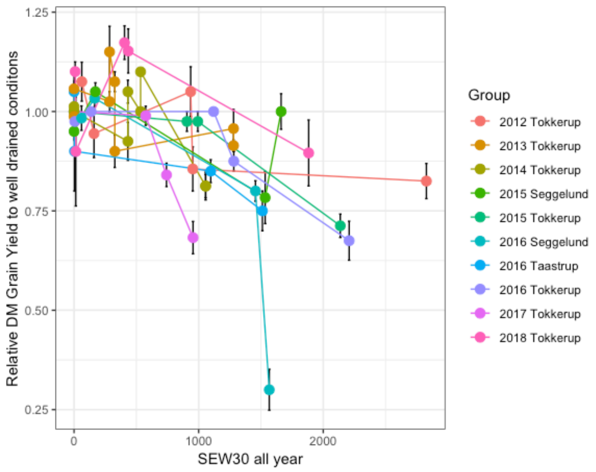
Appendix Figure 17 Relative N yield in grains related to SEW_{30}. The data are for winter wheat (WW) and spring barley (SB) for all years and for all test locations. The symbols differentiate into results for the different N application levels expressed relatively to what is considered to be normal for the crop, i.e. 50% (WW: 90 kg N/ha; SB: 70 kg N/ha), 100% (WW: 180 kg N/ha; SB: 140 kg N/ha), and 150% (WW: 255 kg N/ha). The curves represent the fitted model at each N level.



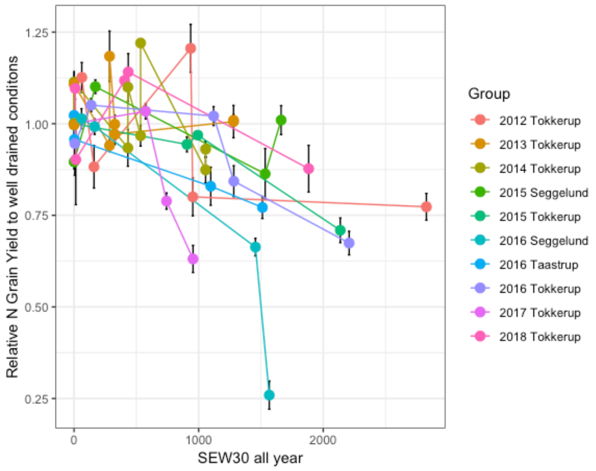
Appendix Figure 18 Relative DM yield to N norm fertilized better drained yield as a function of drainage conditions shown as drainage index SEW$_{30\ \text{growing season (1/3-1/8)}}$,divided in year and location. Standard error for the relative yield at each SEW value is given as SE.



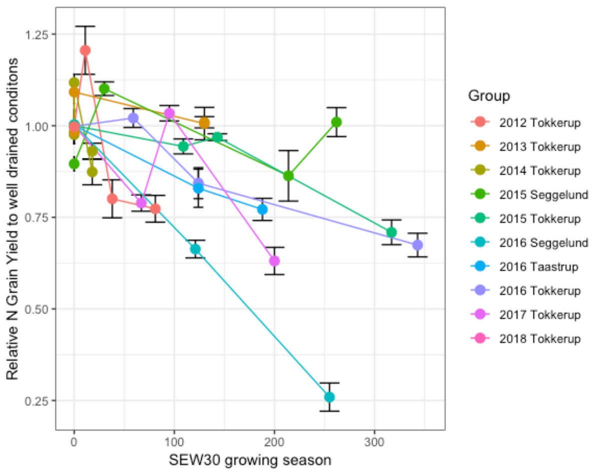
Appendix Figure 19 Relative DM yield to N norm fertilized better drained yield as a function of drainage conditions shown as drainage index SEW$_{60\ \text{all year}}$, divided in year and location. Standard error for the relative yield at each SEW value is given as SE.



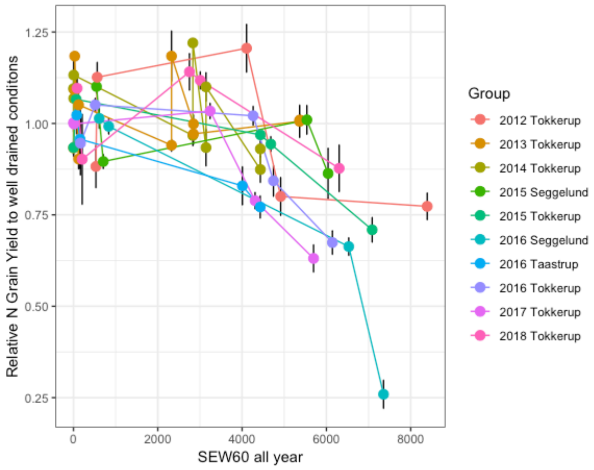
Appendix Figure 20 Relative DM yield to N norm fertilized better drained yield as a function of drainage conditions shown as drainage index $SEW_{30\ all\ year}$, divided in year and location. Standard error for the relative yield at each SEW value is given as SE.



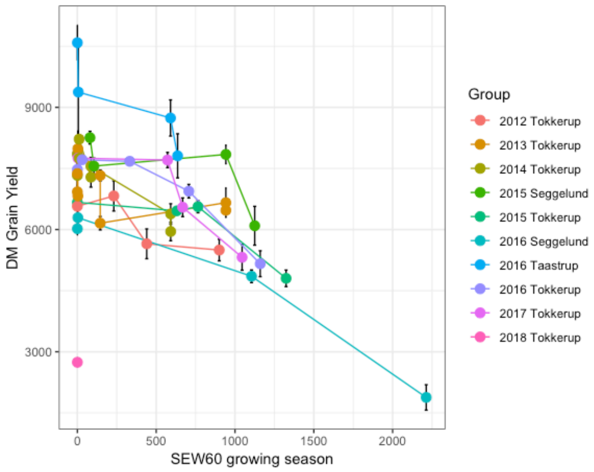
Appendix Figure 21, Relative N yield to N norm fertilized better drained yield as a function of drainage conditions shown as drainage index $SEW_{30\ all\ year}$ divided in year and location. Standard error for the relative yield at each SEW value is given as SE.



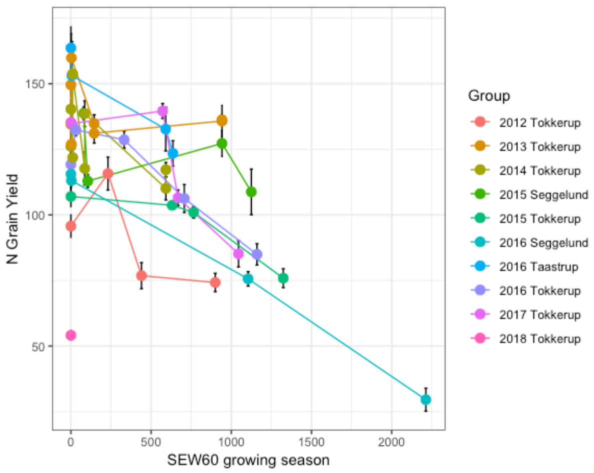
Appendix Figure 22 Relative N yield to N norm fertilized better drained yield as a function of drainage conditions shown as drainage index $SEW_{30\ growing\ season\ (1/3-1/8)}$ divided in year and location. Standard error for the relative yield at each SEW value is given as SE.



Appendix Figure 23 Relative N yield to N norm fertilized better drained yield as a function of drainage conditions shown as drainage index SEW$_{60\ all\ year}$, divided in year and location. Standard error for the relative yield at each SEW value is given as SE.

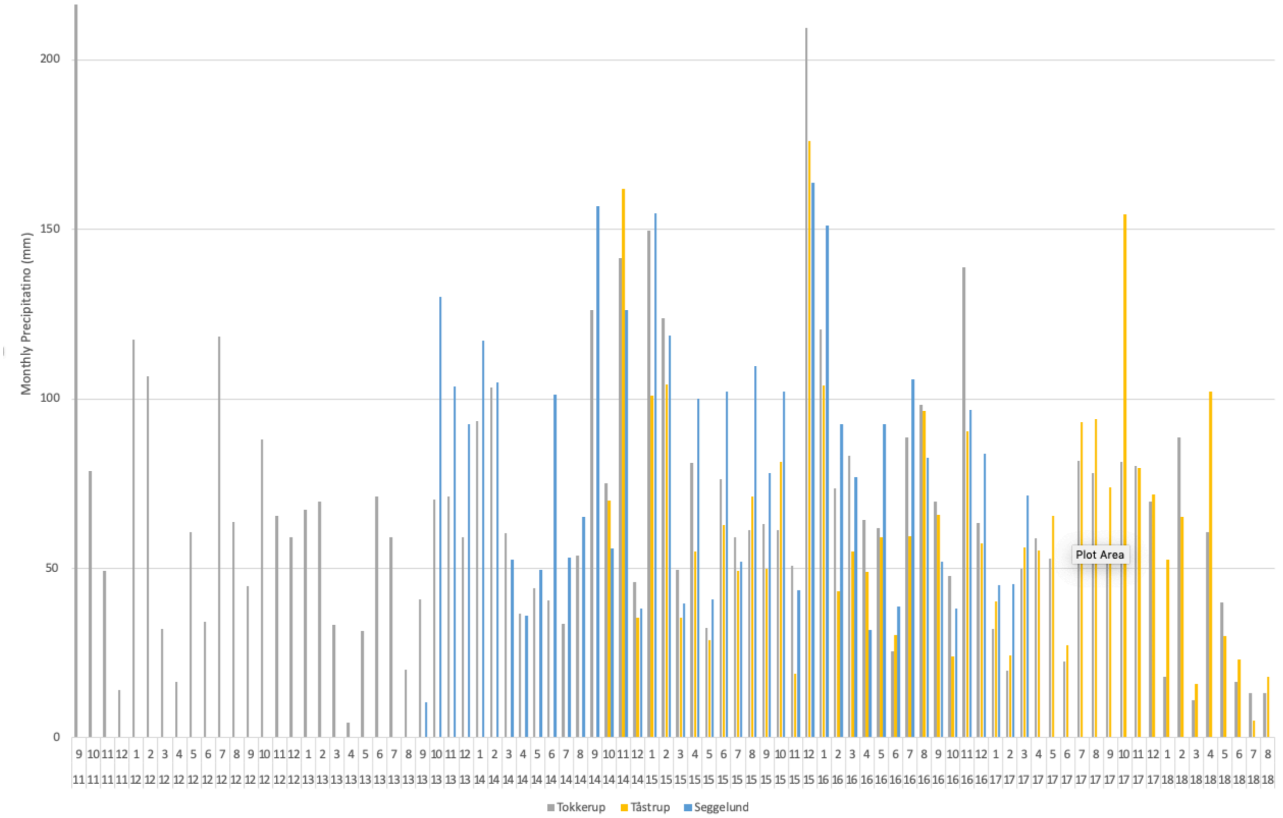


Appendix Figure 24 Absolute DM yield as a function of drainage conditions (SEW$_{60\ 1/3-1/8}$) , divided in year and location under norm N application rate. Standard error for the relative yield at each SEW value is given as SE.



Appendix Figure 25 Absolute N yield as a function of drainage conditions (SEW$_{60\ 1/3-1/8}$) , divided in year and location under norm N application rate. Standard error for the relative yield at each SEW value is given as SE.

F Monthly precipitation measurements



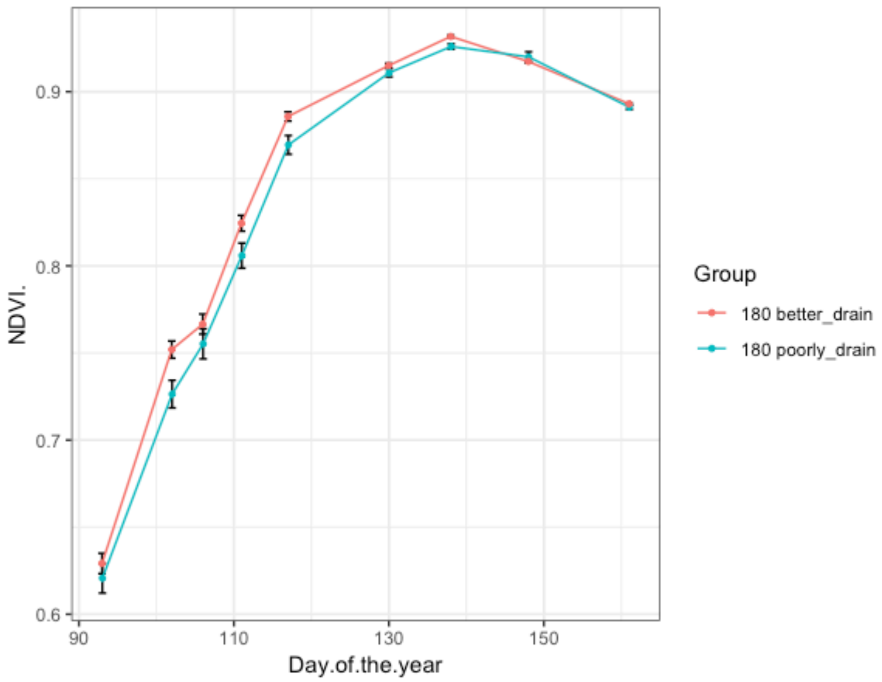
Appendix figure 26 Monthly precipitation at the three trial locations

Appendix table 4 Monthly precipitation at the three trial locations

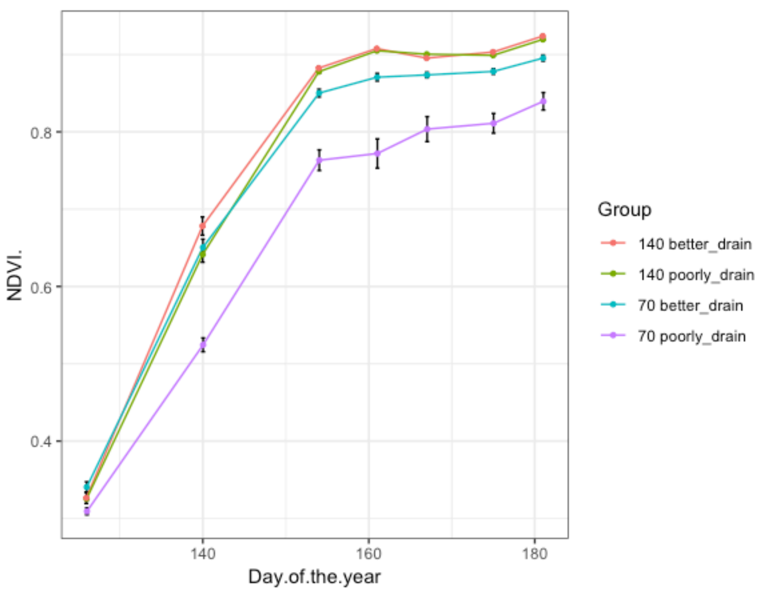
year	month	Tokkerup precipitation mm	Taastrup mm	Seggelund mm
2011	9	223		
2011	10	79		
2011	11	49		
2011	12	14		
2012	1	117		
2012	2	107		
2012	3	32		
2012	4	16		
2012	5	61		
2012	6	34		
2012	7	118		
2012	8	64		
2012	9	45		
2012	10	88		
2012	11	65		
2012	12	59		
2013	1	67		
2013	2	70		
2013	3	33		
2013	4	5		
2013	5	31		
2013	6	71		
2013	7	59		
2013	8	20		
2013	9	41		10
2013	10	70		130
2013	11	71		104
2013	12	59		93
2014	1	93		117
2014	2	103		105

2014	3	60		52
2014	4	37		36
2014	5	44		49
2014	6	41		101
2014	7	34		53
2014	8	54		65
2014	9	126		157
2014	10	75	70	56
2014	11	142	162	126
2014	12	46	35	38
2015	1	149	101	155
2015	2	124	104	119
2015	3	49	35	40
2015	4	81	55	100
2015	5	32	29	41
2015	6	76	63	102
2015	7	59	49	52
2015	8	61	71	110
2015	9	63	50	78
2015	10	61	81	102
2015	11	51	19	43
2015	12	209	176	164
2016	1	120	104	151
2016	2	74	43	92
2016	3	83	55	77
2016	4	64	49	32
2016	5	62	59	93
2016	6	26	30	39
2016	7	89	59	106
2016	8	98	96	83
2016	9	70	66	52
2016	10	48	24	38
2016	11	139	90	97
2016	12	63	57	84
2017	1	32	40	45
2017	2	20	24	45
2017	3	50	56	71
2017	4	59	55	
2017	5	53	65	
2017	6	23	27	
2017	7	82	93	
2017	8	78	94	
2017	9	54	74	
2017	10	81	154	
2017	11	80	80	
2017	12	70	72	
2018	1	18	53	
2018	2	89	65	
2018	3	11	16	
2018	4	61	102	
2018	5	40	30	
2018	6	16	23	
2018	7	13	5	
2018	8	13	18	
Sum (okt2014-mar2017)		2 316	1 956	2 429

G NDVI development curves



Appendix Figure 27 NDVI development as a function of drainage conditions under typical N application rates in Winter wheat Tokkerup 2014.



Appendix Figure 28 NDVI development as a function of drainage conditions under typical N (140kgN/ha) and half "norm" (70kgN/ha) application rates in Spring barley 2015 Tokkerup.

Chapter 4 Drainage effects on soil surface temperature, a field trial on loamy sand in Denmark

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Summary

Soil surface temperatures in agricultural systems, as affected by drainage conditions, fundamentally affect most biological, chemical and physical soil processes. In agricultural studies, surface temperatures are often substituted with more easily measured air temperatures, but this approach may be too simple.

Soil moisture conditions and temperatures were measured continuously (2 years) in plots with different drainage conditions and analyzed by detailed metrological observations under different time scales. The data were analyzed to understand the physical mechanisms and interactions determining soil temperatures, including the effect of drainage on topsoil temperature.

The monthly average of daily maximum soil temperatures was up to from 4ºC warmer (March) that the equivalent air temperature, and down to 1.5ºC colder (December). The thermal drainage effect measured as daily maximum (day-time) and minimum (night-time) surface temperatures showed greater amplitude for the well-drained soil and were approximately 1 ºC higher and 1ºC lower compared with the poorly drained soil in spring. Good agreement between measured and modelled soil surface temperatures was obtained despite some difficulties in describing the dynamics of the thermal properties of the top soil. On a daily basis, the drainage effect primarily derived from less energy used for evaporation on the well-drained soil. The results offer possibilities to improve the simulation of thermal impacts of drainage conditions and climate change on crop growth and soil processes. More detailed information on thermal end hydraulic properties of the uppermost topsoil layers are required to further improve the description of energy fluxes of the system.

Keywords

Drainage, waterlogging, soil temperature, surface energy flux, agriculture

Background/Introduction

Drainage is the basis for agriculture in large areas of the humid temperate zone. Møller et al. (2018) found clay content, geological origin and local high groundwater pressure to be the most important indicators for the need of artificial drainage under Danish conditions. Approximately 50% of the agricultural land is drained in Denmark, mainly using subsurface pipe drains Olesen, (2009). The main drainage campaigns took place in Denmark between 1860-80 and 1930-70. Drainage are also a very widespread practice in England and Wales, Robinson and Armstrong, (1988) showed that over only a decade in the 1970's 10% of the agricultural area in England and Wales where drained stating the implication of drainage in the temperate zone of Northern Europe. In a global scale Feick et al. (2005) estimated that 167 million hectares drained. Poor drainage conditions often reduce yields considerably, but the scientific research in drainage related problems date back to the extensive establishing period of the drainage infrastructure. The main soil-chemical and -physical effects of drainage, such as reduced denitrification and higher surface temperatures in the spring are well-known and research on this topic goes centuries back. However, the detailed drainage related interactions between physical, chemical and biological processes are less well described, and only few field studies of drainage effects and waterlogging have been conducted in the last decades, while modern industrialized agricultural practices have developed. Furthermore, changing weather conditions affects the demand for drainage. With a predicted increase in winter precipitation for north-western Europe, e.g.(Frei et al. 2006; Rasmussen et al. 2018) the need for drainage will expectedly increase. This will challenge the capacity of the drainage infrastructure, which is established under lower precipitation conditions. At the same time, emphasis on environmental issues has increased, meaning that production requirements have to be balanced with environmental considerations. Consequently, solid quantitative understanding of the effects of drainage in modern agricultural system is currently needed. Of high importance is the understanding of the daily soil temperature fluxes affecting both biotic and abiotic processes in agricultural systems.

The temperatures in the soil-, water-, plant-, atmosphere-system are driven by energy fluxes that are governed by weather conditions. When assuming no exchange of heat by advection and no storage of heat in any canopy, the following energy balance can be established for the soil surface:

Equation 1 $$R_n = G + H + \lambda E$$

R_n is the net radiation consisting of the net shortwave radiation and (S_n) and the net longwave radiation (L_n), G is the soil heat flux, H is the sensible heat flux to the atmosphere, and λE is the latent heat used for evapotranspiration (E).

Soil water content in the top soil and thereby drainage conditions have an immediate effect on four out of the five variables in equation (1).

- The latent heat flux (λE) can be limited by decreasing hydraulic conductivity when the soil dries out under well-drained conditions. Smaller latent heat fluxes can thereby be converted to larger soil heat fluxes and consequently higher surface temperatures on well-drained soils.
- The soil heat flux (G) is a function of thermal conductivity and temperature gradients between the soil surface and deeper layers. Soil water bridges the soil particles is replaced by air when the soil is drying. Thermal conductivity will decrease, leading to a higher temperature in the topsoil in the spring and steeper vertical temperature gradients. Top soil temperatures are also affected by the volumetric heat capacity which decreases with decreasing water content.
- The net radiation on the surface is generally reduced in drier soils. The short-wave reflectance (albedo) increases with lower soil water contents. According to Stefan-Boltzmann's law for grey bodies, long-wave emission increases with increasing surface temperature which further decreases R_n (Eq. 1). On the contrary the emissivity is lower when the topsoil is dryer an reduces the outgoing radiation.
- The sensible heat flux (H) is more indirectly affected by soil water content. The higher temperature gradient between soil and air occurring under dry conditions in the spring likely increases the sensible heat flux and counteract the temperature effects caused by the other variables in the energy balance equation.

The emphasis of each of these processes and energy fluxes shifts rapidly during a day and over the year, challenging the description of the system. The processes are an interaction of weather factors, soil structure and crop cover. Crop cover and plant residues reduce the irradiance at the soil surface and increase the resistance to heat transfer between soil and atmosphere, thereby reducing the exchange of energy between the atmosphere and the soil. To test whether our quantitative understanding of the soil-plant-atmosphere system is adequate to describe temperature effects of drainage, it is necessary to use a suitable process-based model and to investigate whether the processes can be parameterized to describe observed temperature differences and dynamic energy fluxes during a day under variable weather conditions. The Daisy model system (Hansen et al. 2012) combined with the Sun-Shade Open Canopy (SSOC) module (Plauborg et al. 2010) can be used for this process analysis.

Objective

The objective of this study is to quantify soil temperature in a 2-year field trial with different drainage conditions and investigate whether the observations can be understood and modelled from energy fluxes based on well-known physical relationships and readily available meteorological data. Furthermore, the aim is to test the sensitivity of different descriptions and parameters and thereby to point out the earlier mentioned factors of most importance for the soil surface temperature. The spring period is in focus, because the strongest effect of drainage differences on topsoil temperature may be expected in this period caused by the low plant cover, high global radiation rate, and the highest expected differences in groundwater level.

Materials and Methods

Field experiment

A trial was established in April 2015 in Eastern Denmark (55^{O}40`20`N 12^{O}17`20` E) (Snubbekorsgård, Taastrup) on a loamy sand field with a gradient in drainage conditions. Consisting of two poorly drained plots (PD), defined as close to the wettest conditions possible on farmed land, and two well-drained plots (WD) with drainage conditions equipped with subsurface pipe drains according to recommended prescriptions (depth 1-1.2m, drain spacing 16m)

The field area is 16m wide and 80m long and is orientated with a drainage gradient at the long side. All measurements were carried out in plots at the ends of the field, representing the extremes in drainage conditions, with two repetitions placed with a 10m's distance. A map of the trial area is shown in supplementary material figure B.

Soil profiles and horizon depths from the field were described from soil cores of 8cm diameter driven into the ground by a hydraulic hammer to 1 m's depth. Bulk density was quantified for each horizon from the whole soil core volume (5024cm^3 per core). Samples for soil texture analyses were taken in each horizon and analyzed by the pipette method (SSSA, 2002) as well as for organic matter content by Loss-On ignition method (SSSA, 1996). The deeper soil horizons were described visually by hand drilling to 2m depth.

Soil temperature (T_s) and water potential were measured with a frequency of 1minute in 3cm, 20cm, 40cm, and 70cm depth with a MPS-6 sensor (Decagon Devices, Pullman, WA, USA) during the trial period and logged as average values for each hour. During installation, care was taken to ensure good sensor contact to the soil matrix. The average of the two readings at each depth of temperature and water potential from each plot were used in the analyses. In addition, soil surface temperature was measured in 15 minutes intervals using infrared radiation thermometers, view angle 44^o (Apogee instruments, Logan, UT, USA, model SI-411) installed 0.65m above the surface with a fixed emissivity of 0.97.

Drainage conditions were primarily described measurements of groundwater level and secondly verified by the water potential measurements. The groundwater wells were installed to a depth of 2.1m, with good hydraulic contact obtained by repacking with soil from the respective soil horizons. The pressure transducers (CTD-10,(Decagon Devices, Inc, 2017)) were placed near the bottom of the well. The water level compared to soil surface level was measured and quality controlled by a series of manual measurements. In addition, the water level in the stream situated 27m from the PD plots was recorded monthly to assess the hydraulic boundary condition of the field.

Hourly weather data consists of hourly average values with a measuring interval of 1minute. Air temperature (T_a), air humidity, global radiation, wind speed and precipitation was derived from weather station at the Copenhagen university experimental farm 700m from the experimental field. All weather variables were measured with two replications and compared to ensure data quality. Precipitation of rain and snow was measured hourly at 1.5 m and adjusted for wind effects according to Vejen et al. (2014). The average yearly precipitation at the site is 672mm (DMI, 2018) and measured average temperature for the decade 2000-2010 was 9.1^{o}C at the site. All datalogger time notifications were recorded in local normal time (GMT +1)

Winter wheat (Triticum aestivum) was grown conventionally on the field from the establishment of the trial in spring 2015 and the next growing season 2016, followed by winter seed rape in autumn 2016. Sowing dates were 23/9-2014, 9/9-2015 and 22/8-2016. The soil was ploughed a few days before sowing and power-harrowed just before seeding. Fertilization consisted of 180kgN/ha in total, split in two applications 1/3 medio March and 2/3 mid-April.

The plant cover was monitored through four NDVI-measurements in the spring, with a Skye Instruments "Skye light sensor 2 Channel" calibrated at 647nm, 799nm peak bandwidth and 12, 13nm, measuring an area of 0.66m^2 with approximately 20 repetitions per plot in 24 plots. Cover of plant residues was noted after harvest. NDVI-measurements were converted to LAI-values using the relation by Tanaka et al. (2015).

Model setup

The DAISY model described by Hansen et al. (2012) was used to model T_s based on the hourly measured weather data in whole trial period. The model was selected because it contains descriptions of crop growth and Leaf Area Index (LAI) development, interactions with soil water, soil water movement (Richards equations) and the optional module SSOC (Sun Shade Open Canopy model) that calculates the energy fluxes. The module is described in details by Plauborg et al. (2010). The SSOC module was originally developed to describe the exchange of gasses and energy between the soil surface, the canopy and sunlit and shaded leaves, respectively. Hence, the model includes the soil surface energy balance equation (1) divided into the soil, sun- and shaded leaves, making it possible to describe temperatures in the spring situation of low and increasing plant cover.
The reference evapotranspiration was calculated using the FAO-Penman-Monteith-equation modified by Allen et al. (2006) on hourly weather data, following the crop coefficients suggested by Kjaersgaard et al. (2008).

Model setups were implemented for the WD and PD sites, respectively. The soil parameterizations were based on the horizons identified from the performed field profile descriptions. Measured texture, organic matter and bulk density were used to describe the different horizons (Table 1). Below 1m's depth the estimated texture, based on field observations, was used, and the organic matter content in the soil was reduced to 0.2%. From 160cm and deeper, the bulk density was increased due to calcareous subsoil (glacial deposits) which is common on the location for this soil type. The lower boundary of the soil columns was defined at 600cm depth. The top of the soil column was given a fine discretization of soil layers than the deeper layers. The discrimination of soil layers are as follows 0-5cm 0.5cm, 5-10cm 1cm, 10-50cm 2cm, 50-100cm 5cm and 100-600cm 10cm.

The hydraulic properties were estimated using the pedotransfer function HYPRES (Wösten et al., 1999) Macropores were included (macro default) and parameterized as recommended by Nielsen et al. (2010). The hydraulic lower boundary conditions were set as aquitard with an underlying aquifer pressure.
For the WD site, tile drains were added at a depth of 1.1m and the modelled location situated 1.5m distance from drain. Hooghoudts equation was used to describe water pressures related to the distance to the drain Mollerup et al. (2013) in the 1D setup. No drains were included at the PD site. The aquifer boundary pressure was estimated based on monthly measurements of water level in the stream close to the PD end of the field trial and adjusted with a slope of 5‰ from the stream in the WD end during the calibration process. Aquitard conductivity and the description of the tile-drains were used to calibrate the drainage conditions supported by the groundwater measurements.

The parameterization of the lower thermal boundary condition was established based on a Fourier analysis of local monthly T_a from 2010-16 (Table 1) and converted to the lower boundary T_s by the model Hansen et al. (1990).

Table 1 Yearly air temperature parameters used to calculate lower boundary temperatures for the experimental farm at Taastrup.

Parameter	New 2000-2010	Old 1962-1990
Average yearly air temp	9.1	7.8
Temperature amplitude	8.0	8.5
Julian Day Number with max temperature	224	209

The crop management description consisted of dates and types of soil tillage, sowing, harvest and N application in the trial period and from 2009 to 2015 prior to the trial period, serving as an initialization period.

The roughness height of bare soil is part of the aerodynamic conductance influencing the sensible heat flux. It was investigated in the range of 0.2-0.02m to test the impact of different soil structures derived from soil tillage. This analysis showed limited impact on soil surface temperatures and a value of 0.02m was used.

Results and discussion

Soil profiles

Texture data from the experimental field is shown in Table 2. The textural and density differences between the well drained (WD) and poorly drained (PD) plots were generally small even though the poorly drained site was texturally coarser in the B and top C horizons (-45cm to -100cm). The whole field had a dense lower C horizon with higher clay and silt content. Modelled hydraulic properties are standard HYPRES. However, to reflect measured soil moisture data two compacted soil horizons were defined (plow- and harrow-pans) and re-parameterized with reduced hydraulic conductivity. Furthermore, the uppermost soil layer, the soil crust, was given a higher bulk density due to suspected rainfall impact resulting in less structural stability.

Table 2 Hydraulic conductivity, texture and bulk density Data obtained by laboratory-measurements are shown in black and measurements/estimations were done in situ are shown in green ("--II--" value as row above).

	Horizon	K sat	Bulk density	Clay	Silt	Silt	Fine Sand	Coarse sand	Org. Content
Poorly drained		cm/h	Mg/m3	< 2um %	2-20um %	20-50um %	50-200um %	200-2000um %	%
Ap	0-4cm	Hypres	1.6	7	15	9	31	35	3.7
harrowpan	4-6cm	16% of Hypres	1.6	--II--	--II--	--II--	--II--	--II--	--II--
Ap	6-20cm	Hypres	1.35	--II--	--II--	--II--	--II--	--II--	--II--
Ap	20-26cm	Hypres	1.49	--II--	--II--	--II--	--II--	--II--	--II--
Plow pan	26-32cm	1% of Hypres	1.6	--II--	--II--	--II--	--II--	--II--	--II--
E	32-47cm	Hypres	1.68	8	8	6	43	33	0.9
B	47-81cm	Hypres	1.83	7	7	5	46	35	0.4
C	81-100cm	Hypres	1.87	3	3	1	23	70	0.2
C	100-180cm	Hypres	1.87	8	3	1	23	65	0.2
C	180-300cm	Hypres	1.97	23	17	10	29	22	0.2
Better drained									
Ap	0-4cm	Hypres	1.6	8	17	9	27	35	3.5
harrowpan	4-6cm	1% of Hypres	1.6	--II--	--II--	--II--	--II--	--II--	--II--
Ap	6-15cm	Hypres	1.44	--II--	--II--	--II--	--II--	--II--	--II--
Ap	15-26cm	Hypres	1.59	--II--	--II--	--II--	--II--	--II--	--II--
Plow pan	26-30cm	10% of Hypres	1.59	--II--	--II--	--II--	--II--	--II--	--II--
E	30-45cm	Hypres	1.73	11	20	12	27	29	0.9
B	45-80cm	Hypres	1.83	22	18	8	22	29	1.1
C	80-100cm	Hypres	1.87	17	19	8	24	33	0.5
C	100-160cm	Hypres	1.87	17	19	8	24	33	0.2
C	160-300cm	Hypres	2.07	--II--	--II--	--II--	--II--	--II--	--II--

Measured soil temperatures (T_s)

Soil temperature differs significantly from air temperature

Air temperature and temperature measured in the topsoil were very dynamic and expectedly closely connected to weather conditions. An example of this is shown in Figure 1 for a spring situation 2016. An overview of the measured temperatures is presented in Table 3 as monthly averages of temperature and monthly averages of daily maximum and minimum values. Surface temperatures were only measured in the later part of the experiment to test the linkage to the measurements of T_s (-3cm).

Figure 1shows that $T_{s,}$ at 3cm depth ($T_{s\ 3cm}$) was higher and differed considerably from T_a in spring, even on the cloudier days. High radiation on sunny days increased the difference between T_a and $T_{s\ 3cm}$ due to the larger energy input. The mean monthly T_s were generally higher than mean monthly T_a during summer and especially spring in this study (Table 3, columns 4, 5 and 6). This difference peaked in April, which is characterized by increasing net radiation and low plant cover.

The fact that the soil surface layer temperature is different from the T_a shows that detailed studies of process near the surface can be improved by the use of surface temperatures (measured or simulated) instead of air temperatures.

Drainage effect on temperatures

T_s were affected by the drainage conditions in the field. The Soil Temperature Drainage Effect (STDE) was defined as the difference between the soil temperature measured in WD and PD plots, respectively. The average daily maximum temperatures were higher, and the average daily minimum temperatures were lower on the WD soil. The whole day average temperature showed less difference, but STDE tended to be positive during the warmup period in the spring and negative during the cooling period in the autumn (Table 3; column 7, 8 and 9). The STDE showed large variations (Figure 1) and was usually positive during the day, peaking at midday with the highest temperatures and negative during the night. The opposite negative STDE are also found in periods characterized by generally falling temperatures. The STDE strongly indicate a lower thermal diffusivity (conductivity divided with heat capacity) in the WD plots with lower soil water content.

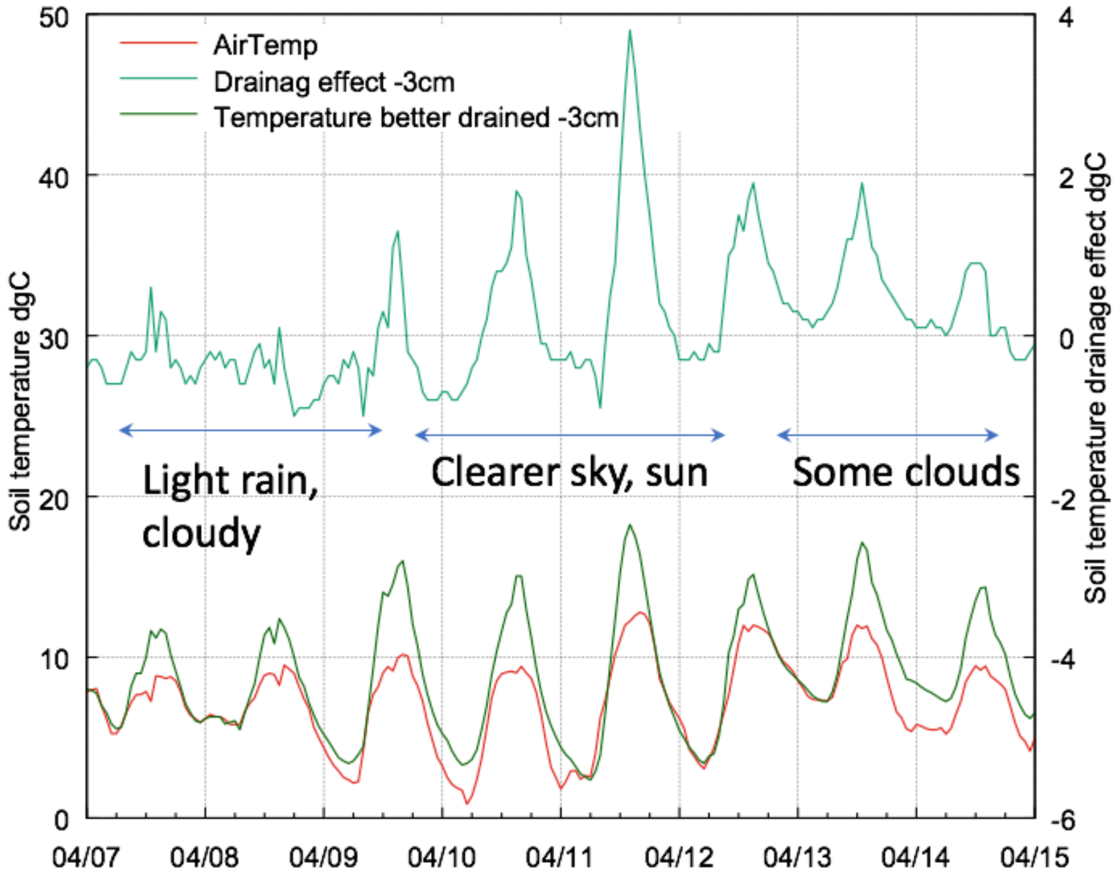

Figure 1 Measured soil- (-3cm) and air-temperatures spring 2016 WD and PD plots. Drainage effect on soil temperatures (STDE)(-3cm).

The highest positive STDE was found in the months with partly bare soil, and low plant cover particularly in the spring and early autumn (September). The STDE´s were most pronounced close to the soil surface in -3cm but propagate to -20cm, -40cm and -70cm (three latest not shown) though with a lower amplitude.

The temperature distribution in the deeper soil layers is found in Table 3; column 10, 11 and 12. Expectedly the yearly amplitude of these temperatures decreased with depth, and the maximum temperature occurred later with increasing depth.

Table 3 Measured monthly averages and average daily minimum and maximum soil- and air Ts and STDE (Soil Thermal Drainage Effect) in different depths (April 2015 - may 2017). Relatively larger differences or of particular interest for the study is marked with red.

	Air T	Air T	Air T	Diff SoilT and airT	Diff SoilT and airT	Diff SoilT and airT	STDE	STDE	STDE	Soil temp	Soil temp	Soil temp
	avr	avr max daily	avr min daily	avr	avr max daily	avr min daily	avr	avr max daily	avr min daily	avr	avr	avr
Soil depth				3cm	3cm	3cm	3cm	3cm	3cm	20 cm	40 cm	70 cm
Jan	0.6	2.5	-1.6	0.2	-0.9	1.6	-0.3	0.1	-0.8	1.5	2.3	3.4
Feb	2.2	4.0	0.2	0.1	-0.1	0.9	-0.1	0.6	-0.6	2.6	2.9	3.5
Mar	4.0	7.1	1.2	1.0	2.5	0.8	-0.1	1.3	-1.1	4.9	4.6	4.8
Apr	7.0	10.4	3.5	1.5	4.0	0.9	-0.1	1.1	-1.0	8.5	7.6	8.1
May	11.8	15.6	7.3	1.2	1.4	2.3	0.1	0.9	-0.6	12.4	12.2	10.9
Jun	15.0	18.4	10.9	1.1	0.7	2.6	0.1	0.5	-0.3	15.5	16.1	13.9
Jul	16.8	20.2	12.8	1.0	0.5	2.5	0.0	0.4	-0.5	17.3	16.8	15.9
Aug	17.2	21.1	12.8	0.3	0.1	1.7	-0.1	0.6	-0.6	17.3	16.5	16.3
Sep	15.1	18.5	11.5	-0.3	2.1	2.0	-0.1	1.1	-0.8	15.4	15.0	15.3
Oct	9.3	11.5	7.0	-0.6	0.1	-0.3	-0.6	0.5	-1.2	9.9	10.5	11.3
Nov	5.8	7.9	3.4	-0.3	-1.0	0.6	-0.6	0.1	-1.3	5.9	6.7	7.7
Dec	5.6	7.4	3.5	-1.0	-1.4	-0.4	-0.2	0.5	-0.9	5.0	5.4	6.1

Drainage conditions and parametrization

The measured groundwater levels modeled fit of the WD and PD plots are shown in Figure 2 as indicators of the drainage conditions. An example of the pressure potential (a spring period) in the top soil layers is given in Figure 3. The groundwater level and pressure potential differed between the WD and PD sites.

Groundwater levels are a sensitive measure which can fluctuate much even during small changes in soil water. Thus, the simulated groundwater levels are considered suitable as lower boundary condition for the simulations and in this perspective to correspond fairly well to the measurements.

The drying of the top soil and the drainage related difference in soil water content (Soil Water Drainage Effect SWDE) were relatively well described by the model, but the extent of drying was underestimated by the model. This was the case even though the original model setup of the soil hydraulic properties were modified during the work process to ensure that the water content, particularly in the top layers in spring, corresponded to measurements. Realistic changes introduced included equipping the A-horizon with a denser soil crust and introducing a plough- and harrow-pan with lower hydraulic conductivity to decrease capillary rise of water, see Table 2. The harrow pan should mimic the difference between the harrowed seedbed and the soil just below.

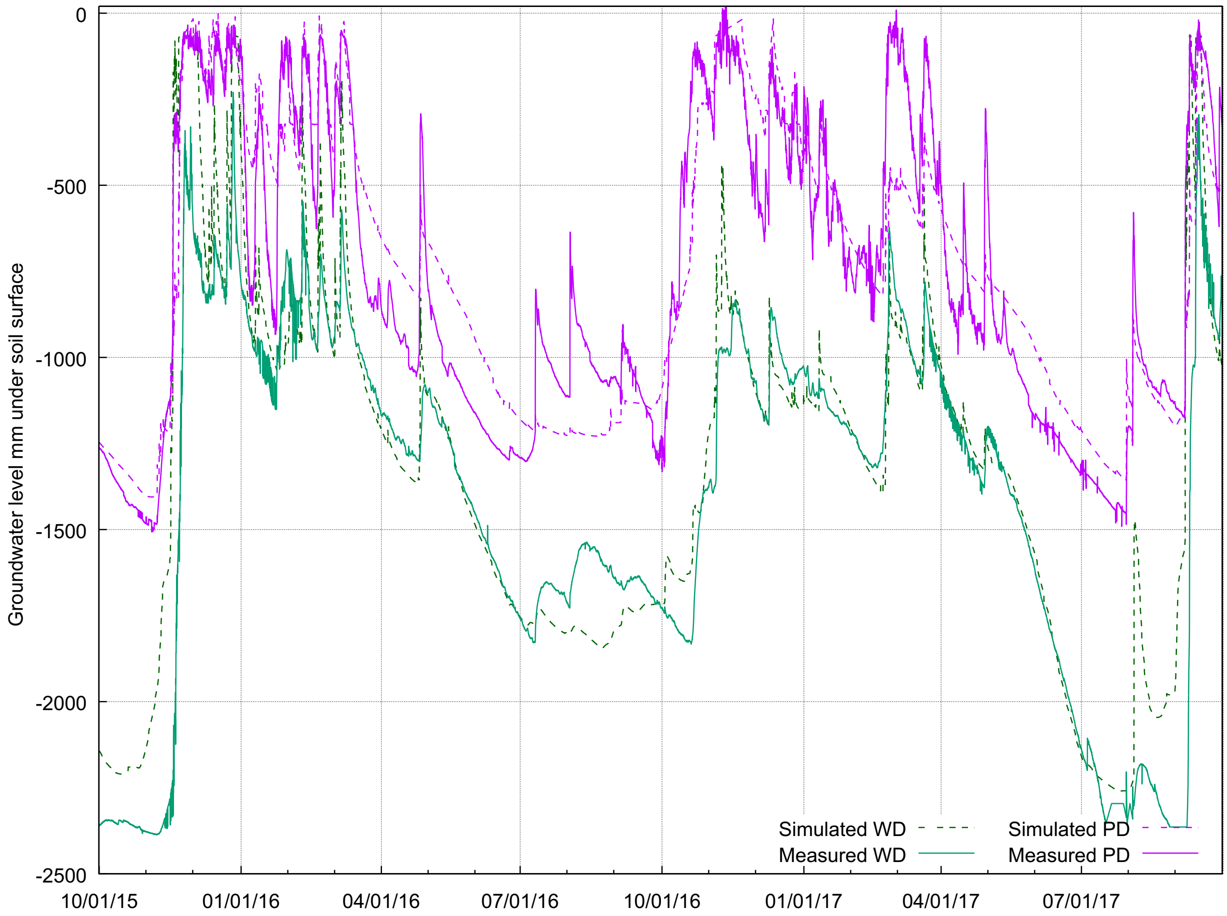

Figure 2 Measured (full drawn line) and simulated (dotted line) hourly groundwater levels (mm under soil surface) for the two different drainage conditions (Well drained WD and Poorly drained PD) from spring 2015 to spring 2017.

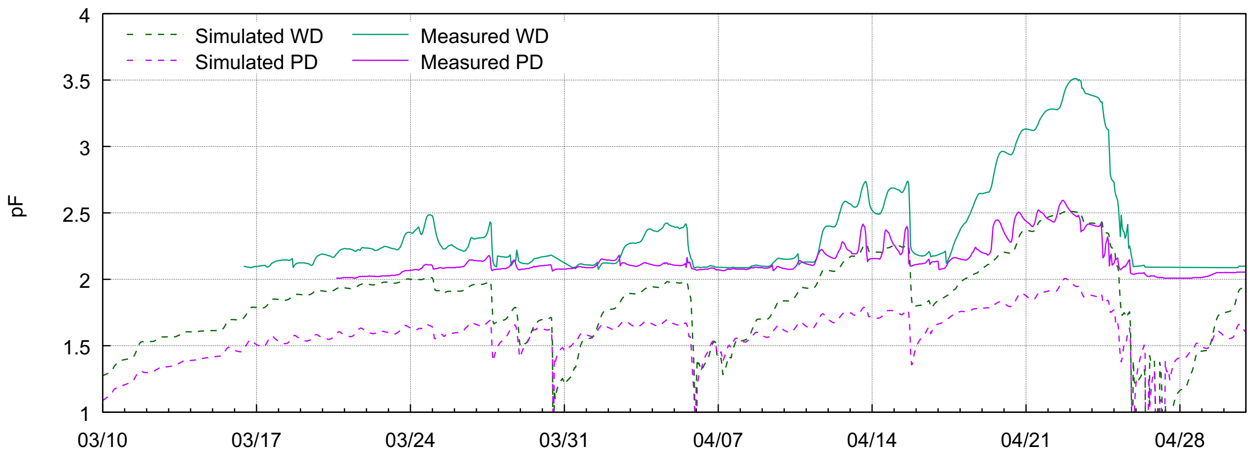

Figure 3 Soil water pressure potential (pF units) measured (full drawn lines) and simulated (dotted lines) hourly at 3 cm depth in March, April and May 2016 for WD and PD plots. The detection limit of the sensor is pF 2 which is therefore the minimum of the measured values.

As soil water content has a great influence on the thermal properties of the soil horizons, a good description of moisture conditions/soil water conditions is indispensable. The relatively good hydraulic model description obtained was considered a good basis for an analysis of the effect of drainage differences on energy fluxes (Soil Surface Energy Flux Drainage Effect, SSEFDE).

Crop measurements and parametrization

Crop growth and crop cover had a significant influence on the temperature and energy flux description. A solid model fit to the measured LAI and crop height is therefore required. The crop thermal response has been parameterised on the basis of the measured T_s and LAI to meet the demand given by the sensitivity to the crop factor. Measured LAI (converted form NDVI) and simulated LAI is shown in Figure 4 a, b.

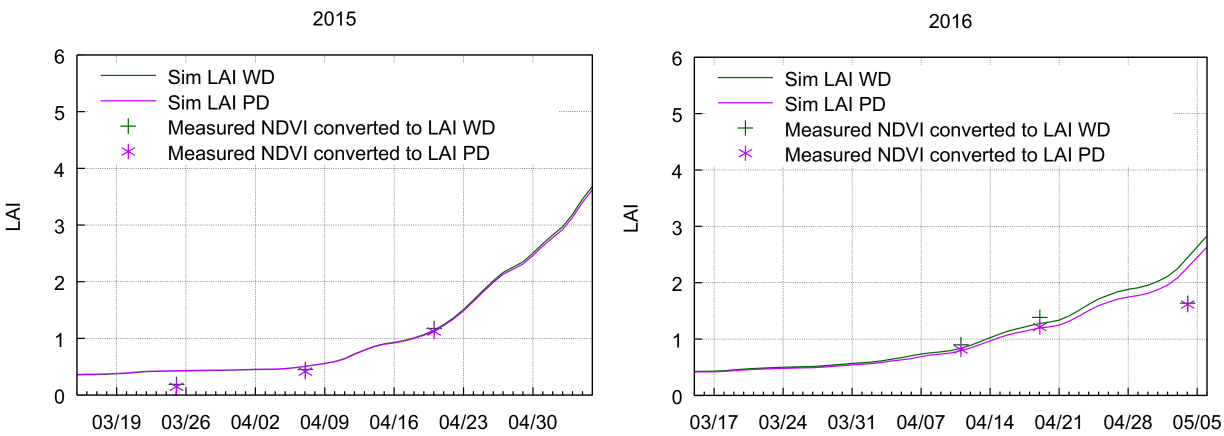

Figure 4 a and b Measured (+) and simulated WD (green) and PD (purple) LAI from Spring 2015 and 2016, 15/3-6/5.

Energy fluxes

Energy fluxes and temperatures are modelled and parametrized on basis of the measured temperatures.

An example of the temperature fit and the energy fluxes are shown in the appendix figure A and the SSEFDE in Figure 5. Simulated temperatures reflect the measured temperatures in terms of level, fluctuations and STDE.

Measured STDE are reflected by the modelled energy fluxes showing higher soil heat flux during daytime (red line), despite a higher sensible heat flux (green line) and lower net-radiation (yellow line) on the WD plots. The deviations basically originate from a lower energy consumption on evapotranspiration (ET) (blue line) (Figure 5). Measured drainage temperature effect is well timed which the SWDE both in terms of water content and -potential and simulated SSEFDE (Figure 5). The effect is illustrated in Figure 5 showing a period with close to equal soil water contents and -potentials in the two plots due to rainfall before the shown period (weather conditions previously described in Figure 1) resulting in no STDE and SSEFDE. In the following days (from 9/4) the weather gets sunnier without precipitation and underlying drainage conditions resulting in faster drying up of the top soil in the WD plots. This results in a clear STDE outcome of the SSEFDE. Hence, the simulated energy fluxes respond well in timing to the weather and soil water conditions, and it´s feasible to consider a longer period with daily sums of the energy fluxes, which results in figure 6.

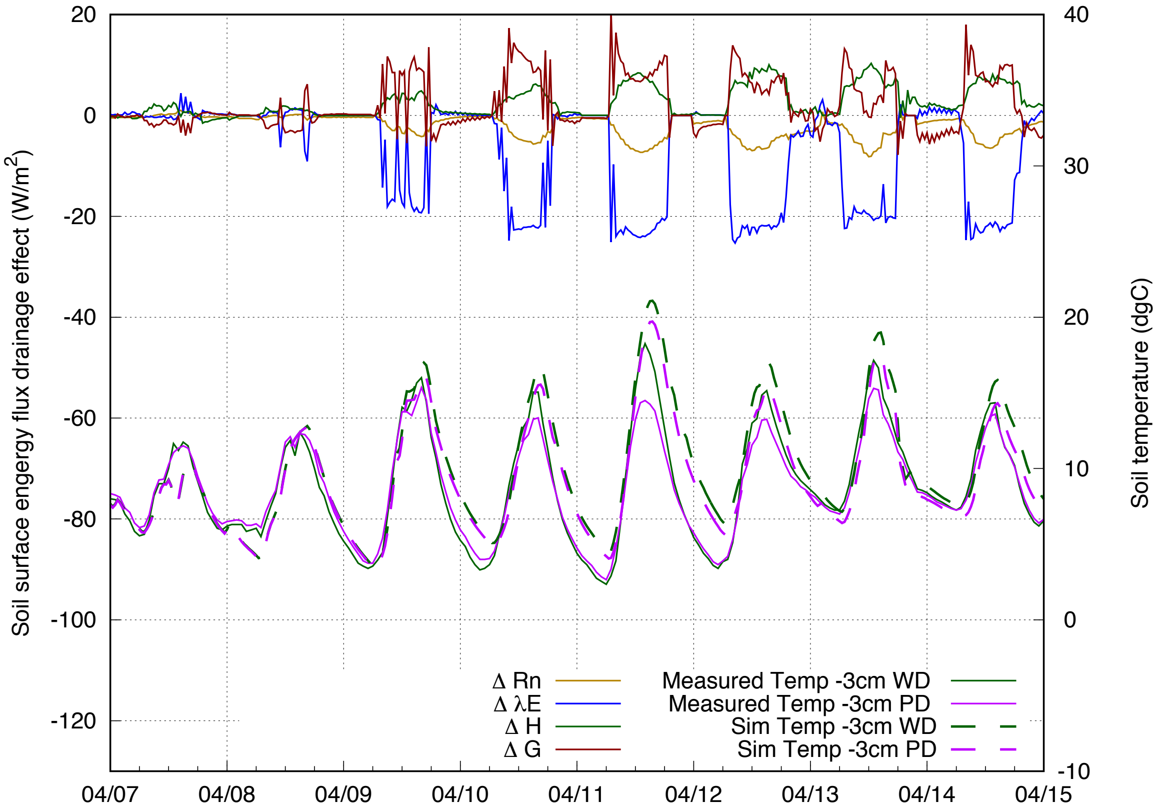

Figure 5 Measured upper soil layer temperatures (-3cm) and simulated soil surface drainage effects on energy fluxes (SSEFDE), hourly values from April 2016. Results from iterations with no solution in the numerical model are removed (three hours).

Drainage effects on energy fluxes

The SSEFDE are summed up monthly in Table 4. Figure 6 represents part of the trial period (spring 2016) and focus on the link between drainage effect on soil water content, SSEFDE and STDE.

As seen in Figure 5 the spring is characterized by periods of lower energy use on ET in the WD plots, leaving more energy to soil heat flux during daytime and higher sensible heat flux to the atmosphere due to the higher surface temperatures. The average day-time STDE are highest in March (0.68ºC) and April (0.76ºC) which is seen as high values of G and λE during increasing net radiation (Rn) which is seen in Table 4 and Table 5. The STDE's are decreasing in May due to increasing LAI (Figure 4) and effects of the canopy on the energy fluxes.

Table 4 Daytime monthly simulated soil surface energy fluxes and corresponding drainage effect (SSEFDE) in combination with Soil thermal drainage effect (STDE) average 2015-2017.

	SSEFDE				Sim STDE
	Rn	G	H	E	
Month	W/m^2	W/m^2	W/m^2	W/m^2	dgC surface
Feb	-0.6	0.0	0.9	-1.0	0.19
Mar	-2.9	3.6	2.9	-8.6	0.68
Apr	-1.7	3.8	4.1	-9.3	0.76
May	1.0	0.4	1.7	3.2	0.05

Table 5 Monthly daytime average Soil surface energy fluxes well drained (WD) 2015-2017 (W/m^2)

	Rn	G	H	E
Feb	59.0	25.4	10.9	22.7
Mar	112.0	52.3	31.0	28.7
Apr	171.9	54.8	66.2	51.0
May	211.2	32.6	66.5	112.2

The simulated drainage effect on temperature (STDE), energy flux (SSEFDE) and soil water content (SWDE) reflected the measured data and showed reasonable correspondence. The modelling, combining all data on drainage conditions (soil water content), plant growth and detailed weather thereby provide an explanation of the measured T_s under the two differently drainage conditions plots.

The importance of different describing factors for T_s sensitivity and uncertainties are discussed in the following sections divided into components of the energy equation (Equation 1).

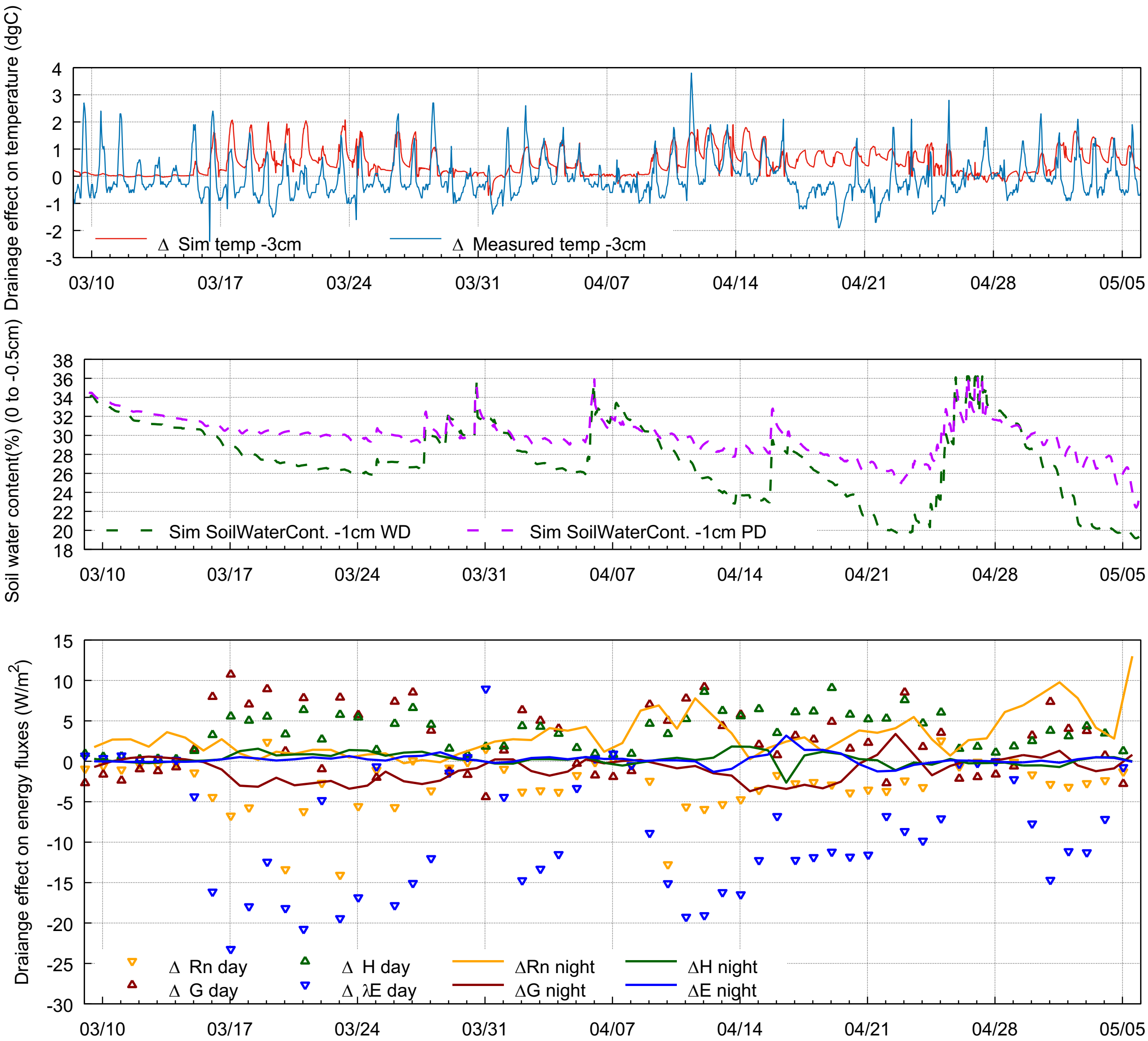

Figure 6 from top a, b and c. Measured and simulated drainage effects on soil temperature (STDE) (–3cm). Daily average drainage effects on energy fluxes (SSEFDE), divided in day-time and night-time 2016 and soil water content in top soil layer (o to 0.5cm).

Radiation

Higher surface T and lower soil water content in the WD plots affects the Rn (Figure 5 and Figure 6). Higher temperature lead to the higher emission of longwave radiation. The shortwave reflectance increases at lower water contents resulting in lower absorption of shortwave radiation at the soil surface and thus lower Rn. Emissivity is also connected to soil water content and decrease at lower water contents. Soil water content related reflectance and emissivity of the soil was therefore included in the model based on descriptions by Mira, (2007) and Bowers and Hanks, (1965). All reflectance values were introduced as a piecewise linear function (PLF) of pF. The applied reflectance coefficients are shown in Table 6.

The drainage effect (WD minus PD) on radiation in spring 2016 is shown in Figure 7.

Table 6 Reflectance and emissivity function (PLF) of pF

DAISY parameters	Reflectance		Emissivity
pF	PAR %	NIR %	
0			0.975
1	2.5	11	
1.65			0.968
2	4.0	17	
3	5.0	22	
4	6.5	27	
5	9.0	31	0.947
6	11.0	34	
7			0.94

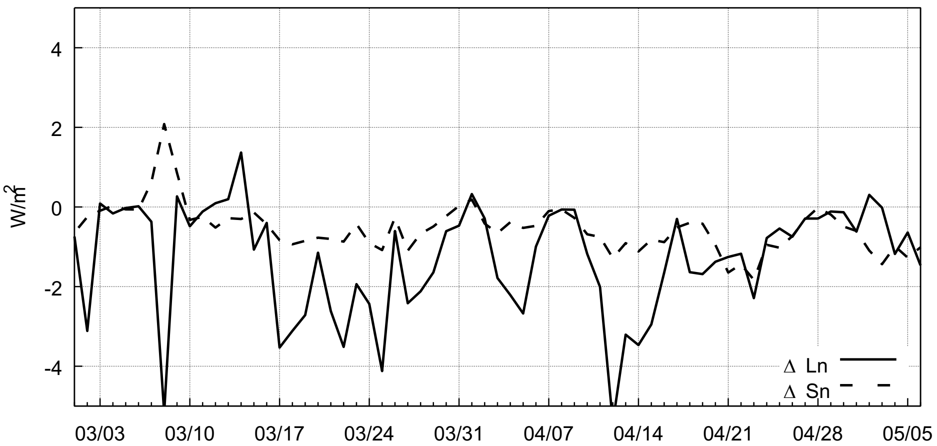

Figure 7 Drainage effect (The difference between radiation components on the well and poorly drained plots in spring, (WD minus PD) on short- (Sn) and long-wave (Ln) components in net radiation (Rn), daily values spring 2016.

The description of the surface temperature and distribution of energy between components was found very sensitive to crop cover, and therefore a good simulation of the development of LAI during spring was necessary. This is supported by the SSOC-module in DAISY which divides net radiation into three components representing the areas covered by soil, sun and shaded leaves, as described under "model setup".

As LAI increases exponentially in the spring the radiation and direct energy input to the soil surface are reduced equally fast. LAI, therefore, have considerable influence on the STDE which can be seen in the table as low STDE under high LAI in May.

Soil heat flux

Soil heat flux (G_{soil}) depends on thermal conductivity and the temperature gradient at any given time and depth. The calculation of these terms by the DAISY model is based on the content of mineral and organic constituents and most important the content of moisture (and ice) Hansen et al. (1990). Hence, the temperature description relies on a well-described hydrology, especially in the top soil layers.

The hydraulic parameters are notoriously dynamic in the top layers of the soil due to soil tillage, rainfall impact and frost-thaw cycles affecting soil structure. The application of fixed hydraulic parameters, therefore, causes some issues which can be seen in the results. From Figure 6 it´s seen that the negative STDE during night time was not reproduced in the modelling results and the maximum STDE at midday was less in the simulations than observed.

The measured trait of higher daily temperature amplitude (STDE) in spring under WD conditions was found to be a general characteristic in this study (Table 3). This strongly indicates that soil thermal diffusivity depends on the specific drainage conditions in this trial. Since all other remaining parts in the energy equation (Rn, H and E) (Equation 1) counteracts STDE at night time, the most likely explanation to a negative STDE is lower thermal diffusivity at the WD plots affecting the soil heat flux. The difficulties describing the soil thermal diffusivity in the model is addressed to the following main limitations of the model. The use of the Richards equation in the top soil layers is close to the limit of the application when the roughness of the soil surface is larger than the discretization and soil structure changes over time. Also the level where evaporation takes place moves deeper into the soil during soil drying events. The explanation for the over-estimation of the thermal diffusivity in the model is therefore likely to be found in the description of the hydraulic and thereby thermal properties in the top soil layers. Figure 3 shows that the water pressure at 3 cm depth was overestimated by the model, which supports this assumption and emphasizes that a good description of energy fluxes requires very detailed descriptions of the hydraulics in the top soil layers.

The description of thermal diffusivity seems less challenging in the deeper soil layers. Figure 8 shows a good compliance between measured and modelled T_s in deeper layers. However, discrepancies were present in periods represented by frost or when the soil was covered with plant residues in the autumn. Those conditions were not analysed further in this study.

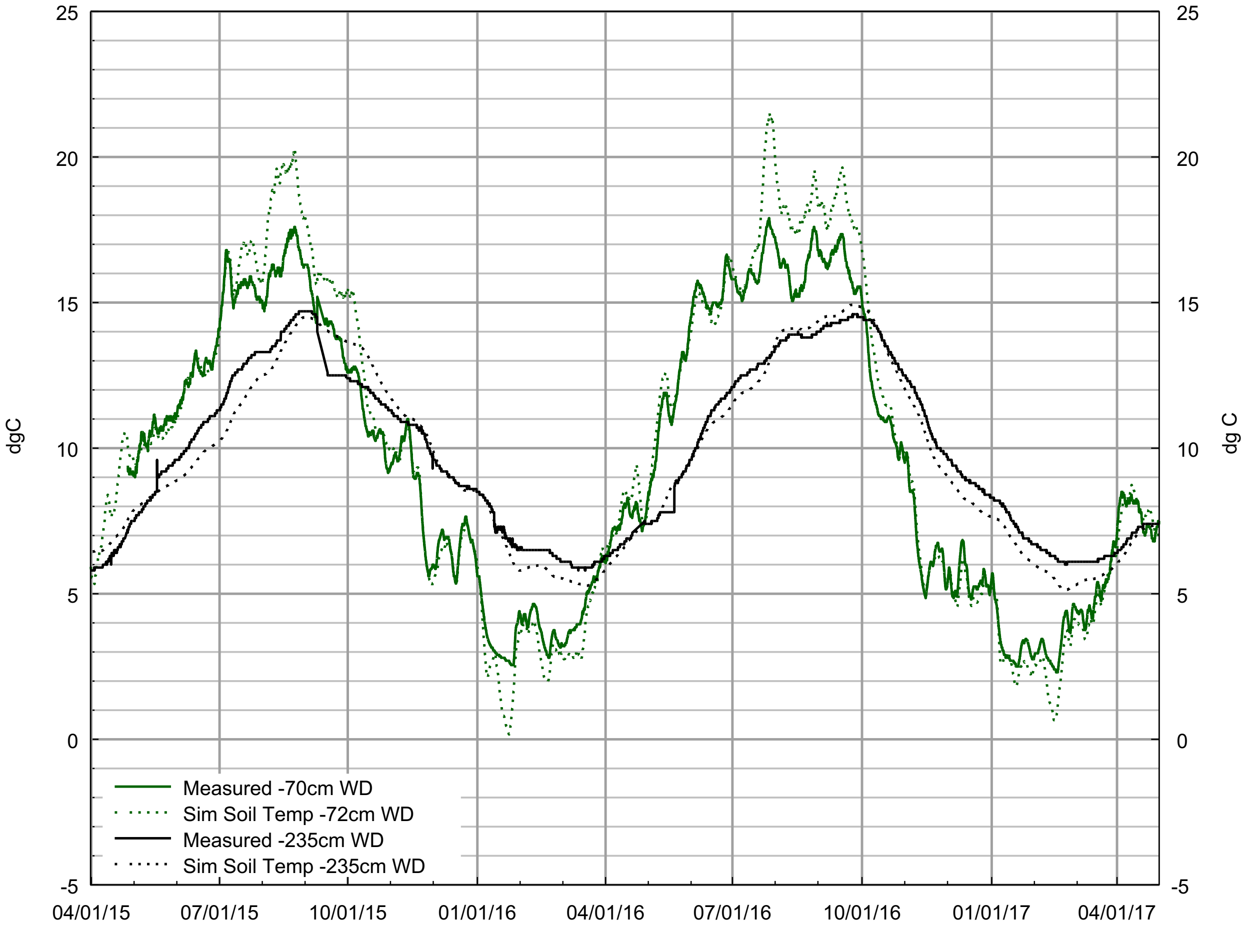

Figure 8 Measured and simulated soil temperatures and yearly dynamics in deeper soil layers on well drained (WD) plots (-70 and -235cm).

Lantent heat flux and evapotranspiration (ET)

On the basis of the hourly weather data the distribution of evaporation from the soil surface and transpiration from the plants were calculated as the latent heat flux from the surfaces.

The evaporation from the soil is of particular interest because a significant part of the energy input is converted to latent heat (Table 4). The modelled STDE also primarily derived from a smaller latent heat flux due to lower soil water content in the WD plots (Figure 5 and Figure 6). The drainage related differences in soil evaporation and sensitivity to limitation of evaporation when drying is therefore essential. The potential evaporation from bare soil is estimated with a fixed factor (0.65 (Plauborg, 1995)) multiplied on the reference ET and is further limited by the ability of the soil to supply water from deeper layers to the surface under drying. This limiting function is termed exfiltration. The use of the default SVAT model lead to overestimation of the evaporation from the soil surface. A reduction of the default exfiltration was therefore necessary to improve the description of the soil surface temperature and the STDE. This was expected since the use of Richards equation in the top soil layers have limitations related to dynamic and rough soil- and surface-structure, similar to the issues described under soil heat flux. It also illustrates the problems of a model concept consisting of evaporation from a “surface point”. Evaporation may take place deeper in the soil when soil dries. Reference ET could also be underestimated in spring due to raising soil temperatures and related issues of estimating net radiation.

Sensible heat flux (to the atmosphere)

The sensible heat flux primarily acts as a moderating part of the energy equation on the STDE, since it´s driven by the temperature gradient between surface and atmosphere, and more extreme temperatures are present in the WD plots both during day- and night-time due to previously mentioned SSEFDE on soil- and latent heat flux. The aerodynamic conductance is a key parameter in the calculation of both sensible and latent heat fluxes (model described by Plauborg et al., (2010) and in the supplementary section). It depends on agrometeorological parameters and the canopy parameters vegetation height (h_{veg}), Leaf Area Index (L_{ai}), and the mean leaf width. The canopy properties are therefore very important regarding the convective heat transfer between the soil surface and the atmosphere since a growing canopy changes the aerodynamic conductance. The observations was confirmed by the modelling showing high sensitivity to the canopy development, and STDE´s are therefore most prominent in March and April. Finally, the observations support the hypothesis that an integrated plant, atmosphere and soil model is a prerequisite when modelling temperatures and STDE in at the field scale.

Conclusions

Results from a two-year field trial clearly illustrated limitations in the common use of air temperature (T_a) as upper boundary for calculations of soil temperature (T_s), particularly during the spring period characterized by low plant cover and warm-up of the soil. On a monthly basis, daily average soil surface temperature (at 3cm depth) was up to 1.5ºC higher, and monthly averages of the daily maximum T_s up to 4ºC higher than the corresponding T_a at 2.0m height. Drainage conditions had clear effects on average soil surface temperatures as well as daily temperature fluctuations. The daily maximum and minimum temperatures were significantly higher under well-drained soil conditions. Soil surface temperatures and T_s at greater depths including differences due to drainage conditions could be satisfactorily modelled. The temperature effect of drainage derived primarily from differences in evaporation. The modelling showed great sensitivity to soil water content in upper soil layers as affected, e.g. by different groundwater levels or soil hydraulic properties, and to leaf area index.

Drainage effects on thermal diffusivity were underestimated in some spring periods most likely due to overestimation of soil water content, interacing with the dynamics of the evaporation description. A more detailed description of soil evaporation and top soil hydraulic properties should, therefore, be the next step towards better modelling of soil temperatures.

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Supplementary material:

Equations of particular interest applied by the SSOC-model in Daisy.

Energy fluxes and radiation:

On a bare soil, the energy exchange between atmosphere and soil is determined by net radiation and the aerodynamic resistance, but as plants start to grow, the amount of energy absorbed in leaves, the moisture exchange through stomata and the leaf surfaces to the intra-canopy space play an increasing role in determining the soil surface temperature. The following equations represent the energy balances of the soil, the sunlit and the shaded leaves, respectively:

$$R_{abs-soil} - L_{o-soil} = G_{soil} + H_{S\rightarrow c} + \lambda E_{S\rightarrow c}$$
$$R_{abs-snl} - L_{o-snl} = H_{snl\rightarrow c} + \lambda E_{snl\rightarrow c}$$
$$R_{abs-shl} - L_{o-shl} = H_{shl\rightarrow c} + \lambda E_{shl\rightarrow c}$$

Where

- R_{abs} is the absorbed radiation, [W m^{-2}]
- L_o is the outgoing longwave radiation [W m^{-2}]
- λE is the latent heat flux (water vapour) [W m^{-2}]
- H is the sensible heat flux [W m^{-2}]
- G_{soil} is the ground heat flux at the soil surface [W m^{-2}]

The absorbed radiation comprises incoming short wave as well as long wave radiation. The absorbed short-wave radiation consists of absorption of direct and diffuse radiation in the photosynthetically active area (PAR) and the near infrared area (NIR) and depends on the soil surface reflectance (ρ_s) in the respective domains. The amount of shortwave radiation absorbed by the soil can be calculated for the PAR and NIR areas as:

$$I_{abs-soil} = I_d\left(1 - \rho_{d,c-s}\right) + I_b\left(1 - \rho_{b,c-s}\right) - I_{abs-can}$$

Where

- $I_{abs-soil}$ and $I_{abs-can}$ are shortwave radiation absorbed by the soil and canopy, respectively
- I_d and I_b are the diffuse and direct beam shortwave radiation, respectively

- $\rho_{d,c\text{-}s}$ and $\rho_{b,c\text{-}s}$ are the diffuse and direct beam canopy-soil reflectance, respectively. For bare soil, these values equal the soil surface reflectance. In case vegetation is present, their values also depend on leaf absorptance, sun elevation angle and leaf area index.

The amount of absorbed longwave radiation is proportional to the area not covered by vegetation:

$$L_{abs-soil} = (1 - f_{can})L_i$$

The total amount of absorbed radiation equals the absorption in the two shortwave and the longwave ranges:

$$R_{abs-soil} = I_{abs-soil}^{PAR} + I_{abs-soil}^{NIR} + L_{abs-soil}$$

The absorbed net radiation for the soil equals the absorbed radiation minus the outgoing long wave radiation which can be written as:

$$L_{0-soil} = (1 - f_{can})\varepsilon_s \sigma (T_a + (T_s - T_a))^4$$

Where

- F_{can} is the fraction of soil covered by vegetation,
- ε_s is soil emissivity
- σ is Stefan-Boltzmann constant [5.67 * 10^{-8} W $m^{-2}K^{-4}$]
- T_a is the air temperature [K], and
- T_s is the soil temperature.

The important governing parameters in the radiation balance for soil are therefore the soil surface reflectance and the emissivity.

The aerodynamic conductance:

Both latent heat and sensible heat is transported from the soil surface to the canopy and further out in the atmosphere. The aerodynamic conductance is in both cases dependent on vegetation height (h_{veg}), Leaf Area Index (L_{ai}), wind speed (u_z), air temperature [K]. The conductance for heat transport from the soil to the canopy also depends on the mean leaf size and can be expressed as:

-
- $g_{soil}^{H} = 0.004 + 0.012u_s$
- $u_s = u_c \exp\left(-a\left(1 - \frac{0.05}{h_{veg}}\right)\right)$

- $$a = 0.28 L_{ai}^{2/3} h_{veg}^{1/3} l_m^{-1/3}$$

Where

- g_{soil}^{H} = the conductance for heat transport between the soil surface and the height of the canopy [ms-2]
- u_s is the wind speed characterizing conditions in the canopy air space just above the soil surface [ms-1]
- u_c is the wind speed at the top of the canopy [ms-1], which also is dependent on vegetation height as well as the soil and air temperatures.
- h_{veg} is the vegetation height [m]
- L_{ai} is the leaf area index and

l_m is the mean leaf size [m], calculated as four times the leaf area divided by the perimeter.

The weather data are provided as input, and leaf area and vegetation height at any time are generated by the plant growth model in Daisy.
In addition the leaf width is important for the calculation of leaf boundary layer conductance for heat and water vapour, due to free convection. This parameter has to be specified for the crop on the field:

$$g_{lbf}^{H} = D_h \left(\frac{\sqrt[4]{g w_l^3 v^{-2} (T_l - T_a) T_a^{-1}}}{w_l} \right)$$

$$g_{lbf}^{w} = \begin{Bmatrix} 0.5 g_{lbf}^{H} \left(\frac{D_w}{D_h} \right) & hypostomotous\ leaves \\ g_{lbf}^{H} \left(\frac{D_w}{D_h} \right) & amphistomatous\ leaves \end{Bmatrix}$$

Where

- w_l is the leaf width, m
- T_l is the leaf temperature of sunlit or shaded leaves
- v is the molecular viscosity
- g is acceleration due to gravity.

Dw and D_h are diffusion coefficients [m^2s^{-1}] of water vapour and heat respectively.

Calculation of lower thermal boundary

Eq. (5-44) from (Hansen et al., 1990) is used to calculate the lower thermal boundary from the Fourier series of monthly air temperatures.

$$T(t, z) = T_{av} + A_t e^{-z/d} \cos(\omega(t - t_0) - z/d) \qquad (5-44)$$

$$d = \left[\frac{2K_h}{C_s \omega} \right]^{1/2}$$

d is the damping depth.

Eq. (5 − 44) is used as a lower boundary condition with

T_{av} = annual average of air temperature [°C]
A_t = amplitude of the annual variation in air temperature [°C]
ω = $2\pi/365$ [day^{-1}]
t = day in the year [day]
t_0 = day number when $T(t, 0) = T_{av} + A_t$ [day]
K_h = average thermal conductivity of the soil profile [$W\ m^{-1}\ °C^{-1}$]
C_s = average volumetric heat capacity of the soil profile [$J\ m^{-3}$]
z is chosen as the deepest computational point.

Example of the energy fluxes

The energy fluxes are divided in Net radiation (Rn), soil heat flux (G), sensible heat (H) and latent heat flux (λE Evapotranspiration) are shown in figure A. Rn are the driving factor of the system, which is illustrated by comparing the energy levels the 7th of April 2016 and the 11st of April 2016. As a result of clouds the first day Rn are reduced to approximately half effect which affects all fluxes. In the day time shown in the period most of the energy goes into warmup of the soil by a high soil heat flux, secondly the energy is converted to sensible heat flux and least of the energy goes to ET. During night Rn turn negative, because of dominating outgoing radiation, and the energy are coming from the soil to the surface seen as a negative soil heat flux, and a little eventually comes from the air in the form of negative sensible heat flux.

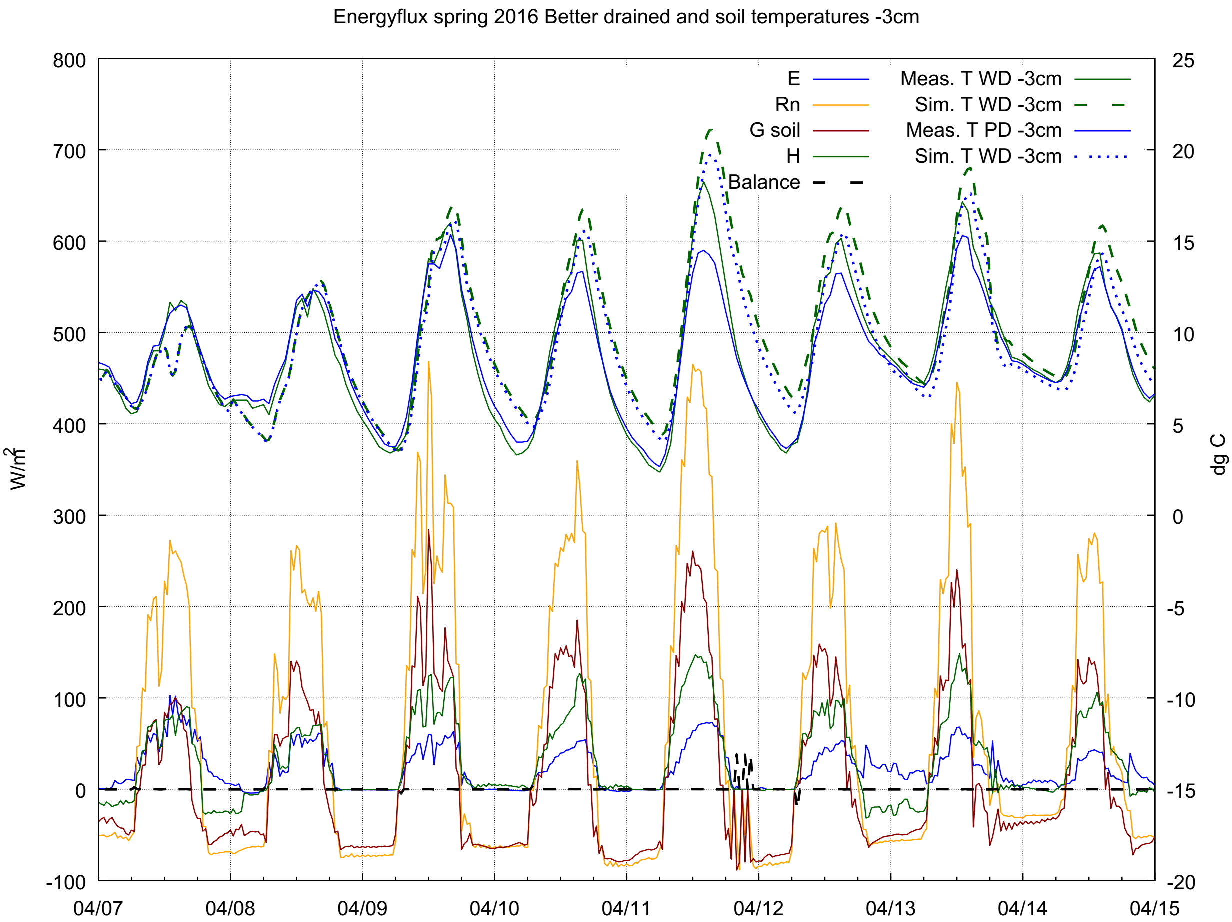

Figure A, Example of the energy fluxes, measured and simulated temperatures, spring 2016.

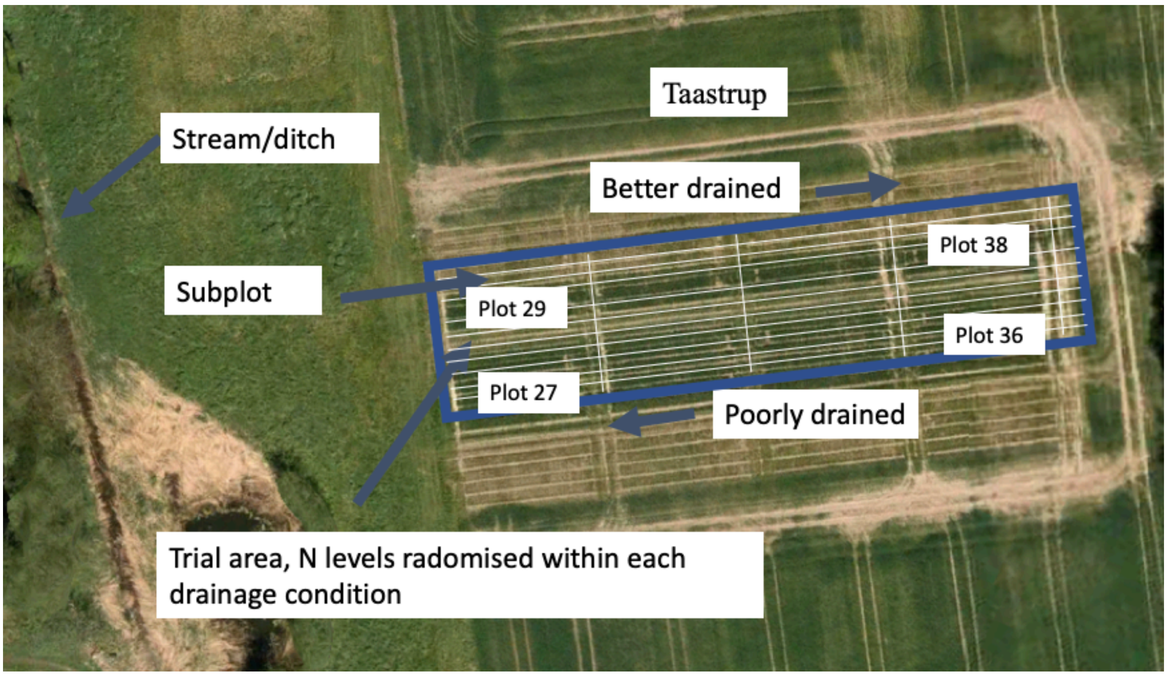

Figure B Taastrup trial setup. There is a gradient in groundwater depth from the poorly drained plots closest to the stream in the left side of the map and the better drained plot in the right side. The total area is approximately 0.5ha. Root measurements were conducted in all of the plots.

Chapter 5 Conclusion and Perspectives

Conclusion

Limited field scale studies of drainage effects in modern agricultural systems in Northern Europe serve as motivation for this study. The main objective has been to quantify effects of variable drainage conditions on cereal crop yields within a range of fields with old tile drain systems on sandy loam soil. Drainage conditions were characterized annually and expressed as SEW_{60} on the basis of continuous measurements of water table depths and correlated to the yields across years, crops, and field sites. Energy fluxes at the soil surface and soil surface temperature were modelled successfully in a growing crop during the spring months, on the basis of soil properties, groundwater levels and hourly measured weather data.

Based on the stated hypotheses in the introduction, the following main conclusions are reached:

From the yield article in chapter 3:

- Consistent yield reductions of up to 25% were measured on the poorest drained plots compared to the well-drained plots across 11 trial site years.
- Yield of dry matter (DM yield) and nitrogen uptake in grains (N yield) were related to SEW_{60} as:

$$\text{Relative DM yield} = \log(-5.45e\text{-}04 * SEW_{60} + 2.78)$$

$$\text{Relative N yield} = \log(-5.75e\text{-}04 * SEW_{60} + 2.79)$$

- There was no significant interaction between SEW_{60} and nitrogen application level with respect to yields. Hence, the negative effect of poor drainage on dry matter and N yield could not be compensated by extra N fertilizer.

From the temperature article in chapter 4:

- The drainage conditions had a clear effect on soil temperature and daily fluctuations in the top layers measured in spring under field conditions in a growing crop.
- Simulated energy fluxes could explain the observed daily temperature variations in the soil surface layer.

Perspectives

Drainage strategy, water management and environmental impact

The significant impact of drainage on plant production found in this study is believed to have the potential to contribute as decision support in water management, both at large scale and at the farm or field level. At the field level, the lack of clear signs of poor drainage on the crop and the connected significant hidden yield loss indicates that mapping of the drainage conditions can be an important measure to raise productivity and mitigate the future drainage demands in a changing climate. This is emphasised in fields with older drainage systems or lack of maintenance. The results also showed that severe yield losses due to waterlogging in the root zone can be nonvisual and occurs before flooding of the crop is visible.

Economical estimations and cost benefit analyses of drainage projects or changes in water management as well as environmental impact assessments can be improved on the basis of the achieved yield functions. This can hopefully assist in finding future sustainable solutions in the conflict between the purpose of streams as drainage water infrastructure and/or nature both from an economical and environmental point of view. Expected increases in surplus precipitation will likely raise the demands for drainage capacity all the way from the field to the sea, assuming that the current drainage state should be maintained. Our results also highlight the need to include the consequences of poor drainage in land use politics. A potential yield increase of 20% as an effect of improved drainage conditions on poorly drained land clearly outline the choice between improving the land use- and nutrient use efficiency and the possibility to convert marginal agricultural land to nature.

The combined dataset of soil properties, hourly weather data, plant growth measurements and yield data of DM and N facilitates the option to investigate the processes of particularly N in the system by mechanistic modelling. The measured N yield response to drainage showed lower nutrient use efficiency of the applied N fertilizer on poorly drained soil, which leaves a question of the fate of lost N in the system. The loss can primarily be divided in denitrification, leaching and changes in the organic pool, all of which lead to different environmental issues. This emphasises the need to quantify the division of N loss into components in order to use integrated mitigation strategies. The reduction of nitrate leaching to the streams is a problem that needs to be addressed but also climate gasses is getting an increasingly important topic. Drainage can lead to higher mineralisation and corresponding CO_2 emissions, especially if the area was not cultivated before, but presently the tendency is towards taking land out of production rather than cultivating new land. However, the risk of N_2O emission under fertilized conditions and CH_4 emission is reduced by proper drainage.

Tile drainage typically results in faster discharge of excess precipitation at the field scale compared to undrained unsaturated soil and may lead to capacity problems in the streams. On the other hand, increased storage capacity in well-drained soil may reduce peak flows in streams compared to the situation with poorly drained soils or surface drained areas. Even though macropore flow in the tile connected macro pores can lead to preferential flow of contaminants from the surface to the streams, the infiltration of water through the soil on well-drained soils reduced the risk of P and pesticide leaching. All these drainage related issues of poor drainage vs well drained have major environmental impact due to the fundamental impact on soil physics, chemistry and biological activity and therefore deserve attention in future research.

Scientific methods and future research

One essential rationale in the economical assessments of drainage projects has not been addressed in this study and therefore needs to be emphasised as a fundamental perspective. The effects of drainage on management possibilities are crucial and inscribed in relation to the yield effects in chapter 3. The timing of operations is limited by the trafficability, and poor workability on poorly drained areas can lead to delayed sowing, fertilisation and harvest, which is all important factors in reaching the potential plant production on the field. Analyses of this management factor is therefore important in order to estimate the full yield potential of drainage. In relation to this heterogenic drainage conditions within a field can be very cost full since areas of the field cannot be cultivated and managed as the rest of the field. This leads to irrational management, which also can be an environmental issue of nutrient loss due to poor plant establishment or soil compaction.

The effect of waterlogging on roots is basic in understanding the plant effects, and many studies have shown this in lysimeters under controlled treatments of waterlogging. However, the effect on root growth and rooting depth under dynamic groundwater conditions in the field is very limited. In order to understand the measured lower nutrient use efficiency, description of the root response could be valuable. Root data in relation to drainage conditions were collected in one of the trial sites (Taastrup) in this work and is planned to be published in the near future.

The method of quantifying the drainage state in the soil used in this study had the great advantage of capturing the dynamics of the groundwater under natural conditions in a SEW index. In this perspective formerly used measures of drainage conditions such as tile depth and spacing between the tiles or constant groundwater levels have clear limitations. Hopefully this study can encourage us to do more field-based studies based on dynamic water table measurements.

The sensitivity to waterlogging is likely to be crop specific, since this study focussed on the drainage response in cereals other the response of other crops might lead to different yield correlations. The potential in canola was described by Williamson and Gray, (1973) who found yield reductions and chlorosis in brassicas under high groundwater levels and Jafari-Talukolaee et al. (2016) found canola yields to increase by 318% after installation of subsurface drainage. This show that other major crops grown in Northern Europe would be interesting to examine.

The influence of drainage on other yield depressing factors might also be of interest. Cannell et al. (1980) found the amount of take-all "Gaeumannomyces graminis var. tritici" was increased by waterlogging, and increased weed pressure in the poorly drained areas was observed in this study. Both factors can lead to significant yield decrease as a side effect of drainage.

Modern agriculture also makes use of much heavier machinery, and the important interaction between drainage and soil compaction also deserves further attention.

Temperature process understanding and modelling.

To the authors knowledge the description of water content and corresponding temperature effects in the top soil have not been described at the scale of field conditions under a growing crop. This basic soil physical effect on temperature and model description can be an important step in improving the understanding of processes in the system. The temperature article (chapter 4) showed that there still is work to do in improving the description of evaporation from the soil surface involving a better understanding of hydraulic properties of the soil surface layers.

The clear response of drainage conditions on daily temperature amplitudes at the soil surface might be utilised as an inexpensive mapping method of drainage conditions by thermal photos of whole fields taken under the right weather conditions. The different reflectance of soil reveals some of the information of the soil water content that can be captured by the human eye, but the temperature signal is conceived to be clearer. Hence this method might have the potential in combination with the capacity of the drones as an example. Work is ongoing in a different project to investigate the benefits of this approach.

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