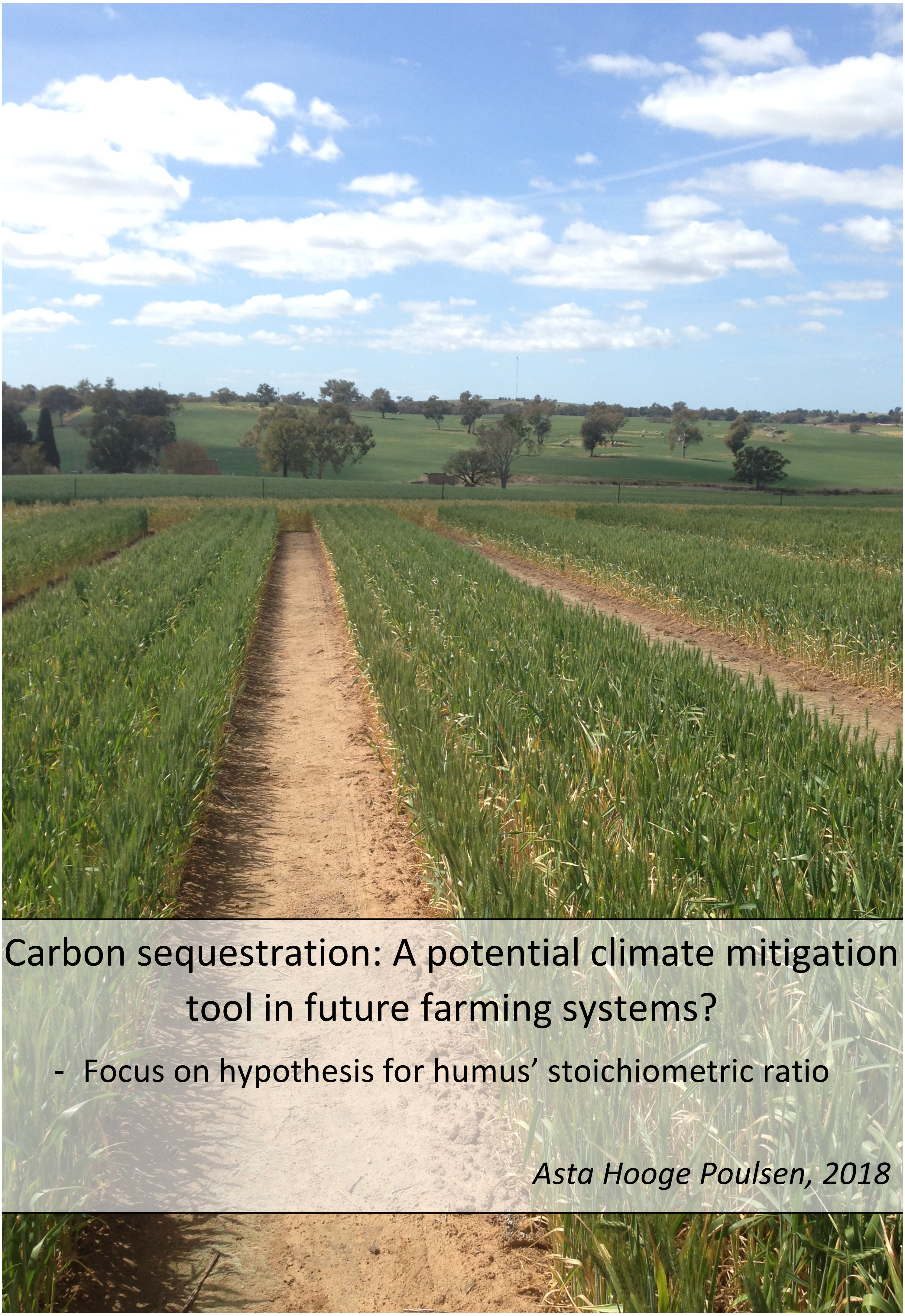

Carbon sequestration: A potential climate mitigation tool in future farming systems?

- Focus on hypothesis for humus' stoichiometric ratio

Asta Hooge Poulsen, 2018

EXPERIMENTAL MASTER THESIS – ENVIRONMENTAL PLANNING

Roskilde University – Fall 2018

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Front: Personal picture taken at field site Harden in Australia, where the sequestration method focused on in this project was tested in a farming system for five years by C Kirkby.

Abstract

Focus of this project has been on a new method to increase carbon sequestration in farming systems to reduce greenhouse gas emissions from agriculture. The method takes outset in the stoichiometric ratio for humus, and is based on a changed fertilizer application to a field. This project is focused on an investigation of the methods applicability in Denmark, since the method has only been tested on Australian soils. The method impact on greenhouse gas emissions, influence on the environment and costs relating to an implementation in Danish farming systems is investigated in this project.

To investigate this a number of experiments have been conducted to examine the methods influence on carbon sequestration and soil organic matter. Furthermore the modelling tool APSIM has been used to simulate crop rotations, where the method has been applied. This was done to determine the long term effect of the method on a farming system.

Results showed that the method has a high potential as a climate mitigation tool. It was however not possible to detect an increase in carbon sequestration with the method on Danish soils. However this can be due to the length of the incubation period not being long enough. Results also showed that there are risks associated with the method. These involve uncertainties in regards to the mobility of nutrients in the soil. To be able to determine the methods applicability in Denmark, it is necessary to identify the methods full potential in regards to sequestrate carbon and its effect on soil dynamics. It is in addition to this essential to investigate the methods impact on the mobility of nutrients in the soil, to increase immobilisation so potential hazards for the environment can be reduced. Finally, it is necessary to define a balance between environmental and climate considerations in regards to the efficiency of the method.

Resumé

I dette projekt fokuseres der på en ny metode til at øge kulstofpuljen i landbrugsjorde, for at reducere udledningen af drivhusgasser fra landbrugssektoren. Metoden tager udgangspunkt i stoichiometriske ratio for humus og en ændret gødningstilførsel til landbrugsjorde. Denne metode har kun været afprøvet under australske forhold, og der arbejdes i dette projekt derfor med en undersøgelse af hvorvidt metoden kan anvendes i Danmark. I den sammenhæng fokuseres der på metodens indflydelse på udledning af drivhusgasser, påvirkning på miljøet og omkostninger forbundet med en implementering i dansk landbrug.

Til at undersøge dette er der udført en række eksperimenter for at undersøge metoden indflydelse på jorden kulstofpulje og jorden organiske pulje (SOM). Derudover er modellen APSIM anvendt til at simulere afgrøderotationer med metoden integreret, for at undersøge langsigtede effekt af metoden.

Resultater viste at metoden har et stort potentiale til at reducere udledningen af drivhusgasser fra landbrugssektoren, dog var det ikke muligt at detektere en øget kulstoflagring med metoden på danske jorde. Dette kan dog skyldes at eksperimentet ikke kørte længe nok. Derudover viste resultater også at der kan være en risiko ved metoden grundet usikkerheder forbundet med mobiliteten af næringsstoffer i jorden. For at kunne arbejde med en mulig fremtidig implementering, skal metodens fulde potentiale og effekt på danske jorde identificeres. Dertil er det nødvendigt at undersøge hvordan metodens påvirkning på mobilitet af næringsstoffer kan reduceres, så miljøpåvirkning kan reduceres. Ydermere skal der defineres en balance i vægtning af miljø - og klima hensyn i forhold til metodens effektivitet.

Extended abstract

The extended abstract can be found in Appendix 17, since the length of the section made it unsuitable to keep in the beginning of the thesis.

Foreword

This project has been written during Fall 2017 and Spring 2018, and is the final master thesis in a two year master program in TekSam – Environmental planning at Roskilde University. The project was started in Australia during an internship with Commonwealth Scientific and Industrial Research Organisation (CSIRO), where I during the 6 months internship investigated a new method to sequestrate Carbon (C) in farming systems. The project is addressed to people who already have a thorough understanding of the mechanisms in a farming system, in particular processes happening in the soil, since this will be a main focus in the project.

My interest in C-sequestration is due to its potentially beneficial effects on both fertility of the soil and the reduction in greenhouse gas (GHG) emissions. We currently have a farming system with high GHG emissions, where soils are losing their fertility. Therefore I thought it would be interesting to investigate a method that could potentially help decrease these effects in agriculture. The method to increase C-sequestration, focused on in this project, was also the method I examined in Australia. I have worked closely with the researcher, Clive Kirkby, who initially developed the method.

I want to send a big thanks to my supervisor Henrik Hauggaard-Nielsen, who has been a great support. I have really enjoyed our good collaboration and very interesting discussions throughout my studies. He has also helped me establish the contact with CSIRO, so I could study the C-sequestration method first hand. Additionally I want to send a big thanks to the staff at CSIRO who have helped me a lot, and from whom I have learned so much: A special thanks to John Kirkegaard for being my supervisor during my stay, and also Clive Kirkby for guidance relating to my experiments. Furthermore I also want to thank Julianne Lilley, Elizabeth Coonan, Alan Richardson and Tony Swan for all their help.

Asta Hooge Poulsen

Roskilde University, 2018

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1. Introduction

Climate change has been a topic of discussion for a long time now, and the temperature is still rising (Food and Agriculture Organization of the United Nation 2013). Since 1995 the countries of the world have gathered together during the annual COP meetings, to discuss what actions to take, to reduce climate change. These actions are more commonly resulting in goals for overall reductions in greenhouse gasses (GHG) (UNFCCC 2016). In EU the goal is to reduce GHG emission by 80-95% in comparison to emissions from 1990 before 2050.

In Denmark this has resulted in an ambition to have Denmark's GHG emissions reduced by 40% before 2020 (Regeringen 2013). Main focus is on reductions in the energy sector, however emphasis is also put on reductions in other sectors such as in agriculture (Figure 1.1). In Denmark agriculture is currently responsible for 21% of the national GHG emissions, which makes it the third biggest sector in Denmark in regards to emissions, with transport and energy sector being the first and second highest emitters (Figure 1.1). It is necessary to find efficient solutions to minimise GHG emissions from the sectors. Solutions to reduce GHG emissions are often based on restrictions on levels of GHG emissions or on new technologies to meet the goals for reductions (Food and Agriculture Organization of the United Nation 2013).

In agriculture it is not possible to merely make restrictions to how much each farmer is allowed to emit, since there is a production necessary to uphold. Therefore it is necessary to come up with managing solutions, which are "cleaner" alternatives to the current managing of the farming system. To determine the most crucial places to find alternatives that reduce emissions, it is necessary to identify the part of the production, which has the highest GHG emissions.

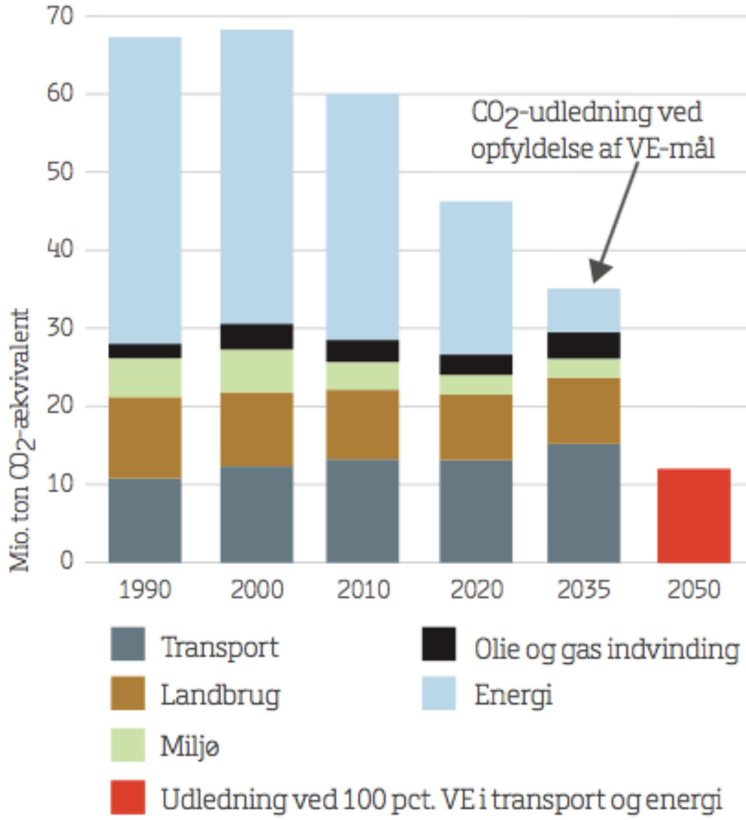


Figure 1.1 *GHG emissions from the different sectors in Denmark. Years after 2010 are forecasts of the desired emissions to reach the goals from Danish government and EU. Brown colour indicates the emissions from agriculture, which are the emissions in focus in this project. This sector the third biggest emitter of GHG in Denmark. Grey is transport, green is environment, black is oil and gas, blue is energy and red is the emission if transport and energy sector had 100% renewable energy (Regeringen 2013).*

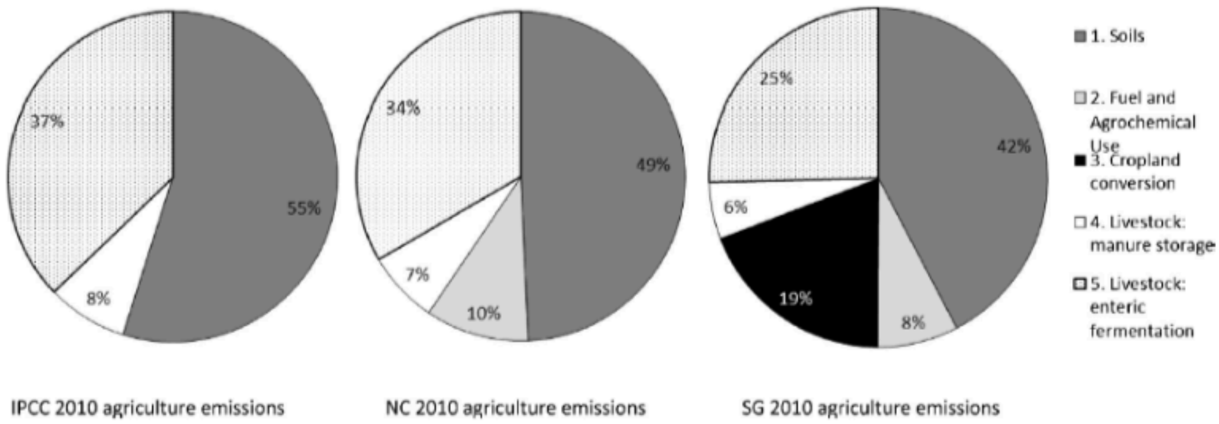


***Figure 1.2** GHG emissions from agriculture. Causes of emissions are divided into five different categories. Diagrams are from 3 different sources and the level of details in categories therefore also varies. For all three diagrams the soil is the main source of GHG emissions (Bell et al. 2014).*

The distribution of emissions from agriculture is shown in Figure 1.2. Fuel and agrochemical use are responsible for approximately a third of the emissions from the sector. However emissions from the soil is the main source of GHG in agriculture (Bell et al. 2014). This is due to processes relating to the nitrogen (N) cycle where nitrous oxide is released or the carbon (C) cycle where carbon dioxid (CO_2) or methane are released (IPCC 2013). In this project focus will be on reductions in CO_2 from the system. The reason for this will be explained in the following.

One of the processes in the soil that leads to emissions is the degradation of a carbon-pool (C-pool) in the soil (Sand-Jensen 2000; Lal & Follett 2009). This C-pool in the soil can serve as a C-sink and is on global level the largest terrestrial sink and can hold up to twice as much C as there is in the atmosphere (Kirkby et al. 2013). Because of this an increase in the C-pool in the soil, through C-sequestration, can serve as an interesting mitigation tool to climate change. This focus on increasing C-pools in the soil is also important if the global temperature is to reach a temperature increase of only 1,5 °C. To reach this it will be necessary to remove pre-existing CO_2 from the atmosphere. According to IPCC (2014) one of the only tools to increase the uptake is through C-sinks in the soil. C-sequestration can thereby potentially balance some of the anthropogenic GHG emissions from other sectors (Lal & Follett 2009).

In agricultural systems this C-pool is continuously decreasing due to the way the system is being managed (Richardson et al. 2014). This decline in the C-pool is happening in agricultural soils across the world (IPCC 2014a) and it is common that the capacity to store C as soil organic carbon (SOC) in the soil declines with 50-75% from before the area was cultivated (Richardson et al. 2014; Kirkby et al. 2014).

The management of the farming system influence the decline in the C-pool in different ways. It can either accelerate the loss of soil organic matter (SOM) (Richardson et al. 2014) and through this increase loss of SOC and the C-pool. The management can also limit the formation of SOM or limit retention in the soil (Richardson et al. 2014) which limits the formation of SOC and through that limit an increase in the C-pool.

Such decrease in the C-pool through a decrease in SOM not only influence the GHG emissions, it also has an impact on the fertility of the soil (Zomer et al. 2017). This is amongst others because SOM is related to humus (Petersen 1994). Humus, which is a part of the soil and SOM, has features, which improve beneficial conditions in the soil for plant growth. These are increased porosity, higher water holding capacity, higher nutrient retention and permeability (Stevenson 1994).

By a decrease in SOM, there will also occur a decrease in humus and through that a reduction in the beneficial conditions. This reduction in soil fertility can make the farming system vulnerable to future abiotic changes, amongst others as a result of climate change. This vulnerability of the system can increase the risk of an impact on the productivity of the system. It is forecasted that a decrease in yield as a result of climate change will be growing over the next 100 years (Smith et al. 2014). As shown in Figure 1.3 it is projected that increase in yield will decrease over the 21st century and that it will be more common with decreased yield in the global crop productions.

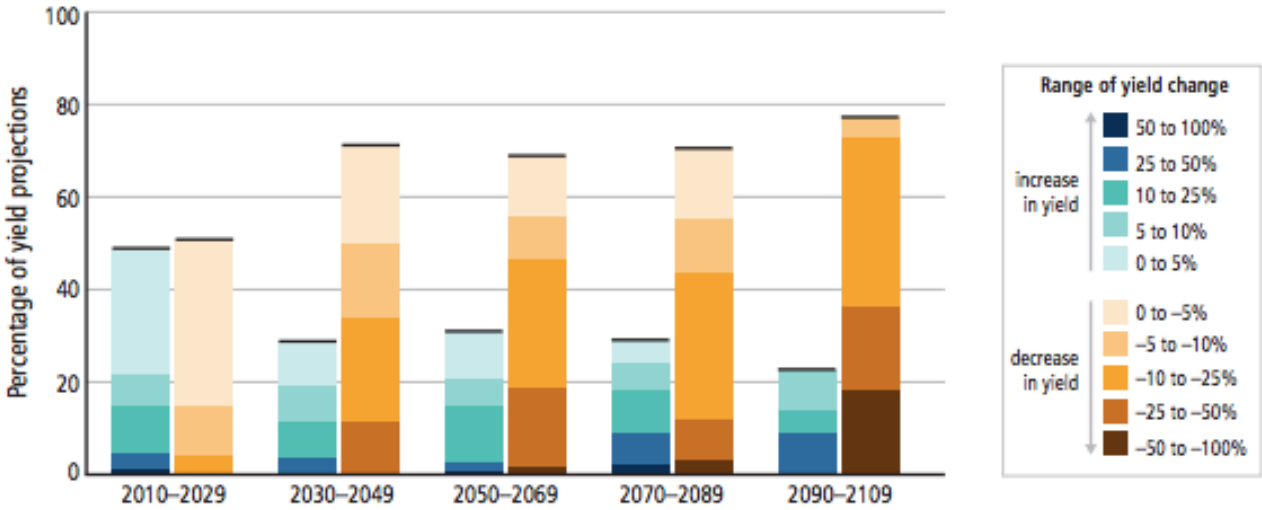


Figure 1.3 *Summary of projected crop yields resulting from climate change. Projections show yield increases versus yield decreases. The projections are based on different emission scenarios from both tropical and temperate regions* (Smith et al. 2014)*. Figure shows that increase in yield will be less likely in the future as a result of climate change, whereas it is more likely that there will be an decrease in yield. This yield decrease has an increased impact on yield change the further into the future projections are.*

These projections show that it is necessary to reduce the crop productions vulnerability to climate change, so yield does not decrease so significantly as the projections forecast. To do so it is essential to focus on the farming systems resilience to future climate variability as a result of climate change (Smith et al. 2014). One of the ways this can be achieved is through increased C-sequestration (IPCC 2014b). Through C-sequestration it can be possible for the soil to withstand erosion, hold soil moisture and enrich biodiversity, which can all be helpful in adapting to future climate change (Smith et al. 2014).

C-sequestration is therefore not only a tool to mitigate climate change, but also a way to adapt to future changes.

In Denmark a range of methods to mitigate climate change has been developed. These include synergies with the energy sector and reduced fertilizer application to the farming system (Miljøministeriet et al. 2013). In regards to C- sequestration the primary method is to change the land use to forest (Miljøministeriet et al. 2013). However this method does not focus on changing the management of the individual farming systems and the production, and thereby does not change the continuous decline in SOM in agricultural soils. To decrease future vulnerability, increasing fertility in agricultural soils and increase C-pools in farming systems, it is therefore necessary to investigate methods that does not merely change the land use, but instead try to change the management practice of the individual fields.

Even though there are changes in the Danish weather, the impact of climate change and necessity for urgent solutions is not as pressing as other places in the world. In Australia farmers have gradually experienced longer and more intense drought periods (Gunasekera et al. 2007). This has influenced their farming systems and many farmers are working closely together with scientists in Australia to change their farming practice to increase water efficiency in their systems. The water scarcity has become one of the most limiting factors for farmers yield (Hughes et al. 2017). Another limiting factor is their infertile soils, which are continuously being depleted of nutrients. By increasing SOM in Australian soils fertility would increase, which would have a beneficial impact on the soils water holding capacity.

Scientists at Commonwealth Scientific Industrial Research Organisation (CSIRO) in Australia have worked on a new method to increase SOM in the pre-existing farming systems to potentially reduce the impact of climate change on the fields (Kirkby et al. 2013; Richardson et al. 2014). This method is a new way to sequestrate C in agricultural soils. The sequestration method takes outset in a changed nutrient input to a farming system.

Farmers are currently applying nutrients to fit the plants need to increase yield (Kirkby et al. 2013). However if the right amount of nutrients are not applied to the soil, there can be a potential risk that the microorganisms are mobilising nutrients from SOM to satisfy the plants need for nutrients, and thereby reducing SOM in the soil and through this SOC. In Australia it was shown that the crop had a higher uptake of nutrients, than the amount which was added to the soil. This could result in a decrease in SOM (Kirkby, Richardson, Wade, Conyers, et al. 2016).

Therefore farmers have to not only be aware of the crops need for nutrients when fertilizing their fields. It is necessary to change the fertilizer use so it is not the crop that is being fertilized, but instead the entire system, so crop production does not end up depleting the soil for its nutrients.

In Australia it was found that by applying nutrients in accordance to a set ratio for Carbon:Nitrogen (C:N), Carbon:Phosphorus (C:P) and Carbon: Sulphur (C:S) it was possible to increase SOC in farming systems (Kirkby et al. 2016; Richardson et al. 2014; Kirkby et al. 2013). The application of additional nutrients increased the systems efficiency to increase SOM and through this sequestrate C (Kirkby et al. 2013).

This additional application of nutrients is somewhat controversial when discussing climate change, since one of the methods, usually recommended to reduce emissions, is to decrease the inputs of fertilizer to the soil (Miljøministeriet et al. 2013; Smith et al. 2014).

The sequestration method from Australia is based on doing the exact opposite, but results have shown that SOM can be increased significantly with the sequestration method (Richardson et al. 2014; Kirkby et al. 2016; Kirkby et al. 2013).

This sequestration method is neither a radical change in farming systems nor a fast solution to an urgently pressing problem concerning GHG emissions. However it is necessary to investigate this method to sequestrate C through increased SOM if there is a wish to obtain a more resilient agricultural production in the future, that does not mine the soil for its nutrients, but instead build on a holistic fertilizer management approach. In addition to this it is crucial to investigate new ways to increase C-pool in the soil, to reduce the pre-existing levels of GHG in the atmosphere.

The sequestration method has only been applied in Australian farming systems. Their climate and soils are different from Danish farming systems. It is therefore relevant to investigate how Danish soils react to the sequestration method and whether it is a method applicable to Danish conditions.

In this project there will therefore be a focus on a potential implementation of the sequestration method in Danish farming systems.

How is SOM influenced by the sequestration method and how applicable is the sequestration method in the current farming systems in Denmark?

When investigating how useful the sequestration method is in Denmark, focus is set on a couple of different aspect. This is in particular the environmental impact of an increased fertilizer application, how efficient the sequestration method is as a climate mitigation tool and whether farmers can afford to implement the method. A more detailed overview of the analysis and discussion can be found in chapter 1.2. Throughout the report the method investigated will be referred to as sequestration method.

In relation to the problem formulation a couple of work questions have been laid out. They are as follow:

1) How efficient is the sequestration method in Danish soils?
2) How stable is SOM, which is formed with the sequestration method?
3) When is SOM formed with the sequestration method?
4) How efficient is the sequestration method under current fertilizer regulation?
5) When is it profitable for farmer to integrate the sequestration method?
6) What is the sequestration methods impact on nitrate leaching from a field?

The questions are in particular linked to the experiments and modelling conducted in the project. Therefore the questions primarily relates to the analysis in the report.

When the sequestration method, throughout the report, is being referred to as a potential mitigation tool, there should for the reader be an underlying understanding that the word 'mitigation tool' refers to both the potential to increase C-pool, but also to increase fertility of the soil and through that adaptation to future climate change. It is therefore not merely a mitigation tool, but also an adaptation tool to climate change.

1.1 Limitations

The following is a walk through of some subjects, which could have been interesting to implement in the project, but for various reasons have not been included.

Since focus in this project is on the specific sequestration method as a climate mitigation tool, other types of agricultural managements that have influence in C-sequestration are excluded. Furthermore it could have been relevant to investigate how to change the overall farming practice to support sequestration rather than focus on merely the nutrient input. However this is also outside the scope of this report.

The nutrients currently focused on in the Danish farming system are N, Phosphorous (P) and Potassium (K) (Landbrugs- og Fiskeristyrelsen 2017). K will not be investigated in this project, since it is the ratio between C:N, C:P, and C:S which is in focus according to Kirkby et al. (2011). This is due to the initial research in the field, where the researcher, who came up with the sequestration method decided to only focus on N, P and S, since he observed that these were the nutrients influencing the microbial biomass the most. In this project focus will be on the same nutrients as the ones, which were initially investigated in the research. However it could be interesting to consider other nutrients impact on C-sequestration as well. This is not within the scope of this project, since it is the pre-existing sequestration method, which is being examined.

It is necessary for the reader to understand the nutrient cycles, primarily N and C cycles, since the project revolves around the application of nutrients to a farming system. However these cycles are not explained in depth in this project. This is due to the structure of the project, where most emphasis will be laid on the analysis and discussion. Some element from the cycles will be used, since sequestration relates to the C-cycle (Baines & Worden 2004) and nitrate leaching as an environmental impact relates to N-cycle. But a thorough description of the two nutrient cycles is not included in this project.

Focus is on the processes in the soil and not so much the biomass above ground. This is because C-sequestration is happening in the soil. However seen from a farmer´s perspective the biomass above ground is the crucial part in the production and it is therefore necessary to focus on this as well, when the potential for an implementation of the sequestration method in Denmark is being assessed. Farmer´s costs are also an important factor to take into account, since too high costs for an implementation can decrease incentives for the farmer. This focus on farmers results in less emphasis on the political aspect of an implementation. It would be interesting to investigate an implementation at different planning levels, especially in relation to the possibilities within pre-existing regulations. It could have been interesting to see if the sequestration method goes against principles in various regulations and directives, such as the water frame directive (Vandrammedirektivet). However this is not possible with the timespan for the project, and it is therefore being limited to focus on the benefits and constraints regarding the practical implementation in a farming system. Therefore policies as a factor will not be taken into account in the project.

As mentioned in the last section of the introduction, the focus of the project is on the sequestration methods impact on the environment and climate change, but also the economical aspect of integration in a farming system (Figure 1.2.1). This economical aspect is seen as an important element to investigate as it can have an impact on the possible integration of the sequestration method in a farming system. Though this aspect is seen as important, the focus is still primarily on the sequestration methods impact on environment and climate change. An analysis for the cost relating to integration of the sequestration method will be made. However this is not a comprehensive cost benefit analysis, but rather to give the reader an idea of the cost relating to an integration of the method seen from a farmers perspective. Therefore costs as a term in this project only relates to the farmers costs for an integration of the method in the field. These costs are only based on the immediate costs for nutrients, where revenues are based on the subsidies given, when a reduction in GHG emissions is obtained from a field.

Since some of the empirical data collection has taken place in Australia, there will be some comparisons between Denmark and Australia, yet this is limited to comparisons when it is seen fit and does not involve a comprehensive comparative analysis between the two agricultural practices.

1.2 Project disposition

This chapter is written to give the reader an overview of the projects disposition. This is in particular in regards to the disposition of the analysis and discussion. The following is a description of the parameters in focus in the project. Abbreviations used in the thesis are lined up in Appendix 16.

In the project a specific method to sequestrate C is being investigated. This is to determine whether it is applicable in Denmark. Three parameters have been selected as important to base the evaluation of the sequestration method on. These are the sequestration methods impact on **1)** *climate change* **2)** *environment* and **3)** *farmers costs*.

In the analysis these three parameters will be dealt with through experiments, simulations and modelling. A thorough introduction to the methods applied can be found in chapter 2. Main focus will be on the sequestration methods impact on climate change and in relation to this the environmental impact. Therefore least emphasis will be laid on the costs for the farmer.

For the analysis six topics, which relate to the overall parameters, are investigated (Figure 1.2.1). The following is a description of how these topics relate to each other and the three parameters. The words in bold indicates the six topics.

Since the method has only been applied in Australia it has not yet been investigated how stable the increased SOM, as an output of the method, is. The ***stability*** (Chapter 4.1.2) of SOM can have an influence on how long sequestrated C stays in the ground. It is important when sequestrating C that C is immobilised in the soil for a long period of time to have a mitigating effect on climate change. In addition to this it is also important to understand when microorganisms are degrading the material and when C-sequestration is occurring. This ***timing of the sequestration*** (Chapter 4.1.3) can have an effect on the availability of nutrients in the soil. More nutrients available at inappropriate times can result in an increased nitrate leaching and through that an increased environmental impact. This timing of sequestration also gives an indication of how C-sequestration occurs in the immediate time period following the application to the field.

It is also important to understand how ***nitrate leaching*** (Chapter 4.3) in general changes when more nutrients are applied to the field as part of the sequestration method. This is to understand how much the method affects the surrounding environment and to estimate whether the sequestration method has too high an impact on the environment, since nitrate leaching has a damaging impact on the aquatic environment.

As mentioned before, the sequestration method has only been applied in Australian farming systems, it is therefore important to investigate how Danish soils react to the method, to determine how ***efficient*** (Chapter 4.1.1) the sequestration method is in Danish soils. This efficiency of the method does not merely relate to the impact on climate change, but can also affect the integration of the method in Denmark. If the efficiency of the sequestration method is too low, then it might have an impact on the costs relating to the integration of the method. For an integration to occur it is therefore important to investigate what the ***costs*** (Chapter 4.2) will be for the farmer. If costs are too high compared to the gains through reductions in GHG emissions with the method, it can be a barrier to implement the method in Denmark. In addition to this it is also important to investigate what is ***possible in Danish farming systems*** (Chapter 4.2, 4.3) and how big areas need to integrate the method to accommodate national goals for reductions in GHG emissions (Miljøministeriet et al. 2013). This is another approach to investigate the efficiency of the method. Instead of focusing on the efficiency in the soil, focus is rather on the efficiency necessary to obtain the desired reductions in emissions in Denmark.

These six topics in the analysis lead up to the discussion, where the sequestration method is to be assessed, to determine if it is applicable in Denmark. This assessment is based on the three parameters (Climate change, Environment and costs). An overview of the three sections in the discussion is shown in Figure 1.2.1. Firstly the sequestration methods impact on climate change is assessed. Afterwards potential constraints are pointed out, amongst others in relation to environmental impact and costs. Thirdly these constraints are compared to the sequestration methods impact on climate change to determine if the method is applicable in Denmark and what might inhibit an implementation in Danish farming systems.

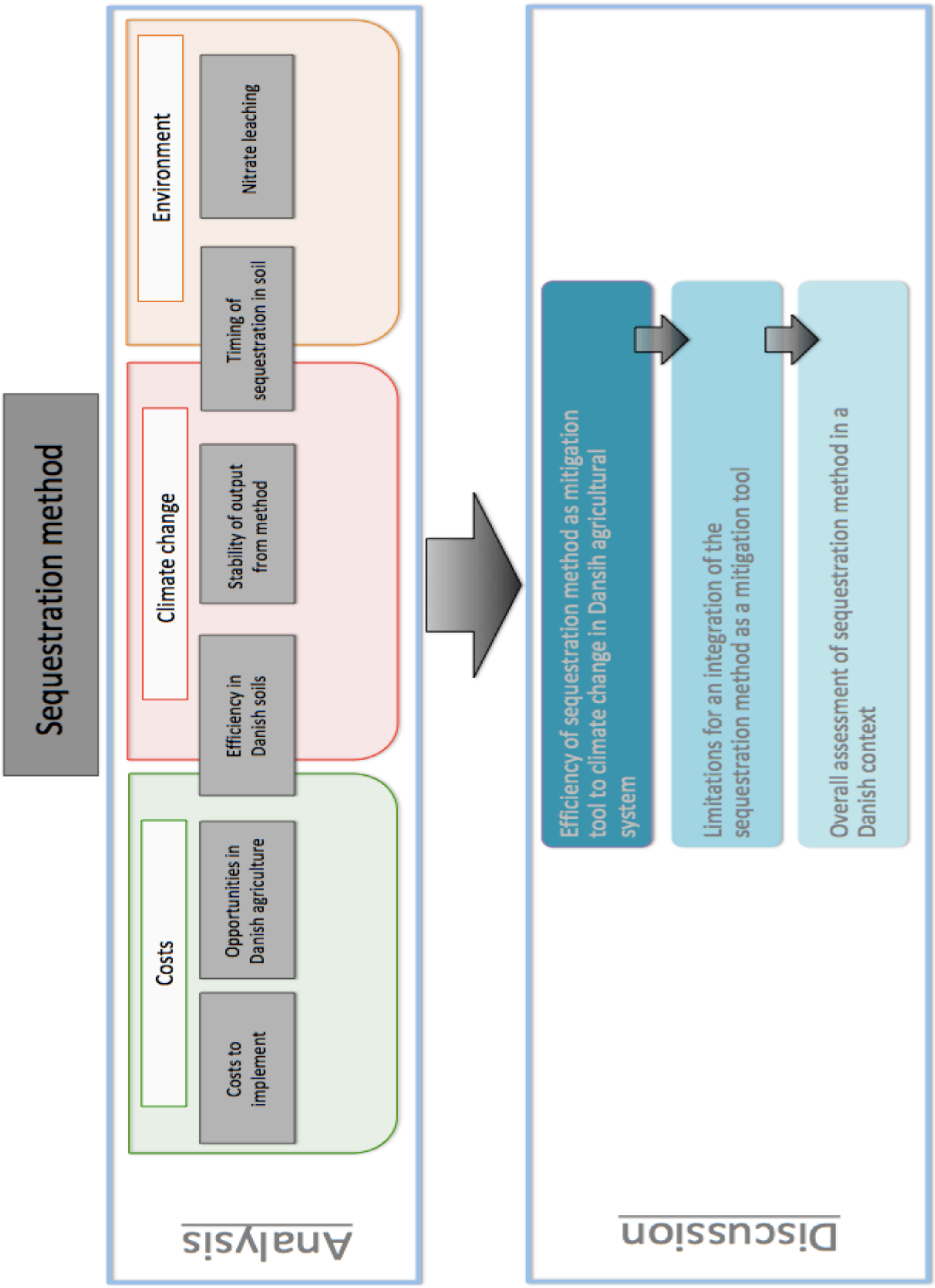


***Figure 1.2.1** Overview of the topics in the analysis and discussion. Three boxes (Green, red and orange) in the analysis indicate the three parameters in focus in this project. The smaller boxes in the analysis each represent a section in the analysis. These sections are linked to the work questions in the introduction and the methods used to investigate each of the sections is elaborated on in the methods chapter. The second part of the overview it the discussion, which has three sections. The sequestration method is to be assessed on its effect as a mitigation tool, the limitations in Danish farming systems in regards to integration of the method. Afterwards there will be an overall assessment of the sequestration method.*

2. Methods

This chapter contains a specified introduction to the methods applied in the project. Both quantitative and qualitative methods are used to investigate the sequestration method.

To understand the sequestration methods applicability and efficiency in a Danish farming system, a range of experiments have been conducted, with additional statistical analysis.

In relation to the sequestration methods impact on climate change, it is also important to investigate the environmental impact of an implementation in a farming system. Therefore modelling in Agricultural Production Systems Simulator (APSIM) has been used to simulate crop rotations with the applied sequestration method. This was amongst others to investigate nitrate leaching as an environmental hazard.

It is important to examine whether it is possible to implement the method and if the costs are too high for the farmer. Interviews have been used to collect empirical data of opinions on C-sequestration as a tool to mitigate climate change in Australia.

Overall the focus of the project is on the sequestration methods impact on climate change; the environment and the costs as mentioned in chapter 1.2. In Figure 2.1 is an overview of how the different methods are used to investigate the three different parameters relating to C-sequestration in this project. Main focus will be on the sequestration methods impact on GHG emissions and the environment, since these are considered the main reasons to investigate a potential integration of the method in a farming system in this project. The sequestration methods impact on climate change through its impact on SOM and C-sink in the soil will be investigated through three different experiments, which will be explained in detail in chapter 2.1. Two of these experiments can also be used to understand the environmental impact of the sequestration method. This is in regards to the mobility of nutrients in the soil and stability of formed SOM. In addition to this a model is used to investigate the nitrate leaching from a farming system when applying the sequestration method. The last parameter is the costs relating to the sequestration method. Experiment 1 can help determine the efficiency of the sequestration method, which can help identify the costs for an implementation.

A large amount of the empirical data was collected in Australia, this include the interviews. Figure 2.2 is an overview of the timeline of the empirical data collection. The reasoning for conducting interviews in Australia is due to the fact that the sequestration method had already been tried out in fields and farmers have knowledge about the method.

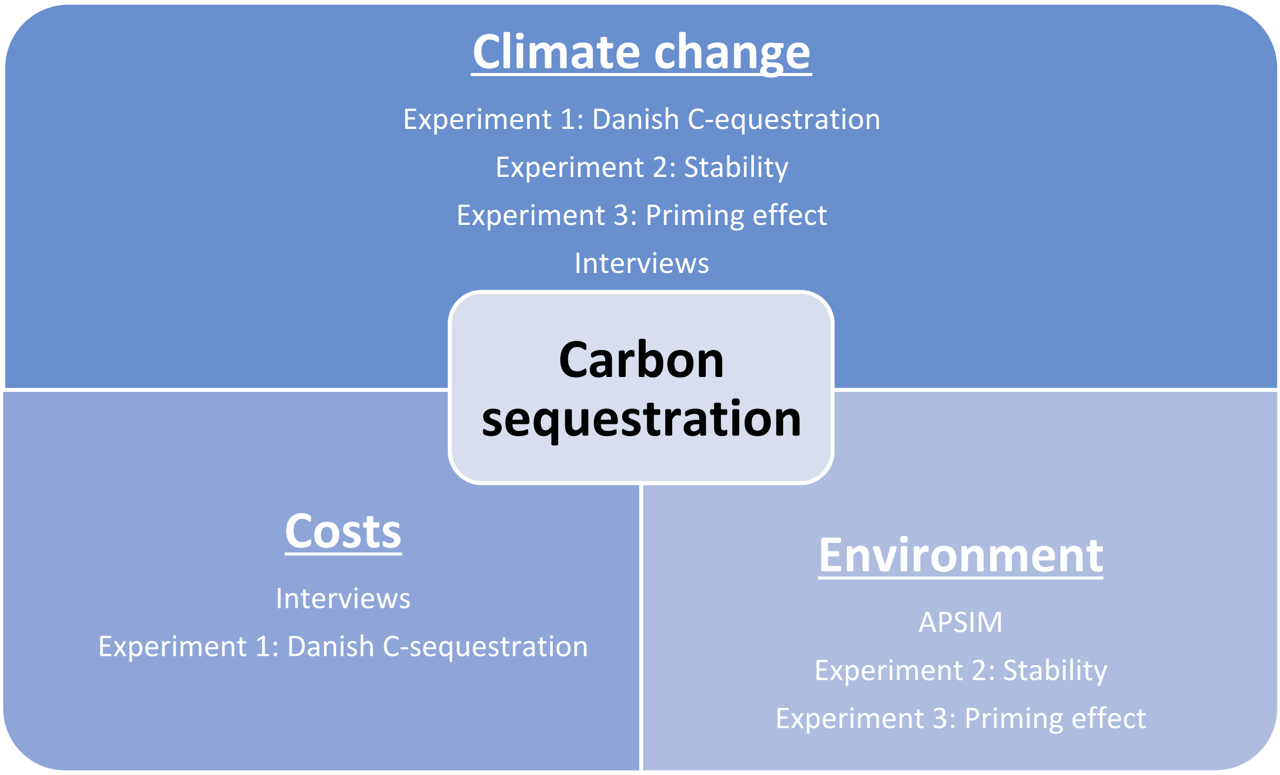


Figure 2.1 *Overview of usage of methods in project. The three boxes each indicate the three parameters the project is based on. These are also visualised in Figure 1.2.1. The bullet points under each parameter are the methods, which are used to investigate each of the parameters. The methods are linked to the 6 chapters in the analysis given in Figure 1.2.1.*

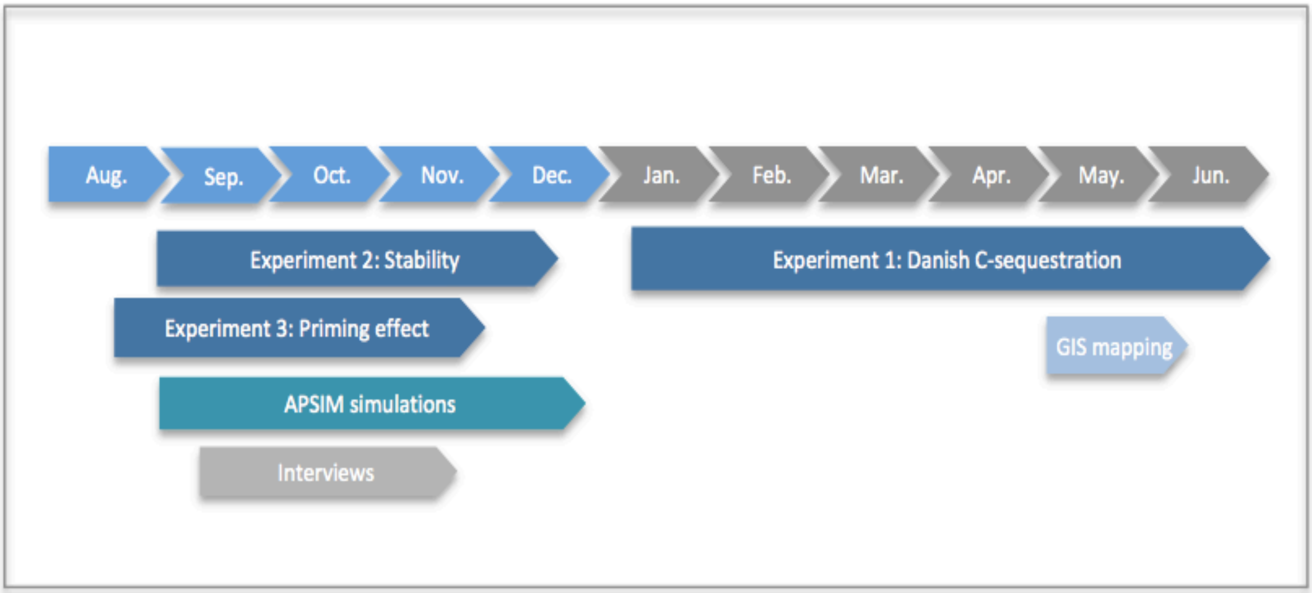


***Figure 2.2** Overview of timeline of empirical data collection. Blue colour for the months indicate the time period, which was spend in Australia. Grey colour for months indicate time spend in Denmark. The arrows below the timeline represent the different empirical data collection tasks and the time it took for each of the tasks.*

2.1 Experiments

A range of experiments was completed to investigate the sequestration method.

The following is a short description of the experiments conducted in the project. A thorough description of the used methods for each experiment can be found in Appendix 2-4. Experiment 1 was conducted in Denmark, whereas the other two experiments were conducted in Australia at CSIRO (Figure 2.2).

All the experiment have taken outset in the cleaning procedure used in Kirkby et al. (2013), with usage of a windowing of the soil to get rid of unwanted organic matter (Kirkby et al. 2011)*. The sample analysis following the incubation have also taken outset in the procedure found in Kirkby et al., (2013).*

2.1.1 Experiment 1: Danish C-sequestration

The aim is to investigate changes in SOM in Danish soils, when extra nutrients are applied. The method can be found in Appendix 2.

The sequestration method relating to stoichiometric ratio has only been applied on Australian soils, it is therefore important to examine if Danish soils respond in the same way as the Australian soils, by increasing SOM. In this experiment it is also important to investigate the net humification efficiency (NHE), to find out how much this is increasing. This can have an impact on how beneficial the method is to implement in a farming system in Denmark. The impact of soil disturbance is also investigated in this experiment. This is due to the fact that many farmers work with reduced tillage. It is therefore necessary to investigate whether less disturbance and mixing of the soil will decrease NHE and the build-up of SOM.

The hypothesis is that Danish soils will have a similar increase in SOM as seen in Australian experiments (Kirkby et al. 2013).

The experiment was conducted at Roskilde University, where an incubation of soils from six Danish farmers took place. The incubation was set up in the same way as incubation study by Kirkby et al. (2013). However treatments differed. The treatments used in this experiment can be found in Appendix 2. The main focus in treatments was on application of nutrients according to the stoichiometric ratio and the impact of soil disturbance. The placement of plastic containers in the incubation conditions also differed from Kirkby et al., (2013). The plastic containers did not have holes at the bottom and were placed directly in 1 cm. of water in big plastic boxes. This resulted in less airflow through the soil. For this experiment the temperature was also lowered to 20 °C instead of 30 °C. This was due to Denmark having colder climate than Australia.

Figure 2.1.1.1 shows the setup of the experiment with the plastic boxes. Each box contained a number of plastic containers with soil. This looked like the setup of containers in Figure 2.1.2.1. The incubation was conducted in a constant temperature climate room, which was completely dark, and the incubation lasted for two months, where soils once a week were weighed to add water to get a 70% field capacity.

Figure 2.1.1.1 *Setup of plastic boxes for experiment. In each of the boxes are plastic containers with soil in them.*

2.1.2 Experiment 2: Stability

The aim is to investigate the stability of SOM, which has been made through the usage of the sequestration method. This experiment takes outset in an earlier experiment conducted by Kirkby et al., (2013), where 4 different soils had undergone seven incubation periods using the sequestration method. These soils had undergone three different treatments with and without extra nutrients applied during Kirkby et al. (2013). Kirkby's experiment showed that the addition of nutrients increased SOM.

This experiment was done in Australia on the soils also used in Kirkby's experiment. The method can be found in Appendix 3. The experiment conducted in this project focus on how the increased SOM (from Kirkby's experiment) change during a 60 days incubation study. The hypothesis is that SOM created with the added nutrients will have a high stability and therefore there wouldn't be a larger loss of SOM from these soils than from soil without initial addition of nutrients.

The incubation was set up in the same way as Kirkby et al. (2013). However no nutrients were applied. The treatments used in this experiment can be found in Appendix 3. Some of the soils had extra straw added. This was to see if applied OM would increase a degradation of SOM. The setup of the experiment looks like experiment 1 as shown in Figure 2.1.1.1. On Figure 2.1.2.1 some of the soils for the experiment are shown. There is a difference in the soils texture, which is caused by the origins of the soils, since they are from four different fields.

Figure 2.1.2.1 *Picture of some of the soils with and without straw in experiment 2. The difference in texture of the soil between the containers is due to soils being collected from different sites.*

2.1.3 Experiment 3: Priming effect

The aim is to investigate the timing of priming effect and humification with and without extra nutrients. The method can be found in Appendix 4.

The aim of this experiment is to see if there is a gap between the peak of priming effect and the start of humification. Hypothesis is that there is a gap before the humification starts. If this is the case, then there will be a big amount of nutrients available in the soil, as a result of the extra nutrients added, and the nutrient becoming available through the priming effect. This can be important in Danish soils due to precipitation and potential leaching of mobile nutrients available in the soil.

The incubation was set up in the same way as the experiment to estimate time for incubation cycle in Kirkby et al. (2013) and the experiment in Kirkby et al. (2014). This was based on a closed jar method (Alef & Nannipipieri 1995). This experiment differed from the initial setup since a small amount of soil was removed from the jars every time the CO_2 traps were changed. The treatments used in this experiment can be found in Appendix 4. In Figure 2.1.3.1 the setup of the jars and the entire experiment is shown. The see-through glass flask on the right in picture A is the CO_2 trap, and was changed according to the scheduled change given in Appendix 4.

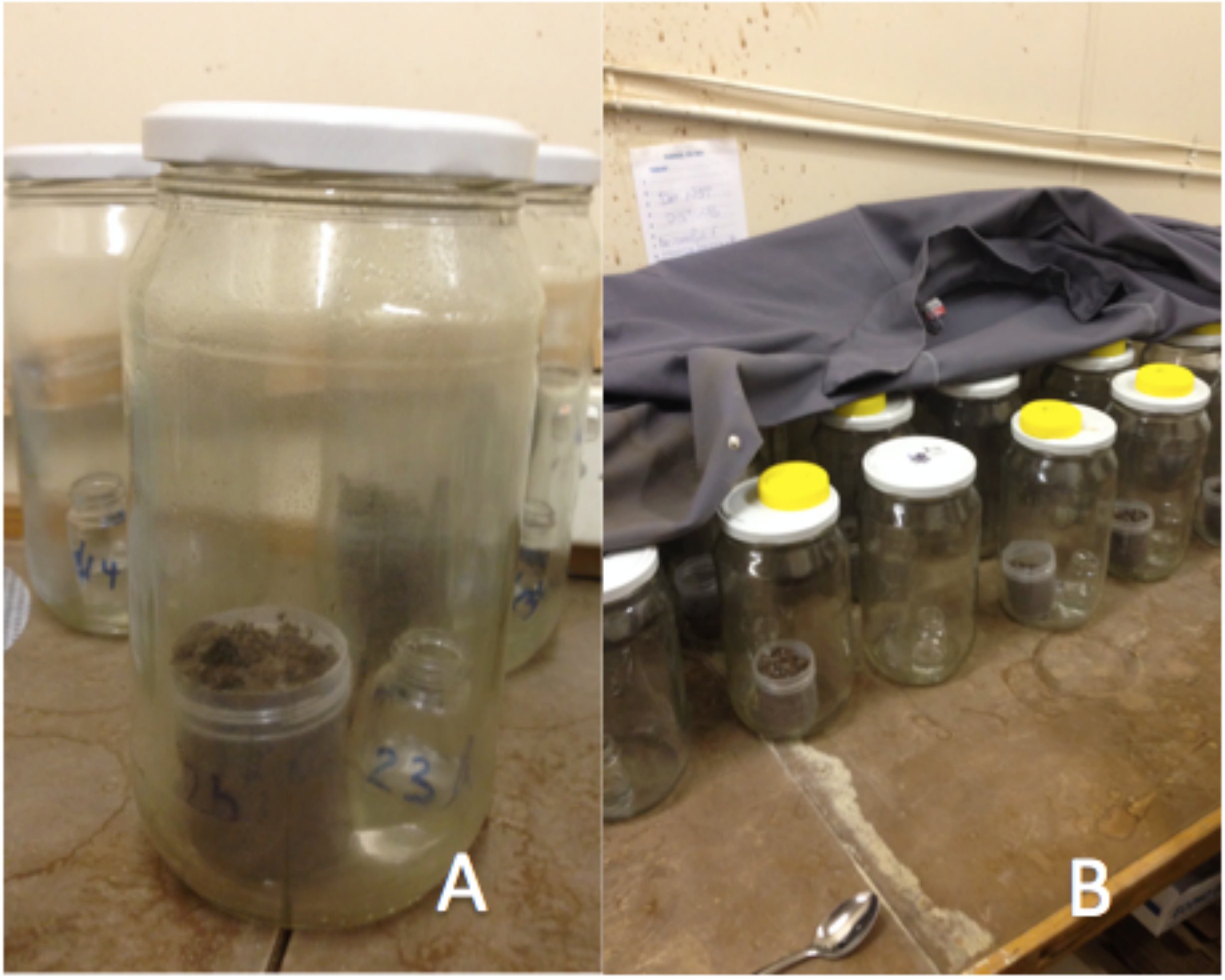


Figure 2.1.3.1 *Picture A shows the setup of the experiment in the jar. Picture B shows the entire setup of the experiment. Coat over jars was to secure that the jars were kept in the dark, even if the light in the room was turned on. Each jar had a* CO_2*-trap and a container with soil.*

2.2 APSIM

APSIM is used in this project to investigate the environmental impact of the sequestration method to examine the results of increased fertilizer input to a farming system. The simulations are based on scenarios with and without extra nutrients added. The usage of simulations is to investigate the long-term effect of a changed management of the farming system, which the sequestration method will cause. Since C-sequestration is a slow process, the long-term impact will be interesting to investigate to see both how C-sink and nitrate leaching is affected by the sequestration method. This is to be done on five different soil types, to investigate whether there are differences in soil types response to the sequestration method.

APSIM was developed to examine different management practices impact on ecology and farmers economy (APSIM Initiative 2018). The model was developed in Australia, but can be used on cropping systems around the world, given that data input for weather, soil and management practice are available (Hammer et al. 2017).

APSIM is a production system model, where there is a focus on the dynamic interactions between parameters (Figure 2.2.1)(Hammer et al. 2017). The cropping system, which is the focus of APSIM, is based on the soil, crop, organisms, weather and management of the system.
APSIM is structured around modules (Cox et al. 2000). These modules are based on the major processes happening in the soil and in the crop. By separating the major processes in the farming system into modules more detailed information can be incorporated into each module. This also means that researchers can work on adjusting a specific process in the soil and through that increase the models representativeness to the actual farming system (Hammer et al. 2017). It also means that different types of research can be integrated and researchers from different disciplines can strengthen each others work and benefit from each other (Cox et al. 2000). The modules in APSIM amongst others involve various crops, soil nitrogen, soil water and soil movement.
Since the model is based on a number of modules with a high level of detail, it is necessary to have enough data input from a specific farming system to simulate the processes in the actual field. This is both data for a detailed soil profile, the weather for the period of time in question and how the farming system is managed.

Data input for the usage of APSIM in this project is gathered through Skov- og Naturstyrelsen (2000). This is data for each of the five soil types used in the simulations, with focus on humus content in the soil, soil pH and plant available water. In addition to this the amount of residue and fertilizer application has been calculated based on Kirkby et al. (2013) and Landbrugs- og Fiskeristyrelsen (2017). The timing of fertilizer application and harvesting is based on earlier studies and simulations of Danish farming systems (Poulsen & Hartkopp 2016). Additional data input for the model has been gathered from APSIM's own database for soil types and crops.

The user of the model determines the desired output data from APSIM. In this case focus is on nitrate leaching in addition to yield and changes in SOC. This is both to investigate the environmental impact of the sequestration method along with the long-term effect the sequestration method might have on productivity (yield) and sequestration (SOC).

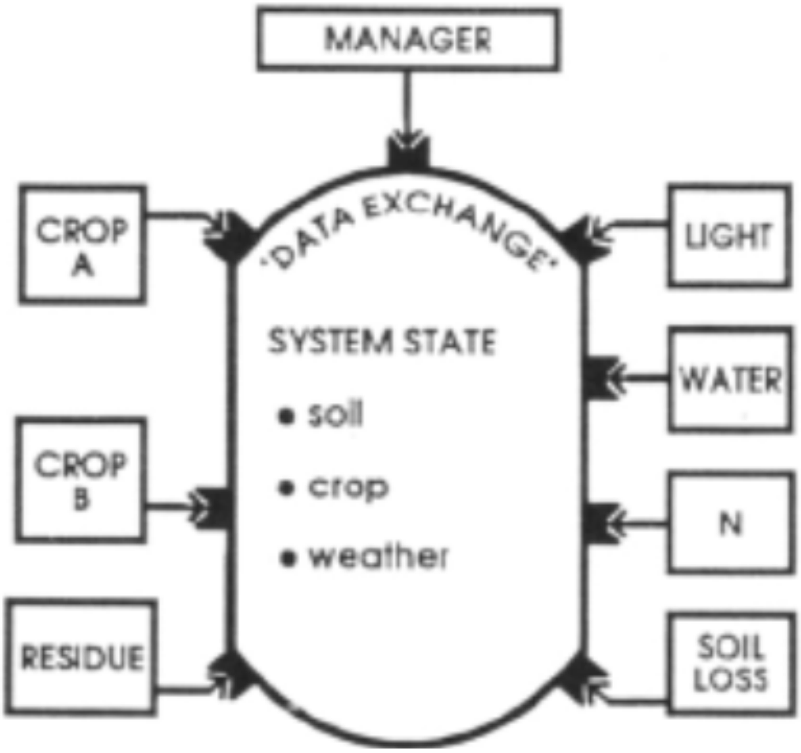


Figure 2.2.1 *Overview of modules in APSIM and the structure of the model. System state is the input data, which explains the farming system in question. The boxes around are the parameters, which can be changed to influence the system state. These are the parameters the modeller changes to examine how system change (Hammer et al. 2017).*

2.3 Statistical analysis

Statistical analysis is used to analyse data from experiments and the results from the modelling in APSIM. This is to investigate changes in SOM and clarify the impact of the sequestration method on environment and climate change. The program SPSS will be used to conduct these analysis.

Firstly all datasets will be analysed for normality, to determine whether the data is parametric or non-parametric. Testing for differences *t*-test or paired *t*-test will be used when data is normally distributed and Wilcoxon signed rank or Mann-Whitney U test will be used when the data is not normally distributed. Besides checking for normal distribution it is also important to check whether samples are related or not, since this determines if a *t*-test or a paired *t*-test should be used (Hawkins 2014).

For APSIM a Kruskall- Wallis test is used to investigate whether there is a difference between more than two samples. This is done to get an overview of the datasets. Afterwards *t*-test, paired *t*-test or their counterparts are used to examine differences between two datasets.

For the experiments it is necessary to start by examining the difference between all the different treatments. Therefore a one-way ANOVA will be used to analyse the difference between the individual soils or treatments t-test, Wilcoxon signed rank, paired *t*-test and Mann-Whitney U test will be used as the main statistical analysis. Regression will be used for experiment 3, to investigate the link between the CO_2-effluxes and C-content in the soil. This is to examine whether the built up of SOM is linked to the microbial activity.

2.4 GIS

Geographic Information System (GIS) is a mapping tool that can be used to map conditions in a catchment area. The tool is based on geographic data, which through GIS becomes organised and visualised as maps. These maps can be used for geographic analysis of specific areas (Donnelly 2015).

GIS is in this project used to map soil types in Denmark to identify which areas are fit, or unfit for an integration of the sequestration method. The maps are made up by a number of different data layers. The primary source for these layers is Roskilde University's database. This database is regularly being updated with data from databanks such as Danmarks Statistik (2016) and Danmarks Miljøportal (2016).

There are different types of formats in GIS; Vector and Raster data. Vector data are primarily points, lines or specific shapes on a map, such as roads, buildings or rivers. Raster data on the other hand is visualised as continuous changes in colours in the maps grids. Such as seen on satellite images.

The maps in this project are primarily based on vector data. This is because data for both land use and soil types, which are the primary data inputs, are polygons on vector levels. However since vector data on cultivated areas in Denmark was not available, such layer was made using raster data. A number of tools have been used to create the maps. These involve intersect and field calculator, which were used to merge layers in the map to find the areas suitable for an integration of the sequestration method. Statistical tools were also used in GIS to summarize the data in the layers attribute tables.

2.5 Interviews

The interviews are used to set focus on the respondents' opinions on methods to sequestrate C. This specific focus on opinions emphasises the need for qualitative interview examination, so interviewer is able to investigate and interpret the respondents' views on a given phenomenon, in this case C-sequestration (Brinkmann & Kvale, 2009:30).

The interview will mainly be conducted as a semi-structured interview. This type of interview builds on an interaction between the respondent and interviewer (Brinkmann & Kvale, 2009:100). To conduct such an interview it is necessary that the interviewer has a large knowledge about the subject being discussed in the conversation. In addition to this, it is crucial that the interviewer is able to navigate in the conversation, to get answers to the important issues brought up in the interview.

The interviews are structured around three themes to investigate potential constraints and opportunities linked to C-sequestration. *The first theme* focuses on the existing farming system and limitations and opportunities relation to climate change. This is important to understand the respondents' current attitude towards climate change and the overall limitations for farming systems today. For the *second theme*, focus is on the future farming systems and like the first theme with a focus on climate change. This is to get an understanding of what the respondents perceive as future hazards for the farming systems and their wishes for future productions. In the *last theme* the aim is to investigate C-sequestration more in depth as a mitigation tool, to be able to map respondents' views on opportunities and constraints relating to the sequestration method. Interview guides for the interviews can be found in Appendix 1.

2.5.1 Respondents

Decision making for choosing respondent has been based on respondents work with farming systems and potential work with climate change in relation to such farming systems. Interviews were only conducted in Australia, where the sequestration method has already been used in field trials. It is in Australia not allowed to record interviews, so instead notes have been taken throughout the interviews.

Description of respondents

Following is a short description of the respondents in the interviews.

JACQUELINE KNOWLES – FROM NATIONAL FARMING FEDERATION (NFF)

Knowles works for NFF, which is a non-governmental organisation helping farmers deal with policies and changes in regulations in Australia. The organisation also comes with suggestions to changes in policies to help farmers in the future. Interview was focused on their work and C-sequestration in Australia, since the sequestration method has already been tried on Australian soils. The notes from the interview can be found in Appendix 13.

FARMERS AT FARMLINK DAY

FarmLink is a day where farmers and researchers related to Grains Research and Development Corporation (GRDC) gather to exchange knowledge. Researchers present their findings, which are then discussed with the farmers. Notes from this day are summaries from a number of conversations with various farmers and from different discussions with researchers. The interviews were therefore shorter and it varied in terms of questions asked from the interview guide. The notes found in Appendix 14 are summary of the different farmers opinions.

ANONYMOUS PERSON FROM AUSTRALIAN GOVERNMENT

Person works with policies relating to mitigation and adaptation tools in Australian farming systems. These are linked to a carbon trading, where farmers are economically rewarded if they reduce their emissions. Person chose to be anonymous given their position in the Australian Government. Notes from the interview can be found in Appendix 15.

3. Theory

This chapter is an introduction to background information on C-sequestration and the processes that lead to an increased sequestration of C in the soil. It is expected that the reader has a general understanding of the processes in the soil already, since common terms used in soil science are not defined in this chapter.

When C-sequestration is being mentioned it is important that the reader understands that this relates to increased SOM. The sequestration method is therefore based on increasing SOM, which ultimately increases SOC as well. The dynamics between these will be explained in the following.

3.1 SOM

There are various definitions of what SOM is. This is in particular in regards to the stage of decomposition of organic matter (OM) in the soil. In this project SOM is defined as OM in the soil, which is build up by microbial residues, together with decomposed plant and animal material present in the soil. This is also the definition used in Kirkby et al. (2011).

When sequestrating C in the soil, it is actually a process involving the increase in SOM and in particular humus. Humus is a part of the OM in the soil. It is difficult to break down, due to its close connection to the inorganic part of the soil and the composition of the humus particles (Stevenson, 1994). Humus particles are built up around an aromatic ring, which is difficult for microorganisms to break down. Humus is therefore a stable part of the SOM and is slowly degraded (Petersen, 1994). Kirkby et al. (2011) found that the ratio between the nutrients C:N:P:S was constant for the stable part of SOM. This ratio did not differ between soils across the globe, which can indicate that humus across the world is similar, despite that the formation of soils is also influenced by geological processes, management of the farming system now and in the past, climate etc. This set ratio between nutrients in the soil is defined as a stoichiometric ratio and will be explained more in depth further down in this chapter. The mentioning of the ratio here is for the reader to understand that the project takes outset in Kirkby et al. (2011) in regards to the ratio between C:N:P:S in humus being constant.

SOM can improve the stability of the soil (Stockmann et al. 2013; Petersen & Hoyle 2015). An increase in SOM has amongst others shown to reduce bulk density of the soil, increase water holding capacity and aggregate stability (Murphy 2015). These features are some of the factors that increase the fertility of the soil and can increase soil health. SOM can increase the resilience of the farming system to climate change, and making the farming system able to respond and adapt to hazards like sudden droughts or heavy precipitation patterns, which are expected to increase in the near future (Food and Agriculture Organization of the United Nation 2013).

Furthermore SOM and in particular humus has a slow turnover time (Stevenson 1994), which is one of the reasons why it can be regarded as a stable part of the soil. The turnover time of SOM is suggested by researchers to be related to the microorganisms access to OM for a mineralisation (Six et al. 2006; Dungait et al. 2012; Lehmann & Kleber 2015). Microorganisms need nutrients to break down OM to gain energy and thereby growth. If the nutrients are not available, then the microorganisms can potentially start breaking down SOM, to get access to the necessary nutrients for energy. If there is not enough available C in the soil, then it will lead to a breakdown of SOM (Stevenson 1994). SOM is therefore also a pool in the soil, which can help stabilise the microbial activity and uphold a stable nutrient pool for the crop (Petersen & Hoyle 2015).This indicates that microorganisms can have an influence on the stability of SOM, since they affect the SOM dynamics.

The process where microorganisms use SOM as an energy input is also given as mineralisation of SOM. This mineralisation, in addition to stabilisation of SOM, is controlling the size of SOM. Mineralisation results in a decrease in SOM and release of immobilised nutrients, which then become available for plant uptake (Chen et al. 2014; Murphy 2015).

Stabilisation happens when SOM is physically isolated from microbial mineralisation. This can either be done if SOM is stored deep enough in the soil away from microbial activity, or if other factors are limiting the microbial activity (Petersen 1994; Berthelsen & Fenger 2005). These can amongst others be changes in temperature, moisture levels or oxygen availability (Lavelle 2015; Six et al. 2006).

It appears that to increase stability of SOM it is necessary to reduce accessibility for microorganisms to the pool.

Changes in SOM can occur through an application of OM to a field. This change in SOM as a result of applied OM is called priming effect (Stockmann et al. 2013; Kuzyakov 2000).

The priming effect occurs when there is a change in the microbial activity due to an input of OM. This priming effect can either increase or decrease SOM. When increasing SOM the priming effect is considered to be negative, whereas a positive priming effect results in a mineralisation of SOM (Stockmann et al. 2013). The availability of nutrients are in this case important since a lack of nutrients in the soil can result in a positive priming effect, so microorganisms can get access to necessary nutrients to break down the OM as an input to the soil (Stevenson 1994; Appe et al. 1988; Kuzyakov 2000). The nutrient ratio in the OM, which is added to the soil can have an influence on the priming effect. If the ratio of nutrients does not fit the microorganisms needs, then they can potentially start to mineralise SOM (Petersen 1994; Chen et al. 2014). This priming effect can possibly explain why the loss of SOM is greater than the formation of SOM through humification (Kirkby et al. 2014).

3.1.1 C-sequestration as mitigation tool

As mentioned in the introduction, C-sequestration can be used as a tool to both mitigate climate change and adapt to future changes (Lal & Follett 2009). According to IPCC (2014a) C-sequestration is one of the most important tools in future work with climate change. The following is an introduction to the process related to C-sequestration.

C-sequestration in the soil occurs when C from the air, represented as CO_2, is incorporated into the soil. This sequestration of C results in a C-pool in the soil (Baines & Worden 2004). This C-pool is a part of the C-cycle, which can be seen in Figure 3.1.1.1.

The C-sequestration occurs when OM is mineralised and integrated into SOM through humification (Lal & Follett 2009). The stability of SOM and long turnover time makes it possible to build up the C-pool (Stevenson 1994; Lal & Follett 2009). This C in SOM is defined as SOC.

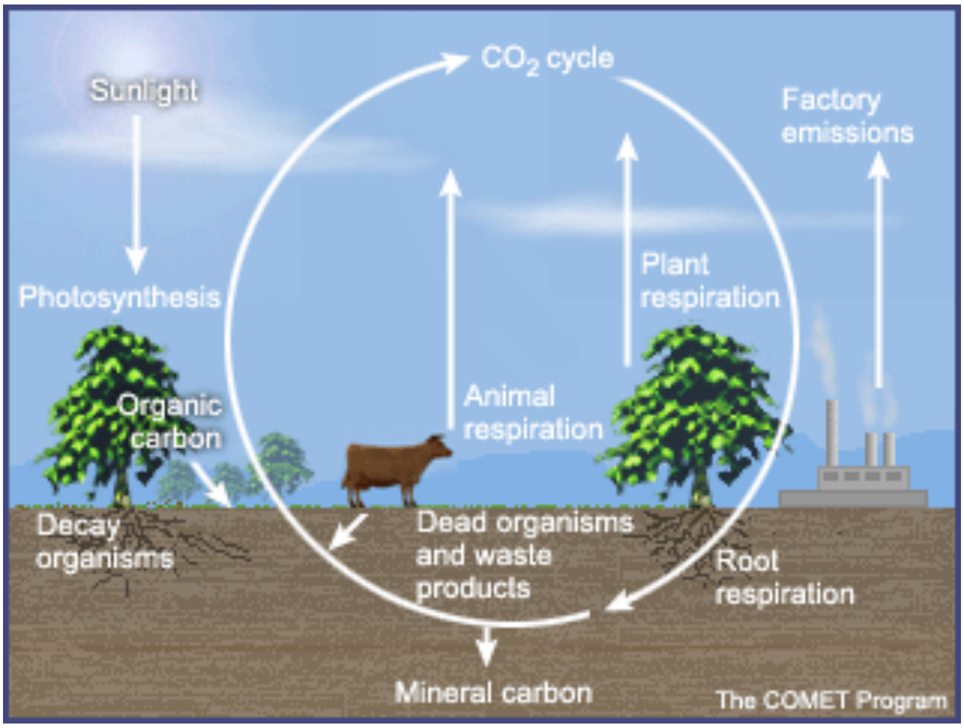


Figure 3.1.1.1 *Carbon cycle. Mineral carbon represent the C-pool in the soil. In this figure anthropogenic factor is also included as emissions (Big Picture Agriculture 2014).*

To increase C-sequestration it is necessary to increase humification of OM as input to the soil, which result in an increase in SOM (Sand-Jensen 2000; Lal & Follett 2009; Stevenson 1994). Microorganisms play, as mentioned before, an important role in the stabilisation of SOM, both through their ability to build up and break down SOM. Microorganisms use C as an energy source, so through a mineralisation of SOM C is lost from the soil through microorganisms respiration (Sand-Jensen 2000).

The amount of C lost from the soil depends on the magnitude of microbial activity when OM is added to the soil (Stevenson 1994; Food and Agriculture Organization of the United Nation 2002) and through this the positive priming effect. A higher microbial activity can lead to an increased mineralisation of SOM and through that an increased loss of SOC.

3.1.2 Land managements impact on SOM

This section is focused on how current management of farming systems influence SOM. This is amongst others to get an understanding of current incentives to increase SOM in the fields. The main managing type which is being focused on in this section is tillage and in addition to this the impact of no tillage, which is used in conservation agriculture (CA).

Denmark is a country with a high amount of cultivated areas. Figure 3.1.2 shows the different land use in Denmark, where intensive cultivated areas are dominating the landscape.

When changing the land use to agriculture there is commonly a decline in SOM of 50-75% (Richardson et al. 2014; Kirkby et al. 2014). This initial decline in SOM reduces the C-pool, which additionally influence the GHG concentrations in the atmosphere.

In addition to this agricultural soils have a tendency to lose SOM over time, since the farming practice deplete the soil for its nutrients (Richardson et al. 2014; Kirkby et al. 2011), amongst others through tillage (Kirkegaard et al. 2014). Hereby the soils capacity to store C is lowered through the management of the farming system (Richardson et al. 2014).

Therefore, land management can influence SOM dynamics in different ways, and it is important that farmers are aware of such impacts on SOM, since it can result in a decreased fertility of the soil and thereby soil productivity (profit). The initial decline in SOM and the ongoing depletion of the soil and decrease in SOM are necessary to stop, if the fields are going to be resilient to climate change in the future.

To stop the initial decline in SOM, it would be necessary to reduce the land use change to agriculture. Especially the land use change from forest to agriculture, since forests have one of the highest C-sinks (Lal 2003). To minimise land use change it would be required to increase the efficiency of the pre-existing farming system, so less area would be needed to produce the same yield. However, increased efficiency of the farming system is not the aim of this project, even though one could argue that efficiency of the farming system could be increased with a higher fertility of the soil, as a result of increased SOM.

Instead focus is on the ongoing impact land management has on SOM. Tillage is one of the primary reasons why there is an accelerated mineralisation of SOM in the soil (Food and Agriculture Organization of the United Nation 2013). This is amongst others due to the turn over of the soil. This way microorganisms potentially gain access to layers of SOM, which otherwise were stabilized. In addition to this OM applied to the field, commonly as residues, is mixed into the soil and the microbial activity increases. This increase in microbial activity can lead to a positive priming effect. It would be beneficial if farmers were aware of this tendency occurring in the soil, and worked on changing the management, to reduce the mineralisation of SOM (Richardson et al. 2014). This could amongst others happen through a higher consideration of the microbial activity, when fertilizing the soil and considering the effect of for example a changed tillage.

A reduced tillage has been one of the main focuses in CA, which is a management type, that builds on a wish for soil conservation, moisture retention and reduced labour and fuel costs (Kirkegaard et al. 2014). Adaptation of a reduced or no tillage is amongst others based on a wish to reduce the impact on the soil and soil structure, which ultimately should lead to less impact on SOM. However according to Kirkegaard et al. (2014) CA and no tillage does not necessarily have a beneficial impact on C-sequestration. It was found that no tillage had no significant influence on SOC, and therefore did not increase the C-pool in the soil (Kirkby et al. 2014). Therefore an ongoing decline in SOM in agricultural soils still occurs.

It is because of this necessary to investigate other alternatives, which can increase SOM in cultivated areas, to maintain productivity of the farming systems and increase fertility and resilience of the fields, in addition to increasing C-sequestration.

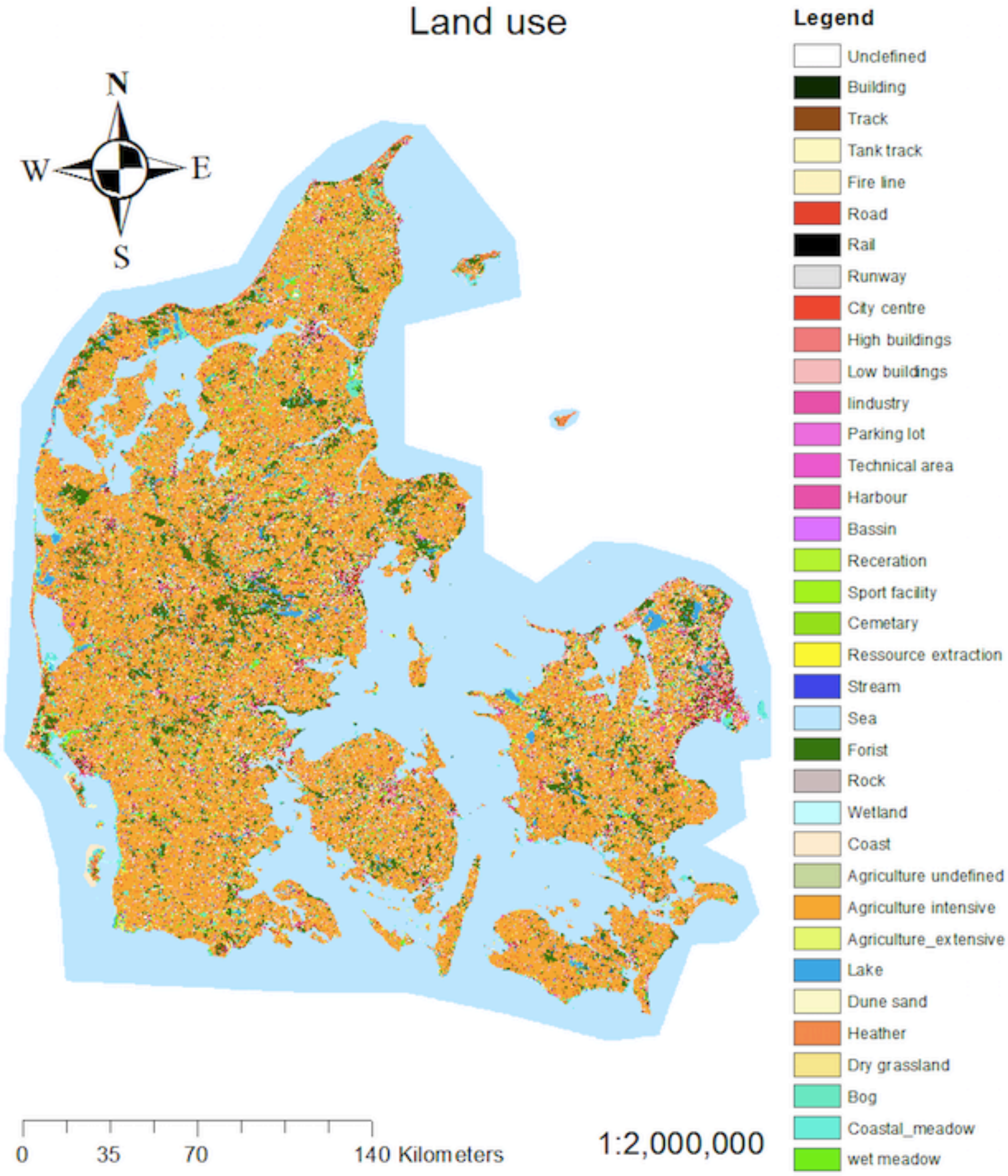


Figure 3.1.2 *Figure of land use in Denmark. Orange colour indicates intensive agricultural areas. Data for map from RUC database.*

3.1.3 Stoichiometric ratio and the sequestration method

In this section the sequestration method investigated in this project is being presented. This is an alternative way to increase SOM in agricultural soils.

As mentioned in Chapter 3.1 humus, as the stable part of SOM, has a set ratio between C:N:P:S (1000:90:19:14). This ratio in humus is not influenced by geographical location, management history or soil type (Richardson et al. 2014). According to Richardson et al. (2014) humus nutrient ratio is very similar to the ratio in microorganisms. In addition to this, research suggest that SOM is partly formed by microbial by-products (Kirkby et al. 2011; Six et al. 2006). This has lead to the suggestion that SOM is largely build up by dead microorganisms (Kirkby et al. 2011). By suggesting this, a large emphasis is laid on the microorganisms' importance for the formation of SOM.

The sequestration method is based on this stoichiometric ratio between C:N:P:S for humus, which can therefore also be set in relation to the microbial activity in the soil.

The sequestration method takes outset in the potential impact crop residues can have on C-pools (Richardson et al. 2014). Crop residues have a high C content, though the ratio for the nutrients in crop residues differs from humus' nutrient ratio. This influence the conversion from crop residue to SOC (Richardson et al. 2014). The humification of crop residues is approximately 5%, which means 5% of applied OM is humified. By increasing the humification of crop residues SOC would increase. In relation to this it is important to understand how much C is converted into SOM. This is done through the humification efficiency (Kirkby et al. 2011). The net humification efficiency (NHE) indicates how efficient the humification is. This is based on how much C of the original OM applied to the field is humified. It is suggested by Kirkby et al. (2011) that the NHE is limited by the availability of required nutrients for the microorganisms to break down OM. This limitation based on nutrient availability lead to the investigation of applying more nutrients to the soil, hence the sequestration method. In addition to this there was a focus on priming effect, since loss of SOM could possibly be explained by positive priming effect being greater than negative priming effect in the soil (Kirkby et al. 2014)

It was hypothesised by Kirkby et al. (2014) that by increasing microbial growth through an application of nutrients and added OM, then the formation of new SOM would overcome the positive priming effect of pre-existing SOM. This was based on the hypothesis that SOM is largely built up by dead microorganisms.

It was found that by applying nutrients according to the stoichiometric ratio for humus with crop residues an increase in humification occurred (Richardson et al. 2014; Kirkby et al. 2014). This application of additional nutrients is done by firstly determine the C:N:P:S ratio in the applied OM and afterwards add N, P and S accordingly to match the stoichiometric ratio for humus. This method is what is referred to as the sequestration method in the project.

The sequestration method was first tried out in an incubation study under controlled conditions. The setup for the incubation study is the one experiment 1 takes outset in.

NHE was increased by 7-15% for all soils in the incubation (Kirkby et al. 2013). In Figure 3.1.3.1 the changes in nutrients can be found. It shows that after seven incubation cycles C has increased significantly along with the other nutrients in the soil. In Figure 3.1.3.2 it is shown how C-sequestration is increased.

For Leeton (name of field site soil was taken from) NHE had increased with approximately 40% (Figure 3.1.3.2). This shows that the addition of extra nutrients increase a change in C, and the sequestration was at least doubled after the seven incubation cycles (Kirkby et al. 2013). However Figure 3.1.3.2 also shows that NHE differs between the soils, which indicate that other factors may also affect the efficiency of C-sequestration. It is suggested that this difference may be due to the microbial biomass responding differently to the extra nutrients or variations in the pre-existing nutrient availability in the soil. Another explanation is the pre-existing levels of SOC in the soil. It was found that soils with lower C-levels in the soil had a higher NHE and were therefore more efficient to sequestrate C (Kirkby et al. 2013).

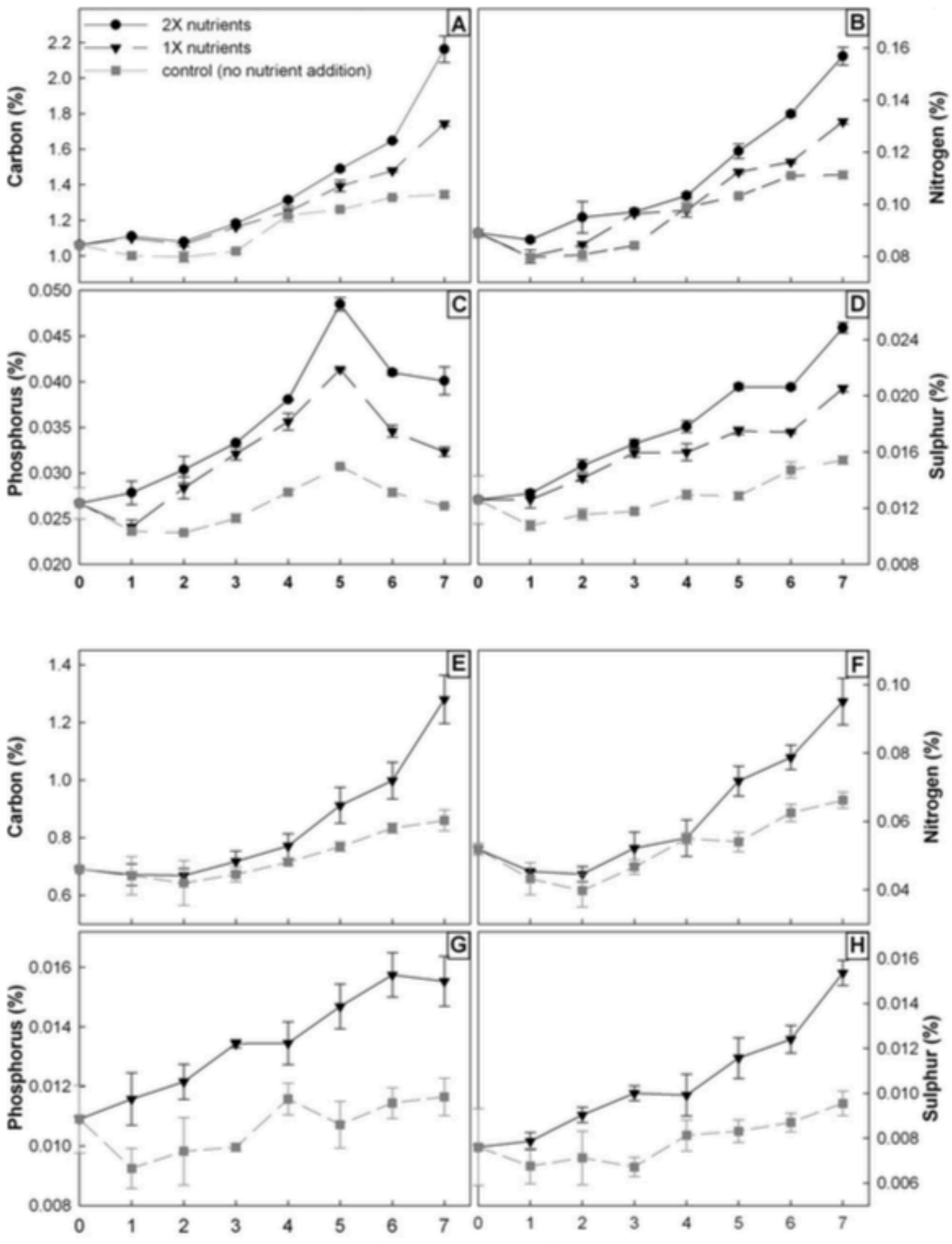


***Figure 3.1.3.1** The effect of the nutrient treatment from the sequestration method. A-D is changes in nutrients for one soil type, where E-H is for another. Seven incubations cycles were done and a subsample after each end cycle was analysed. Results show for three different treatments: A control, one with nutrients according to the stoichiometric ratio and one where the amount of nutrients are doubled* (Kirkby et al. 2013).

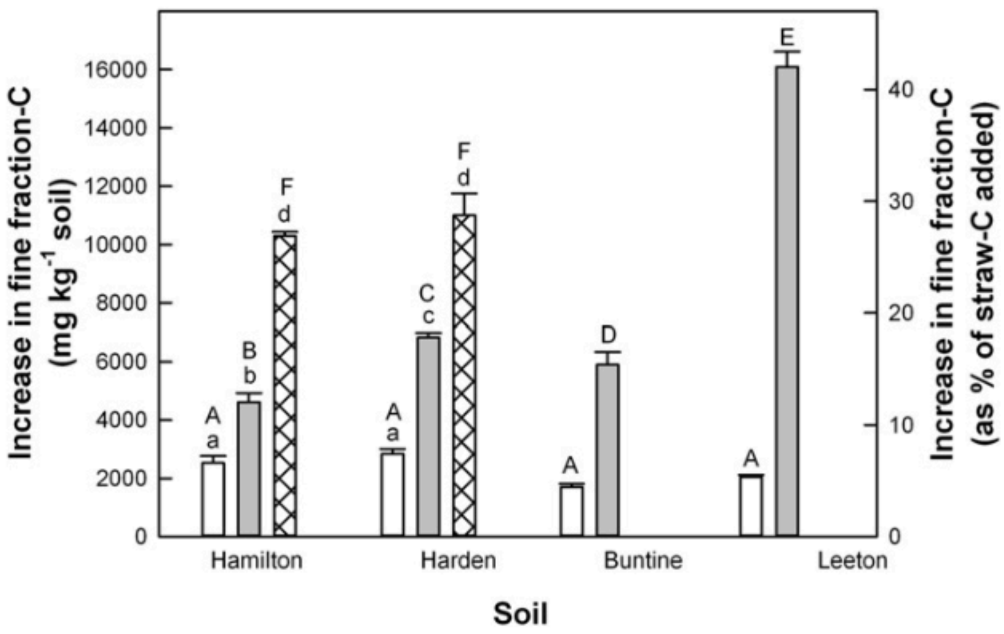


Figure 3.1.3.2 *Effect of the three treatments of C-levels in the soil. No additional nutrients are open bars. 1x extra nutrients are closed grey bars. 2x extra nutrients are bars with pattern. Incubation was done on four different soils, and the results in the figure is after the seven incubation cycles. Only two of the soils received three treatments* (Kirkby et al. 2013).

One of the reasons for applying the extra nutrients was to have the formation of new SOM overcome the mineralisation of stable SOM through positive priming effect. In Figure 3.1.3.3 it is shown that by adding extra nutrients there was a significant increase in new SOM formed. The treatment with no extra nutrients also showed a higher formation of SOM than mineralisation (Figure 3.1.3.2), though the use of extra nutrients increased the formation more.

It is also shown in Figure 3.1.3.3 that the sequestration method increased the positive priming effect compared to when no nutrients applied. This may be caused by the higher microbial activity, since higher activity can increase the mineralisation of SOM (Kirkby et al. 2014).

This mineralisation was done on stable pre-existing SOM, whereas it is uncertain how stable the formed SOM is. This stability of the new SOM can be a potential risk, if it is found out that it is not as stable as the mineralised stable SOM. This could possibly mean that the sequestration method decreases the stable SOM more rapidly than no treatment would do, and that the SOM formed is in fact not stable SOM. This is being investigated in Experiment 2 in the analysis, where the stability of new SOM is being determined (Chapter 4.1.2).

The increased microbial activity with the treatments can also be seen in the CO_2-effluxes in the experiment, which represent microbial biomass respiration. These are shown in Figure 3.1.3.4. Results showed that even though the mineralisation of C in the straw was higher for the treatment with extra nutrients, then the CO_2-effluxes were only 9% higher. This indicates that C-straw is incorporated into microbial C rather than diffuse as CO_2. For both treatments with and without extra nutrients the activity appears to peak within the first seven days. The high effluxes in the beginning suggest that the mineralisation of straw, as added OM, occurred in this period (Kirkby et al. 2014). It has not yet been investigated when the formation and the mineralisation of SOM occurs with the application of the sequestration method. Therefore there is a possible risk that the high microbial activity in the beginning of the incubation study not only relates to the breakdown of straw, but also boosts a positive priming effect, even though nutrients added to the soil should reduce this, since needed nutrients should already be available for the microorganisms. It is therefore necessary to investigate the changes in SOM and C-levels in the soil during the first weeks, where the microbial activity is high, to understand what processes are happening in the soil before the end-results as shown in Figure 3.1.3.3. This investigation of the priming effect during the first weeks of the incubation is done in Experiment 3 in the analysis in this project.

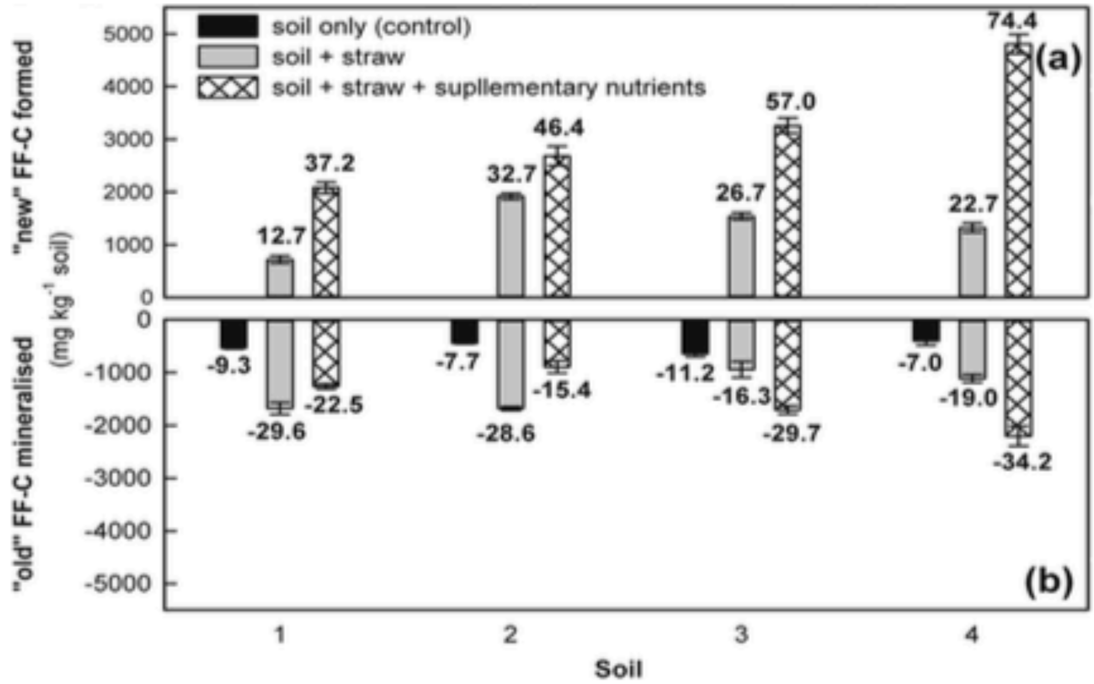


Figure 3.1.3.3 *The effect of treatments (no nutrients and nutrients) on the formation of SOC and mineralisation of SOC after a 56 day incubation period. Experiment involved four different soil types. Values above and below the bars are C given as % of the straw-C added to the soil* (Kirkby et al. 2014).

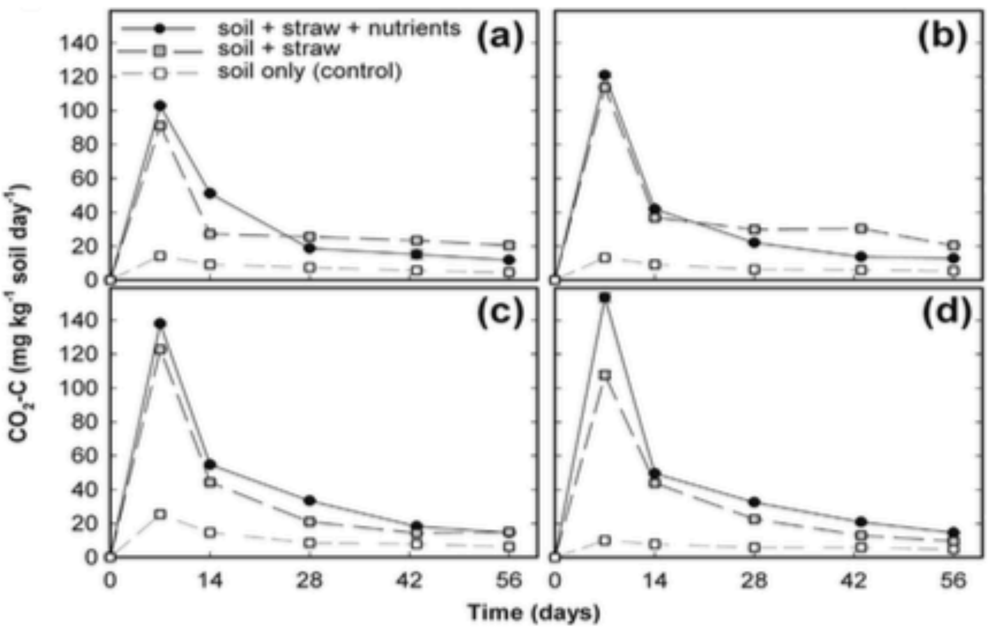


Figure 3.1.3.4 *Treatments effect on CO_2-effluxes from the four soils. The letters a-d represents soil 1-4. CO_2-effluxes are given over the 56 days incubation study (Kirkby et al. 2014).*

After incubation studies showed that the addition of extra nutrients according to the stoichiometric ratio had a significant impact on C-sequestration, the sequestration method was applied to a field, to investigate the impact outside of a laboratory. Nutrients were applied with stubble over a 5 years consecutive trial period (Kirkby, Richardson, Wade, Conyers, et al. 2016). It was found that the sequestration method resulted in an increase of SOC of 8.7 t C ha^{-1}. For the soil, where no extra nutrients were applied, a decrease in SOC of 2,9 t C ha^{-1} was detected. Hereby losing C from the system. This decrease in C-levels may be a result of positive priming effect. In relation to this it was found that for the soils without the sequestration method more N was removed from the soil through the grain, than what was added. This may indicate that N was mobilised from SOM, through a mineralisation of SOM (Kirkby, Richardson, Wade, Conyers, et al. 2016).

Results from the field trial also showed that there were more nutrients left in the soil after the sequestration method, than in the soils without the additional nutrients applied (Kirkby, Richardson, Wade, Conyers, et al. 2016). In addition to this the nutrients increased early vegetation, which suggested that some of the extra nutrients applied remained plant available (Kirkby, Richardson, Wade, Conyers, et al. 2016; Kirkby, Richardson, Wade, Batten, et al. 2016). This mobilisation of the extra nutrients in the soil may not pose as a big hazard in Australia, since there is a lack of precipitation (Kirkby, Richardson, Wade, Conyers, et al. 2016) and thereby not a high leaching of nutrient. However in Danish conditions this mobilisation of the extra nutrients can potentially increase the environmental impact, in particular for N and P leaching. The extra nutrients could be a threat to the aquatic environment in Denmark, which makes it important to investigate what happens in the soil immediately after nutrients are applied, and how nutrient leaching changes with extra nutrients applied. This is being investigated in the modelling in the analysis.

In the introduction two ways of losing SOC was presented. This was either through an accelerated loss of SOM or a limiting formation of SOM.

Applying nutrients, as part of the sequestration method, would increase nutrient availability in the soil, which according to Richardson et al. (2014) would reduce positive priming effect. This could thereby reduce the mineralisation of SOM and thereby reduce the acceleration of loss of SOM, which was the first way SOM could be lost from the soil. In addition to this studies have shown that the sequestration method increase NHE (Kirkby et al. 2013; Kirkby, Richardson, Wade, Conyers, et al. 2016), and therefore increase the formation of SOM. On paper the sequestration method hereby reduce both types of losses of SOM. However some potential problems have been outlined in the chapter above. These are amongst the impact of extra nutrients on the environment, the stability of the new SOM and when the formation of new SOM occurs. These issues will be addressed in the following analysis

4. Analysis

In this chapter results from collected empirical data will be presented. This involves results from the three experiments and output of simulations in APSIM. Furthermore there is also a section focusing on NHE under current regulation, to find the limitations in existing fertilizer application and costs relating to an integration of the sequestration method.

In Figure 4.1 is an overview of how the chapters in the analysis relates to the sequestration method. Most of the analysis involves SOM and changes in SOM, but there is also a focus on emissions, costs and nitrate leaching.

A larger amount of data will be presented in the analysis. To make sure the reader gets the important points from each of the sections in the analysis, a summary for each section is included. These summaries take outset in the work questions outlined in the introduction (Chapter 1.1).

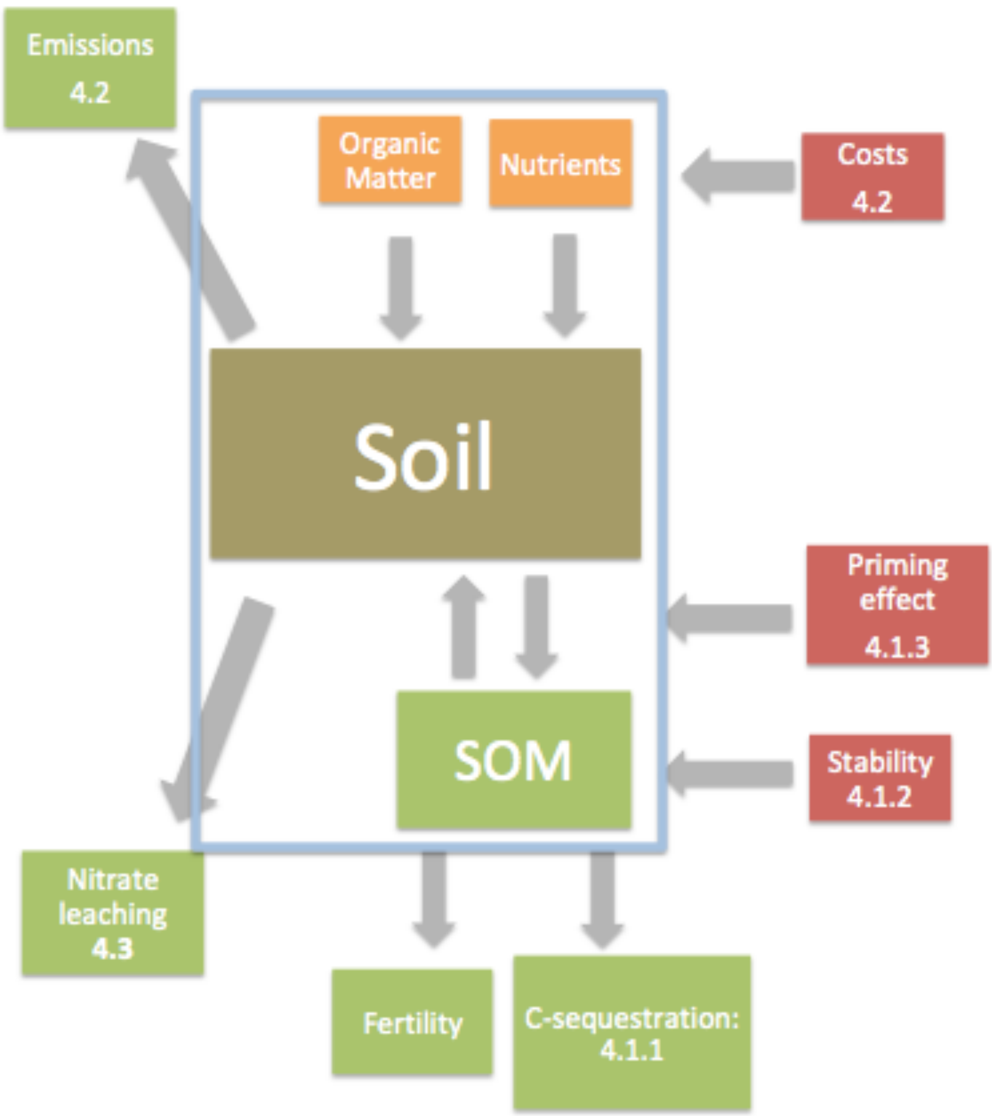


Figure 4.1 *Overview of the process the sequestration method revolves around. Boxes within the blue square are the dynamic the sequestration method is based on. Orange boxes are inputs, where green boxes are outputs. Red boxes are parameters that affect the sequestration method. The numbers in some of the boxes indicate the chapter in the analysis the given box relates to.*

4.1 Experiments

Three experiments have been completed in this project. The first one is focused on how Danish soils react to the sequestration method to investigate how efficiently SOM is increased. In the second experiment the stability of the increased SOM is being tested. This is to investigate the long-term effect of the sequestration method. Last experiment focus on the initial processes when sequestration method is applied. This is to understand the conversions of OM and the activity in the soil within the first couple of weeks after nutrient application.

Hereby there is both a focus on the method overall in Denmark, but also the impact of the method in the first critical stage, when nutrients are applied and the long-term changes after C-sequestration has occurred.

4.1.1 Danish C-sequestration

Since the sequestration method has only been investigated under Australian conditions, it is relevant to examine how Danish soils react to the method. This is necessary for further investigation of the applicability of the sequestration method in a Danish farming system. This is focused on the efficiency and effect of potential SOM build up (Figure 4.1).

This experiment was conducted using Danish soils for a two months incubation study to test the sequestration methods impact on C-sequestration in Danish soils.

This was done on six different soils taken different places on Zealand. The areas are shown in Figure 4.1.1.1. Only three places are marked on the map. This is because the soils were taken from three farmers, who work with CA and from their neighbours' field, which has conventional practices (Table 4.1.1.1). A part of this analysis is therefore also focused on the sequestration methods impact on soils from different farming practices. It is shown in Table 4.1.1.1 that there is a difference in how long the farmers have practices CA.

The treatments used in the experiment can be found in Appendix 2. Treatments included the soils having the sequestration method applied with and without soil disturbance. The treatment with no soil disturbance was included to investigate the potential impact of the sequestration method in a farming system with reduced tillage, such as in CA.

Table 4.1.1.1 *Overview of farmers used in the experiment. Data on farmers collected from Bach & Andersen (2016). Percentage in soil texture is based on the intervals in JB-system. Overview of JB-system can be found in Appendix 6.*

Number	Soils origin	CA	Number of years with CA	JB-classification	%Clay	%Silt	%Sand
1	Farm A	X	10	6	10-15	0-30	40-90
2	Farm A Neighbour	-	-	6	10-15	0-30	40-90
3	Farm B	X	16	6-7	10-25	0-35	40-90
4	Farm B Neighbour	-	-	6-7	10-25	0-35	40-90
5	Farm C	X	42	5-7	10-25	0-35	0-90
6	Farm C Neighbour	-	-	5-7	10-25	0-35	0-90

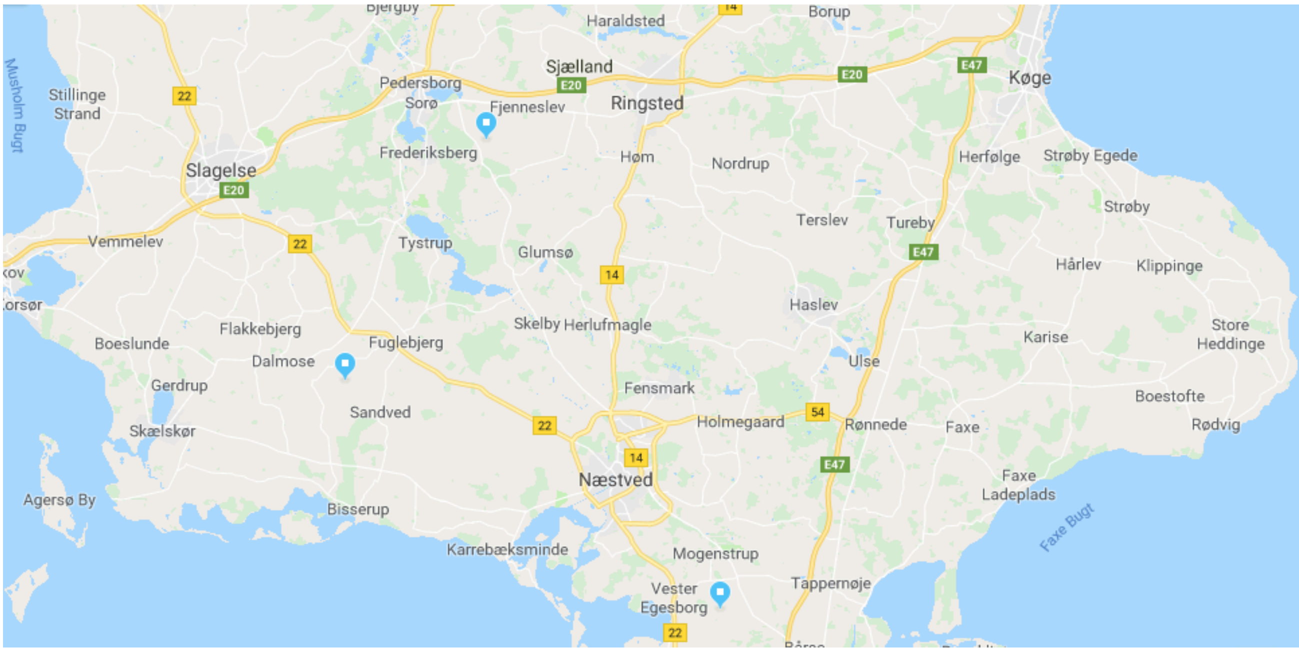


Figure 4.1.1.1 *Map of farmers locations. Blue points indicate the three areas from where soils were taken from for the experiment.*

Change in C content

In this section the sequestration methods impact on C-pool in the soil is investigated.

All the farmers using CA have an initial higher C content in their soils than conventional farmers (Appendix 9). In particular Farm C, who have used CA for 42 years (Table 4.1.1.1). This could indicate that CA may have an impact on SOC, even though studies have shown that it does not have a significant impact (Kirkegaard et al. 2014).

After the incubation the soils C-content were measured again. Results showed that there was a significant change in SOC for the soils where extra nutrients had been applied. Both treatment with only nutrients (Paired *t*-test: t_{18}=-3.115, P=0.026), sequestration method and soil disturbance (Paired *t*-test: t_{18}=-3.280, P=0.022) and sequestration method without soil disturbance (Wilcoxon signed-rank test: T= 0, n=6, N=6, P=0.028) had a significant impact on SOC in the soils (Appendix 9).

However, as shown in Figure 4.1.1.3, the sequestration method was not as expected increasing SOC, but instead overall decreasing SOC. Figure 4.1.1.4 shows how much SOC changed with the nutrient application for the three treatments, where there was a significant change in C content in the soil. Farm C's neighbour is the only one where the sequestration method increases SOC in the soil. This is an increase of 7% from initial C-content in the soil. For the other soils there was a significant decrease in SOC. In particular Farm A's neighbour had a high decrease in SOC: 24% from initial C-content.

A reason for the sequestration method not increasing SOC could be the short incubation period. In Figure 3.1.3.1 picture E it is shown that C content in the experiment declines in the first incubation cycle before an increase occurs around the third incubation cycle (Kirkby et al. 2013). Figure 3.1.3.1 also shows that the highest increase in SOC happens in the last incubation cycle. Therefore the results shown in Figure 4.1.1.3 and Figure 4.1.1.4 could be similar to the progress of the first incubation cycles for one of the soils in Kirkby et al. (2013). However the results could also indicate that the sequestration method does not have the same impact on soils in Denmark as they do in Australia.

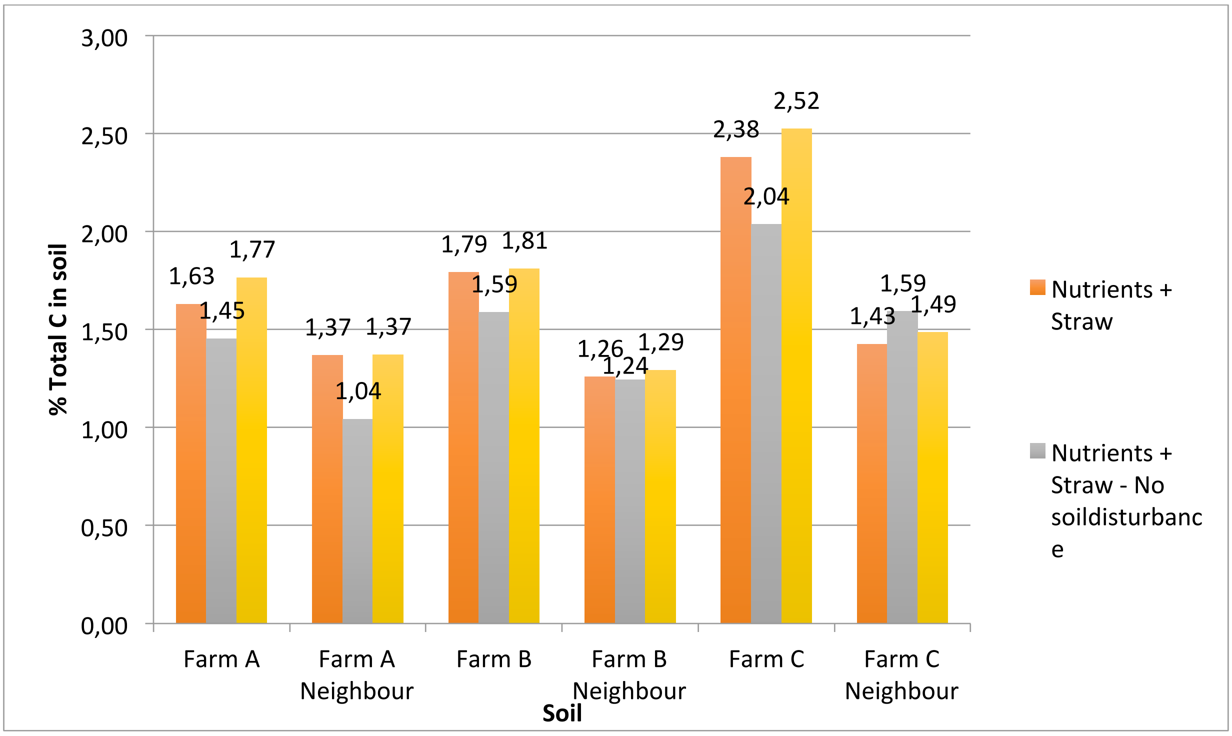


Figure 4.1.1.3 *Change in C content in the soils for the two sequestration treatments with and without soil disturbance. The change in C is given in percentage and numbers above the bars are the total C content in the soils.*

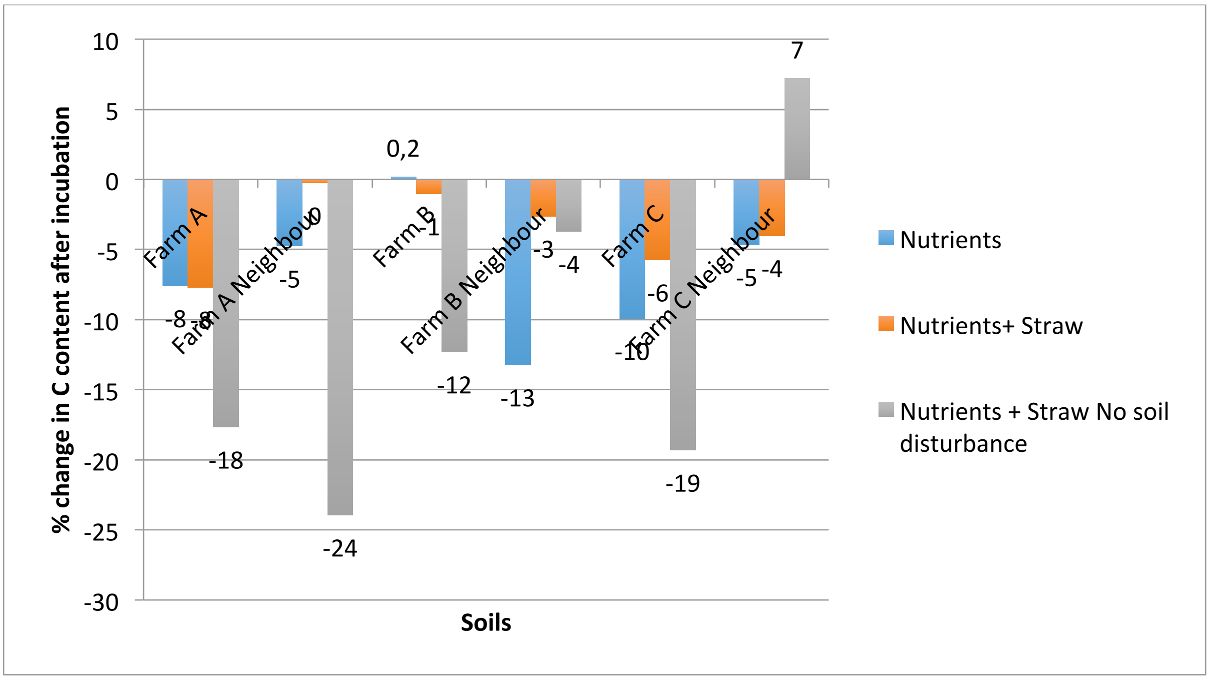


Figure 4.1.1.4 *Change in C content in the soil with nutrients applied. Change is in percentage of the initial C content. Negative values indicate that there was a decrease in SOC from initial stage, when sequestration method was applied.*

It appears on Figure 4.1.1.4 that the sequestration method without soil disturbance has a higher impact on SOC than the sequestration method with soil disturbance, but the statistical analysis shows that there is no significant difference in the change of SOC between the two sequestration methods (Wilcoxon signed-rank test: T= 122, n=18, N=18, P=0.112) (Appendix 9). This could indicate that soil disturbance does not have an impact on the sequestration method. However since the sequestration method did not in fact increase SOM, then the impact of no soil disturbance could possibly change if the sequestration method increased SOM.

Even though results in Figure 4.1.1.4 show that there is a significant decline in SOC with the application of nutrients, then the results in Figure 4.1.1.5 shows how the sequestration method has influenced SOC compared to if only straw was applied to the soil. The changes in Figure 4.1.1.5 are the change in SOC in percentage of the impact of only straw in the soil. Negative values therefore indicate that the sequestration method decreased SOC more than if only straw was applied, where positive values indicate that SOC is higher with the sequestration method than with only straw.

There is generally a decline in SOC with the sequestration method, especially with no soil disturbance. However it is also shown that besides Farm Cs neighbour who had an increase in SOC with the sequestration method (Figure 4.1.1.3, Figure 4.1.1.4), then Farm C’s neighbour and Farm Bs neighbour also has a positive effect of the sequestration method compared to an application of only straw. In Figure 4.1.1.6 it can be seen that the decline in SOC is not as high when the sequestration method is applied as if only straw was applied. Even though SOC still declines, then the sequestration method has slowed down the mineralisation of SOM for this particular soil. Other changes could potentially have been discovered if incubation had run for longer.

It appears that for the rest of the soils the sequestration method boosted the positive priming effect, which resulted in a higher loss of SOM than if only straw was added to the soil (Figure 4.1.1.5). This could indicate that the application of the sequestration method did not satisfy the microbial biomass need for nutrients, but increased the microbial activity, which resulted in a necessity for the microorganisms to mineralise SOM to get access to nutrients. When comparing the effect of an application of only nutrients compared to nutrients and OM, then Figure 4.1.1.5 shows that only nutrients had less influence on SOM than if OM was applied in addition to the nutrients. This could indicate that the application of the sequestration method triggers the microbial activity, but the applied OM and nutrients did not have the right ratio to satisfy the microorganisms need and therefore the negative priming effect did not overcome the positive priming effect.

It would have been interesting to investigate the microbial activity and respiration during the experiment, to understand how the microbial activity changed with the different treatments. This could possibly have given an estimate as to why the sequestration method did not increase SOC and SOM as expected.

Results show that there is a significant difference in C content between treatment with only straw and sequestration method without soil disturbance (Paired *t*-test: t_{17}=-2.394, *P*=0.028)(Appendix 9). It appears that no soil disturbance with the sequestration method has a higher negative impact on SOC than the sequestration method with soil disturbance. This can be due to the microorganisms not getting access to the nutrients and OM applied to the soil, because these are not mixed thoroughly continuously, as is done for all the other treatments. However, as mentioned above, the sequestration method did not increase SOM, and therefore it is uncertain how the soil will react to no disturbance if the sequestration method did increase SOM.

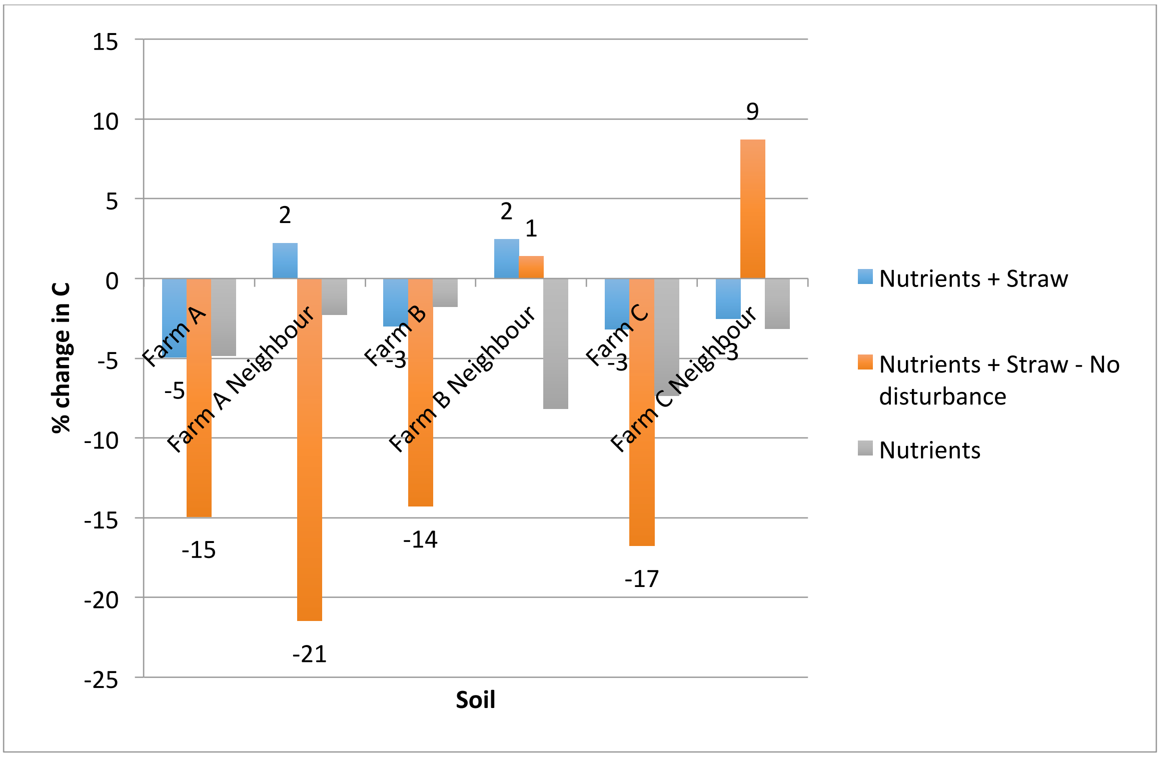


Figure 4.1.1.5 *Change in C content in percentage compared to only straw applied to the soil. Positive values indicate that C content increased with the method compared to if only soil was applied. Negative values indicate that C content decreased when the sequestration method was applied. Positive values does not necessarily mean that C content increased, but could also mean the acceleration of decrease in SOC was slowed down.*

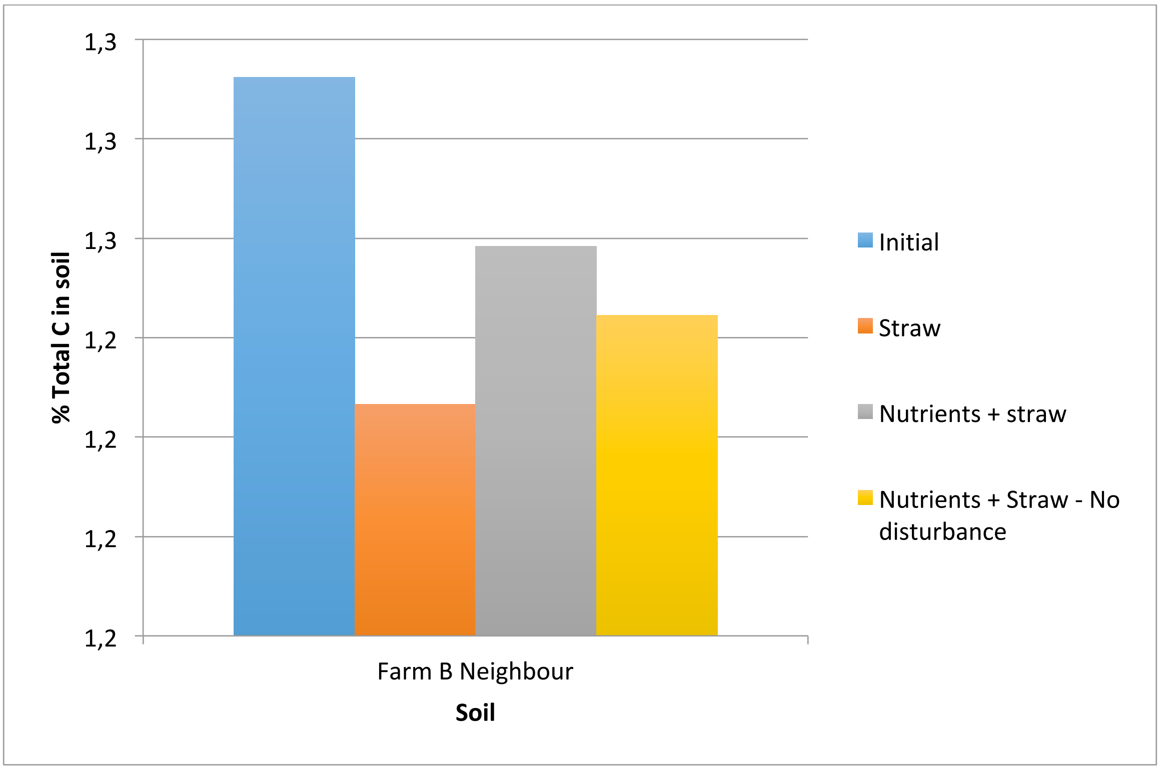


Figure 4.1.1.6 *C content in soil at the beginning and after the treatments. Three treatments are shown for the soil at Farm Bs neighbour. Nutrients + straw had the highest C-content, even though it is still below the initial C-content.*

Net humification efficiency

Since the positive priming effect and thereby mineralisation of SOM is higher than the build up of new SOM with the sequestration method in the experiment, then it is not seen fit to investigate the NHE further, since this has not increased with the sequestration method. In the following chapters in the analysis where NHE is used, it is therefore the NHE needed for the sequestration method to be potentially applicable in Denmark, and not the NHE detected in Experiment 1. It may seem unnecessary to calculate the needed NHE in Denmark and costs relating to an implementation of the sequestration method, when this experiment has shown no increase in SOM. However as shown by Kirkby et al. (2013) there can be a decline in C-levels in the soil, before an increase occurs. This is why a possible application of the sequestration method is not ruled out only based on Experiment 1 in this project, and why the other parts of the analysis are still relevant in the assessment of the sequestration method in a Danish context.

Conservation agriculture and conventional agriculture

This section is focused on the sequestration methods impact on soils from two different types of farming practices (Conventional farming and CA). This is to investigate if earlier farming practice and management of the soil can have an influence on the sequestration method.

The statistical analysis shows that there is a significant difference in SOC between the two farming practices, when the sequestration method with soil disturbance is applied (*t*-test: t_{16}= 0.739, *P*= 0.005; difference = 3.002, 95% C.I. = -5.615 to 11.619)(Appendix 9).

All the farming systems except Farm As neighbour have a decline in SOC with the sequestration method. The two highest reductions in SOC are in CA farming systems (Figure 4.1.1.3). This could indicate that soils from these systems are more prone to loss of SOC when the sequestration method is applied. Hereby, the sequestration method is either reducing the negative priming effect or boosting the positive priming effect in these CA soils.

It is, in relation to this, shown in Figure 4.1.1.5 that it is only soils from conventional agriculture, which has an increase in SOC with the sequestration method, compared to if only straw was applied to the field. The additional application of nutrients decreases the loss of SOC from these soils. This could indicate that the microbial biomass is influenced in different ways in the soils from the two farming practices. It would therefore be interesting to examine the impact of the sequestration methods on various farming practices, to understand the potential impact earlier management practices can have on SOM dynamics.

Another reason for the difference in SOC between soils from the two farming practices could be due to the initial stability of SOM in the soils collected. The soils used in the incubation study are topsoil from different fields. Studies have shown that CA has higher SOC than conventional agriculture in the top 0-10cm layer, where conventional agriculture has higher SOC in the 10-30 cm layer (Brandt 2015). The farmers gathered the soils for the experiment and it is therefore not certain how far down in the soil they dug, when gathering the soil.
Overall SOC is not increased with CA, but rather redistributed in the soil. The stability of the pre-existing SOM and SOC in the soils was not investigated before the incubation was started. If the redistribution of SOM in the soil profile had influenced the amount of stable SOM in the topsoil, this could possibly be a reason for the higher decrease in SOC in soils from CA in the experiment.

Summary

In this section the main conclusions from the first experiment will be outlined. The summary is also linked to the work question: *How efficient is the sequestration method in Danish soils?*

Results showed that Danish soils did not have an increased NHE with the sequestration method, meaning the efficiency to sequestrate C in the soil did not increase. The lack of response in Danish soils could be due to the incubation period. Results in Australia showed that some soils did not have an increase in SOM during the first incubation cycle either (Kirkby et al. 2013). The effect of the sequestration method on priming effect differed between the soils, where some soils had an increased positive priming effect, other soils had a decrease in positive priming effect, reducing the rate of which SOM is being mineralised. The lack of negative priming effect could be due to microorganisms in Denmark responding differently to the sequestration method than in Australia.

There was a difference in SOC between soils from the two initial farming practices (conventional farming and CA). This could be due to the microbial biomass responding differently to the sequestration method between the two farming practices. Soils from CA had a higher decrease in SOC than soils from conventional farming. This could also be due to the initial stability of SOM in the soil and the distribution of SOM in the soil profile, since this differs between the two farming practices (Brandt 2015).

4.1.2 Stability and impact

In this experiment there is a focus on the stability of the new SOM created with the sequestration method. As mentioned in chapter 3.1.3 it has not yet been investigated how stable this formed SOM is. In Figure 3.1.3.3 it was shown that the sequestration method increase the positive priming effect, but that the build up of new SOM is higher than this positive priming effect. It is therefore crucial that the new SOM is of the same stability as pre-existing SOM, which is mineralised, for the sequestration method to have a long-term effect on C-sequestration. As shown on Figure 4.1 this section takes outset in a parameter influencing SOM dynamics – the stability of SOM.

This experiment takes outset in soils used to investigate the sequestration method by Kirkby et al. (2013). The initial state of the soils used in this experiment are therefore the end soils from the seven incubation cycles mentioned in Chapter 3.1.3. In Table 4.1.2.1 is an overview of the texture of the four soils.

Table 4.1.2.1 *Distribution of components for each soil texture in the experiment. The soils are from different field sites, which CSIRO have trials on (Kirkby et al. 2013).*

Soil	%Clay	%Silt	%Sand
Hamilton	25	19	56
Harden	15	10	75
Buntine	8	3	89
Leeton	60	12	28

Soils used in this experiment are four soils with and without the application of extra nutrients. The two different initial treatments of the soils from previous incubation were with or without extra nutrients applied according to the stoichiometric ratio. The initial C-contents in the soils for this experiment are shown in Appendix 10. The soils have all undergone the sequestration method during experiment conducted by Kirkby et al.(2013). NHE varied from 7% to 60% between the soils in the incubation leading up to Experiment 2.

One of the treatments in this experiment is the application of straw as OM to the soils. This is to investigate the impact of stubble on the stability of the sequestration method. Even though the incubation study does not represent an actual farming system, the application of OM can still to some extend be linked to how the soil in a farming system could react to the sequestration method. For the use of OM it is to investigate consequences of a change in farming practice, where one go from a usage of the sequestration method, to stop the application of additional nutrients to determine what happens to SOM.

Change in SOM

This section is focused on the change in SOM and hereby SOC during the two months incubation of the soils.

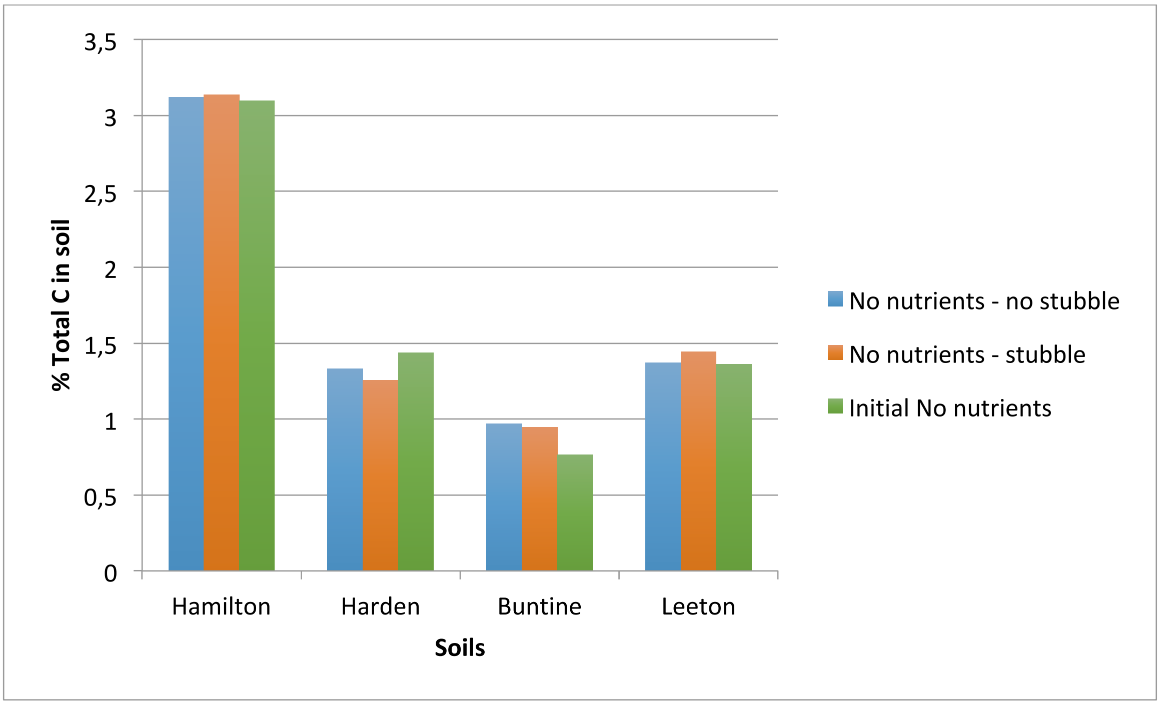
The change in C-content in the soil can be found in Figure 4.1.2.1. It appears that some of the soils have an increase in SOC, whereas other soils have a decrease in SOC during the incubation. It is found that there is no significant difference in SOC from initial state to the end of the experiment. This is for both soils with and without the sequestration method applied (Paired *t*-test: t_{11}=-1.670, P=0.123)(Appendix 10). This indicates that even though SOC changes, the amount of SOC in the soil is not changed significantly. This lack of significant change could imply that the new SOM created with the sequestration method has the same stability as pre-existing SOM, since there is no significant change in neither of the soils. The risk of losing the newly formed SOM is therefore not significantly greater than losing SOM from soils that have not had the sequestration method applied (Paired *t*-test: t_{11}=-1.659, *P*=0.125)(Appendix 10).

It is still necessary to remember that the incubation only ran for two months, so even though the stability of SOM has not changed significantly during the incubation, a change after a longer period of time could still occur. As seen in Figure 3.1.3.1 drastic changes in C-content in the soil occurred after a couple of incubation cycles. Therefore it would be interesting to examine the tendencies for the changes in SOC in the soils, to understand potential future changes in SOC stability, if the use of the sequestration method was stopped.

Even though no significant change in C is found (Paired *t*-test: t_{11}=-1.659, *P*=0.125)(Appendix 10), it still appears that there is a change in SOC. Both Hamilton and Harden have a decrease in SOC with the application of nutrients (Figure 4.1.2.1). The difference between these two is that there is an increase in SOC for Hamilton, where no nutrients were initially applied (Figure 4.1.2.1). For Leeton there is an overall increase in SOC for all treatments, where Buntine is similar except stubble decreased SOC in the soil (Figure 4.1.2.1). The changes occurring as a result of stubble will be analysed further down in this chapter.

The changes in SOC are also shown in Figure 4.1.2.2. Both Harden and Buntines SOC content are greatly affected, though Buntine's increase in SOC could be seen as a favourable outcome.

The four soils hereby act in very different ways when comparing the two initial treatments (with and without nutrients). Therefore there is not a clear answer to how SOM and the stability of SOM changes over time, other than there is no significant change as presented earlier in this analysis. A reason for the differences shown in Figure 4.1.2.2 could be the composition of the microbial biomass in the soils. Higher activity in some soils could increase the mineralisation of SOM, or the availability of nutrients left in the soils from earlier treatments could influence the activity as well.



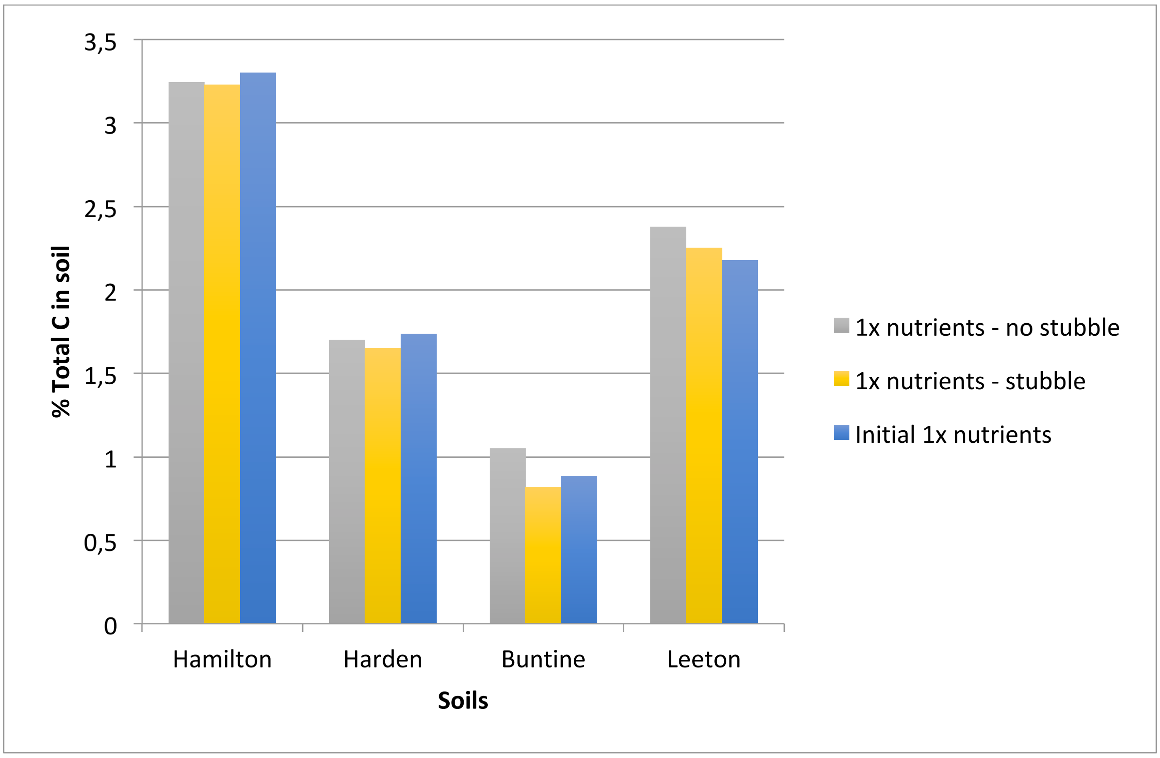


Figure 4.1.2.1 *The change in SOC for the soil with and without the sequestration method initially applied. Top graph shows the change in SOC when no initial nutrients were applied. This is for both with and without straw. Bottom graph is the change in C for soils where sequestration method was applied.*

The changes in SOC for the soils with nutrients compared to changes in SOC for no nutrients are shown in Table 4.1.2.2. The negative values indicate that SOC for soils with the sequestration method initially applied are decreasing with a higher rate than for soils without the sequestration method applied. This could imply that even though there was not found a significant difference in the change of SOC between the two initial treatments, then there could potentially have been created a new SOM pool which is not as stable, or the microbial activity has increased as a result of the sequestration method resulting in a higher mineralisation of SOM, than if no additional nutrients were applied.

It appears that something is influencing the SOM dynamics differently according to whether nutrients have been applied to the soil or not. In addition to this the application of stubble may have an effect on the stability of SOM as well. This will be analysed in the following section.

Table 4.1.2.2 *Changes in C content between the two initial treatments given in percentage of initial state for C-content. Numbers in table show how much soils with additional nutrients have changed compared to soils without additional nutrients. Negative values indicate that SOC has decreased with the addition of nutrients compared to no nutrients.*

	No stubble	Stubble
Hamilton	-2,4	-3,3
Harden	5,2	7,5
Buntine	-8,0	-31,2
Leeton	8,6	-2,4

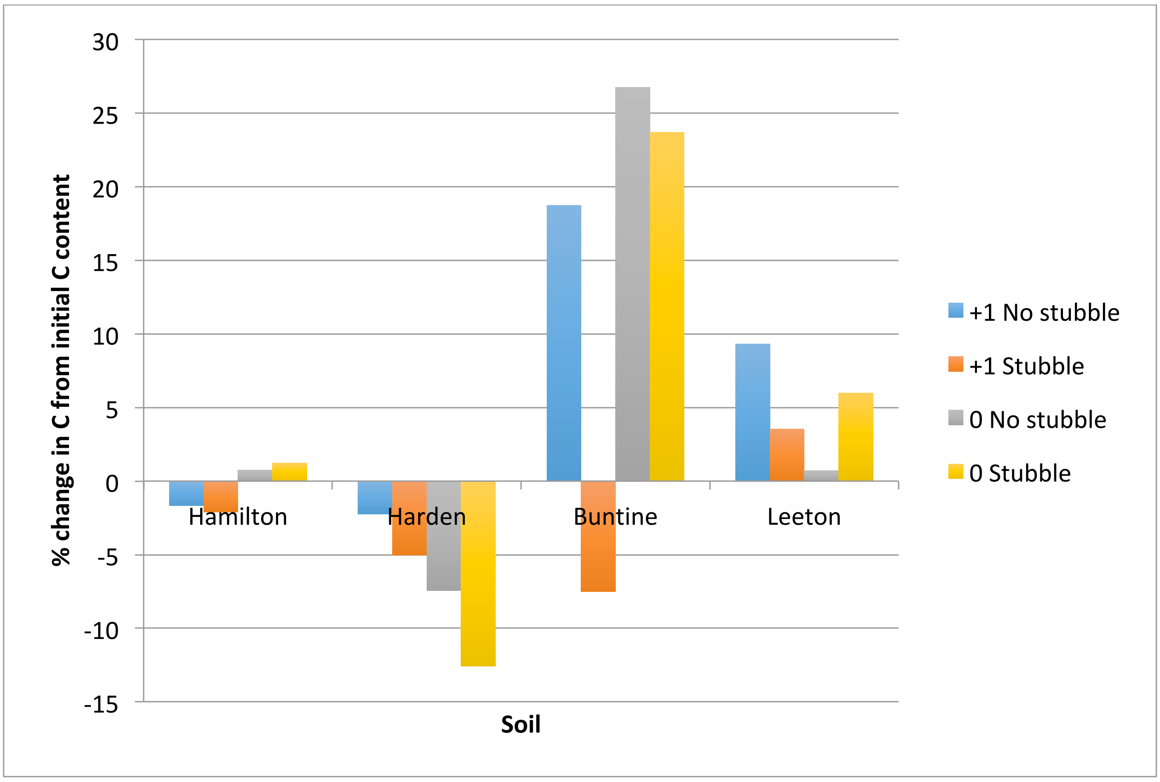


Figure 4.1.2.2 *Change in C content with treatments from initial C content. These are given in percentage of the initial C content. Positive values indicate that there is an increase in C content from initial C, where negative values indicate a loss of C. 0 represent the soils where the sequestration method was not applied, where +1 is indicating the soils, where the sequestration method was applied in previous experiment on the soil.*

Impact of stubble on stability

This section is focused on the impact of OM on the stability of SOM. It has been problematized in chapter 3 that addition of only OM could increase the microorganisms' mineralisation of SOM, to gain access to nutrients.

It can be seen on Figure 4.1.2.2 that for the soils, where extra nutrients have been applied in earlier experiment, stubble decreases SOC more than if no OM was applied. The statistical analysis also shows that there is a significant difference in C-content in the soil if OM is applied to the soil (Paired *t*-test: t_{11}=-3.030, *P*=0.011)(Appendix 10). For the soils that had no extra nutrients applied there is on the other hand no significant difference in C-content when OM is applied (Wilcoxon signed-rank test: T= 40, *n*=12, *N*=12, *P*=0.937)(Appendix 10). SOM for soils, which have had the sequestration method applied is hereby influenced more by the application of OM than a regular soil.

In Figure 4.1.2.3 it is shown how application of straw as OM is influencing SOC compared to no application of OM. The difference between the two treatments is given as a percentage of C-content without OM. It appears that Hamilton is the soil influenced the least by the application of OM, where Leeton and in particular Buntine has a high decline in SOC when OM is applied.

Overall the application of OM decreases C-content in the soil (Figure 4.1.2.3). This could indicate that the nutrients in SOM from the sequestration method is more accessible and possibly not as stable as per-existing SOM, which is present in soils with no additional nutrients where there is no significant change in SOC when OM is applied to the soil. The increased decline in SOC for soils with additional nutrients could also be influenced by the microbial activity in the soil. An amount of nutrients could have been left from the nutrient treatments from earlier experiment. This could possibly have boosted the microbial activity in the soil and potentially increased positive priming effect.

Even though the first part of the analysis showed that there is no significant difference in the stability of SOM, this section shows that there is a significant difference in SOC when OM is applied to the soil. If same tendencies are seen in an actual farming system, then this will have an impact on the farming systems and could potentially mean that farmers have to be aware of their farming practice, when working with the sequestration method. If a farmer stops the usage of the sequestration method and starts to incorporate crop residues into the soil, SOM could possibly decline faster resulting in a loss of the new SOM the sequestration method was used to build up.

It would be necessary to investigate the change in priming effect in the soil after the sequestration method is stopped being used on a soil. This is to see how microorganisms react to the changed input. This could possibly help determine how a farming system should be taken care of, if a farmer decides to stop using the sequestration method, but wishes to retain formed SOM.

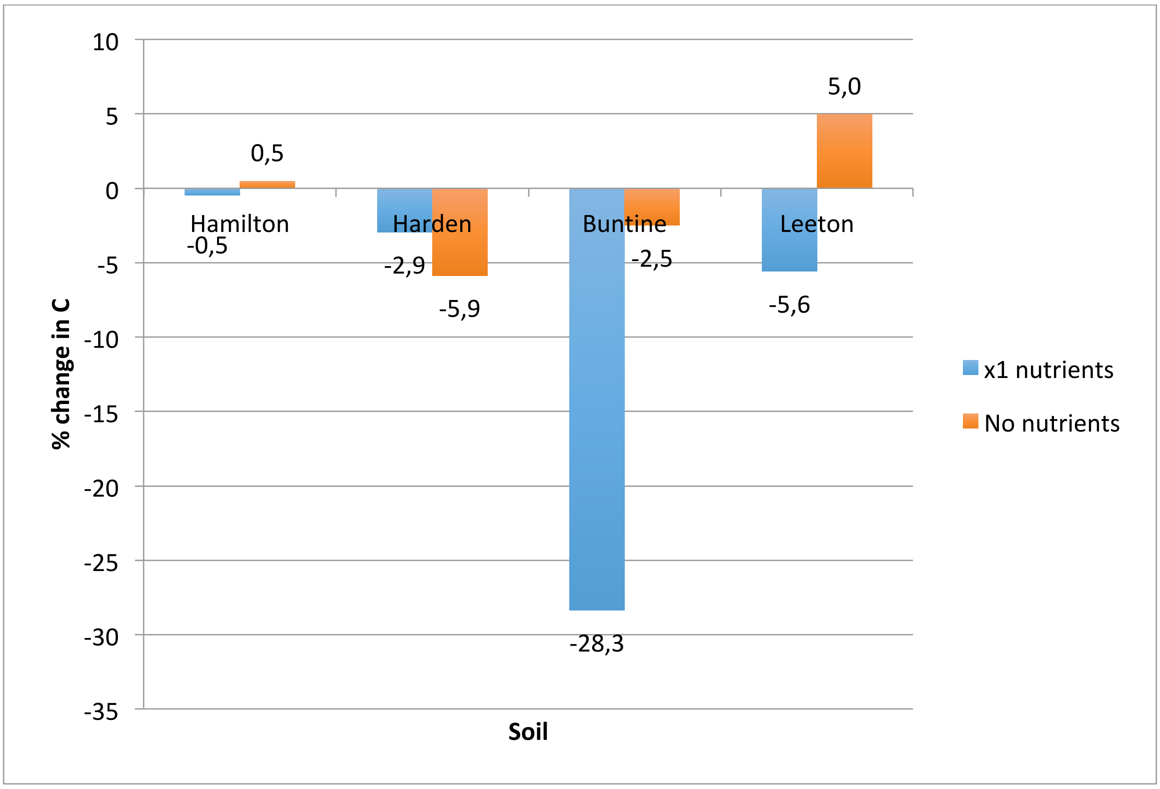


Figure 4.1.2.3 *Change in C content from soil in percentage. The change is the difference between treatment with and without stubble. The percentage shown on the graph indicate stubbles effect on SOC. Negative values shows that stubble decrease SOC more than no stubble, where positive values indicate that stubble increase SOC in comparison to no application of stubble.*

Summary

In this section the main conclusions from the second experiment will be outlined. The summary is also linked to the work question: *How stable is the SOM, which is formed with the sequestration method?*

Results showed that there was no difference in the stability of SOM whether the sequestration method was applied or not, indicating that formed SOM is of the same stability as pre-existing SOM. Results from experiment also showed that some minor changes in SOM occurred. Soils with the sequestration method applied had a tendency to reduce SOM content in the soil faster than if the sequestration method was not initially applied. The incubation only ran for two months, so to see the full effect of these tendencies and determine whether they have an effect on the stability of formed SOM, a longer incubation study would be needed.

It was also found that the application of OM increased the positive priming effect for the soils where the sequestration method had initially been applied. This could indicate that the nutrients in formed SOM are more accessible than those from pre-existing SOM, even though initial results showed that there was no significant difference in the stability between the soils.

4.1.3 Priming effects impact

One of the ways to lose SOM was through accelerated mineralisation. This experiment is focused on how SOM is possibly changed in the first period after nutrients are applied to the soil. This is to investigate if a positive priming effect occurs and to determine for how long applied nutrients are left mobile in the soil. In Figure 4.1 this part of the analysis is focused on the SOM dynamics when OM and nutrients are added to the soil. This SOM dynamic is related to the priming effect and changes in SOM.

It is shown on Figure 3.1.3.4 that the microbial activity is highest in the first week after incubation has been started, and that the microbial activity slows down after approximately 28 days. Therefore this experiment is run for 28 days, to identify the changes in SOM and effluxes in the first critical period after nutrients have been applied. Soil samples were taken for each time CO_2-traps were changed. Experiment was conducted on two different soils, also used in Experiment 2. These are Leeton and Buntine. The reasoning for choosing these two soils was that out of the four soils used to investigate the sequestration method, these two soils had the largest difference in soil texture. Leeton has high clay content, where Buntine is more sandy (Table 4.1.2.1).

The experiment is conducted to see if the application of nutrients increases SOM immediately, or if the increased microbial activity in the first week is a result of a positive priming effect or mineralisation of applied OM. This dynamic in the first period after nutrients are applied are important to understand, since a large amount of nutrients are mobile in the soil and could possible increase nitrate leaching.

Change in CO_2-effluxes

The CO_2-effluxes gives an indication of the microbial activity in the soil during the incubation. CO_2 emitted from the soil represent the microorganisms’ respiration. Higher respiration and through this CO_2 emissions indicates increased microbial activity.

Results shown in Figure 4.1.3.1 and 4.1.3.2 appears to follow the same development in CO_2-effluxes as found by Kirkby et al. (2014). Both soils have a significant increase in CO_2 emissions from the start of the incubation to seven days into the incubation (Wilcoxon signed-rank test: T= 78, *n*=12, *N*=12, *P*=0.003)(Appendix 11). This is the time span where there is the highest increase in microbial activity, which afterwards decreases significantly (Wilcoxon signed-rank test: T= 1, *n*=12, *N*=12, *P*=0.003)(Appendix 11).

If was found that for Buntine the increased microbial activity was already slowing down around day 14, indicated by no significant change in CO_2-effluxes between day 14 and 28 (Paired *t*-test: t_{11}=0.943, *P*=0.366)(Appendix 11). Leeton on the other hand still had a high microbial activity after 14 days, which also lead to a significant difference in CO_2-effluxes between day 14 and 28 (Paired *t*-test: t_{11}=2.604, *P*=0.025)(Appendix 11). The activities' impact on the soil is analysed in the section focused on changes in SOM.

There was also a significant difference between treatments CO_2-effluxes, in addition to the significant change in CO_2-effluxes during the incubation (Paired *t*-test: t_{11}=-6.256, *P*=0.000)(Appendix 11).

For Buntine CO_2 emissions were significantly different between all the treatments. This was in particular between the treatment with no nutrients or straw and the treatment where nutrients were applied with straw. For Leeton the two treatments with straw were not significantly different indicating that the microbial activity and possibly changes in SOC are similar.

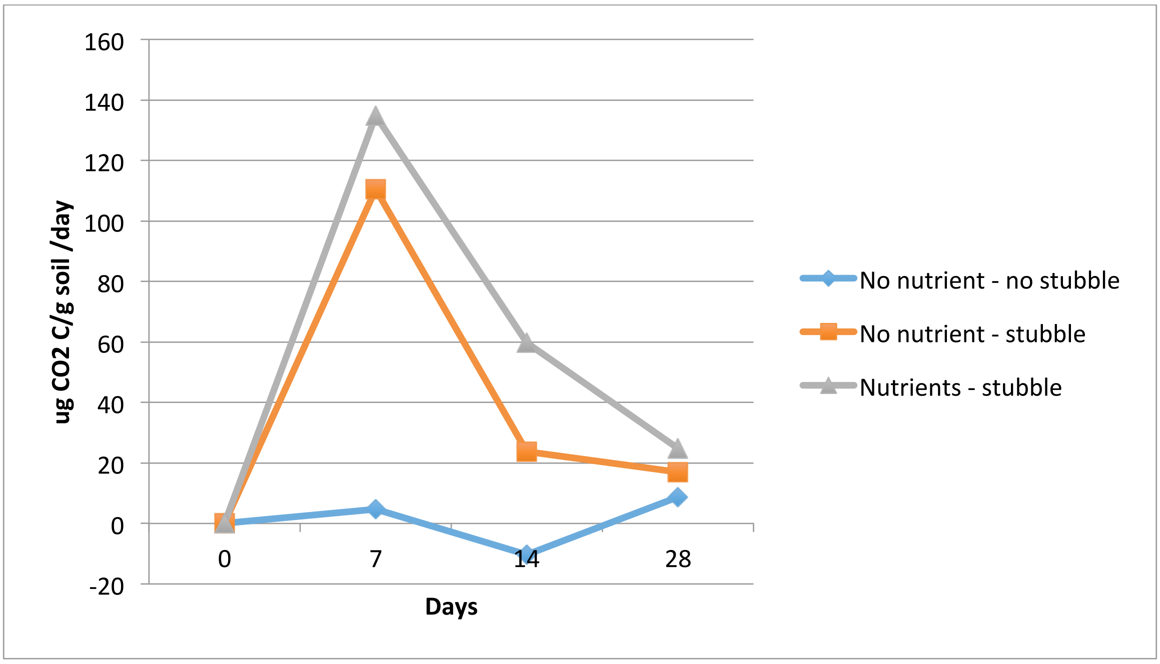


Figure 4.1.3.1 *Changes in CO_2 effluxes for Buntine. Emissions are for the three treatments used in the incubation. Negative value for day 14 could indicates that the jar was not screwed on properly. The changes indicate the microbial respiration from the soil. Grey legend indicates the sequestration method.*

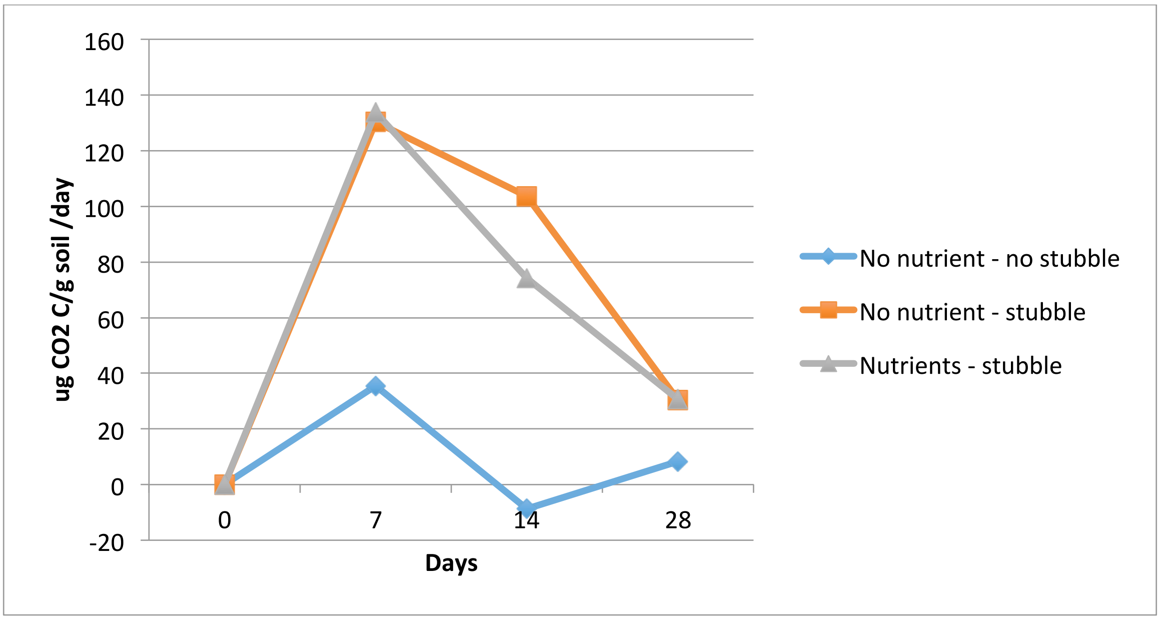


Figure 4.1.3.2 *Changes in CO_2 effluxes for Leeton. Emissions are for the three treatments used in the incubation. Negative value for day 14 could indicates that the jar was not screwed on properly. The changes indicate the microbial respiration from the soil. Grey legend indicates the sequestration method.*

Change in SOM

The change in SOM and hereby C-content in the soil gives an indication of the priming effect occurring at the given time in the incubation. A decrease in C-content could indicate that a positive priming effect occurs, where a negative priming effect could result in an increase in SOC.

Figure 4.1.3.3 and Figure 4.1.3.4 shows the change in C-content in the soil for the two soils. These are the changes for the three treatments. It appears that the two soils react in different ways to the application of nutrients and straw.

Leeton has an overall significant decrease in SOC over the first 7 days, when the microbial activity is highest (Figure 4.1.3.3, Figure 4.1.3.2) (Wilcoxon signed-rank test: T= 72, n=12, N=12, P=0.009)(Appendix 11). This decrease in SOC could indicate a positive priming effect and a mineralisation of SOM. This would result in an increased mobilisation of nutrients in the soil in addition to the nutrients already mobile as a result of the application of additional nutrients. This is a critical stage for the sequestration method, since the nutrients in the soil are not immediately used to increase SOM, but first being used to increase C-content after seven days (Figure 4.1.3.3). It would be a high risk in Denmark that the mobile nutrients available in the beginning of the application of the sequestration method could be leached, if high precipitation occurred. Losing the nutrients within the first seven days hereby seems to be the most critical time for Leeton soil. Nutrients could however possibly be retained in the soil given Leeton's high clay content (Table 4.1.2.1).

Buntine on the other hand has no change in C with the sequestration method during the first seven days (Table 4.1.3.1). This is significantly different from Leeton (Wilcoxon signed-rank test: T= 66, n=12, N=12, P=0.034)(Appendix 11), indicating that the soils react very differently to the sequestration method in the first seven days.

The changes in C content afterwards are not significantly different between the two soil types (Paired t-test: t_{11}=-1.713, P=0.115)(Appendix 11), even though the two soils seem to still react differently to the three treatments in the incubation (Figure 4.1.3.3, Figure 4.1.3.4). Where the application of straw and nutrients increase SOC after the decline in the first seven days for Leeton, Buntine has no significant change in C-content when nutrients are applied (Paired t-test: t_{11}=-1.157, P=0.272)(Appendix 11). Where Buntine has a minor decline in C content after the 28 days incubation cycle, Leeton has a minor increase in SOC. It appears that the increased C-sequestration found with the sequestration method therefore has to occur later on in the incubation cycle.

Leeton's treatments with either straw or straw and nutrients had no significant difference in CO_2-effluxes (Appendix 11). Results show that these two treatments have the same tendencies in regards to development in SOC in the incubation (Figure 4.1.3.4). Buntine on the other hand had a significant difference between all the treatments for both CO_2-effluxes and C-content in the soil (Appendix 11). The correlation between the microbial activity and the changes in SOC has been examined using Spearman correlation test. Results show that for Buntine CO_2-effluxes and the changes in C-content covary in a linear fashion (Spearman correlation: R_s=-0.675, N=36, *P*= 0.000)(Appendix 11). These are negatively correlated due to R_s-value being negative (Hawkins 2014). This means when CO_2-effluxes are decreasing indicating reduces microbial activity, then C-content in the soil increases. This correlation is not present for Leeton (Appendix 11). The negative correlation arises a number of questions, since the microbial activity is a primary driver for the formation of new SOM. If SOM is increased when microbial activity goes down, what are then driving the formation? It would be interesting to see how the C-content in the soil changes throughout a whole incubation cycle of 2 months. The negative correlation for Buntine could quite possibly be due to the two treatments where nutrients are not added, since both treatments have an increase in SOC, while the CO_2-effluxes decrease. In particular treatment with only straw has a continuous increase over the 28 days incubation cycle. The negative correlation could therefore have been given based on these results. However there is no significant change in C-content for the sequestration method in the 28 days time span, so the C-sequestration should occur later on in the incubation cycle, when the microbial activity is ultimately lower (Figure 3.1.3.4). Therefore the results from the negative correlation could still apply.

It would have been interesting to examine how much C was lost from the soil through respiration compared to how much C was build up or lost from the soil. However this is not possible in this experiment, since the CO_2-traps used in the experiment were not large enough to catch all CO_2 emitted from the soil in the first 7 days. Therefore the amount could be higher than what is given in Figure 4.1.3.1 and Figure 4.1.3.2.

None of the soils have an increase in SOC within the first seven days, which means that farmers need to be aware of the weather forecast before applying the sequestration method, since high rainfall could result in loss of applied nutrients and increase the environmental impact these days. This impact of rainfall could still have implications for Buntine, since there is still no increase in C-content in the first month (Table 4.1.3.1).

Table 4.1.3.1 *Change in C over time in percentage of the previous C content. Day 7 is change from initial C-content in percentage. Negative values indicate that there is a decrease in SOC. Column ´Overall´ is the change from start to finish for the incubation. Negative values indicate a decrease in C-content from initial SOC.*

Soil	Treatment	7	14	28	Overall
Leeton	No nutrients	-3	-2	1	-4
	Straw	-3	5	-1	1
	Straw + Nutrients	-3	2	2	1
Buntine	No nutrients	76	-19	4	43
	Straw	10	2	12	29
	Straw + Nutrients	0	1	-2	-1

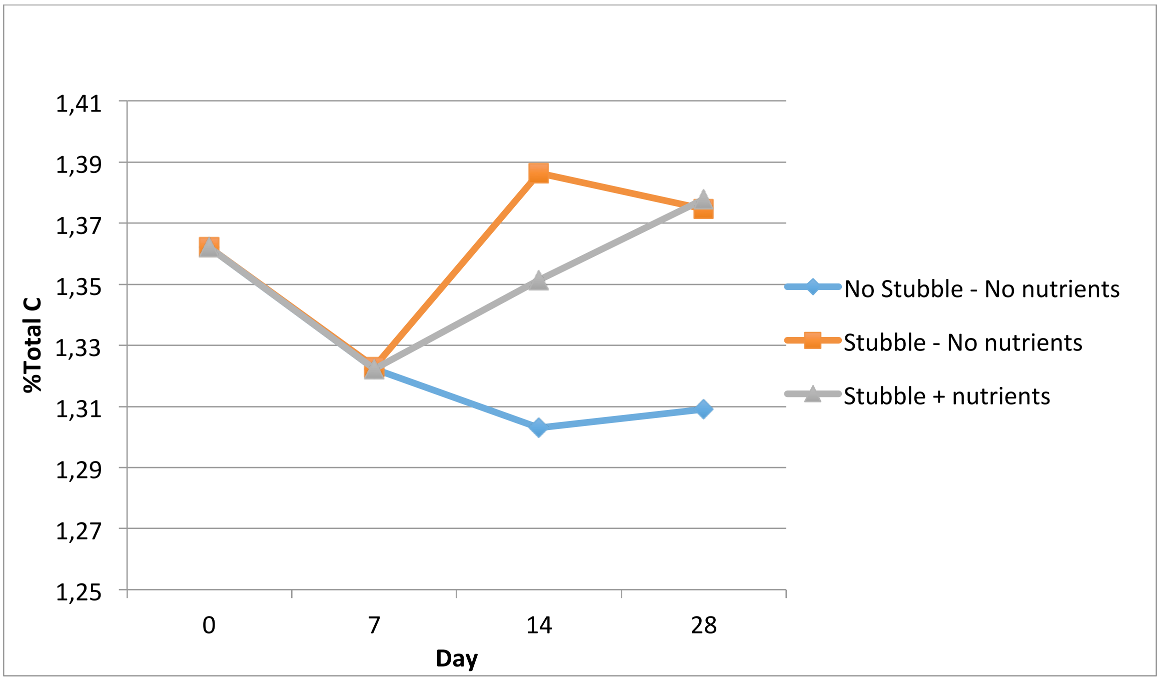


Figure 4.1.3.3 *Change in C content over time in the first 28 days of incubation for Leeton. Results show the changes in soils, which had both the sequestration method applied (stubble + nutrients) and two other treatments to see the effect of each of the components in the sequestration method.*

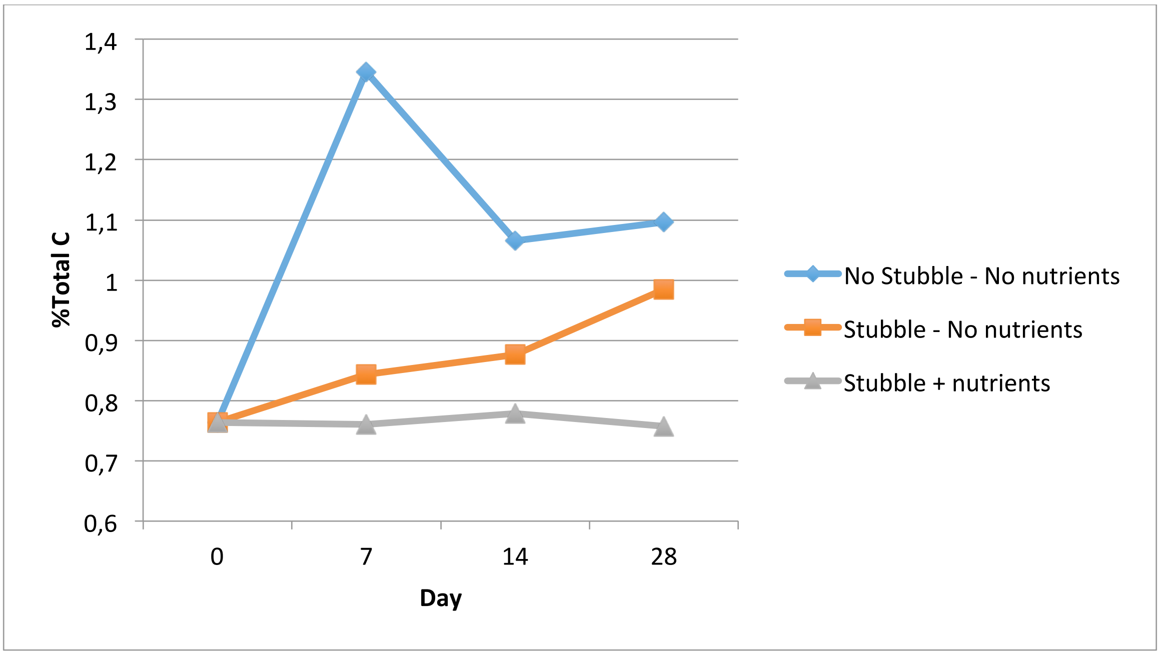


Figure 4.1.3.4 *Change in C content over time in the first 28 days of incubation for Buntine. Results show the changes in soils, which had both the sequestration method applied (stubble + nutrients) and two other treatments to see the effect of each of the components in the sequestration method.*

Summary

In this section the main conclusions from the third experiment will be outlined. The summary is also linked to the work question: *When is SOM formed with the sequestration method?*

It was found that SOM did not increase significantly during the first month of an incubation cycle, indicating that SOM either has to be formed later on in the incubation cycle, or that the expected increase in NHE with the sequestration method did not occur during this experiment. The soils did however react differently to the sequestration method during the first seven days of the incubation, where the microbial activity was the highest. One of the soils had an increased positive priming effect during this period, though no overall change was detected during at the end of the incubation study.

Nutrients stayed mobile in the soil throughout the incubation study. This could pose as an environmental risk if a leaching of nutrients occurred in the given period in a farming system.

4.2 Integration of method in farming system

In these sections the focus is on the integration of the method in a farming system focusing on the consequences of an application in regards to NHE and costs. This part of the analysis takes outset in calculations on NHE from current fertilizer regulations in Denmark and the necessary nutrients added to the system to increase NHE. This approach does not take outset in results in experiment 1, but is rather an examination of what could be expected and possible, if the sequestration method had the same effect on soils as in Australia. Furthermore a rough estimate of the costs to implement the method will be presented to determine whether the method will be beneficial to integrate in Danish farming system. In the last section focus will be set on the reduction of GHG emissions by the sequestration method.

4.2.1 Net Humification Efficiency

Before trying to investigate a potential implementation of the method to increase C-sequestration, it is relevant to investigate NHE under current regulation, to understand the limitations in the regulation and how efficient C can theoretically be stored in the soil in the pre-existing farming system.

In this example application of NPS has been added according to the allowed applications for winter wheat (Landbrugs- og Fiskeristyrelsen 2017). Since the allowed fertilizer application varies between crops (Landbrugs- og Fiskeristyrelsen 2017), the results might differ according to the crop sowed in the system. Straw has been added to the system as a residue of 10 t ha^{-1} (Kirkby et al. 2013). It is the NHE of degradation of this material, which is being investigated in this example. When NHE is referred to it indicates how much of the residue, that will be built into SOM. As a default the aim of NHE is considered to be 30%. This is because this is considered the highest NHE possible for the residue (Kirkby et al. 2013; Kirkby et al. 2014). The nutrient application to the system takes outset in the nutrient ratio in the applied residues. The following calculations are based on the ratio for straw given by Kirkby et al. (2013) (C:N:P:S = 45:0.61:0.0693:0.0629). For both Experiment 1 and 3 the ratio of the straw is different from this ratio (Appendix 9 & 11). For the Danish straw material the available nutrients were in particular low for N (Appendix 9) compared to straw nutrient concentrations in Kirkby et al. (2013). This indicates that the application of nutrients may have to be higher than calculated in the following sections depending on straw used in given experiment. The reason for using the ratio from Kirkby et al. (2013) is because this has been more thoroughly analysed compared to straw used in Experiment 1.

In Table 4.2.1 the first row indicates NHE if the application of fertilizers to the crop were only meant to increase humification. It shows that the application of N is high above the necessary application, since it is not possible to have a NHE of 72%. It is also shown that S is the limiting nutrient in the Danish regulation. If S could be increased to match NHE for P then the NHE aim of 30% would almost be met. The difference between the initial NHE for the different nutrients is also shown in Figure 4.2.1 when $x = 100$.

However it is necessary to take the uptake of nutrients in plants into account, when NHE is being assessed. It is not possible to have 100% of nutrients, added to the soil, available for humification. In row 2 NHE is shown if 30% of the added nutrients stay in the soil. NHE will decrease to 5%, even though the amount of N still available could facilitate a NHE of 22%. It is shown in Figure 4.2.1 how NHE will change in relation to percentage increase in plant uptake. The amount of nutrients taken up by plants differs between N, P and S. Setting an estimate of 70% plant uptake may therefore not be accurate for all the nutrients applied to the soil. However in the following sections this variation between nutrients uptake has not been taken into account.

Table 4.2.1 *NHE for system with regulation. Shows changes when there is and is not a plant uptake. Third row is the additional nutrients necessary for a 10 ha. Farming system with an application of 10 t straw ha^{-1}, and an aim for 30% NHE of the straw.*

Net Humification Efficency				
Nr.	**Variable calculated**	**N**	**P**	**S**
1	Humification in straw w. regulation no uptake by plants	72%	28%	17%
2	Humification in straw w. regulation and 70% uptake by plants	22%	8%	5%
3	Extra Nutrient input for 30% NHE after 70% plant uptake (kg)	497.5 kg.	216 kg.	178.1 kg.
4	Percentage increase in current regulation to reach 30% NHE%	24%	120%	356%

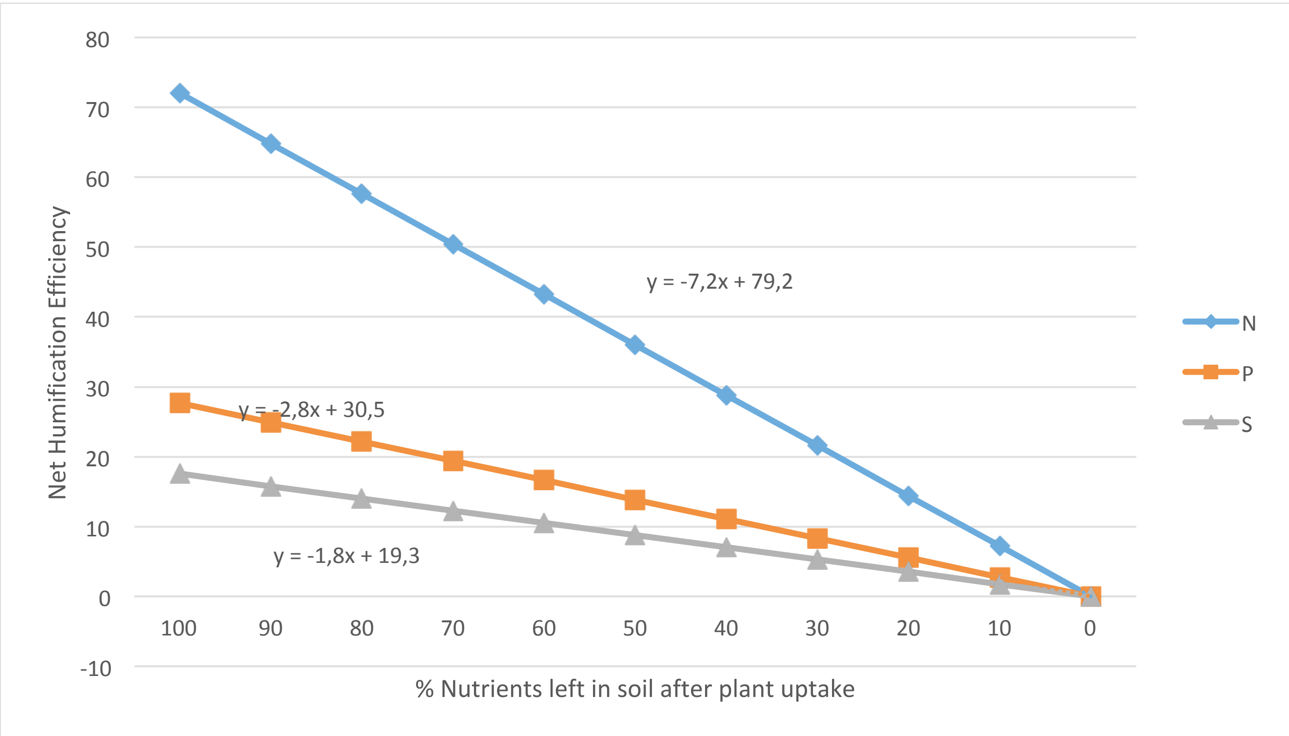


Figure 4.2.1 *Graph showing the change in NHE with changes in nutrients available in the soil. 100% on x-axis represent the NHE if nutrients were applied according to fertilizer regulation for winter wheat, but none of the nutrients were taken up by plants. The equation relating to each of the linear regressions outlines how much NHE is reduced by when plant uptake increase. N has the highest decrease in NHE, where S has the lowest.*

There is a difference in how the NHE changes for the different nutrients in relation to plant uptake. As given by the trend line in Figure 4.2.1 the NHE changes most drastically with changes in N. For each 10% less nutrients available in the soil NHE decreases with 7.2% for N, where it only decreases with 2.8% for P and 1.8% for S. This shows the impact of plant uptake on the nutrients.

It is shown in Table 4.2.1 that S is the limiting nutrient for C-sequestration. However there are not the same restrictions on S application to fields as there are for N and P (Landbrugs- og Fiskeristyrelsen 2017). Therefore the application of S can be increased to fit the desired NHE of the other nutrients. P is therefore the limiting factor under current fertilizer regulation.

To increase NHE to 30% an additional nutrient application would be necessary. If the offset is still fertilizer application for winter wheat and a plant uptake of 30% this would mean that the application of N should increase by 23%, P by 120% and S by 356% (Table 4.2.1). The additional nutrients are a significant increase from current application, which can result in an environmental impact, if NHE ends up being lower than expected, when nutrients are added to the soil. This environmental impact will therefore be due to nutrients not being immobilised in SOM as expected, but instead being mobile in the soil and therefore prone to a potential leaching.

When integrating this method the farmer needs to be aware of what crops he/she has in his/hers crop-rotation since there is a variation in the amount of fertilizer allowed. Especially N varies a lot between the crops. However it has also been shown in this section that it is P and in particular S that are the limiting factors (Figure 4.2.1). And it would therefore be beneficial for the farmer to focus on these, in particular S, to increase NHE.

4.2.2 Costs

Since the method involves an increased nutrient input to meet a higher NHE (Chapter 4.2.1), there will be some immediate upfront costs relating to the method. A minor analysis on the costs will be presented in this section. The benefits are in this section only presented as the subsidies from increasing the C-pool in the soil, and are not related to the possible impact the sequestration method might have on yield.

Costs are in this section determined as the costs relating to the fertilizer application. This is merely the costs for the actual nutrients and not costs relating to distribution on fields and other tasks relating to application in farming system.

Benefits are based on the economic benefits as calculated in GreenCarbon (2005). Costs are based on the prices for 1 kg. of each nutrient from Landbrug & Fødevarer Planteproduktion (2014). Other potential costs linked to the sequestration method, such as fuel, are not incorporated into the following calculations.

In Figure 4.2.2.1 it is visualised when it will be profitable for the farmer to invest in additional nutrients. In the figure there is focused on both nutrients left in the soil and different NHEs. The graph shows what NHE would be beneficial under different initial conditions. It is shown that if more nutrients are left in the soil, a higher NHE will be beneficial for the farmer.

If 40% of initial fertilizer application is left in the soil after plant uptake, then it will be economic beneficial for a farmer to aim for a NHE at 21% (Table 4.2.2.1). This involves a decrease in pre-existing N application of 2.3%. This might have a beneficial impact on the environment, since N input will be decreased. However both P and S application needs to be significantly increased. Especially S application needs to be increased with 230% from current application, to reach a NHE of 21%.

A reduction in N application to the system is over all the main cause for the beneficial outcomes for the calculations in Figure 4.2.2.1. If the application of N is not reduced by 2.3% for a 60% plant uptake, then the integration of sequestration method will be accompanied by a cost instead of a gain.

This emphasises the importance of an accurate and correct application of fertilizers, so both the desired NHE and economical profit can be met.

If the farmer wants to increase NHE to 30% it will be an economic cost. The loss to increase NHE to 30% varies between -348 kr. pr. hectare and -1093 kr. pr. hectare from 40% left in soil to 0% left in soil (Figure 4.2.2.1). If the farmer is willing to adapt the method disregarding the costs, then it is necessary to be sure of how much the method can mitigate climate change. As shown in Experiment 1, there was no immediate increase in SOC with the method nor NHE, uncertainties in the sequestration methods impact on reducing GHG emissions is therefore still uncertain.

***Table 4.2.2.1** Overview of the highest NHE, which is beneficial for farmer when different % of initial fertilizer is left in the soil. First column shows how many % of fertilizer is left in the soil after plant uptake. NHE in the second column relates to Figure 4.2.2.1 and is the NHE where benefits are higher than the costs for each of the different nutrient uptakes (Appendix 5). The fertilizer applications under current regulation are as follow: N P S. The columns N, P and S indicate how much these applications has to increase of decrease in % of current application* (Landbrugs- og Fiskeristyrelsen 2017). *Last column shows the economic benefit pr. hectare for each of the plant uptakes.*

Nutrients left in soil	NHE	N (% of regulation)	P (% of regulation)	S (% of regulation)	Benefit (kr. ha^{-1})
40%	21	-2.3	65	230	4.0
30%	15	-3.1	45	163	29.5
20%	10	-2.1	30	109	19.7
10%	5	-1.0	15	54	9.8
0%	0	0	0	0	0

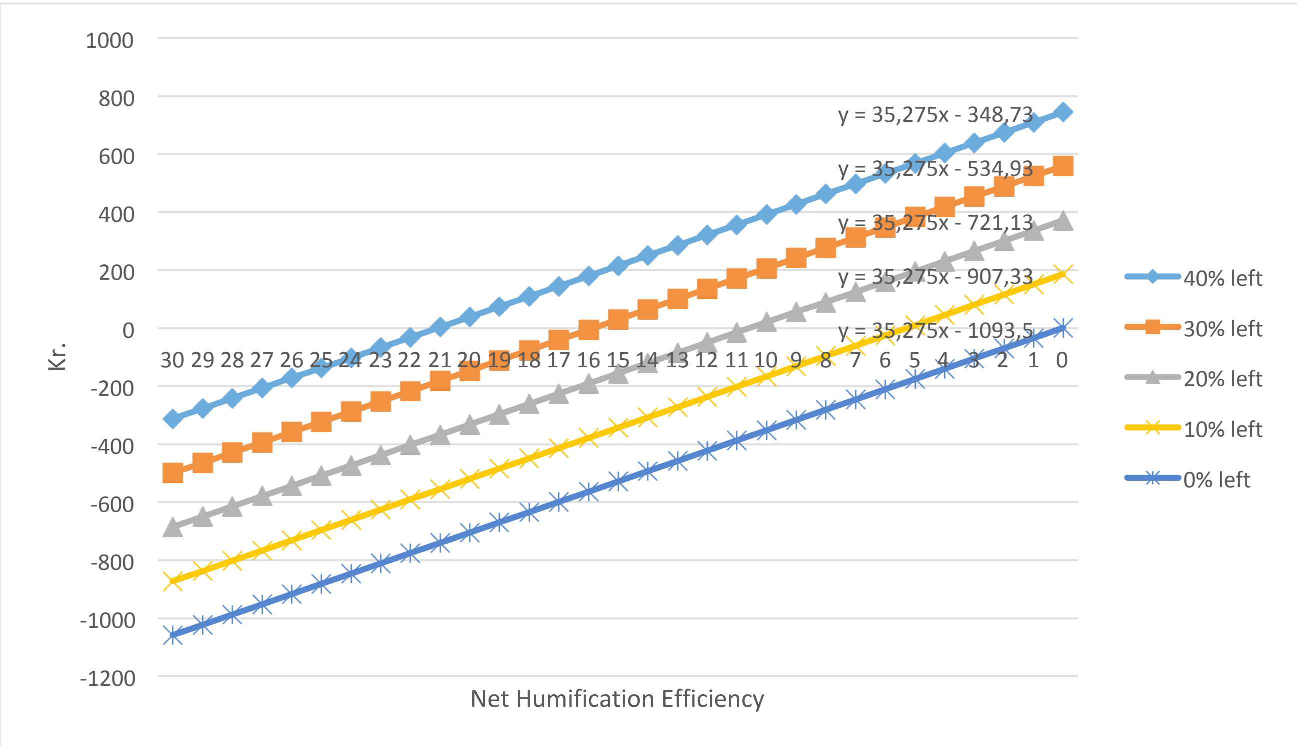


***Figure 4.2.2.1** Changes in economic benefit for increasing NHE for 1 ha. Negative values indicate a loss for farmer at different NHEs. Where positive values indicate an economical gain for the farmer. The legend indicates different initial stages of the soil. The percentage is an expression for how much of the applied fertilizer is left in the soil, after the plant uptake. This is linked to Table 4.2.2.1.*

4.2.3 Mitigation

This section will contain calculations relating to the reduction in GHG emissions from an integration of the method. These reductions will be set in relation to different NHE, to investigate the potential for the sequestration method as a mitigation tool, if NHE was as found in Australian experiments. Calculations for C-sequestration will be based on calculations in GreenCarbon (2005) and by usage of data from the bank of statistics (Danmarks Statistik 2016b).

The following example is focused on the GHG reduction from the sequestration method in relation to the requirements for 2020 with an overall reduction of 40% in national GHG emissions (Miljøministeriet et al. 2013). The example takes outset in a NHE of 30%:

> *With an addition of 10 t straw residue* ha^{-1}*/year 4.5 t* C ha^{-1}*/year will be added to the soil (Appendix 5). With a NHE of 30% 1.35 t* C ha^{-1}*/year will be humified which is an equivalent of 4.95 t* CO_2 *ha*$^{-1}$*/year.*
>
> *If the entire cultivated area in Denmark (2,662,030 ha) increased NHE by 30%* (Danmarks Statistik 2017b)*, then 13.2 million tonnes* CO_2 *would be sequestrated pr. year.*
>
> *Agriculture in Denmark accounts for 21% of all emissions in the country (Regeringen 2013; Klima- energi- og bygningsministeriet 2012; Energi- forsynings- og klimaministeriet 2015). This is approximately 19.7 million t* $CO_{2\text{-}eq}$*/year out of a total of 93.9 mio t* $CO_{2\text{-}eq}$*/year* (Danmarks Statistik 2018)*. By sequestrating 13.2 million tonnes* CO_2*/year, emissions from agriculture could potentially be reduced by 67%. This is also shown in Figure 4.2.3.1.*

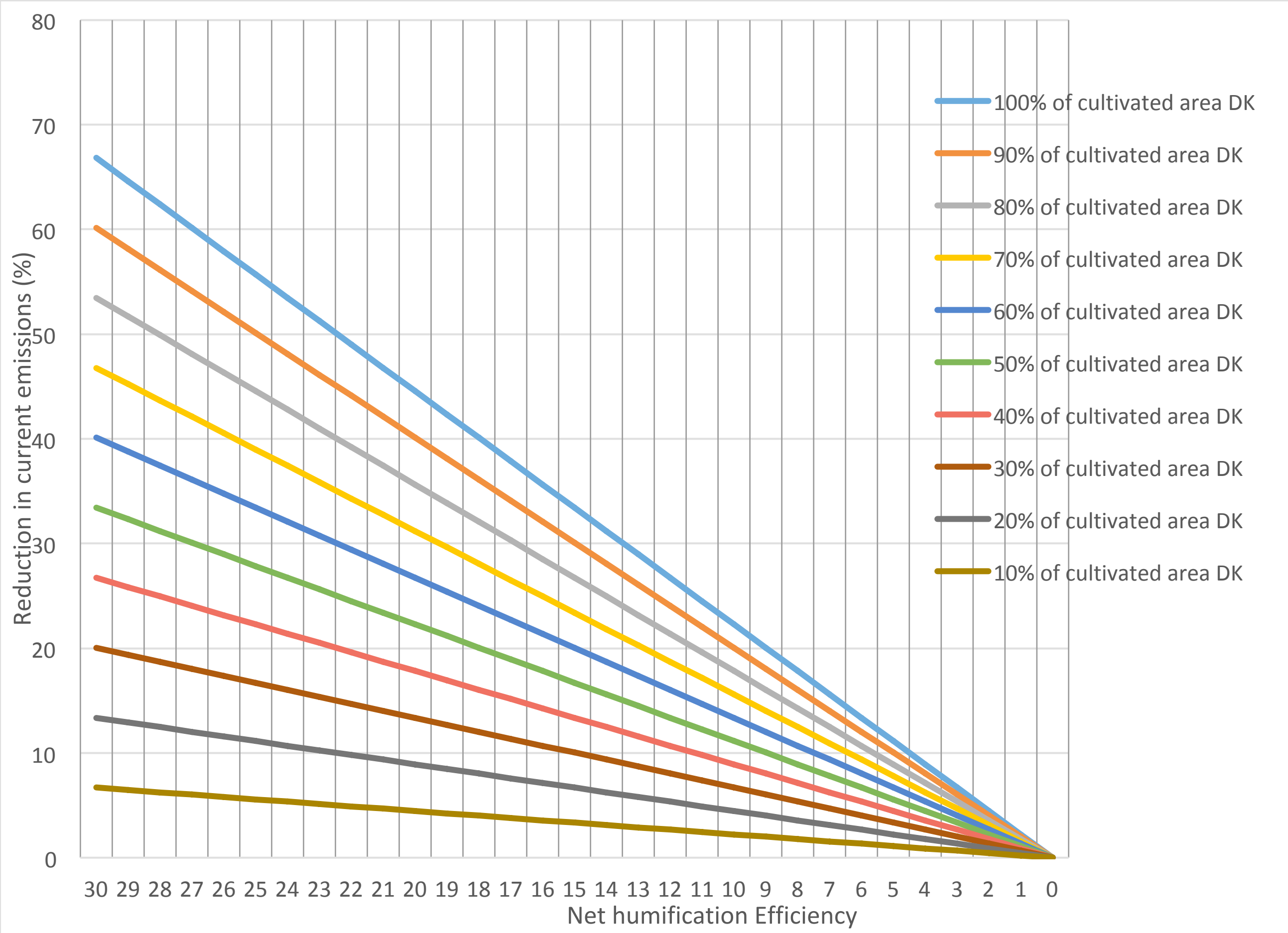


Figure 4.2.3.1 *Graph showing how big a reduction in GHG from agriculture that will be possible from different NHE. legend indicates how big a percentage of Denmark´s cultivated area, which needs to be used to accomplish the different emission reductions.*

In Figure 4.2.3.1 the potential reduction in emissions for different NHE is shown in relation to how big a percentage of the agricultural area in Denmark the practice is applied to.

In the cost section it was shown that an NHE of 21 was beneficial if 40% of nutrients were left in the soil. In the discussion the potential reductions in emissions with the sequestration method will be set in relation to mitigation tools used in Denmark, to determine how efficient the sequestration method could be compared to other mitigation tools.

It is necessary in addition to examining how much is mitigated and the costs regarding the sequestration method to also investigate the environmental impact, to understand whether there are areas in Denmark where the method is not applicable. This is done in the following chapter.

4.2.4 Summary

In this section the main conclusions from the calculation will be outlined. The summary is also linked to the work questions: *How efficient is the sequestration method under current fertilizer regulation?* and *When is it profitable for farmer to integrate the sequestration method?*

The sequestration under current fertilizer regulation is primarily restricted by the application of S. However the application of S is not a subject to the same restrictions in application as N and P. Therefore P can end up being the limiting nutrient under current fertilizer application. A significant increase in primarily S and P would be necessary to meet a NHE of 30%. However a NHE of 30% is not found cost efficient in the analysis above. It was found that highest NHE possible without any further costs for the farmer is a NHE of 21%. This profitable NHE is primarily based on a reduction in N application to the farming system, where the other two nutrients are increased significantly. It is important for a cost efficient sequestration method that the nutrient application is accurate, since a variation of 2% in N application can make the sequestration not financially beneficial for the farmer.

4.3 APSIM

This chapter will contain an analysis of the output from simulations conducted in APSIM. The model has been used to investigate the leaching of nutrients from a farming system and how this will change, if there is an increased fertilizer use.

For the simulations a crop rotation of spring wheat and spring barley has been used. This is based on crops used in crop rotations in Danish farming systems (Danmarks Statistik 2017a; Danmarks Statistik 2016a). The simulation is run for 38 years from 1963 to 2000.

Two simulations were conducted on various soil types in Denmark. The use of different soil types was done to investigate whether the environmental impact differ significantly between soil types, since this might help the strategic planning of fertilizer application in agriculture and to determine areas which are fit and not fit for an integration of the sequestration method. 5 different soil types have been used: Coarse sandy soil, Fine sandy soil, clayey sandy soil, clayey soil, and heavy clayey soil. Descriptions of the soil profiles can be found in Appendix 6. The name of the soil types are based on the JB-system and the distribution of clay, silt and sand in the soil. In the following chapter the soil simulated will be referred to by the name of the soil type.

It is assumed in the simulation that 70% of added nutrients under regulation will be taken up by plants. The extra nutrients are, as a result of this, calculated based on the nutrients left in the soil compared to the necessary nutrients for a 30% NHE of added residue, which in this case is 10t ha^{-1} wheat straw (Table 4.3.1). The increase in N application is higher than the ones calculated in chapter 4.2 (Table 4.2.1). This is because spring wheat and spring barley have been used in the simulations instead of winter wheat, which was used in Chapter 4.2.

It is only the application of N which is being investigated in these simulations, since simulations of the nutrient cycles for P and S, has not been integrated sufficiently into APSIM yet.

Table 4.3.1 *Overview of fertilizer application in simulations. 'Regulation' indicates the amount allowed to apply to field under current fertilizer regulation* (Landbrugs- og Fiskeristyrelsen 2017). *Extra nutrients are calculated based on the stoichiometric ratio. Assumed 30% of added nutrients under regulation are left in the soil. The aim is a NHE of 30%. Overview of calculations can be found in Appendix 7.*

Soil type	JB-system	Crop	Regulation	Extra nutrients
Coarse sandy soil	1	barley	126	201
Fine sandy soil	2		120	196
Clayey sandy soil	3-4		125	200
Clayey soil	7		131	204
Heavy clayey soil	8-9		131	204
Coarse sandy soil	1	wheat	122	198
Fine sandy soil	2		115	193
Clayey sandy soil	3-4		119	196
Clayey soil	7		124	199
Heavy clayey soil	8-9		124	199

4.3.1 Yield

In this section the yield is investigated to determine the potential impact of extra nutrients on the productivity of the farming system.

Since none of the data sets for yield are normal distributed (Appendix 8) a Wilcoxon signed rank test has been used to test for difference between the two fertilizer applications. The null-hypothesis is that there is no difference in yield between the two fertilizer applications. Results showed that there was a difference in yield for Barley on some soil types and a difference in yield for wheat on other soil types (Table 4.3.1.1). In Figure 4.3.1.1 the difference in yield is visualised. It is shown for wheat, that the extra nutrients increase yield for heavy clayey soils, clayey soils and clayey sandy soils from 6% up to 13%. Barley on the other hand has a decrease in yield when extra nutrients are applied which results in yield for fine and coarse sandy soil are decreasing with approximately 3.5%. For fine sandy soil and coarse sandy soil the extra nutrients will therefore overall have a negative impact on the productivity of the farming system, where the extra nutrients will have a positive impact on heavy clayey soil and clayey sandy soils. Clayey soil will both have an increase in yield in wheat, but also a minor decrease in yield in barley, but overall this will result in a positive impact on productivity. Therefore yield is not only influenced by the crop used in the system, but also influenced by the soil type of the farming system.

Table 4.3.1.1 *Overview of P values from statistical analysis (Appendix 8). Orange colour indicates a change in yield when extra nutrients are applied. The actual changes in yield are shown in Figure 4.3.1.1.*

	Barley	Wheat
Heavy Clayey soil	0.826	0.000
Clayey soil	0.024	0.034
Clayey sandy	0.163	0.002
Fine	0.004	0.126
Coarse	0.001	0.093

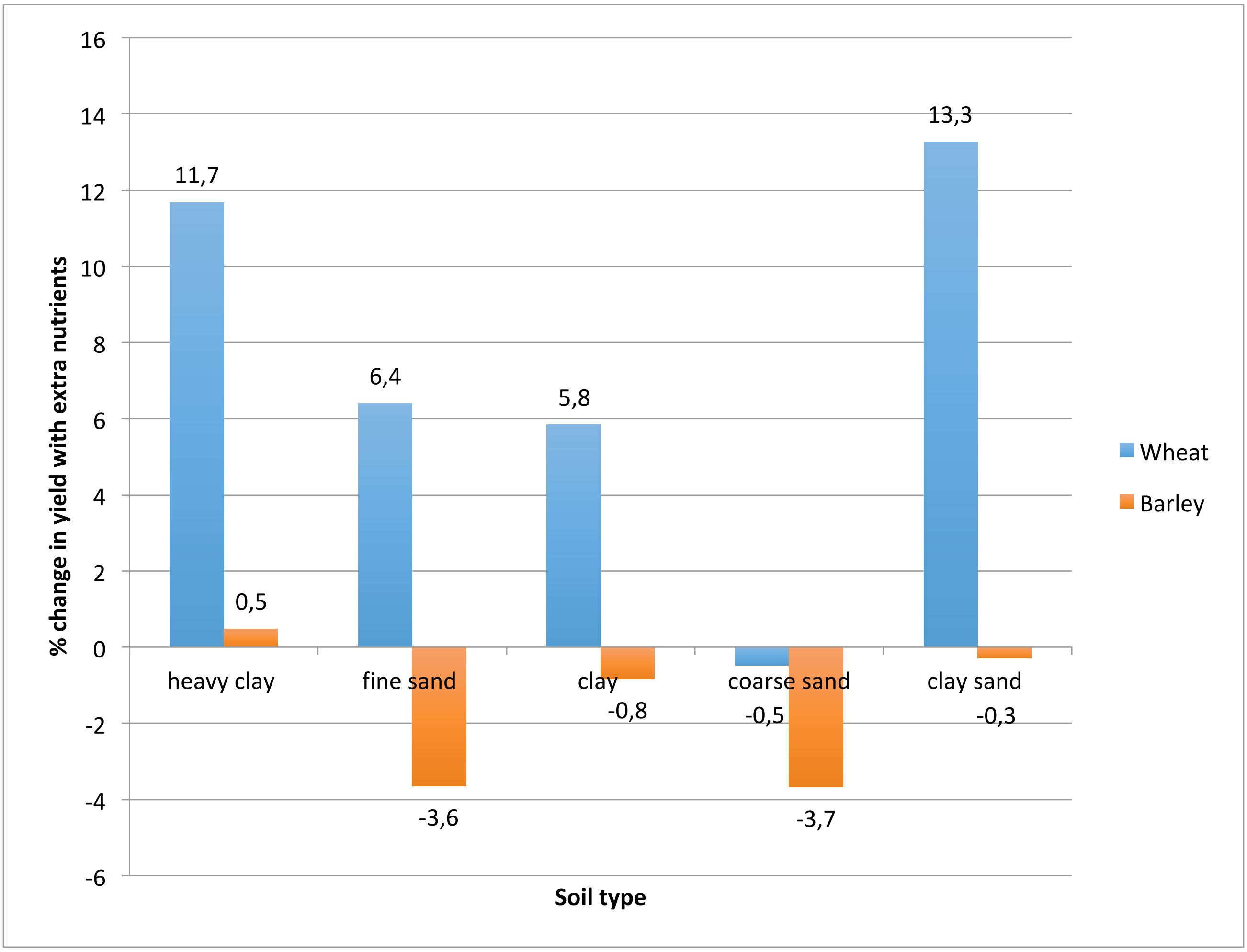


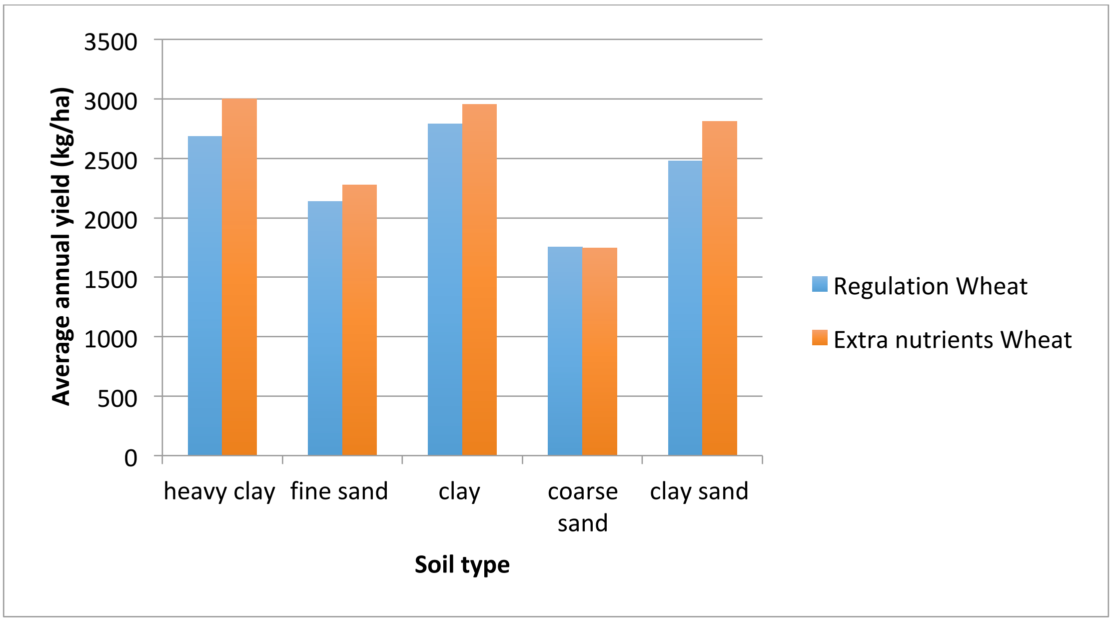
***Figure 4.3.1.1** Overview of how yield changes when extra nutrients are applied on average/year. The percentage indicates how much yield increase or decrease from current regulation with extra nutrients. Wheat primarily has an increased yield with the extra nutrients, where the effect on barley is a decrease in yield.*

Since there is a difference in yield for all the soil types the farmer should be aware of the potential impact the sequestration method can have on the productivity. It is necessary to investigate the impact on SOC to see if APSIM can simulate the increase in SOC with the sequestration method. If SOC is not increased that means the effect of the sequestration method was not simulated and the extra nutrients have not been immobilised in the stable part of the soil. Instead they will all be available to the plants, which could explain the high increase in yield shown in Figure 4.3.1.1.

On some soils the farmer could potentially expect an economical benefit when applying the sequestration method. However this also indicates that there is a risk connected to the increased fertilizer application, since it appears there is a large variation in how soil types deal with the extra nutrients and also how the two different crops deal with the extra nutrients. It is important that the farmer understands these uncertainties if wanting to implement the sequestration method.

In Figure 4.3.1.2 the yield for the different soil types is shown. For both barley and wheat coarse sandy soil has the lowest yield overall, where soils with the highest clay content have the highest yield. This difference can be due to the amount of clay particles in the soil.

This difference in yield between soil types indicates that productivity of the farming system can vary given the soil type in the field. As shown in Figure 4.3.1.1 fine sandy soil and coarse sandy soil are the soil types affected the most in regards to decreased yield and these are also the soil types that have the lowest yield overall for both crops (Figure 4.3.1.2). Applying the sequestration method would therefore be least beneficial on these soil types based on productivity of the system.



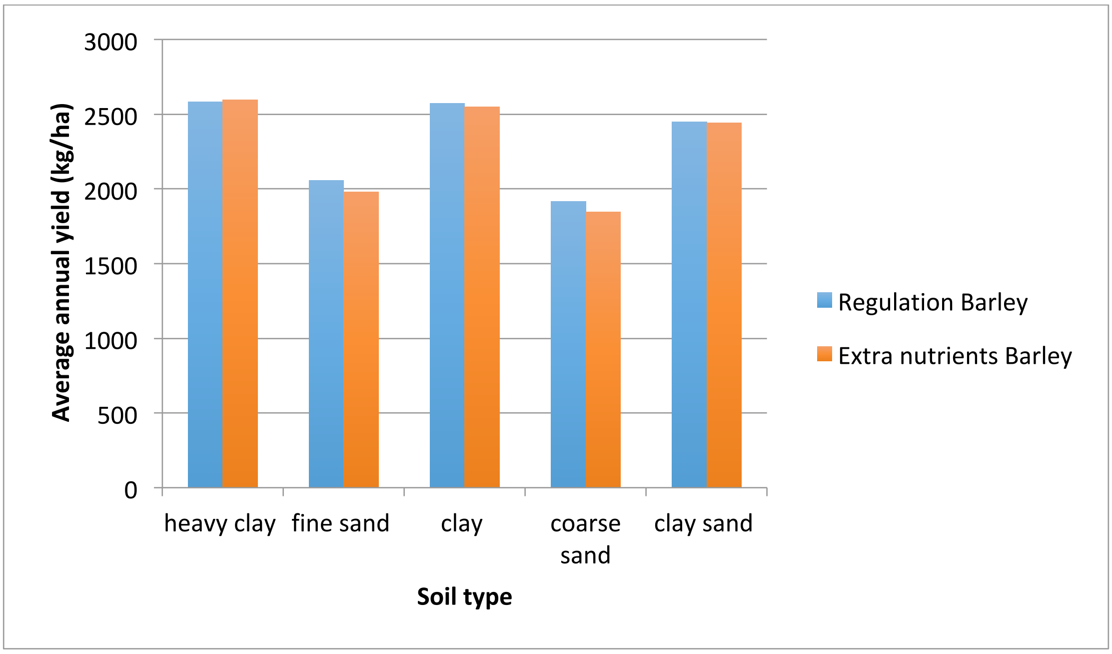


Figure 4.3.1.2 *Average yield/year for wheat (top) and barley (bottom) over the 38 years time span. Figure shows the yield under current regulation and when extra nutrients are applied. This is done for each of the soil types.*

4.3.2 SOC

In this section SOC as a parameter is being examined. This is to understand how APSIM deals with SOC as a parameter. The two simulations are compared to each other for each soil type, to investigate how the model deals with the extra nutrients in relation to SOC.

For all the simulations it is shown in Figure 4.3.2.1 that SOC decreases over time, though the annual reduction is different between the soil types. For example in Table 4.3.2.1 it is shown that for Clayey sandy (extra nutrients) soil SOC decreases with 0.012% each year, where SOC decreases with 0.086% for clayey soil (extra nutrients). Clayey soil has a 727% higher decrease in SOC than clayey sandy soil. As shown in Figure 4.3.2.2 most of SOC in the clayey soil profile is located in the top 30cm. layer, where SOC in clayey sandy soil is distributed more evenly throughout the profile, and has a larger amount in the deeper layers (Appendix 7). There is a higher turnover and mineralisation in the top layer in a soil, and this activity can lead to a faster degradation of SOC in this layer (Stevenson 1994). This difference in distribution in the profile is could have an impact on the difference in changes in SOC between soil types in the simulation. The distribution of SOC in the soil profiled is determined by the soil profiles used in the simulation (Appendix 6). This could indicate how much an impact the distribution of SOC in the simulation can have on the output of the simulation.

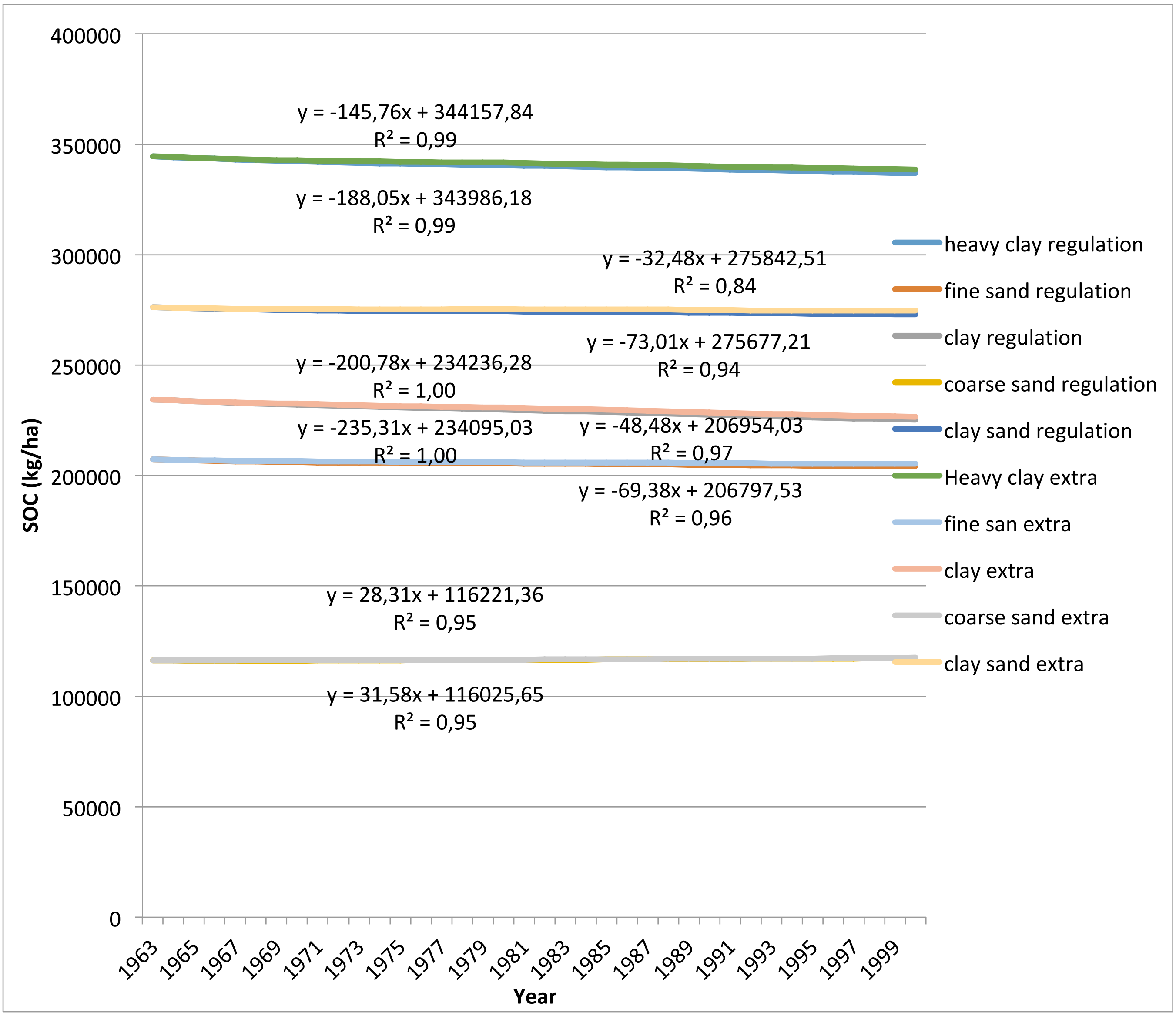
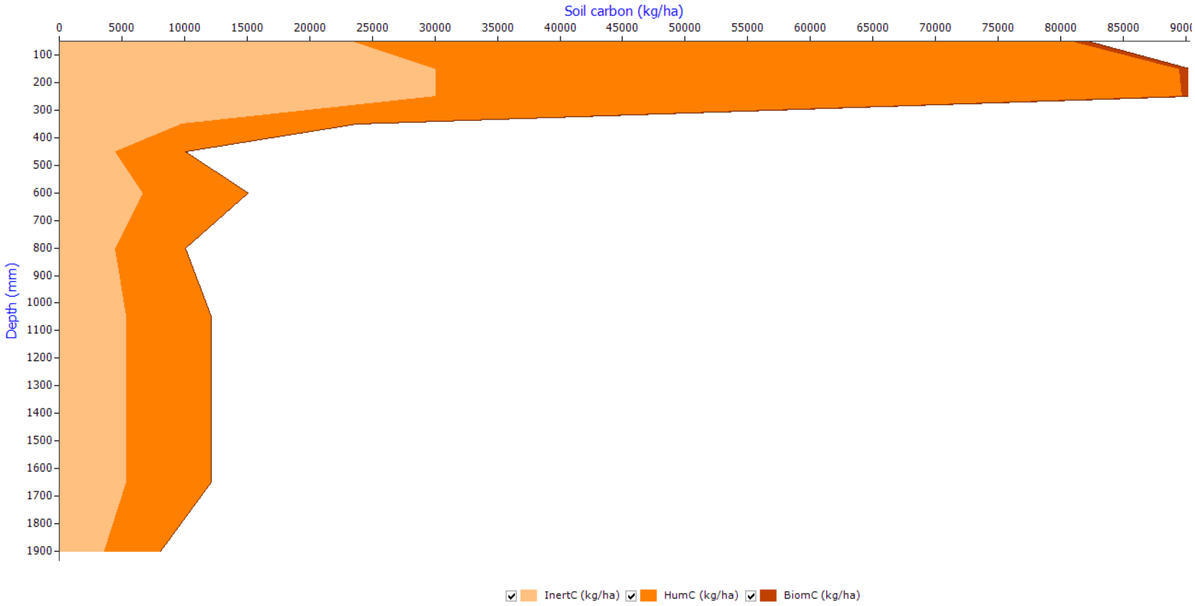


Figure 4.3.2.1 *Shows the change SOC over the 38 years simulation span. For each line a linear trendline has been added, to show the change over time. The equation above a line represents the trendline for the simulations with extra nutrients, where the trendline equation below a line represents fertilizer application according to regulations.* R^2 *shows how much of the data can be explained by a linear trendline. The reason why the initial SOC is different between the soil types is because the soils types the simulations were built on had different amounts of C available in the soil (Appendix 6).*



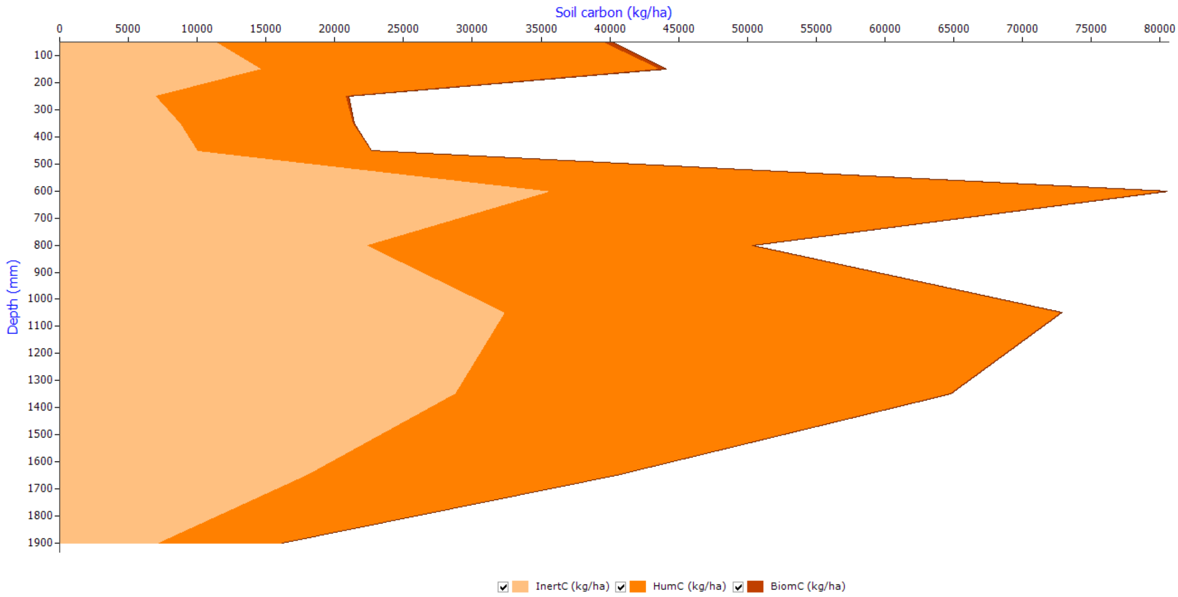


Figure 4.3.2.2 *Distribution of soil carbon in soil profiles. Top is for Clayey soil soil, bottom is for clayey sandy soil (Appendix 7). De different colours indicate type of C and gives indication of stability of C-pool. Lightest colour is inert C, orange colour is Humus C and red colour is Biomass C. Inert C is least available for mineralisation, where biomass C is the most available.*

If comparing the different fertilizer applications it is shown that for all the soils the additional nutrients increased SOC significantly (Appendix 8). Results show that for all the simulations the null-hypothesis was rejected, and there is a significant difference in SOC between the two fertilizer applications (Paired *t*-test: t_{37}=-12.452, *P*=0.000)(Wilcoxon signed-rank test: T= 741, *n*=38, *N*=38, *P*=0.000)(Appendix 8).

In Table 4.3.2.1 the difference in SOC between the fertilizer applications is shown. The largest difference in degradation of SOC is for clayey sandy soil, where reduction of SOC is lowered by 55%. Overall the extra nutrients reduced the reduction of SOC with 10%/year up to 55%. This may indicate that the extra fertilizer application may be able to have an impact on SOC and reduce the degradation. However at this stage the sequestration method slows down the positive priming effect, but there is still no increase in SOC with the method.

With the extra nutrients there was an expectation that 30% of added residue would be incorporated into SOM and through this SOC. Experiments on fields in Australia showed that over a five years period SOC had increased from 58t C ha^{-1} to 63.5t C ha^{-1}, when residue of 10 t ha^{-1} was added and nutrients were applied to match a 30% NHE (Kirkby, Richardson, Wade, Conyers, et al. 2016). This is not just a slowed down decrease in SOC as results from APSIM show (Figure 4.3.2.1, Table 4.3.2.1), but rather an actual increase in SOC from the initial state (Figure 4.3.2.3). This experiment in Australia resulted in an increase of 1.6% in SOC /year, where APSIM predicted that SOC on average would decrease by 0.04 %/ year with extra nutrients. Since these results contradict each other, it appears that APSIM was not able to simulate the impact extra nutrients could have on SOC.

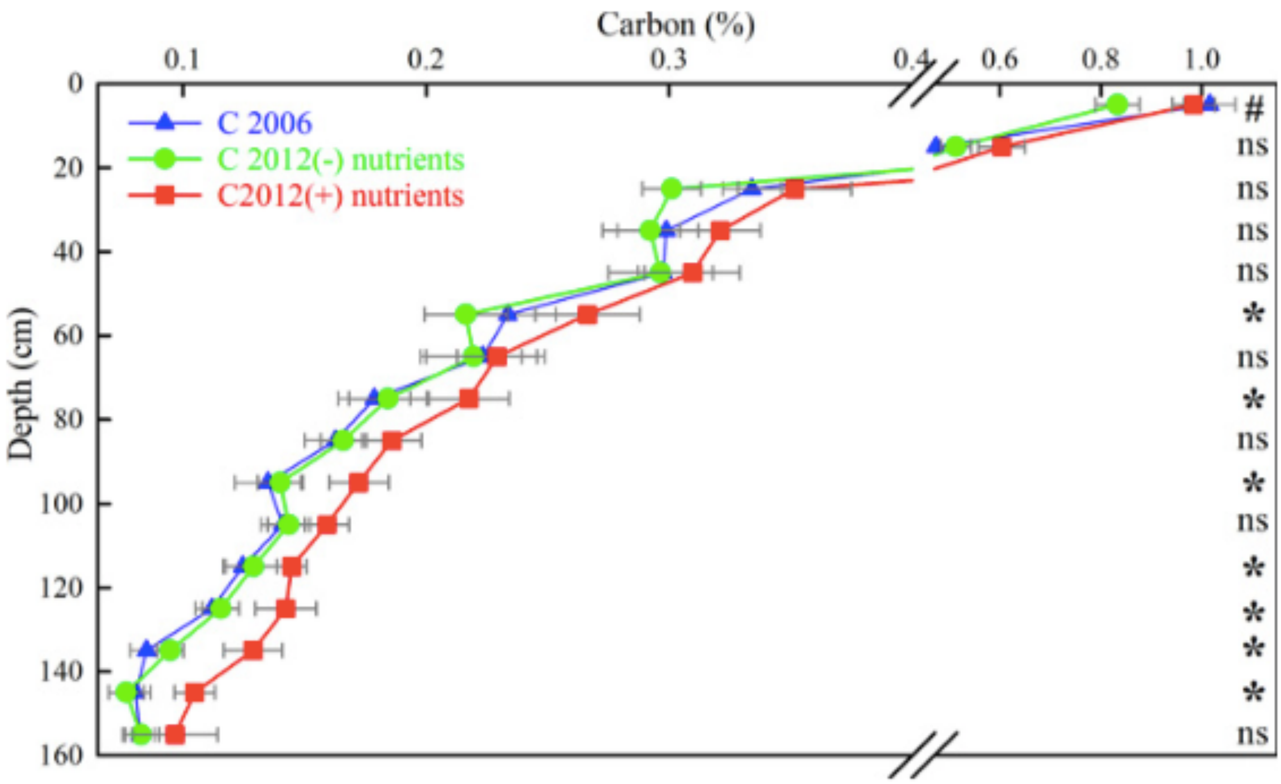


Figure 4.3.2.3 *Results from experiment in Australia. Green curve indicate C in soil depth with no extra nutrients applied. Red curve indicate C in soil depth with extra nutrients according to 30% NHE. Blue curve indicate the initial C content in soil depth (Kirkby, Richardson, Wade, Conyers, et al. 2016).*

The lack of increase in SOC indicate that APSIM does not show the change the sequestration method can have on the farming system, even though the simulations show that extra nutrients decrease the reduction in SOC. This lack of difference may be because APSIM has not been built to take the impact of changed fertilizer applications impact on SOM into account yet. This could amongst others be due to the fact that the sequestration method is a fairly new discovery and needs to be investigated further, before accurate forecasts can be simulated in APSIM. The conclusion from this section is therefore that it is possible to see a change in SOC with the sequestration method in APSIM. However this change is not merely as significant as seen in experiments (Kirkby, Richardson, Wade, Conyers, et al. 2016; Kirkby et al. 2014; Kirkby et al. 2013). Therefore APSIM is not used with focus on changes in SOC in this project, but rather with a focus on nutrient leaching from the system.

This lack of change in SOC will also have an impact on yield. Since the nutrients applied were not integrated into SOM, this means they were available for plant uptake and through this potential increased yield. When applying the sequestration method the availability of these extra nutrients to the plant will decrease hence yield will potentially decrease as well. Therefore the changes in yield when extra nutrients are applied (Figure 4.3.1.1) indicates the largest effect the extra nutrients can have on the productivity, since less nutrients will be available if SOM and SOC are increased with the sequestration method.

Table 4.3.2.1 *For each simulation the change in SOC/ year. This is given as the annual reduction in SOC. For each soil type a comparison for the two fertilizer applications was made. EX stands for extra nutrients, RE stands for regulation. The comparison of fertilizer application is shown as the difference %, which indicate how much more SOC is reduced with current regulation compared to a changed fertilizer application.*

Name	% reduction in SOC/year	% reduction of SOC after 38 years
Heavy clayey soil ex	0.042	1.567
Heavy clayey soil re	0.055	2.023
Difference %	**22.5**	
Clayey sandy ex	0.012	0.436
Clayey sandy re	0.026	0.980
Difference %	**55.5**	
Clayey soil ex	0.086	3.172
Clayey soil re	0.101	3.719
Difference %	**14.7**	
Fine sandy soil ex	0.023	0.867
Fine sandy soil re	0.034	1.241
Difference %	**30.2**	
Coarse ex	0.024	0.901
Coarse re	0.027	1.007
Difference %	**10.5**	

4.3.3 Nitrate leaching

In this section the potential changes in nitrate leaching caused by increased fertilizer application will be investigated. This is to determine the environmental impact of the sequestration method. Since it was shown in section 4.3.2 SOC that APSIM is not able to increase SOC in relation to the sequestration method, this section does not represent the nitrate leaching if the sequestration method worked in a Danish farming system. It is rather an investigation of the environmental impact in a worst-case scenario if none of the extra nutrients applied increase SOC, but were left mobile in the soil instead.

The application of extra nutrients results in a significant increase in nitrate leaching. A Wilcoxon signed rank test was conducted (Appendix 8). From the test it was concluded that there is a difference in nitrate leaching when extra nutrients are applied to the system (Wilcoxon signed-rank test: T= 1,321,949, n=13,870, N=13,870, P=0.000) (Appendix 8). In Figure 4.3.3.1 it is shown how much nitrate leaching is increased pr. year when extra nutrients are applied. For coarse sandy soil, which has the highest rise in nitrate leaching this is an increase of 211% from current leaching (Table 4.3.3.1). The lowest rise is for heavy clayey soil, where nitrate leaching is increased by 72%.

Textures with higher amounts of sand are more prone to leaching (Petersen 1994). This is also shown in Figure 4.3.3.1. Results show that clayey soil has a higher increase in nitrate leaching than clayey sandy soil. This can amongst other be due to the turnover of SOC. Clayey soil had a faster degradation of SOC than clayey sandy soil (table 4.3.2.1). By decreasing SOM and SOC the ability to immobilise nutrients are also decreased and more nutrients can therefore be mobile in the soil and prone to leaching.

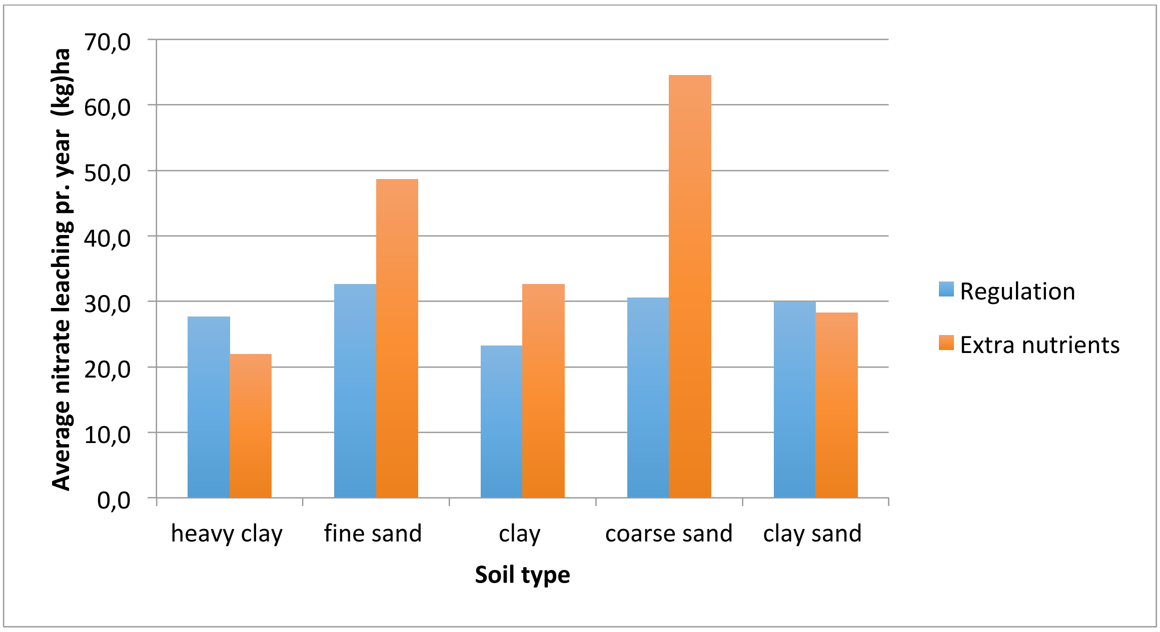


Figure 4.3.3.1 *Average annual nitrate leaching from the five soil types. Blue columns are the leaching with current regulation. Orange columns indicate leaching when extra nutrients are applied.*

Table 4.3.3.1 *Annual average nitrate leaching for the five soil types. First row shows the annual average in nitrate leaching for the two fertilizer applications. Second row shows the difference in leaching between the two fertilizer applications, and indicates how much nitrate leaching increases with extra nutrients. This is given in percentage of the leaching from current fertilizer application.*

	heavy clayey soil		fine sandy soil		clayey soil		coarse sand		clayey sandy	
	Regulation	Extra	Regulation	Extra	Regulation	Extra	Regulation	Extra	Regulation	Extra
Annual average (kg ha^{-1})	29	50	33	81	23	56	31	95	30	58
Increased leaching w. Extra nutrients %	72		149		141		211		94	

It is not just the difference in nitrate leaching between fertilizer applications, which is being investigated in this section. It is also the difference in nitrate leaching between soil types. This is to determine if some soil types in Denmark are unfit for an integration of the sequestration method. As shown in Figure 4.3.3.1 and Table 4.3.3.1 a difference in soil types nitrate leaching was detected.

To investigate this further a Kruskall- Wallis test was used to determine if there was a difference in leaching between soil types. Results showed that there is a significant difference in leaching. All combinations of soil types, except one, showed that there is a difference in leaching (Appendix 8).

When extra nutrients were applied clayey soil and heavy clayey soil did not differ significantly on a daily basis over the 38 year time span. However when looking at the accumulated nitrate leaching from the different soil types in Figure 4.3.3.2 it appears that there is a significant difference in the overall leaching from the two soil types. Therefore all the soil types differ from each other in nitrate leaching. Hereby it is possible to determine if some soil types are more fit for an application of the sequestration method. This indicates that it is important to be aware of the soil type in the field, when applying the nutrients, since there is a significant difference in leaching between all the soil types both before and after the extra nutrients are applied.

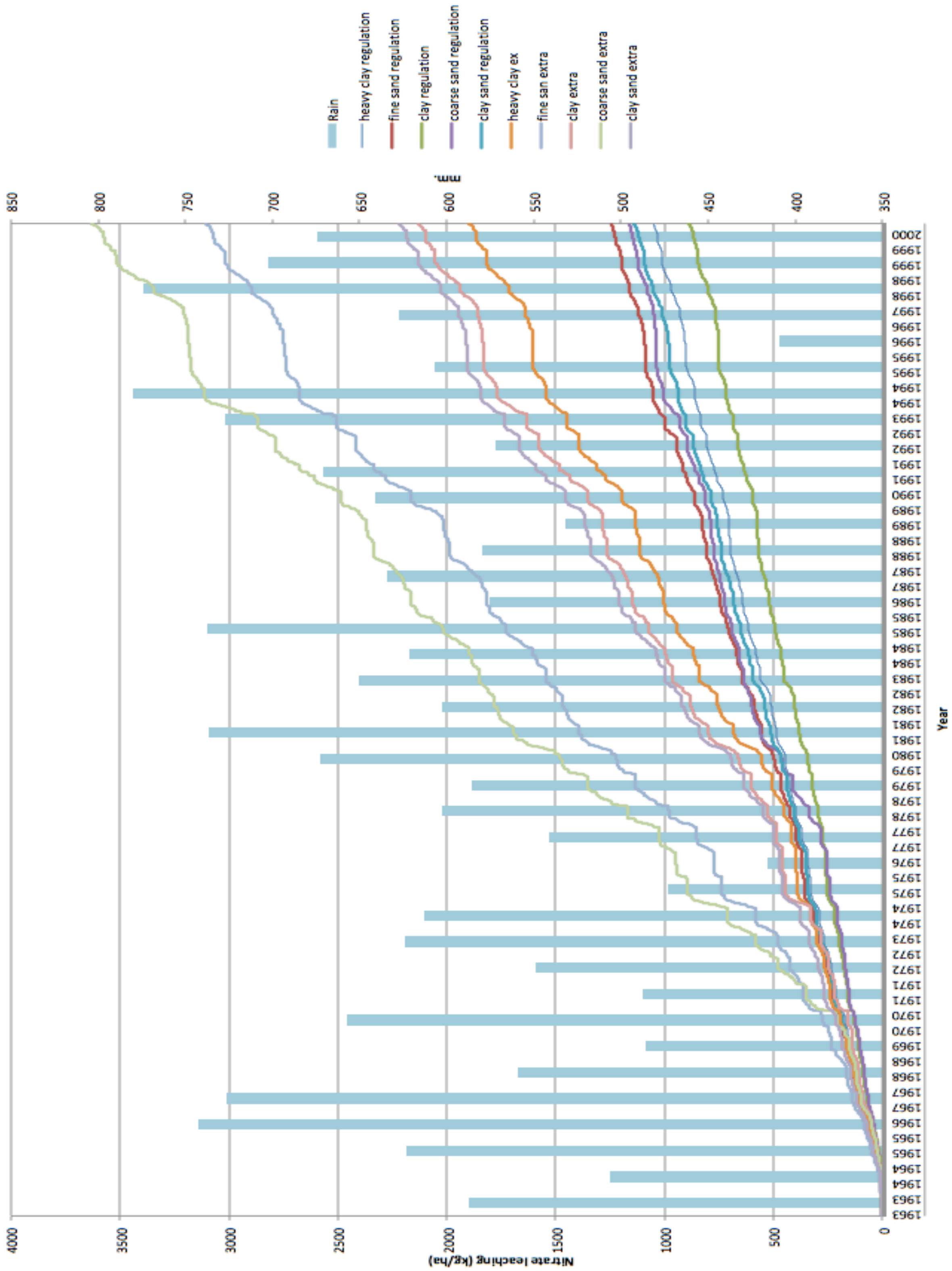


Figure 4.3.3.2 *Accumulated nitrate leaching over the 38 year simulation period. Bars are the amount of rainfall the given year. This graph shows how long-term usage of the two fertilizer applications influence nitrate leaching.*

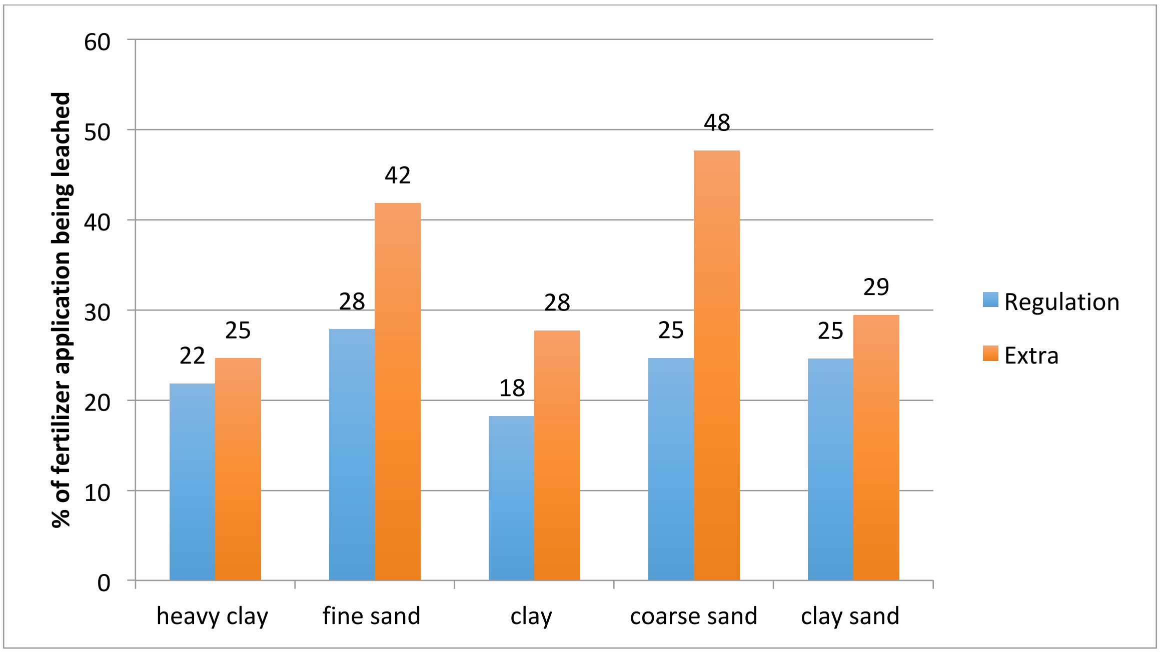


Figure 4.3.3.3 *Average leaching in percentage of fertilizer application to the field over 38 years. This indicates how big a percentage of input is leached. Higher values for the extra nutrients indicate that a higher percentage of applied nutrients are leached from the soil.*

It was shown in Figure 4.3.3.1 that nitrate leaching increased with the extra nutrients. However this was also suspected, since an increased input often, input in this case being extra nutrients, will lead to an increased output, input in this case being nitrate leaching. In Figure 4.3.3.3 it is shown on average over the 38 years how much nitrate leaching as an output represent of the fertilizer application as an input. The percentage tells how much of the applied nutrients leave the soil through nitrate leaching.

On average the fertilizer input was increased by 55-60% with the extra nutrients from current regulation (Table 4.3.2). In Figure 4.3.3.3 it is shown that some soils withhold the extra nutrients more efficiently than others. For heavy clayey soil there is no significant difference in the percentage of fertilizer application leached from the system (Paired *t*-test: t_{37}= 1.687, *P*= 0.100)(Appendix 8). However this does not mean that the leaching is not higher, which is also shown in Figure 4.3.3.2. It merely means that there is not a significant increase in the percentage of fertilizer application, which is being leached. The rate of leaching is therefore unchanged for heavy clayey soil. For the other four soil types there is a significant increase in percentage of fertilizer application being leached (Paired *t*-test: t_{37}= 5.257, *P*= 0.000)(Appendix 8). Coarse sandy soil has the highest increase in leaching, where leaching of fertilizer application is 23% higher than under current regulation. This increase in leaching of input could indicate uncertainties in regards to application of extra nutrients. Since heavy clayey soil did not change in the rate of leaching of input, the knowledge on degradation and leaching under current regulation could still apply. For the other soils the increase indicates that there is a change in the processes in the soil that increase nitrate leaching. It is therefore necessary to understand how and why the nitrate leaching as percentage of input is increased, to be able to minimise risks of leaching with an increased fertilizer application. It could be that the soil for the four soil types has reached a limit for immobilisation or usage of nutrients in the soil.

Since the sequestration methods effect on SOC was not simulated, the leaching could differ from what is shown in Figure 4.3.3.3, since SOM and SOC should increase with the sequestration method, and thereby increasing the ability to immobilise nutrients (Murphy 2015). This could potentially lead to a lower rate of leaching and reduce the percentage of fertilizer input being leached.

4.3.4 Assessment of soil types

This section contains an overall assessment of APSIM output to determine soil types, which would be fit for an integration, based on the impact on yield, SOC and nitrate leaching. This assessment is based on results where the impact of the sequestration method was not simulated. The final assessment of results from APSIM is therefore lacking the efficiency of the sequestration method, but instead focuses on other parameters influenced by the method. The results from this assessment are therefore a selection of soil types based on a worst-case scenario, where the sequestration methods efficiency to sequestrate C was not obtained.

Figure 4.3.4.1 presents an overall assessment of the five soil types. This assessment is based on six assessment themes, which are related to earlier analysis in this section. ***Yield change*** relates to how much yield changes for the different soil types when extra nutrients are applied. This relates to Figure 4.3.1.1. ***Yield average*** is the overall average yield output from the different soil types (Figure 4.3.1.2). ***SOC*** relates to how much degradation of SOC is lowered when applying extra nutrients (Table 4.3.2.1). For nitrate leaching there are three assessment themes. ***Nitrate leaching fertilizer application*** indicates the increase in nitrate leaching with extra nutrients from regulation (Table

4.3.3.1), where ***nitrate leaching soil type accumulated*** represent the overall nitrate leaching from each of the soil types when extra nutrients are applied (Figure 4.3.3.2). Lastly ***Nitrate leaching: Percentage of regulation*** indicates how much of the applied nutrients are leached from the soil (Figure 4.3.3.3). Figure 4.3.4.1 is based on a 1-5 point system, where 5 is “the best”. The usage of a point system instead of the actual numbers is due to the actual units and values varying too greatly between the six assessment themes, which would make results in Figure 4.3.4.1 appear less clear.

It is shown that Heavy clayey soil has the highest score in four out of six assessment themes (Figure 4.3.4.1). Overall this soil type had the highest score. Second came clayey sandy soil, then clayey soil, fine sandy soil and lastly coarse sand. Coarse sandy soil had the lowest score for all the assessment themes, and it is therefore assessed that this soil type is not fit for an integration of the sequestration method. This also goes for fine sand, which had the second lowest score in all the assessment themes except for SOC.

It would seem that heavy clayey soil, clayey soil and clayey sandy soils could be the most applicable soil types to apply the sequestration method to out of the five soil types, even though the nitrate leaching is still relatively high for all the soil types.

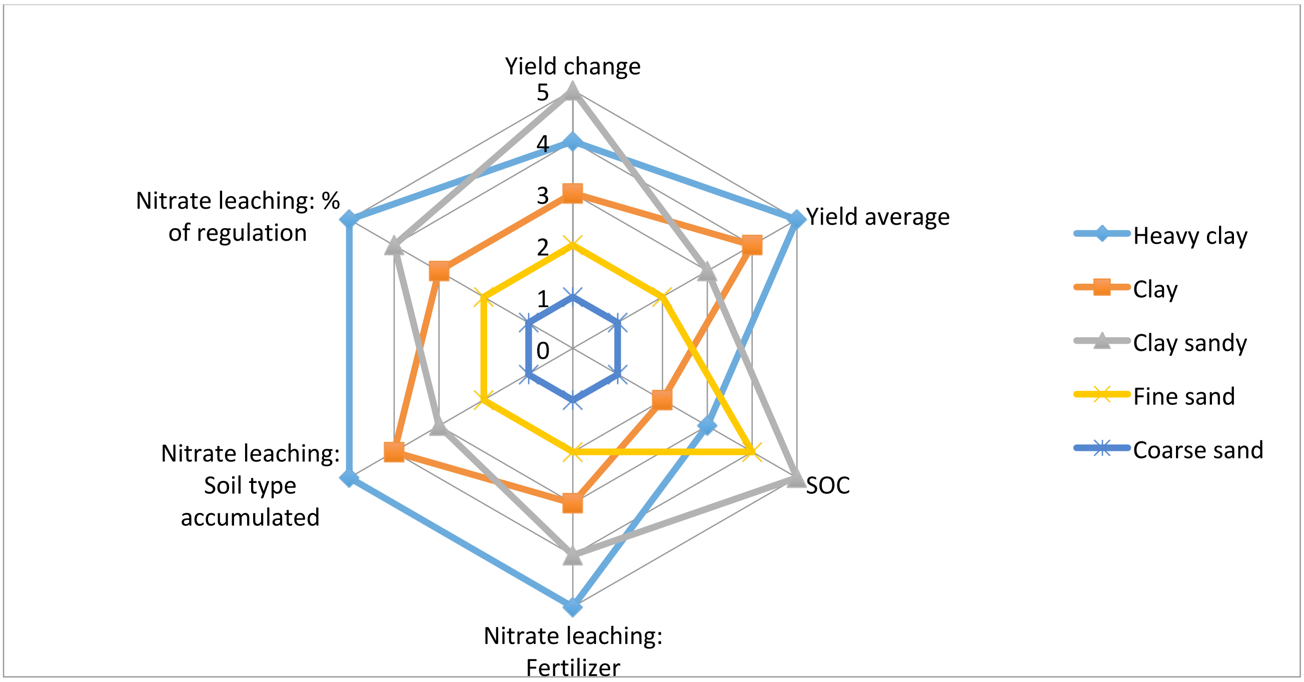


Figure 4.3.4.1 *Radar figure of soil types. Ranked on a scale from 1-5, where 5 is defined as “the best”. For yield and SOC this means that 5 is an equivalent to the highest yield and SOC, where for nitrate leaching 5 equals the lowest amount of leaching.*

Integration areas

This assessment of the soil types can not only be used to determine what soil types the sequestration method would be beneficial to be applied to, it can also be used to investigate how big these areas are in Denmark. This is done to see how big an area it is possible to integrate the sequestration method on, and how well of a mitigation tool the sequestration therefore could be.

GIS was used as a tool to firstly determine the distribution of soil types in Denmark and afterwards mapping the areas where the sequestration method could be integrated, based on soil types and cultivated areas in Denmark (Figure 3.1.2, Figure 4.3.4.2).

In Figure 4.3.4.2 the distribution of soil types in Denmark is shown. Eight soil types are listed in the legend, however in the simulation in APSIM only five soil types were used. As mentioned earlier this was due to available data on the soil profile of the soil types. It could have been beneficial if sandy clayey soil as a soil types had been investigated as well in APSIM, since it appears that this soil type is well represented especially on Zealand (Figure 4.3.4.2).

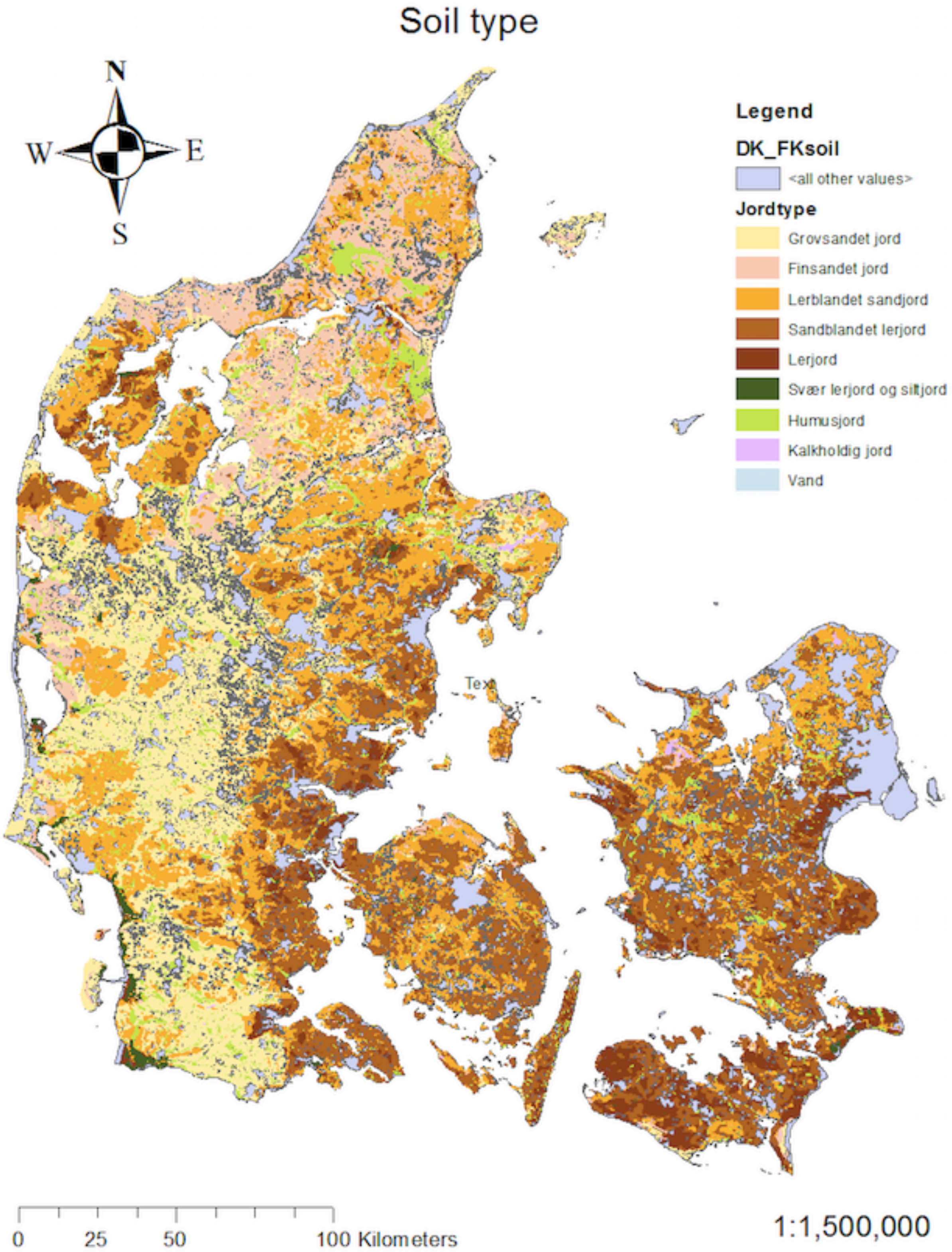


Figure 4.3.4.2 *Soil types in Denmark. Bornholm is not on the map. Legend in right corner shows what the different colours on the map represent. Made by Asta Poulsen, 2018. Yellow is coarse sandy soil, pink is fine sandy soil, orange is clayey sandy soil, light brown is sandy clayey soil, brown*

is clayey soil, dark green is heavy clayey soil, light green is humus, purple is soils with high calcium content, blue is water and blue-purple is unidentified.

The combinations of soil types used to map cultivated areas are found in Table 4.3.4.1. When creating the maps, calculations on the size of the areas were done as well. In Table 4.3.4.1 it is shown how big of an area of Denmark cultivated areas each of the combinations of soil types covers. It was only a small amount of the cultivated areas in Denmark which had heavy clayey soil as a soil type, therefore only 1.2% farm land in Denmark would be able to implement the sequestration method. Since the percentage is so low, it is not clearly visualised on a map, which is why there is not a map showing the option with one soil type. The map can be found in Appendix 12.

However if clayey sandy soil, which was the second “best” soil type, was used as well, then there is a leap in how big a percentage of cultivated areas that can have the sequestration method integrated. In Figure 4.3.4.3 the areas for where the sequestration method can be integrated are shown. From the map it is possible to identify the areas in Denmark where the sequestration method could be applied. West of Jutland appears not to be a suitable area, whereas Zealand and Fyn could be areas where one should look closer into applying the sequestration method (Figure 4.3.4.3). This distribution of where to apply the sequestration method does not differ greatly with the usage of three soil types (Appendix 12). If using these three soil types it would be possible to integrate the sequestration method on 39.1% of cultivated areas in Denmark. This is the limit for areas suitable for integration of the sequestration method based on the assessment of soil types (Figure 4.3.4.1). Fine sandy soil and coarse sandy soil were in the assessment of soil types found not suitable based on the high nitrate leaching and impact on yield.

However if these soil types were taken into consideration then the areas, applicable for an integration of the sequestration method, would have been larger (Table 4.3.4.1). Maps of how the distribution of integration would change with four and five soil types are shown in Appendix 12.

Table 4.3.4.1 *Overview of the area each of the combinations of soil types cover. The area is a percentage of the overall cultivated area in Denmark. The percentage indicate the how big an area the sequestration method could be applied on with the given soil types.*

Combination of soil types	% of cultivated area in DK
Heavy clayey	1.2
Heavy clayey + Clayey sandy	33.8
Heavy clayey + Clayey sandy + clayey	39.1
Heavy clayey + Clayey sandy + clayey + Fine sand	51.5
Heavy clayey + Clayey sandy + clayey + Fine + Coarse sand	79.5

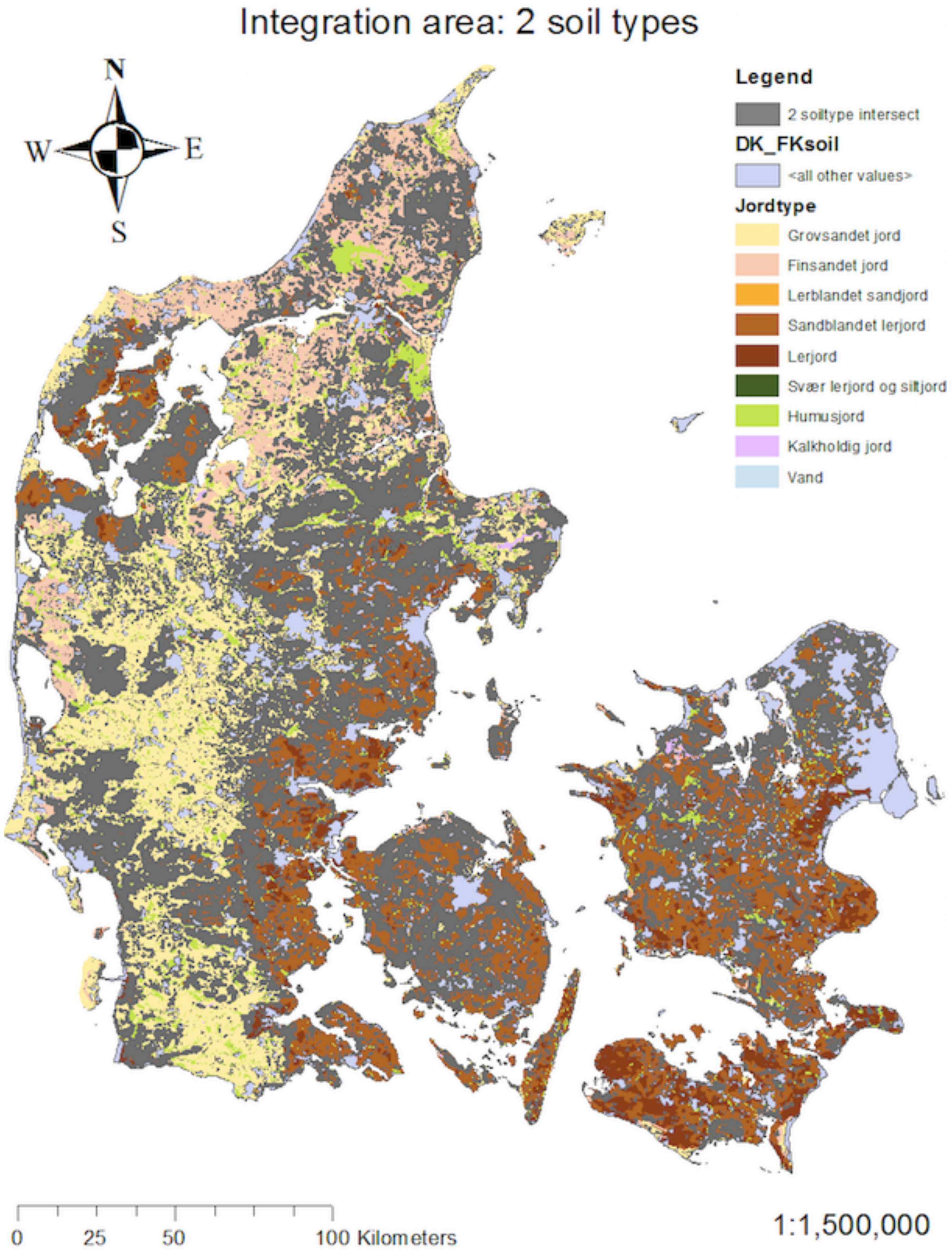


Figure 4.3.4.3 *Map of soil types in Denmark. Grey area indicates the areas where it would be possible to integrate the sequestration method. This map is based on two soil types being used in the integration. These soil types are heavy clayey soil and clayey sandy soil. Map shows in which parts of Denmark the sequestration method could be applied. Made by Asta Poulsen, 2018.*

4.3.5 Summary

In this section the main conclusions from APSIM will be outlined. The summary is also linked to the work questions: *What is the sequestration method's impact on nitrate leaching from a field?*

Results showed that the sequestration method increased nitrate leaching significantly for all the soil types used in the simulations. However results also showed that SOC did not increase significantly during the 38 years simulation, indicating that the effect of the sequestration method was not simulated. The nitrate leaching and changes in yield and SOC are therefore the output from a scenario where all additional nutrients are left mobile in the soil. Results on nitrate leaching are hereby a worst-case scenario, showing the effect of no increased NHE.

This chapter also included an assessment of the five different soil types, to determine whether the sequestration method was more applicable on some soil types than others. This was based on the worst-case scenario, and the assessment of soils could therefore differ if the efficiency of the sequestration method increased.

It was found that based on the sequestration methods impact on yield, SOC and nitrate leaching, three soil types were picked to be the most appropriate for an application of the sequestration method. Together these three soil types covers 39% of cultivated areas in Denmark. This sets the limit for how big an area the sequestration method can be applied to in Danish farming systems.

5. Discussion

In this chapter the sequestration method will be evaluated, to determine whether it would be beneficial to implement the method in a Danish farming system. Interviews conducted in Australia will be used to shed light on some of the concerns regarding C-sequestration as a mitigation tool in farming systems. These were presented in chapter 2.5. The discussion is divided into three sections, where the sequestration methods efficiency and impact on SOM is discussed at first. This is followed up by a discussion of some of the constraints for an implementation in Denmark, both in regards to costs, SOM dynamics and nutrient availability. The last section contains an assessment of the sequestration methods applicability in Denmark.

It is important that the reader understands that the data output from APSIM should be subject to reservation. As mentioned in the analysis APSIM was not able to simulate the effect of the *sequestration method. APSIM is used in the discussion to either outline a worst-case scenario of an application of the sequestration method in regards to nitrate leaching where NHE does not increase, or to emphasise the difference between soil types on a number of parameters outlined in Chapter 4.3.4.*

5.1 Impact on C-sequestration in Denmark

Firstly, the sequestration methods impact on C-sequestration as a mitigation tool is evaluated, followed by impacts on more general soil dynamics – both in regards to initial formation and stability of new SOM and the potential effects on Danish farming systems and the initial formation of SOM.

5.1.1 Impact on C-sequestration

It was found in Australia that the sequestration method could increase NHE to approximately 30% (Kirkby et al. 2014). In Denmark it was found that the sequestration method decreased SOC significantly during the incubation for five out of six soils (Figure 4.1.1.3). Therefore, an immediate conclusion would be that the sequestration method is not applicable under Danish conditions.

However, SOC also decreased during the first incubation for some soils in Australia (Kirkby et al. 2013) before a significant increase in SOC occurred. It is therefore not possible to rule out that the sequestration method can have a mitigating effect on climate change in Denmark as well, since the incubation study only ran for one incubation cycle of 2 months instead of seven incubations cycles as it did in Australia.

For one soil in the Danish incubation study there was a significant increase of 7% in SOC from initial C-content. This shows that the sequestration method can also increase SOC in Danish soils, even though the increase is not as high as for Australian soils. It was found by Kirkby et al. (2013) that soils with lower C-content in the soil had a higher NHE. The Australian soils had an overall lower C-content than Danish soils, which could possibly also explain why the sequestration methods impact on Danish soils would be different from the impact on Australian soils. Other factors may also influence the difference between results from Danish and Australian incubation studies. The soils may differ not only in fertility, but also in the geological processes forming the current landscapes and soils in the two parts of the world (Taylor 2012). Some of the soil forming factors are topography, climate and microorganisms. The topography of each of the given sites can influence the soils, since the topography can have an impact on the distribution of sediments in the landscape (Charman & Murphy 2007). In addition to this the weathering of an area can change the composition of a soil due to changes in amongst others temperature and precipitation (Clark 1986) and lastly the microorganisms can redistribute soil and increase SOM (Charman & Murphy 2007; Jastrow et al. 2007). It is therefore uncertain what factors may cause the largest differences between Danish and Australian soils.

In addition to this the specific farming system and earlier management of the farming system may also have an impact on the soils and could also be a suggestion to why the soils and NHE in Denmark and Australia differ. It was shown in Experiment 1 that soils from CA and conventional agriculture reacted differently to the sequestration method. The individual farmer and farming practice could hereby have an impact on the formation of SOM. This impact could also cause variations in NHE.
Overall there are a number of factors which could change NHE and hereby the efficiency of the sequestration method. This emphasises the complexity of the processes dealt with in the sequestration method and why Danish soils may have reacted differently to the sequestration method. To ensure a stable NHE this complexity would have to be understood and the impact of external factors would be necessary to map.

During an interview with Knowles, who works with mitigation tools in Australia, Knowles expressed a concern in regards to C-sequestration as a mitigation tool. Variability in soils components is one of the reasons why Knowles, does not believe there should be a focus on increasing C-sequestration in cultivated areas, since it is difficult to set one norm for all soils (Appendix 13). Even though soils can react differently to the sequestration method, as shown in results for nitrate leaching from APSIM and given by the soil forming factors, then Kirkby et al. (2011) still concluded that humus does not differ greatly across the world, meaning the sequestration method ability to sequestrate C should not be affected greatly by changes in soil type, since the stoichiometric ratio is based on humus. As mentioned above, the Danish soils did not react in the same way to the sequestration method as Australian soils, which mean there could still be variability between soil types, implicating the development of a norm for an integration of the sequestration method. Understanding the processes in the soil influencing the SOM dynamics better could accommodate such variability between soils, which could help reduce this variability as a restriction for an implementation of the sequestration method. In addition to this a strategic approach to selection of soils would be necessary. This is more demanding than setting an overall norm for all soils, but this could increase the applicability to farming systems and help optimise NHE to fit the given system.

Even though the sequestration method only resulted in a significant increase in SOC for one soil, results from the incubation study showed that the application of the sequestration method decreased the mineralisation of SOM (Figure 4.1.1.5), when compared to an application of straw. Hereby the positive priming effect was slowed down with the application of the sequestration method for some soils, though for most of the soils the application of the sequestration method resulted in an increased positive priming effect.

The results from the Danish incubation study could therefore either indicate that the sequestration method is not resulting in the same efficient change in SOC as seen in Australia, or that the incubation study has not run for long enough to detect the actual effect of the sequestration method. The factors influencing the soil and processes in the soil could also be the cause of the difference. There is therefore still an uncertainty in regards to the sequestration methods effect on C-sequestration on Danish soils and the sequestration methods full potential has not yet been determined.

However it is possible to determine the cost efficient potential of the sequestration method in a Danish context. A concern in Australia was that it would not be profitable for the farmer to integrate the sequestration method (Appendix 13). Therefore it was determined, in a Danish context, when the sequestration method would be profitable for the farmer to integrate.

Figure 5.1.1.1 outlines the maximum reductions the sequestration method can accommodate in Denmark. This is based on the NHE, which for the farmer will result in no extra costs and the area of Denmark, where integration could be seen fit based on the sequestration methods impact on soil types. In the analysis a NHE of 21% was determined to be the highest profitable efficiency possible in Denmark (Table 4.2.2.1), and based on GIS maps approximately 40% of cultivated areas in Denmark could integrate the sequestration method (Table 4.3.4.1).

Hereby, the sequestration method can maximum reduce the emissions from agriculture with 18.3%, which on national levels is a reduction of 3,8% in GHG emissions pr. year. As observed in the Danish incubation study an NHE of 21% has not been obtained in the experiment. It is therefore possible that the sequestration methods effect on GHG reductions may be less than 18,3%, if NHE in Danish farming systems have the same effect as seen in the incubation study. Application of the sequestration method has not yet been applied to actual farming systems in Denmark. It is therefore not determined whether results from the incubation study can reflect the effect the sequestration method has on Danish farming systems.

The efficiency of the sequestration method is crucial for the reductions in GHG emissions. Results from Australia showed that even when applying nutrients to accommodate a NHE of 30%, some soils had an even higher efficiency (Figure 3.1.3.2)(Kirkby et al. 2013). The results also suggest that efficiency increase significantly the longer the sequestration method is applied. If these tendencies also apply to Danish soil, then the sequestration methods usage as a mitigation tool would increase over time, potentially result in a higher NHE than expected. However as mentioned above the sequestration method is based on a complex system and a range of processes in the soil. Therefore a lot of factors can influence NHE and the efficiency of the sequestration method as a climate mitigation tool.

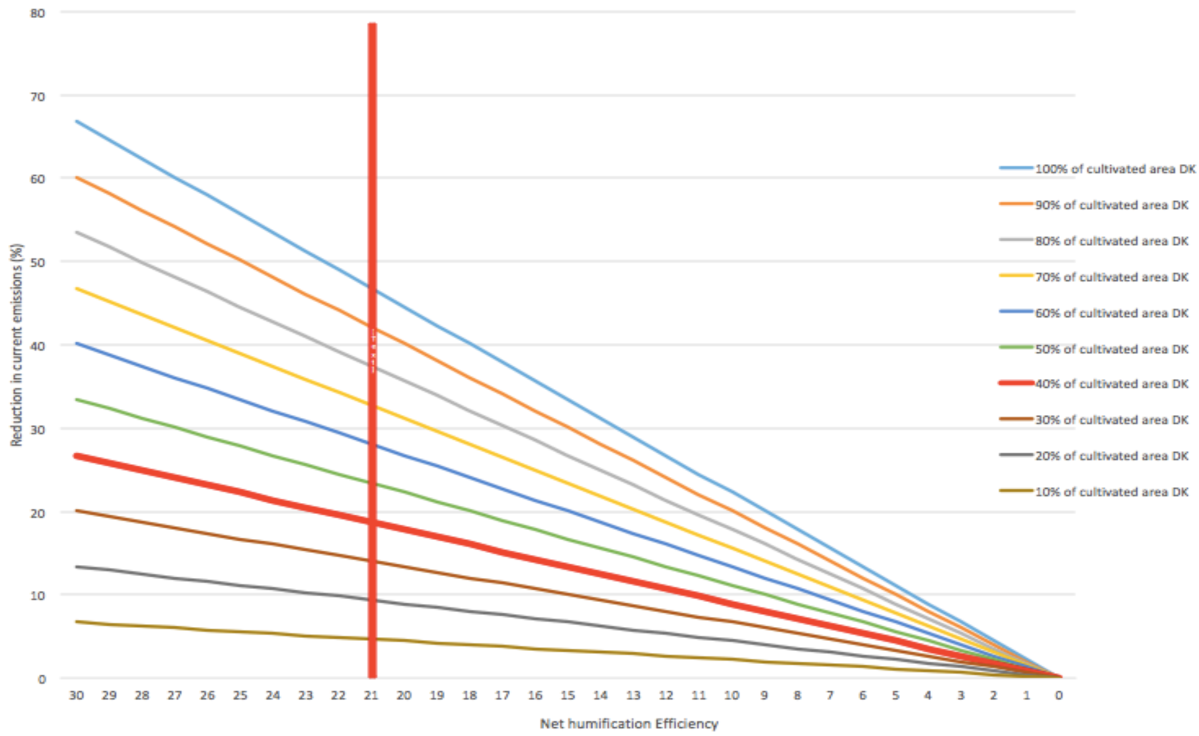


Figure 5.1.1.1 *Modified version of Figure 4.2.3.1. Red lines indicate the maximum cultivated area, which can be used for the sequestration method, along with the maximum NHE, which is profitable for the farmer. Reductions are based on the current emissions from agriculture in Denmark.*

5.1.2 Impact on SOM dynamics

It appears in the Danish incubation study that the sequestration method boosted the positive priming effect in the soils (Figure 4.1.1.4). The idea behind the sequestration method was that the negative priming effect should overcome the positive priming effect, based on adding the nutrients needed by the microbial biomass (Kirkby et al. 2013). Results from Kirkby et al. (2014) showed that the sequestration method increased positive priming effect as well (Figure 3.1.3.3). However sequestration method also resulted in a higher negative priming effect in Australian incubation study, which was not detected in the Danish incubation study. In the section above a number of reasons for such a difference between the two incubation studies has been outlined, including timeframe for incubation period and the impact of microbial biomass.

It is also suggested by C. Kirkby (Pers. comm 2018) that the lack of response in Danish soils can be due to the soils not being thoroughly enough mixed. In the Danish incubation the sequestration method was examined with and without soil disturbance, where it was shown that there was no significant difference (Chapter 4.1.1). This could back up C. Kirkby's suggestion above.

However it is not just important to understand SOM dynamics from beginning till the end of the application of the sequestration method. It is also necessary to understand the soils immediate response to the sequestration method, in addition to the long-term effects of an application. Since the sequestration method is based on biological processes and is applied to a dynamic system, it is important to understand how stable the C-sequestration is and when the sequestration occurs. It is crucial that the stability of formed SOM is equal to the stability of pre-existing SOM, since the sequestration method not only increase negative priming effect, but also positive priming effect (Figure 3.1.3.3, 4.1.1.4).

It was found in Experiment 3 that the soils react differently to the sequestration method the first seven days, where one soil has a decrease in SOC and the other no significant change (Figure 4.1.3.3, 4.1.3.4). This difference between soil types could support Knowles argument on why C-sequestration in farming systems should not be focused on (Appendix 13), since the soils react differently to the sequestration method. Both soils did not have the significant increase in SOC during the first month of incubation (Chapter 4.1.3). Overall the soils did therefore react in the same way to the sequestration method, since no significant change was detected. This also indicates that the C-sequestration for both soils has to occur later on in the incubation cycle, when the microbial activity is lower. Even though no significant increase in C-content was detected in the experiment, Kirkby et al. (2013) found that both soils have a significant increase in C-content after a full incubation cycle. So even though there was a difference in how the soils reacted in the first seven days, the end results showed that both soils had increased humification with the sequestration method possibly counter arguing Knowles concern (Kirkby et al. 2013).

If focusing on stability of the new-formed SOM, results from Experiment 2 showed that there was no significant change in SOM after the sequestration method was applied to the soils (Chapter 4.1.2, Figure 4.1.2.1), indicating that the stability is unchanged even after the usage of the sequestration method is stopped. This unchanged stability of SOM indicates that the new-formed SOM is of the same stability as pre-existing. The concerns regarding the increased positive priming effect with the sequestration method and through this loss of SOM are less concerning since the new-formed SOM with the negative priming effect is of the same stability as mineralised SOM.

However, SOM did differ when the sequestration method had been applied (Figure 4.1.2.2), indicating that there is an uncertainty in regards to the stability of SOM with the application of the sequestration method, and the formed SOM could have a lower stability than pre-existing SOM. This uncertainty in the long-term change in stability could reduce the farmers´ wish for integration. In Australia these uncertainties for future changes are one of the reasons why few farmers commit to long-term projects to reduce climate change. This was one of the points emphasised by government official, who works with climate mitigation tools in Australia (Appendix 15). However farmers do have an interest in the sequestration method (Appendix 14). During interviews with farmers it was found that their biggest concern for the future was not the sequestration methods effect on their stability of SOM, but rather the effect on water holding capacity (Appendix 14). This is due to water shortage being one of the main limiting factors in the current farming systems in Australia (Appendix 14).

The concerns regarding integration of the sequestration method in Australia are not just based on how efficient the method is, but primarily based on the methods impact on productivity and the costs for an implementation (Appendix 13, 14). In the following section these concerns will be investigated further.

5.2 Constraints for an integration in Denmark

In this section possible constraints for integration in Denmark will be outlined. It is necessary to not only be aware of the sequestration methods ability to sequestrate C, but also how the additional nutrients affect the environment and productivity of the system. In addition to this it is necessary to investigate the risks relating to costs for the sequestration method and changes in SOM dynamics.

5.2.1 Environmental impact

It is important to investigate the impact on nitrate leaching, since the sequestration method is based on additional application of nutrients.

Simulations showed that there is a significant increase in nitrate leaching with the sequestration method (Figure 4.3.3.2). This increase is, as mentioned in the analysis, a worst-case scenario, where none of the nutrients applied were used to sequestrate C. Even so, the risks and issues outlined from the results from APSIM are still relevant, since there is a risk that the sequestration method does not result in the expected efficiency.

There was a large difference in the soil types´ nitrate leaching, where soils with higher clay content had lower nitrate leaching (Table 4.3.3.1). Results from APSIM hereby showed that the impact of sequestration method has higher risks on some soil types than other, emphasising the necessity of the farmers’ awareness to soil types.

In Denmark nitrate leaching from agriculture is an ongoing issue. Recently new analysis have shown that the aquatic environment in Denmark have higher concentrations of N, than expected up until now (Bredsdorff 2018). This has increased the debate of the governments actions to implement the agricultural package (Landbrugspakken), which allows farmers to increase their N input to fields by approximately 15% (Christensen 2016). The sequestration method is only economically beneficial if current N inputs are reduced by 2-3% (Table 4.2.2.1). The sequestration method therefore has a lower N input than current regulation and the nitrate leaching would therefore be lower than what it currently is, which could help reduce the impact of nitrate on the aquatic environment, whilst still increasing C-sequestration. The amount of N used in APSIM was based on a NHE of 30%, where it was found in the cost assessment of the sequestration method, that it would not be feasible with NHE of over 21%. Unfortunately the two analyses ran parallel and results from the cost analysis were not integrated in APSIM.

Even though N input should be reduced with the method, then there is still a large increase in the amount of P and S to the system. P has to increase with as much as 65%. This can have an impact on the aquatic environment, since P can have the same effect as N on algae production (Wittrup 2016). The sequestration method would therefore possibly have a high impact on the environment, even if N inputs were lowered. The environmental implications through leaching of nutrients with the method are hereby a high risk if applying the method to a farming system

The stability of the formed SOM also has an impact on the environment. If formed SOM is easier to mineralise, then microorganisms have easier access to the nutrients in SOM. This could possibly lead to a higher amount of mobile nutrients in the soil, which ultimately can result in an increased leaching of nutrients. Experiment 2 showed that application of OM increases the positive priming effect of formed SOM (Figure 4.1.2.3). Hereby the access to the nutrients is increased as well. This possible mobilisation of nutrients in already formed SOM increases the risk of nutrient leaching. There is hereby an increased risk of more mobile nutrients in the soils both while the sequestration is occurring and after it has occurred.

In addition to this it was found that in the first seven days after application of nutrients to the soil, there was no negative priming effect and therefore no C-sequestration (Figure 4.1.3.3, 4.1.3.4), even though the microbial activity was high (Figure 4.1.3.1, 4.1.3.2). This is another step in the sequestration process, where the extra nutrients are prone to leaching, since they are possibly mobile in the soil. The increase in C-content did not occur within the first month either, arising the question, for how long are the added nutrients mobile in the soil, before the humification begins. During interviews it was found that Australian farmer are not worried about losing their nutrients, when they are mobile in the soil, since their biggest limiting factor to plant growth is water scarcity (Appendix 14) and with low precipitation the risk of nutrient leaching is lowered as well. However as mentioned in the analysis Denmark has higher precipitation than Australia, increasing the risk of loss of nutrients, if they are left mobile in the soil.

In Experiment 3 it was also found that the farmer has to be aware of the weather conditions the weeks following an application of the sequestration method, since the nutrient will stay mobile in the soil. In 2017 Danish farmers had problems during their harvest, due to the high frequency of precipitation (Miljø- og Fødevareministeriet 2017). In 2018 water was on the other hand scarce in the fields (Miljø- og Fødevareministeriet 2018). This variation in weather conditions could implicate the usage of the sequestration method in Denmark. The variation implicate the application of nutrients, since seasons with high precipitation would make the farming system unfit for an implementation of the method, since the risk of nutrient leaching would be too high. Such extreme changes in weather conditions are expected to increase in the future with climate change (Food and Agriculture Organization of the United Nation 2013), implicating the use of the sequestration method even more.

On the other hand, these variation in weather conditions increase the necessity for the farming systems to be resilient to changes, especially if drought conditions as seen in 2018 will occur more frequently in the future. Increasing SOM and through this the water holding capacity of the soil would hereby be more urgent, emphasising the need for methods such as the sequestration method. This necessity for a higher SOM fraction in the soil to adapt to climate change through the sequestration method is in opposition to the risk of increased nutrient leaching with the sequestration method. The challenge with the sequestration method is to balance these two opposing issues. It is problematic that the nutrient leaching can be increased with the sequestration method, but it is also problematic that SOM is decreasing and that there is a high GHG emission from agricultural soils. If working towards an implementation of the sequestration method it would be necessary to balance these two issues, so both are integrated into a management solution.

5.2.2 Risks in application

It is necessary to not only be aware of the environmental impact of the sequestration method, but also how the method affects both the soil and the production from the farming system.

SOM dynamics

The stability of formed SOM is crucial for the sequestration method to be beneficial to integrate, since the stability and through this the turnover time, indicate how long C-sequestration is held. Results from Experiment 2 showed that there was no difference in the mineralisation of SOM between soils with and without an earlier application of the sequestration method. However results also showed that soils, which had had the sequestration method applied, had a faster decrease in C-content, even though this change was not significant. This could potentially indicate that over a longer period of time soils, with the sequestration method, have formed less stable SOM, than soils without the sequestration method. This could influence not only the C-sequestration, but also the other beneficial impacts SOM can have on the soil. With a faster turnover time, the incentives to integrate the sequestration method would decrease, since the storage time of C in the soil would be shorter. Government official in Australia believes that this possible uncertainty concerning C-storage in the soil could reduce the use of the sequestration method as a long term tool to mitigate climate change (Appendix 15). This relates to the farmer's willingness to take risks, where the government official could see tendencies in the projects farmers were willing to adopt to mitigate climate change. Project with too high long-term projections were not as popular, amongst others due to the uncertainties of changes in farming systems and climate in the future.

As mentioned in the section above, the stability of the formed SOM has an influence on the mobility of nutrients in the soil. This mobility of nutrients seems to be an issue throughout experiments as well as the modelling. The increased sequestration with the sequestration method did not occur in the Danish incubation study (Figure 4.1.1.4), leaving mobile nutrients in the soil. The NHE is in this context crucial for the mobility. If the additional nutrients do not result in the expected NHE, then an amount of nutrients will be left mobile in the soil. This is also what the simulations showed. Since NHE was not increased in modelling, then all nutrients were left mobile in the soil, resulting in a high nitrate leaching (Figure 4.3.3.1). Additionally it was assumed that C-sequestration would occur when high microbial activity happened, but Experiment 3 showed that no such increased C-sequestration occurred within the first month (Figure 4.1.3.3, 4.1.3.4), meaning the sequestration has to possibly occur, when the microbial activity is lowered. The mobility of nutrients again becomes an issue, since the purpose was to immobilise them through the sequestration, but since the sequestration did not occur within the first month, then the nutrients stay mobile in the soil for a longer period of time, risking to be leached or taken up by plants and thereby influencing the NHE, if too many nutrients are not left to boost the C-sequestration. Lastly the turnover time of formed SOM pose an issue. A lower stability not only results in a potentially shorter storage period of C in the soil, but also poses a threat to the immobilisation of nutrients in SOM. Faster turnover time can result in the nutrients in formed SOM being more prone to mobilise. It hereby seems crucial to thoroughly understand how the specific soil react to the sequestration method, before applying it on a big scale in a farming system, since there can be a risk of an increased amount of mobile nutrients in the soil prone to leaching.

Nutrient availability

Results from Danish incubation shows that the sequestration can be limited by a number of factors amongst others lack of thorough mixing of the soil or the timeframe of the incubation period. In addition to this, Experiment 3 showed that the sequestration did not occur immediately after the application of nutrients (Figure 4.1.3.3, 4.1.3.4). A loss of nutrients could therefore occur before the sequestration started to increase. The two experiments indicate that there are uncertainties and external parameters, which can influence the C-sequestration. Furthermore there can be risks relating to the actual application of nutrients. An application of nutrients with an incorrect ratio could result in a lower NHE. S is the nutrient influencing NHE the most, since this is the nutrient, where the lowest amount needs to be applied, so a minor change in the application can have a larger impact on NHE (Chapter 4.2.1).

It is also shown in the analysis that under current fertilizer regulation S will be the limiting factor for how high a NHE it is possible to obtain in the farming system (Table 4.1.2, Figure 4.2.1). Fortunately, rules for application of S is not as strict as for N and P. Therefore P can end up being the limiting nutrients for humification, since is has been found in the analysis that to obtain a cost efficient NHE, N has to be reduced by 2-3% (Table 4.2.2.1), hereby not exceeding the allowed application of N under current fertilizer regulation and therefore N will not be the limiting factor.

As emphasised in the section above, nutrients mobility poses a risk in different ways when applying the sequestration method. This mobility also has an impact on the application of nutrients. A high leaching of nutrient results in a higher necessity for further application of nutrients to maintain a stable production and to sequestrate C. It was found that P could end up being the limiting factor for NHE, given the restrictions on P application in the fertilizer regulation (Landbrugs- og Fiskeristyrelsen 2017). However in the future, fertilizer regulation could end up not being the only parameter restricting the application of P. The availability of P is set to decrease drastically in the future and within 50-100 years it has been forecasted that the resource will no longer be available (Cordell et al. 2009). With a necessary increase in P of up to 65% (Table 4.2.2.1) with the sequestration method, the need for more P to the farming system will arise. This could potentially increase the dependency on import of P to Denmark, if the nutrients are not retained in the soil and recycled in the farming system. Such dependency on import of P can potentially lead to Danish farming practices being more vulnerable in the future, due to a higher reliance on external stakeholders. This uncertainty on future availability of nutrients necessary for the sequestration method could reduce the incentives to implement the sequestration method in the farming systems. However the need for P would not merely be critical for the sequestration method, but also for the entire cultivated areas in Denmark. Therefore a solution to the availability of P has to be found if productivity as known today is to continue. The risks for the sequestration method are therefore the same as for the entire agricultural system.

Costs

Through interviews it was found that one of the primary concerns for farmers, government official and consultant is the costs relating to the sequestration method and in relation to this the impact on productivity (Appendix 13, 14, 15). To reduce the costs it will not be possible to have a NHE of 30%, but rather a NHE of 21% (Table 4.2.2.1).

It is important to create incentives for the farmer to apply the method, and by making the sequestration method cost efficient such incentives could be increased. This however causes a dilemma. By accommodating the need for a cost efficient solution, the efficiency of the sequestration method is reduced. The sequestration method is hereby not used to its full potential. However, if the sequestration method should be used to its full potential with a NHE of 30%, then there would have to be an increase in not only the application of S and P, but also N. An increase in all the nutrients would also increase the risk of more mobile nutrients in the soil and through this an environmental impact. Focusing on a cost efficient solution would mean reducing the possible hazard of a nutrient leach with the sequestration method.

The primary reason for a NHE of 21% being cost efficient is the reduction in N application. This is a small reduction of 2-3% from current regulation, but it causes the sequestration method to be beneficial for farmers. It is important that the application of fertilizers is accurate for the sequestration method to stay cost efficient. This is in line with risks for nutrient availability, where an inaccurate and too low application of nutrients could cause a reduced NHE and through this lower C-sequestration. A too low application of nutrients could increase the risk of a lower NHE, where too high applications of each nutrient could increase the costs. There is hereby both an upper and lower limit for how much the application of each nutrient can vary from the stoichiometric ratio, if the sequestration method has to both beneficial in regards to costs and NHE.

In addition to this the revenue for the sequestration method is based on the subsidies the farmer gets for reducing emissions from the soil (Chapter 4.2.2). If the sequestration does not meet the expected NHE, then these subsidies could be reduced, since the C-storage will no be as high as expected. For the sequestration method to be cost efficient it is therefore important that there is a low difference between the expected sequestration and the obtained sequestration with the method. Danish incubation studies showed that the soils do not necessarily respond in the expected ways immediately (Figure 4.1.1.3), causing an uncertainty for how much C can be sequestrated with the sequestration method. Results from Kirkby et al. (2013) also showed that it takes some time before the full effect of the sequestration method can be seen. This delayed response could have an impact on the subsidies. In addition to this the stability of formed SOM may also have an impact on the subsidies. For the subsidies to be given it could be necessary to have it clearly evident that the C-storage obtained with the sequestration method is stable, else the C-sequestration with the sequestration method is not a way to mitigate climate change. Results from Experiment 2 shows that the stability of SOM is upheld, even though some changes in SOM are detected.

Productivity

During interview with Jacqueline Knowles from NFF, Knowles does not see the sequestration method as being an important tool in Australia in regards to GHG emissions. This is primarily due to the uncertainty in regards to costs and the productivity of the farming system (Appendix 13). A profitable NHE has already been found in the analysis and costs should therefore not be an issue, as long as the sequestration method performs as expected.

Even though results for yield from APSIM do not represent the effect of the method, there is an increased productivity in the three soil types, which are applicable for an implementation of the sequestration method. The soil types where the sequestration method has a negative impact on yield are therefore not to be considered as applicable for integration of the sequestration method. Knowles concern in regards to the sequestration methods impact on productivity (Appendix 13) can hereby be taken care of through a strategic selection of appropriate soil types based on a selected number of factors, where reduced productivity could minimise the soil types applicability for an implementation of the sequestration method. In addition to this there are shown benefits to the productivity, when SOM increases in the soil. This is amongst others increased water-holding capacity, which was a concern for Australian farmers (Appendix 14).

Knowles also emphasises the variability which is between soil types and how, due to this, it is not possible to set a norm for an application of the method (Appendix 13). The simulations showed that there is a difference in how the soil types respond to the extra nutrients, which is also why it was assessed that only three out of five soil types were applicable. This variation in response is related to the sequestration methods impact on other parameters than the actual C-sequestration. Even though Knowles may be right in her concerns regarding variability between soils, it is necessary to keep focus on the goal with the sequestration method. The aim is not to increase productivity, but increasing C-sequestration. It has already been shown that different soil types all have an increase in C-sequestration with the method (Kirkby et al. 2013). The risks relating to soil types are therefore not connected to the C-sequestration, but rather the impact on processes in the soil, which can cause a changes yield or increased nutrient leaching.

By only selecting soil types with lowest impact on a number of parameters, such as decreased yield and nutrient leaching along with an increased SOM, Knowles concerns can be minimised. The five soil types were assessed and the appropriate ones were selected. By focusing more on a strategic planning of implementation, it would be possible to reduce the risks concerning other parameters influenced by the sequestration method.

5.3 Assessment of applicability in Denmark

This section contains an assessment of the sequestration method to determine whether it is applicable in Danish farming system. In addition to this suggestion on how to deal with the sequestration method in a farming system will be made.

5.3.1 Mitigation tool

There has already been made an overview of actions to be taken to reduce GHG emissions from agriculture in Denmark. These are primarily based on a higher usage of manure in biogas plants, land use change to forestry and changed management practices with focus on less bare soils (Miljøministeriet et al. 2013). An estimate of the different actions impact on GHG emissions shows that the highest reductions vary from 100.000-480.000 ton CO_2-eq in 2020 (Miljøministeriet et al. 2013). The biggest reductions come from a land use change for organogenic soils, which are soils with a high C–content in the soil (>12% C). This land use change could result in a reduction of 0.02% of the GHG emissions from agriculture. However the change can only occur once, and the reductions from land use change are therefore not continuous annual reductions, unless further actions are taken to ensure higher C-sequestration in those areas, including reduced loss of nutrients.

C-sequestration is in a number of the actions mentioned as a side effect. However nowhere in the guidelines is there a quantification of C-sequestration and its efficiency. It is not determined how efficient the sequestration is and it appears that C-sequestration in it self as a management approach, is not considered as a possible action to take to mitigate climate change in Denmark.

C-sequestration is considered as being the reason why there is a reduction in GHG emissions for some of the actions. However it is not with a focus on increasing the efficiency of C-sequestration, but on catching more nutrients, to reduce nitrate leaching.

If comparing the sequestration method to actions considered applicable in Denmark by Miljøministeriet et al. (2013), it is evident that the sequestration method has a high potential in reducing GHG emissions from farming systems. As mentioned in Chapter 5.1.1 the sequestration method could result in an annual reduction in GHG from agriculture of 18.3%, given that a NHE of 21% is possible and the sequestration method was applied to 40% of cultivated areas in Denmark. This is equivalent to a reduction of 3.6 mio t CO_2/year. As mentioned earlier the highest reductions in GHG emissions with the actions available are 0.48 mio t CO_2. However it is not suggested, in the catalogue over actions that these should be applied to as big areas as 40% of cultivated areas in Denmark. Most actions are considered on areas the size of 240.000 ha. If comparing the sequestration method on such areas the reductions are still higher than the ones produced by the actions. With a NHE of as low as 15% on 240.000 ha., the sequestration method results in a reduction of 590.000 t CO_2/year. This reduction in GHG is still 22% higher than the most efficient action stated by Miljøministeriet et al. (2013).

The amount of C sequestrated may occur high, when the sequestration method is compared to other actions in Denmark. However compared to the results from Australia the efficiency could be higher than the one used for calculations in this chapter. According to Kirkby et al. (2016) SOC was increased by 8.7 t C ha^{-1} over a 5 years period. This is approximately 1.74 t C ha^{-1}/year. In the calculations in this chapter an efficiency of 0.95 t C ha^{-1}/year was used. This was due to the sequestration method having to be cost efficient as well, hereby reducing NHE of the sequestration method.

However even with a NHE of 30% this should only result in 1.35 t C ha^{-1} /year for fields trials in AUstralia. Hereby, results from Australia shows that the sequestration method can increase SOC with more than expected.

At COP 21 in Paris a focus was set on C-sequestration. This resulted in a global aim to sequestrate 3.5Gt C annually in soils. Studies conducted by Zomer et al. (2017) showed that på increasing SOC in farming systems by 0.55-1.55 t C ha^{-1} /year globally, agricultural soils could sequestrate 26-53% of this target. A sequestration of 0.55 t C ha^{-1} /year was defined as a medium sequestration, where 1.55 t C ha^{-1} /year was defined as high. The climate mitigation potential which is considered cost efficient in this project has a sequestration of 0.95 t C ha^{-1} /year. This lies in the interval for a needed efficiency necessary for a farming management to react the global target. Therefore the sequestration method not only has a high potential to mitigate climate change compared to Danish actions, but it also has a high potential on a global scale.
Even though increases in SOC was not seen in Danish incubation study, it is evident that the sequestration method has a high potential in reducing GHG emissions from farming systems. Given the uncertainties in the sequestration methods efficiency on Danish soils and the high potential, it would appear irrational to not investigate the sequestration method further in Danish conditions. If the method could have the suggested efficiency, then it could pose as an important climate mitigation tool in the future, given the environmental impact is reduced. It is therefore not possible in this project to reject a possible applicability of the sequestration methods in Denmark, since the method has a significantly high potential in reducing GHG emissions.

5.3.2 Effects on soil

Even though the sequestration method can cause high reductions in GHG emissions and can be integrated without any extra costs for the farmer, then the nutrient leaching will still increase significantly with the additional nutrients. This could seem to be the primary limitation for an implementation in Denmark.

As outlined in Chapter 3 the sequestration method can increase SOM and through this increase the soils stability and fertility (Petersen & Hoyle 2015; Stockmann et al. 2013). This is due to SOM's features, such as higher aggregate stability, water holding capacity and nutrient retention (Murphy 2015). Therefore the sequestration method can increase nutrient leaching, but also the nutrient retention necessary to reduce nutrient leaching. The sequestration method hereby has the solution to the increased nutrient leaching incorporated into the method. Question it then whether this increased nutrient retention can limit an amount of the increased nutrient leaching caused by the sequestration method.

In addition to this there are a number of uncertainties relating to the processes happening in the soil. In particular the stability of formed SOM is crucial to understand in depth. As mentioned above SOM has an impact on the fertility of the soil, which can result in an increased resilience to future climate change. It is therefore important that this formed SOM has a slow turnover time.

In the beginning of the thesis it was mentioned that there are two ways in which loss of SOM can increase. This is either through accelerated loss of pre-existing SOM (increased positive priming effect), or through a limiting formation of SOM (decreased negative priming effect) (Richardson et al. 2014). For the sequestration method to increase SOM, it is necessary to reduce these types of losses.

The sequestration method can both increase positive priming effect, but also negative priming effect (Figure 3.1.3.3), ultimately resulting in a higher formation than loss of SOM. It was found in this project that the timing of these dynamics in SOM are important for the mobility of nutrients in the soil, and hereby the environmental impact. Reduced positive priming effect is important for the stability of formed SOM, and reducing loss of SOM after the sequestration method has been applied is therefore important in this stage. In the application of the method to the field positive as well as negative priming effect are of equal importance, since it is crucial that negative priming effect is higher than positive priming effect, for the sequestration method to have an impact, and increase SOM. Applicability in Denmark is therefore based on the dynamics of SOM. Danish incubation study had a lack of negative priming effect compared to positive priming effect, the same goes for experiment 3, where focus was on changes in SOM dynamics right after nutrients were applied. This should result in the sequestration method not being appropriate to implement in Denmark. However as mentioned before there are uncertainties in regards to the SOM dynamics in the two experiments, primarily based on the length of the incubation study. Because of these uncertainties, it is not possible to rule out that the sequestration method could reduce losses of SOM long term, and increase SOM in the soil.

The increase in SOM with the sequestration method can also have an effect on yield and through this the productivity of the farming system. In general SOM is associated with a possibility for higher yield, given the increased fertility of the soil. However, it is suggested by Bruun (2012) that SOM may not have an impact on yield. It was found that no positive effect of SOM on yield could be detected. Even if SOM does not have an impact on yield, then the sequestration method can still be applicable in Denmark based on the costs. This is because the sequestration methods potential impact on yield was not incorporated into the calculations for costs. It would however increase incentives if the sequestration method could also increase yield in the farming system. In Bruun (2012) the efficiency of nutrient uptake by plants is not increased when more SOM is build up in the soil. Even so, it has been found by Kirkby, Richardson, Wade, Conyers, et al. (2016) that crops take up more nutrients than the ones being applied through fertilization, indicating a mineralisation of SOM to access immobile nutrients in the soil to satisfy the plants nutrient needs. Therefore, even if SOM does not increase yield, it still provides a stable nutrient pool, for a stable yield. This is why it is necessary to continue the work with understanding the sequestration method in depth; to stop the degradation of SOM and the mining of the soil, along with reducing GHG emissions from farming systems, for which there is a high potential in the sequestration method. The SOM dynamics has to be understood, so the appropriate management techniques can be developed to accommodate the sequestration method, if NHE in Danish soils can be increased.

In Chapter 5.2.1 a balance between efficiency of the sequestration method was held up against the environmental impact of the sequestration method. This should also be balanced against the costs of an implementation. It is necessary to not only take the methods impact on climate change into consideration, since the method involves a change in farming practices. In this project the approach has been to determine the applicability of the sequestration method based on more than just its ability to sequestrate C. The applicability in Danish farming systems is not just based on the effect the sequestration method has on climate change, the environment and farmers economy, but also how these three are balanced. To do so it would be necessary to work with different efficiencies of the sequestration method, since it was found that a NHE, which is beneficial for climate change, may not be the most cost efficient nor most beneficial for the environment. It would therefore be necessary to determine a NHE that balance these three parameters in addition to understanding the processes in the soil, that relates to SOM.

The sequestration method has beforehand primarily been assessed based on its efficiency to sequestrate C. By only focusing on one parameter (climate change) a number of risks can arise when integrating the method. It is necessary to have a holistic approach to the sequestration method, since it deals with soil dynamics, which influence the entire farming system. By having a focus on the entire farming system, the managing of the sequestration method becomes more complex, since more processes, hazards and variables are included. However the possible integration will possibly cause less harm to the environment and be better integrated, since more parameters are taken into consideration. From a planning perspective such focus on a holistic approach would increase the necessity to involve the individual farmer in the strategic planning to determine a NHE, which would be seen fit for the individual field.

5.3.3 Impact on farming system

This final section outlines some issues a farmer needs to be aware of when considering applying the sequestration method to his or hers farming system. These are necessary to take into account to minimise the risks relating to the sequestration method. These considerations are based on the assumption that the sequestration method can result in an increased NHE in Danish farming systems and the considerations are therefore issues, which are necessary to investigate further before it would be seen appropriate to apply the sequestration method to a farming system in Denmark. The issues are linked to the analysis in the project, and are therefore based on the results from experiments and modelling.

It was found in the analysis, that S is currently the limiting factor for a higher NHE in Danish farming systems. If applying the sequestration method to the farming system, the first nutrient the farmer has to focus on is therefore the application of S. An initial focus on this nutrient also limits the implications for an implementation in the farming system, since application of S is not as restricted as P and N through regulations.

However before applying the sequestration method, the farmer needs to have knowledge about a number of processes and parameters affecting the soil in his farming system.

It was found, in the Danish incubation study, that there was a significant change in soils C-content between conventional agriculture and CA. CA had a higher loss of C, which could possibly be related to the changed distribution of SOM in the soil with the application of the practice. The pre-existing farming practice should therefore be taken into account, when considering integrating the sequestration method in Danish farming systems. It would be beneficial it the farmer had an understanding of how SOM and SOC was distributed in the soil profile, for researchers to determine how this distribution may be affected by the sequestration method.

The farmer not only has to be aware of the distribution of SOM in his soil, but also the impact of the soil type. Even though an increase in SOM can increase resilience of the farming system, and increase productivity through a more fertile soil, the farmer also has to be aware of crops response to the sequestration method. According to Kirkby et al. (2013, 2014) the soil type should not have an impact on the sequestration. However farmer has to be aware of the nutrients impact and mobility in different soil types. Soil types may not affect the sequestration, but other processes in the soil could change with the extra nutrients. It is therefore necessary that the farmer consider all the aspects of an application of the sequestration method, before applying extra nutrients to the field.

In addition to this, it would be beneficial if the farmer started to focus on obtaining more closed nutrient cycles. By increasing the usage of the mobile nutrients in the soil, leaching of nutrients could be reduced. This is in particular to the P-cycle, since this nutrient can become the limiting factor for the sequestration now and in the future.

When the sequestration methods impact on soil dynamics is understood in depth and the influence of soil types on productivity and leaching is determined, there are still a number of factors the farmer has to be aware of before applying the sequestration method.

In addition to this, the farmer not only has to be aware of the management of the farming system after the sequestration method has been applied and ended, but also each time new nutrients are applied. Experiment 3 shows that the C-sequestration does not occur within the first seven days, when the microbial activity is the highest. Hereby there is period of time where nutrients are available in the soil and a high microbial activity occurs. Risks of losing the nutrients during this period of time is therefore critical and farmer has to be aware of the weather forecasts in the weeks following the expected application of nutrients.

There are still processes in the soil that has to be taken into consideration after the sequestration method has been applied to a farming system, and the farmer has to be aware of his/hers management practice.

It was also shown in experiment 2 that the stability was affected more, when straw was added to the soil. SOM decreased faster when OM was applied to the soil. The farmer needs to be aware of this impact, before starting the usage of the sequestration method, since a stop in the usage of the sequestration method could result in an increased loss of SOM formed. This emphasises the need for an examination on how to manage the farming system after sequestration method has been applied.

For the farmer to gain knowledge on the sequestration methods impact on the specific soil, it is necessary that more research is done on the sequestration methods impact on farming systems, in particular how to manage the system during and after an application of the sequestration method to reduce the risk of losing nutrients and formed SOM.

6. Conclusion

In this project there has been a focus on C-sequestration as a tool to mitigate climate change. This has been investigated based on a new method to sequestrate C through a focus on SOM and increased humification of OM applied to a farming system. This thesis includes an examination of how the sequestration method influence SOM and whether the sequestration method is applicable in Danish farming systems.

It was found that the sequestration method has a high potential to mitigate climate change. Compared to other actions considered appropriate in Danish farming systems, the sequestration method can reduce GHG emissions with up to 22% more than the most efficient action currently available in Danish farming systems. A reduction in GHG emissions with the sequestration method can be obtained with no extra costs for the farmer if nutrients are applied accurately to the field based on the expected NHE. It was found in the project that this accuracy in application of nutrients is crucial, since too high an application can increase the costs and too low an application of nutrients can decrease NHE, reducing the sequestration methods ability to mitigate climate change.

For farming systems in Denmark it was also found that S is the limiting nutrient under current fertilizer regulation, emphasising the necessity to apply more S to the fields to obtain a higher NHE. However P can also be a limiting nutrient, since restrictions of application of S are not as strict as for application of P and N.

It was not possible to detect an increase in NHE with the sequestration method in an incubation study on Danish soils. However this could be due to the incubation period being too short. Further studies on impact on Danish soils would therefore be necessary to accurately determine how useful the sequestration method is in Denmark.

One of the biggest limitations for the sequestration method to be applicable in Danish farming systems is the uncertainties regarding mobility of nutrients in the soil with the sequestration method, since high mobility can lead to an increased leaching of nutrients. It was found that the stability of formed SOM with the sequestration method is the same as for pre-existing SOM, indicating that the turnover time is unchanged. However application of OM to the field can increase the mineralisation of formed SOM, increasing the amount of nutrients available in the soil. It was also found that humification with the sequestration method does not occur immediately after the nutrients are applied to the field, leaving them mobile in the soil.

It is therefore necessary to research how farming systems should be managed, when the sequestration method is being applied, to minimise the mineralisation of formed SOM and decrease the risk of nutrient leaching. Further investigations of the sequestration method should also have focus on soil types, since the soil type can have an impact on processes in the soil influenced by the sequestration method, amongst others leaching of nutrients. A strategic planning approach to the sequestration method could increase the applicability in Danish farming systems, since risks relating to the method could be minimised. A focus should be laid on the application of P and to minimise losses through a more closed nutrient cycle. Both due to the necessary high increase of P with the sequestration method and the possible reduced availability of the nutrient in the future.

It is also necessary to determine the wished NHE in the farming system. High NHE results in more efficient climate mitigation tool, but can also increase nutrient leaching, whereas lower NHE decrease efficiency as mitigation tool but also reduce impact on environment. The desired balance between these two parameters needs to be determined in a Danish context before the sequestration method can be applied.

The SOM dynamics in the soil in relation to the sequestration method has not yet been understood in depth, which is why it is necessary to research this field further, before an application to farming systems in Denmark can be considered appropriate. It is in addition to this important that the individual farmer has a thorough understanding of the processes in the soil in his/hers fields. This is in relation to how the farming system should be managed to minimise hazards relating to the sequestration method, and increasing NHE.

It is important that the sequestration method is investigated further, since increasing SOM as a climate mitigation tool has a high potential both in regards to reducing GHG emissions and increasing farming systems resilience to future climate changes.

7. Perspectives

There is a range of topics, which could be interesting to investigate further in regards to the sequestration method. The following is a short description of some of the topics that could be investigated if more time was available.

Other fertilizer types

In the project it has only been inorganic fertilizer that has been used. Since Denmark has a high usage of manure it could be interesting to investigate the usage of this and other fertilizer types' impact on the sequestration method. This could also be interesting in regards to manure outputs from biogas facilities, so a focus on synergies between sectors was integrated as well. It could also be interesting to investigate which fertilizer type had the biggest effect on SOM using the sequestration method. Furthermore a more thorough examination of nutrients impact on microbial biomass could be beneficial. This could lead to a development of a fertilizer type produced to optimize the microbial activity for a sequestration and not just the crop production. A product like that could potentially help the farmer to start fertilize the system rather than just the crop.

Nutrient change and methods vulnerability

The analysis showed that an accurate application of fertilizer is necessary both to reduce costs, but also to get the desired NHE. It has not yet been investigated how minor changes in one nutrient at a time (N, P or S) can influence NHE. Through an experiment focused on that, the sequestration methods vulnerability to minor changes in fertilizer application could be investigated. This could also have an impact on implementation, since a high vulnerability could decrease incentives, since the method would be harder to control and outcome would be with more uncertainties. It was the intention that this project should include such an experiment, however time as a factor limited the number of experiments in the project.

Long term trials

The Danish experiment was only tried out in an incubation study for a short period of time, where the sequestration method was tried out both in an incubation, but also in the field in Australia (Kirkby, Richardson, Wade, Conyers, et al. 2016). If one were to investigate the sequestration method further, it would be necessary to do short and long term field trials, to see the actual responses in the farming system. This could also be beneficial to investigate the actual impact on yield and to see if it there is an actual change in C-sequestration with the sequestration method, since this was not found in the experiment in this project.

8. Quality assessment

There are a number of elements in this project, which could have influenced the outcome of the report. This is in particular the methods used to investigate the sequestration method. In this chapter an evaluation of some of these elements will take place, to investigate how they have influenced the project and possibly how methods can be improved.

The methods used to investigate C-sequestration will in this section be assessed. This is to clarify weaknesses and strengths in the methods chosen and potential improvements that could have been made to strengthen the data and through that the analysis.

8.1. APSIM

Since modelling is a simulation of the actual processes happening in the system, is it necessary to understand these processes for the simulation to be more accurate and correct. With the usage of APSIM it has been tried to investigate the impact of increased nutrient input, to understand the environmental impact of the sequestration method.

8.1.1 Sequestration method

Since the sequestration method and the increased humification caused by added nutrients is not fully understood yet, it has not been integrated into the model, that a large increase in SOC will occur with the application of nutrients (Chapter 4.3.2 SOC). This lack of response in SOC to the nutrients could result in higher nutrient leaching, since nutrients are not being immobilised through integration in SOM as expected with sequestration method. APSIM is therefore not able to simulate the sequestration method yet, which result in output from the model not being representative for the sequestration method.

To be able to simulate the changes properly, it is necessary that NHE can be changed in the model to present the efficiency found in experiments (Kirkby et al. 2013; Kirkby, Richardson, Wade, Conyers, et al. 2016). However, before this can happen, it is necessary that scientists understand the dynamics in depth. There are different opinions as to what SOM is built of. One of the reoccurring suggestions is dead microbial biomass (Kirkby et al. 2011). It is necessary to understand the link and dynamics between microbial biomass, SOM and OM applied to the field before simulations can be improved. APSIM currently work with three different pools of SOM. The dynamic between these pools have been determined to simulate the real world accurately. However it appears that it is still not possible to simulate the link with microbial biomass.

8.1.2 Soil profile

A thorough description of the soil profile is important to simulate the processes in the soil in APSIM. In particular in relation to water flows in the soil. Water flow is affected by weather and soil water storage capacity in the model. The data used to determine the soil profile in this project has been collected from Skov- og Naturstyrelsen (2000). Soils are initially Australian soils, since APSIM has not been applied to Danish soils before this project. These soils have been modified to represent Danish soils as much as possible, based on information available from Skov- og Naturstyrelsen (2000). However since APSIM has a very thorough soil profile description, it has not been possible to change all the data to Danish conditions. Therefore the output of the simulations may be slightly biased. To increase representativeness and accuracy of data output from APSIM it would be necessary to collect soil cores for all soil types in Denmark. This was not done in this project. This lack of information on the specific soil profiles in Denmark also has an influence on SOC in the simulation.

When preparing the simulations a range of assumptions were made. This was in particular in regards to soil water, water holding capacity and types of SOC in the different soil types. If wanting to make more accurate simulations for SOC it would as mentioned above be necessary to have more information about the initial state of SOM through a more thorough examination of the specific soil profile.

8.1.3 Overall

APSIM has a high potential in forecasting changes in a farming system. This is in particular in regards to crop production and soil dynamics. However APSIM did not contain a thorough mapping of nitrate leaching from the soil. Compared to the Danish model DAISY, APSIM was insufficient in simulating nitrate leaching. In DAISY output data also contains information on which type of percolation that occurred and in what form N was lost from the system. APSIM gave data on how nitrate moved with soil water through the layers in the soil, but not wether it was through macro or micro pores.

The accuracy of APSIM could have been improved it more detailed input data was given to the model. The model is efficient in showing how soil reacts to management changes, however the management change in question in this project, has not yet been integrated into the model, resulting in a reduced impact of the sequestration method. If it had been possible to change NHE for OM then output would have represented the processes in the soil with the sequestration method more accurately.

8.2 Experiments

A number of experiments were conducted in this project. This was done to examine the SOM dynamics and the sequestration methods impact. The following quality assessment takes outset in the methods used during the incubation studies. This is in regards to the length of incubation periods, cleaning of the soils and initial drying of soils.

8.2.1 Incubation time

The experiments did not run for more than two months. This was due to the limited time to conduct the experiments. However it would have been beneficial if the incubations could have run for longer. In Kirkby et al. (2013) seven consecutive incubations were done which resulted in more data and a stronger analysis. It would have been beneficial to keep the incubations going for as long as possible, especially Experiment 2, since this focuses on the stability of the build-up SOM. Since the processes in the soil both have slow and fast turnovers, it would have been interesting to see how SOM would change further down the line. Overall this could have resulted in a stronger analysis of the results and more data to analyse.

In addition to this no significant change in SOC was found in Experiment 1, therefore it was suggested that the experiment should run for longer, to determine whether there is an effect of the sequestration method in Denmark. For Experiment 3 it would also be beneficial with a longer incubation period. Since no significant change in SOC was detected during the first 28 days, it was assumed that increased humification would occur later in the incubation cycle. However this lack of change in SOC during the first month could also be a result of the sequestration method not performing as expected. It would have been beneficial to run Experiment 3 for two months, to see if the increased sequestration did in fact occur, as was shown by Kirkby et al. (2013). It is therefore not possible to determine whether lack of change in SOC during the first month is due to sequestration occurring later in the incubation cycle, or if it was because no increased sequestration happened in the experiment.

8.2.2 Cleaning method

Another thing that could influence the results is the method to isolate SOM in the soil samples. Cleaning method is the method developed and used by Kirkby et al. (2013). The usage of this cleaning method was done to minimise difference in SOM fraction between experiments in this project and earlier experiments with focus on the sequestration method (Kirkby et al. 2014; Kirkby, Richardson, Wade, Batten, et al. 2016; Kirkby et al. 2013; Kirkby, Richardson, Wade, Conyers, et al. 2016). The usage of the cleaning method is therefore to be able to compare results in this project with earlier experiments with the sequestration method.

Dividing the different fractions of the soil is one of the biggest obstacles when analysing soil, since humus is not a separate part of the soil, but is integrated in the soil as a film around soil particles (Stevenson 1994). This is one of the reasons why it is difficult to fractionate the soil.

For this project SOM is identified as the material below 0.4 mm. However there is the possibility that a part of the degraded OM, which has not been transformed to humus is still present in the samples analysed.

While cleaning the samples for analysis, it was possible to remove a large amount of OM from the samples. However OM could have been degraded in such a manner, that it was smaller than 0.4 mm. but not yet SOM, leading to implications in separating SOM from OM. This amount of OM could influence the results, since C-content in applied OM is higher than that of humus.

This can result in SOC appearing larger than in actually is. Especially for the samples with extra nutrients added, because this increase the right conditions for the microbial organisms to break down OM and could potentially mean that SOC has not increased significantly, but the pieces of OM are just too small to separate in the sample.

When cleaning the soils it appeared that after the samples were presumably clean using the available cleaning method, more fractionated OM was left in the sample. When using static electricity very small pieces of OM could be removed from the sample. This indicates that the cleaning process was not complete, even though the cleaning method applied in this project should have resulted in a clean soil with no more OM left.

The uncertainty lies in whether the sequestration method with extra nutrients actually increases SOM or just degrades OM to a state, where the current cleaning method is not thorough enough to get rid of all OM, and therefore whether the increased SOC and SOM are actually interpreted as substantially bigger than they actually are, because OM is still left in the soil after cleaning. It is not yet possible to investigate this, since there has not been developed a method, which cleans the soil, without losing some of the nutrients in SOM. The cleaning method applied is therefore assumed to be the most applicable in these experiments.

8.2.3 Drying of the soil

The initial drying of the soil before the incubation has an influence on the microbial biomass in the soil. The process will result in a large amount of microorganisms dying. This way a large amount of material will be available for mineralisation when the incubation starts. A conclusion from the analysis (Chapter 4.1.1) was that there was a difference in SOC between CA and conventional farming practice. There could be a difference in the microbial biomass between the two farming practices, which could also lead to a difference in the amount of dead microbial biomass, which is left in the soil after drying. This might also have an influence on the results, since a larger biomass left in the soil from the beginning can result in a higher amount of dead biomass when the experiment start. Since it is argued that SOM is possibly made up of dead microorganisms, soils with larger amounts of these from the beginning of the incubation could have a higher SOM content than what is actually present in the soil in the field.

It would therefore be beneficial in the future if these types on incubations did not start with an air-dried soil, but rather a fresh soil sample, so the microbial activity represented that of the field. This could also possibly be done through a pre-incubation of the bare soil, to stabilise the activity before the experiment was conducted.

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10. Appendix

The following is an overview of the appendix. The actual appendix is available in a separate document.

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