Soil health on organic farms

Linking organic farmer practices to soil health and yield

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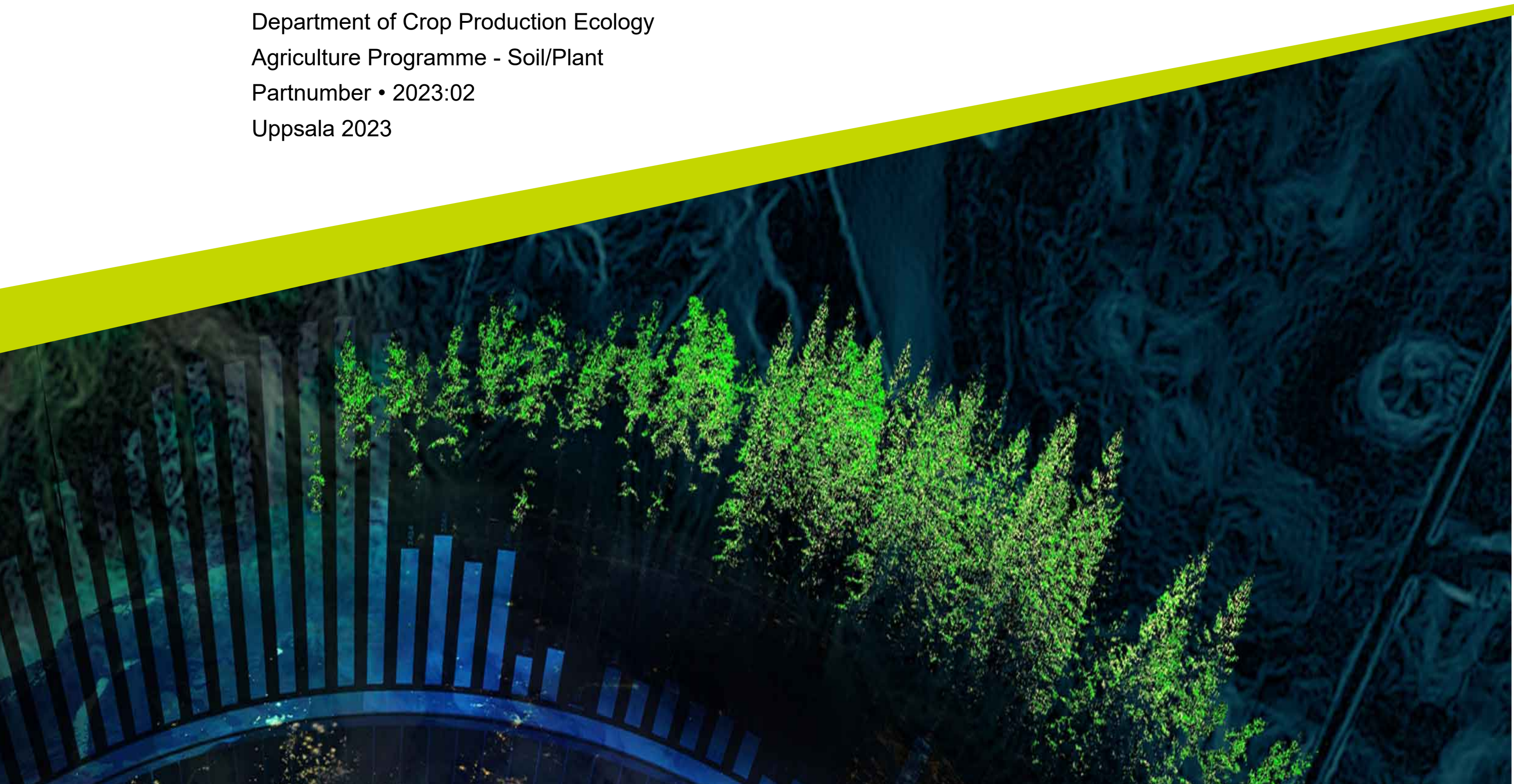

Soil health on organic farms. Linking organic farmer practices to soil health and yield

Jordhälsa på ekologiska gårdar. Koppla ihop lantbrukarens odlingsåtgärder på fältet med jordhälsa och skörd

Lina Johansson

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Abstract

Soil health is a part of the sustainable agriculture which the EU is trying to develop. Organic farming can be one way of working towards more healthy soils. The term soil health can be divided into biological, chemical, and physical aspects of the soil that are necessary to sustain the plants grown. This master thesis was conducted within the CONSTRAINTS-project which aims to provide knowledge to help improve the expansion of organic agriculture systems in regions of high productivity with proportionally few organic farms. The purpose of this master thesis was to assess the soil health on a group of organic fields with varying management in Västra Götaland, Sweden. The fields were included in the CONSTRAINTS-project and had varying management. The soil health was studied by analysing the bulk density (BD), potential mineralisation of nitrogen (pot-min), visible and near infrared reflectance (vis-NIR), clay content, pH, and plant nutrients. The BD, pot-min and vis-NIR were measured using soil samples collected during the summer of 2022. Clay content was retrieved from a digital soil map whereas soil pH and plant nutrients were analysed in an earlier soil sampling during autumn 2021 within the CONSTRAINTS-project. The different soil health indicators were related to the farmers' management, which was collected through interviews, and the yield. The results showed variations in the measured indicators between the different fields and statistical analyses were made to link the measured indicators to the yield. The soil health indicators that were closest related to the winter wheat yield were pH, and vis-NIR measurements (which are strongly related to clay and SOM content). The management practices that were most correlated with yield were connected to the fertilisation, age of the ley and proportion of legumes in the ley.

Keywords: organic farming, bulk density, farm management.

Abstrakt

Jordhälsa är en del i det hållbara jordbruk som utvecklas i EU. Ett sätt att jobba mot en bra jordhälsa är genom ekologisk odling. Termen jordhälsa kan delas upp i biologiska, kemiska och fysiska aspekter som är nödvändiga i jorden för att växterna ska kunna utvecklas och överleva. Detta examensarbete utfördes som en del i CONSTRAINTS-projektet, vars målsättning är att ta fram kunskap för att kunna utveckla den ekologiska odlingen i områden där det finns en hög produktivitet men låg andel ekologiska gårdar. Syftet med detta examensarbete var att kartlägga jordhälsan på en grupp ekologiska gårdar, med varierande odlingsåtgärder, i Västra Götaland. Detta utfördes genom analyser av ett antal indikatorer: skrymdensitet (BD), potentiell mineralisering av kväve (pot-min), vis-NIR, lerhalt, pH och växtnäringsämnen. Skrymdensitet, pot-min och vis-NIR mättes på jordprover som samlades in under sommaren 2022. Information om lerhalt hämtades från den digitala åkermarkskartan medan pH och tillgänglig växtnäring kom från en tidigare jordprovtagning under hösten 2021 inom CONSTRAINTS-projektet. Resultaten visade på variationerna i indikatorerna mellan de olika gårdarna och statistiska analyser utfördes för att relatera indikationerna till skörd. Odlingsåtgärderna på de olika gårdarna undersöktes med hjälp av intervjuer. Indikatorerna för jordhälsa som var starkast relaterade med skörden var pH och vis-NIR mätningarna (som är starkt relaterade till lerinnehåll och andel organiskt material i jorden). Odlingsåtgärderna som korrelerade mest till skörden var gödslingen, vallens ålder och baljväxtinnehåll.

Nyckelord: ekologisk odling, skrymdensitet, odlingsåtgärder.

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Abbreviations

BD	Bulk density
CEC	Cation exchange capacity
PCA	Principal component analysis
PLS	Partial least squares
SLU	Swedish University of Agricultural Sciences
SOM	Soil organic matter
vis-NIR	Visible and near infrared reflectance

1. Introduction

This introduction aims to give a background of why the subject of this thesis was chosen, and to provide a deeper understanding of the main topics before describing the purpose and research questions.

1.1 Sustainable Agriculture

The EU soil strategy aims to improve the sustainability of soil use in Europe (European comission 2021). The Soil strategy (2021) is a way of ensuring healthy soils by 2050 and it points out the benefits of a high carbon content and how the carbon content in soils is essential for biodiversity and soil fertility. Agroecology is mentioned as a way of sustainably managing soil. Agroecology is an approach of agriculture which considers the whole food system, from food production and transports to consumption and waste (FAO 2019). It can therefore be challenging to compare with other types of agriculture such as organic or conventional farming since those management practices typically focus on the food production. Agroecology does however promote diversity in agriculture and recycling of nutrients, aspects that are often found in organic farming (FAO 1999).

The Biodiversity strategy (2020) is promoting organic farming as a way of enhancing biodiversity within agriculture. The importance of insects and pollinators is pointed out and the use of pesticides is described as one aspect that can be harmful. There is a need for high soil organic carbon if biodiversity is to be achieved and Bommarco et al. (2013) describes that manure is a possible way of ensuring that. Organic farming in Sweden can be certified by EU's definition (European comission 2018). This includes limiting the use of pesticides and mineral fertilisers, forbidding the use of GMOs, ionising radiation and hormones as well as limiting the use of antibiotics within animal production. The limitation of mineral fertilisers promotes the use of organic fertilisers, such as manure and biogas digestate instead.

Organic farming is in other words, one possible way of working towards a more sustainable agriculture. To be able to analyse sustainability within farming, several different tests and aspects can be put into consideration (Hayati et al. 2011). There is a possibility to investigate greenhouse gas emissions, nutrient levels, and management systems, as examples. One interesting aspect to study is the soil health of organic farms which is the focus of this study.

1.2 Soil Health

Soil health is a concept that has been given many different definitions by different authors. The definitions usually include productivity, resilience and ecosystem services of the soil (Cardoso et al. 2013; Katyal et al. 2016; M. Tahat et al. 2020). The concept of soil health can also be divided into soil biological, chemical, and physical health or properties (Shahane & Shivay 2021). Biological aspects of a healthy soil include soil microorganisms, their diversity and function, soil organic matter (SOM), soil fauna and the soil's ability to limit pathogens while supporting the crop (Brackin 2017). Chemical properties to consider are pH and plant nutrients (Munoz & Zornoza 2017) and physical soil properties that could indicate good health are usually connected to the soil structure (Dexter 2004). A good soil structure should allow water infiltration and aeration for it to be a functional soil. Organic farming can, as previously mentioned, be one way of working towards a healthy soil. The manure used is a source of organic material that contributes to biodiversity by adding both food and habitats to many soil organisms (Lori et al. 2017). Soil organic matter is also important since it can affect soil structure, and water and nutrient holding capacity (Eriksson 2011).

Soil health is a challenging concept to understand, in this thesis the definition of Idowu et al. (2019) was chosen; *"…'soil health' can be defined as 'the state of the soil being in sound physical, chemical, and biological condition, having the capability to sustain the growth and development of land plants.'"*

Soil health is a growing concept and the good thing about it, no matter the definition, is the increasing interest in soil and what it can do. There have been discussions to define soil health as something more holistic, separating it from soil quality (Lehmann et al. 2020). Soil quality was then described as something more local with focus on agriculture whereas soil health would aim more towards including the whole planet and its ecosystem. The latter was decided to be a too complex concept to cover in this thesis, so the soil health definition used was the one closer to soil quality.

Soil health and soil quality have in other studies been used alternately (Lehman et al. 2015). The author explains how some might relate to the the soil health term as a way of illustrating soil as a part of or its own living ecosystem, whereas others favour soil quality because of the focus it lays on quantitative soil properties. It is however clear that the soil health term is still fairly undecided, and its research can, without a well-defined description, be somewhat indistinct. Today, soil health seems to be the dominating terminology used in both a policy and a research context.

1.2.1 Soil Health Case Studies

In soil health case studies, the soil health is usually verified by comparing it to yield or crop performance (Zhao & Wu 2021). The yield and colour of the soil are aspects usually studied by farmers as a fast way of indicating soil health internationally (Eze et al. 2021). Since it is not always correlated to soil health, it would be beneficial for future farmers to have the possibility to combine their visual observations with soil tests.

Adhikari et al. (2022) studied if the grain quality of corn was related to soil health in a similar way as yield is expected to. They did that using the Haney Soil Health Tool (HSHT) but only found weakly positive results to grain quality. The HSHT measures soil biological activity and was developed as a tool meant to aid in fertiliser recommendations among other things (Yost et al. 2018). This tool is focused on keeping information about the soil as realistic as possible, viewing it as a living system (Haney et al. 2018).

Another soil health test is the Cornell Soil Health Assessment (CSHA), which was used by Congreves et al. (2015). The CSHA emphasises the importance of integrating the soil chemical, biological and physical indicators to form a holistic view of soil health (*Manual | Cornell Soil Health* n.d.). Congreves et al. (2015) used the method to study how different tillage systems and varying crop rotations affect a group of fifteen selected soil indicators. The indicators included pH, SOM content and potential mineralisation of nitrogen, among other things.

1.2.2 Soil Biological Indicators

Soil biology usually includes research on soil organisms, their biodiversity and functions, soil organic carbon or SOM and the soils' ability to sustain the crop (Brackin 2017). Brackin (2017) discusses how, due to its complexity, it is an important and often disregarded aspect of soil health which can be hard to study. More so, the way different parts of the soil ecosystem affect each other might be overlooked.

The soil biology covered in this project included one aspect of soil microorganism functions (potential mineralisation of nitrogen), as well as a sensor measurement including information about SOM (visible and near infrared spectroscopy). Soil microorganisms are a group of organisms that are present in the soil, it consists of fungi, bacteria, algae, viruses and protozoa (Paul 2007 see Alexander 1977). Soil microorganisms are, among other things, able to mineralize nitrogen, making it accessible to plants (Brackin 2017).

Nitrogen is one of the main macro nutrients for agricultural crops. Eriksson (2011) explains how nitrogen is present in several different forms in the soil, and transformations between these can be illustrated by the nitrogen cycle (Figure 1). There is mineral nitrogen and organic nitrogen. The two categories can also exist either dissolved or bound to different compounds in the soil.

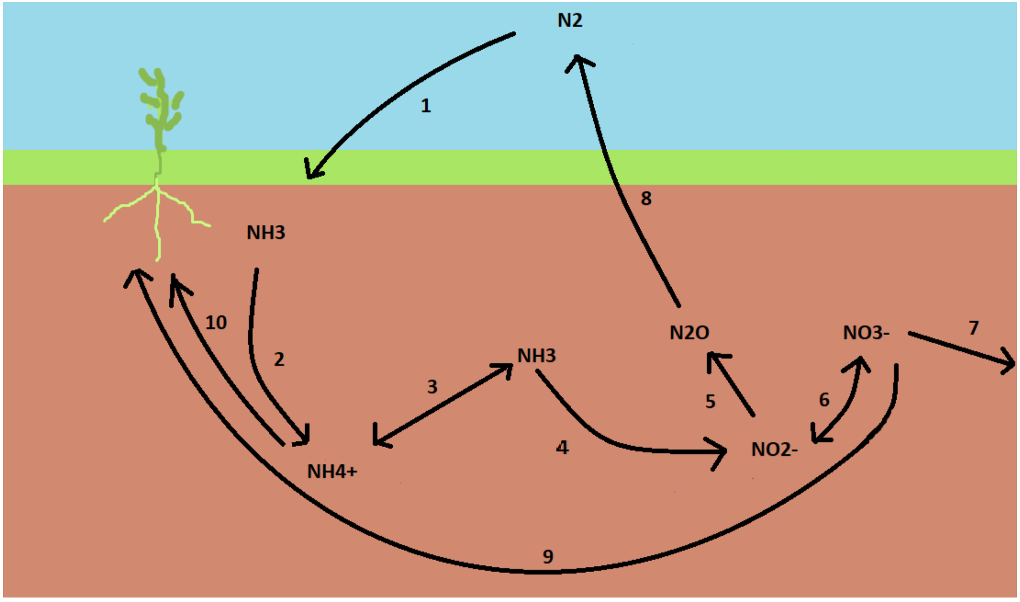

Figure 1. Simplified nitrogen cycle, based on Eriksson (2011). 1) The atmospheric nitrogen being fixated to ammonia by soil or root bacteria. 2) The mineralisation to ammonium, usually done by soil microorganisms. 3) representation of how some ammonium might become ammonia and be part of atmospheric losses. 4) and 6) the ammonia goes through nitrification to become nitrate.5) During the nitrification, the nitrite might go through denitrification and form nitrous oxide, which can become atmospheric nitrogen again, 8). 7) Nitrate lost through nitrogen leakage. 9) Nitrate can, like ammonium 10), be taken up by plant roots.

Brackin (2017) describes how biologically healthy soils usually are the ones that are as close to undisturbed as possible and gives examples such as permanent pastures or fields with high organic input. The fields used in this thesis have been managed by organic farming practices and included ley and/or pastures in the crop rotation as well as organic input. However, they cannot be considered undisturbed in the way Brackin (2017) describes.

1.2.3 Soil Chemical Indicators

Common aspects of soil chemistry that are used as soil health indicators are soil pH and plant nutrients. The soil pH, and nutrient pools of phosphorus and potassium were measured in this master thesis. Alternative indicators could also be the cation exchange capacity (CEC) and electric conductivity (Lehmann et al. 2020). The nutrients discussed in soil can be divided into macro and micronutrients, depending on the amount of nutrient that is needed for plant growth (Whitehead 2000). The macronutrients are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). The nutrients that are available in the soil solution are usually taken up by the plant roots in the form of ions.

Since organic farmers rely on the use of manure, green manure or other organic fertilisers, there can be difficulties to maintain an optimum concentration of nutrients available in time (Das et al. 2020). Phosphorous is the nutrient which usually limits the amount of organic fertilisers that is allowed to be added to a field in Sweden (Jordbruksverket 2019). This is due to the fact that it is only allowed to add 22 kg per ha and year, as an average over five years. This has been decided as a way of limiting eutrophication.

Soil pH is an important aspect of soil chemistry since it has the capacity of effecting many other aspects of the soil, including the availability of nutrients (Oshunsanya 2019). The optimum pH in agricultural soils varies around 5.5-7.5 (ibid.) and a low pH can cause yield loss among other things (Goulding 2016). Mineralisation of SOM can be a cause of soil acidification, which will occur in soil fertilised with manure. However, any fertiliser containing ammonium may also contribute to a lower pH. Legumes are another cause of lowering the pH because of their fixation of nitrogen which causes a release of protons. Organic farming usually includes a varied crop rotation containing legumes, as well as the fertilisation with manure. There are in other words aspects of organic farming which can contribute to acidification. A way to work against the acidification of soil is to apply a liming material which raises the soil pH (Fageria & Nascente 2014).

1.2.4 Soil Physical Indicators

Soil physics include the water, mineral, and air compounds in the soil. The mineral particle size distribution is what makes out the soil texture (Dexter 2004). The soil texture is one thing that affects the pore size in the soil which in turn affects the water and air flow and distribution.

Gehring (2017) describes soil structure as the grouping of soil particles into aggregates. Soil structure affects many aspects of the soil, such as the water infiltration, root penetration and SOM (Rabot et al. 2018). The texture, SOM and biological activity in the soil will in turn affect the soil structure and its stability (Eriksson 2011). A good soil structure is key for any farmer to help improve the biomass production.

Tillage is used mainly to prepare a seedbed by breaking soil into smaller aggregates (Keller & Arvidsson 2010). Tillage can also be one of the main factors responsible for soil compaction (Pagan et al. 2010). Bulk density (BD) is a way to measure compaction. The compaction of the soil gives an indication of how well the soil infiltrates water, allows root growth and can indicate the activity of microorganisms (Han et al. 2016). Bulk density can be used as a way of comparing soil quality locally (Al-shammary et al. 2018), and is the physical indicator selected in this study.

1.3 Purpose and Research Questions

The purpose of this study was to assess the soil health on a group of organic fields. The fields had varying management and information about the variation of management practices of each field was studied through interviews with the farmers. The soil health was assessed by analysing physical, chemical and biological indicators such as the bulk density, potential mineralisation of nitrogen, visible and near infrared reflectance (vis-NIR), clay content, pH, and plant available as well as potential pools of P and K. The different indicators were also combined in an attempt to give a score of the soil health of the fields, and put into the context of the farmers' management and the crop yield through statistical analyses. The following research questions were investigated:

i) How does the soil health and management vary between fields on organic farms in Västra Götaland?

ii) Which indicators correlate the most to crop yield?

2. Method

The method of this master thesis begins with a presentation of the fields studied and the research project this thesis was a part of. It continues with a short general explanation of the methods used before describing the different measurements and methods separately. Finally, it ends with a short analysis of the methods chosen.

2.1 Selection of Study Fields

Ten fields on organic farms were visited during the period of June to August 2022. The fields were chosen from the CONSTRAINTS-project based on a number of criteria. They had to have winter wheat as main crop 2022, ley as preceding crop (with varying species composition and age i.e. years of cultivation on the field), have been organic since at least 2011 and being within the high productive region of Västra Götaland (Figure 2). Some background information for each fields is presented in Table 1.

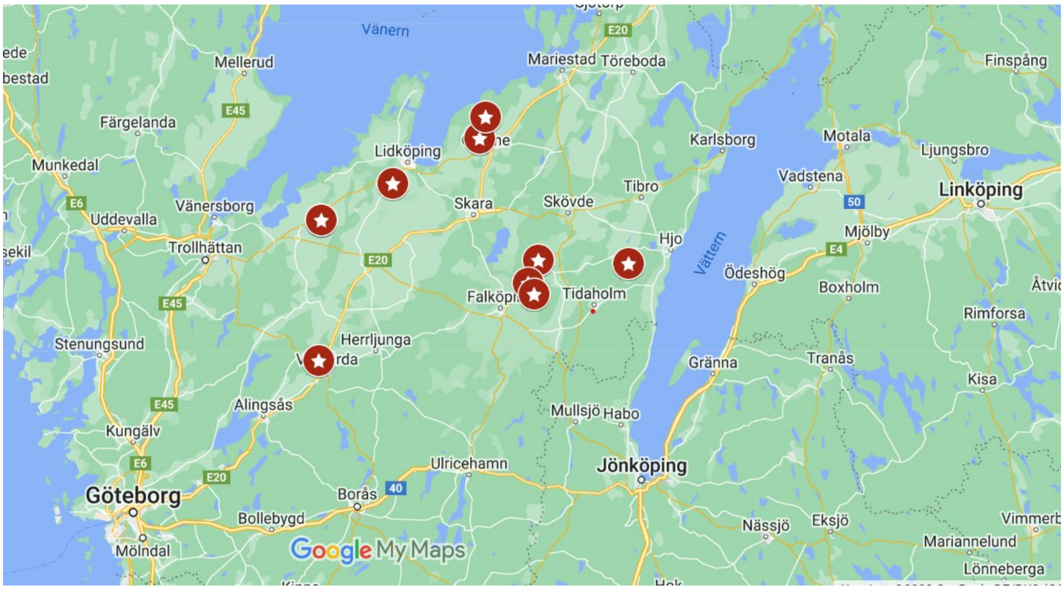

Figure 2. Map of Västra Götaland and the selected fields pinned out (Google maps).

Table 1. Some background information about the fields collected through interviews with the farmers. WW stand for winter wheat and Y/N stands for yes/no.

Field	WW variety	Field size (ha)	Animals on farm (Y/N)	Ploughed (Y/N)	W weed-management (Y/N)	Age of the ley (years)
1	Stava	4	Y	Y	N	6
2	Etana	46	Y	Y	Y	1
3	Hallfreda	8	Y	Y	Y	3
4	Stava	3	Y	Y	N	3
5	Informer Eko	9	Y	Y	N	4
6	Festival	8	N	Y	Y	2
7	Festival	5	N	Y	Y	3
8	Stava	5	Y	Y	N	3
9	Stava	15	Y	Y	N	3
10	Stava	17	N	Y	N	1

The Lanna weather station is located close to the middle of the group of fields studied and the average weather at Lanna weather station is presented in Figure 3 and 4. When looking at the mean temperature and precipitation of Lanna it seems to have been slightly warmer and drier during the crop growth season this year, compared to the reference period of 1991-2020.

Each field had a ley crop in 2021 which was followed by a winter wheat crop sown in the autumn 2021 and harvested in 2022. The variety of winter wheat differed, as well as the type of ley. The age of the ley differed from a one year clover seed ley to a six year grass-clover ley used as pasture. The farms also had varying management practices and production focus, most including animals of some sort. Communication with the farmers was facilitated by the fact that the farms were previously part of observational on-farm trials in 2020.

The fields were included in the CONSTRAINTS-project. ’Constraints on the expansion of organic farming in Sweden’ is a project funded by ’the Swedish Research Council for Sustainable Development Formas (2019-2023)’. The purpose of the project is to provide knowledge to help improve the expansion of organic agriculture systems in regions of high productivity with proportionally few organic farms.

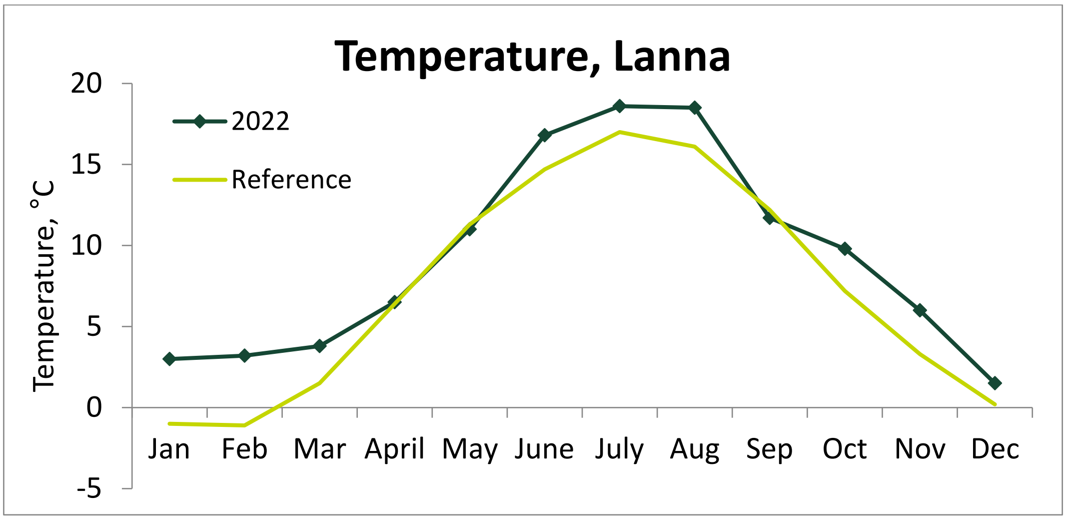

Figure 3. The mean temperature of each month for 2022 and a reference period for 1991-2020, from Lanna weather station.

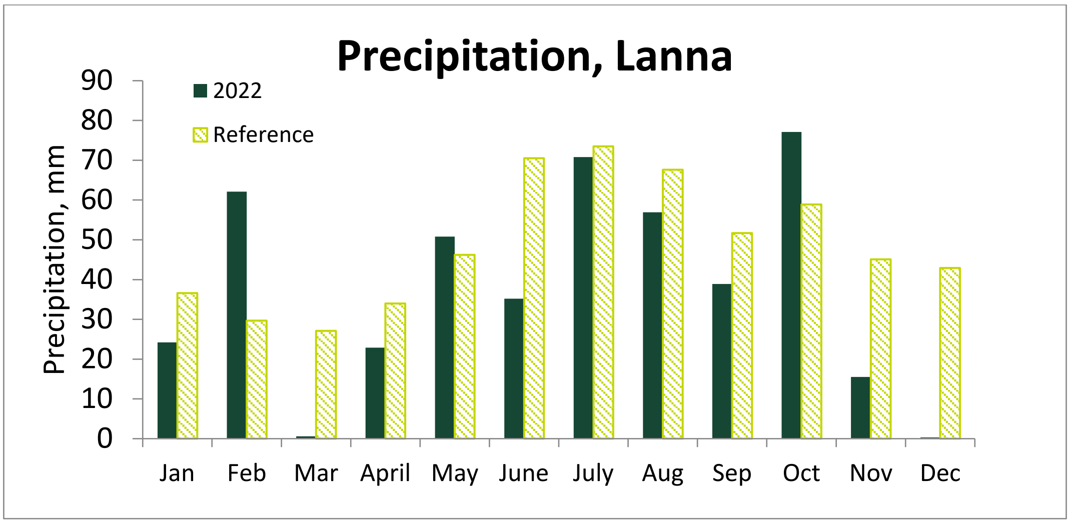

Figure 4. The mean precipitation of each month for 2022 and a reference period for 1991-2020, from Lanna weather station.

2.2 Design of the Study

The method for this thesis was to select a number of different indicators that could be related to soil health. The idea was to cover the three parts, biology, chemistry, and physics, as well as discuss the farmers' management. Most of the data was collected during the crop growth season 2022 while the winter wheat was cultivated. The main location of data collection will be referred to as the representative place of the field. This was an unfertilised plot (in 2022) selected within the CONSTRAINTS-project to be representative for the field. The rest of the field was managed as normal by the farmer (typically including fertilisation).

For the bulk density and vis-NIR measurements, two additional locations on the field were chosen to enable a comparison within the field. These will be referred to as the good and the bad place. To decide the locations of the good and bad places, different methods were used. The entrance of the field was typically located, with help from the farmer, to use as the bad place since it is a place where the soil is expected to be compacted. The good place was mainly chosen by selecting the area with the highest vegetation biomass index (*CropSAT* n.d.). This would indicate a high productivity of that site but might not be related to the physical aspects of the soil.

The yield of the fields were measured in the unfertilised representative area of the field and outside of the unfertilised area were the field was managed according to the farmer practices, including possible fertilisation. No yield data was collected from the good or bad place of the fields. A schematic figure of the general set up is visualised in Figure 5.

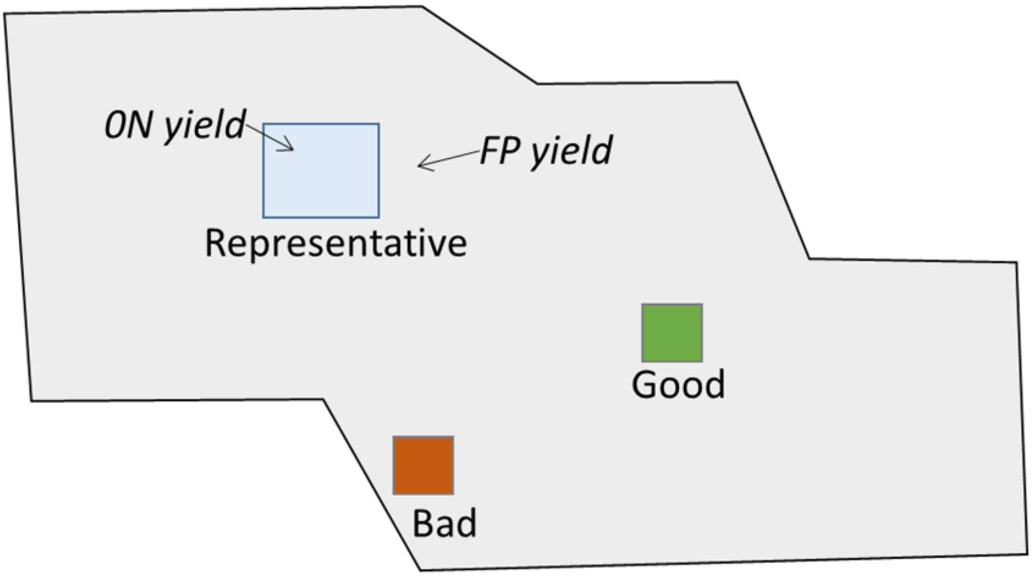

Figure 5. The general set up of the study. The representative place of the field was unfertilised and was were most measurements were taken. The good and bad place were used for additional measurements for the BD and vis-NIR measurements. The yield was collected from the unfertilised (0N) representative place and outside of it for the yield of the farmer practices (FP).

2.3 Bulk Density

Bulk density was measured using cylinders with a volume of 204 cm^2. The cylinders were taken using a drop-hammer (Figure 6) which enabled taking the soil samples with cylinders at 5, 20, and 40 cm depth. The different depths were chosen to give representative samples of the topsoil, possible ploughing pan, and subsoil. For the BD measurements, the three different locations within the field were used.

The three depths were sampled in the same hole and three holes (repetitions) were sampled at each of the good, bad, and representative place of each field, see Figure 7. The subsoil samples (40 cm depth), were only collected in the representative place of the field in an attempt to save some time. This was decided since the subsoil is the depth of the fields which is the least effected by soil management and was expected to be similar over in the separate locations.

Figure 6. To the left, the drop hammer used to put down the cylinders for the bulk density measurement. To the right, a subsoil hole prepared at 40 cm with the bulk density cylinder in the hole.

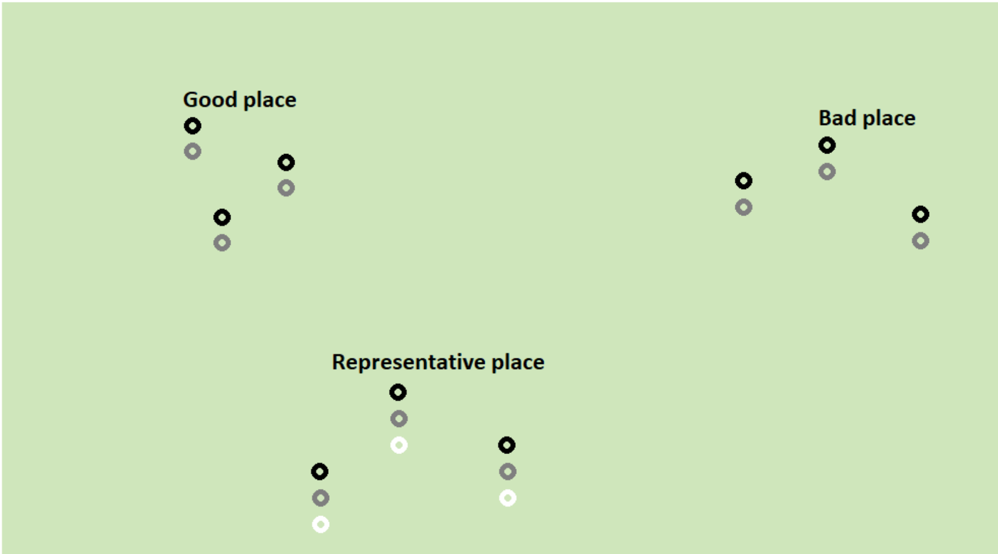

Figure 7. An illustration of the bulk density samples on an imaginary field. The good place and bad place would have three repetitions each of topsoil (black, 5 cm) and ploughing pan (grey, 20 cm). The representative place would have the same samples taken, as well as subsoil samples (white, 40 cm) underneath.

After the samples were collected from the field, they were dried at 55 degrees for 36-48 hours. Finally, the samples could be weighed, and the bulk density calculated through; *dry weight / volume*.

2.4 Potential Mineralisation of Nitrogen

Soil samples were taken in the unfertilised, representative part of the field during crop growth for the potential mineralisation. Five to ten samples were collected with soil augers to 20 cm depth in a Z-pattern across the unfertilised plot. Each soil sample was then sieved at 2 mm to form one pooled sample per field. The samples were then brought to the lab to be frozen until the lab work began.

The lab work was initiated by thawing the soil samples. For each field's pooled sample, the following was done; 10 g of soil was weighed, and 25 ml of deionised water was added. This was repeated five times, resulting in five replicates per pooled sample. Two of the replicates were then separated as controls. For the controls, 25 ml 4M KCl was directly added, and the replicates were then shaken for two hours before being left to sediment for 30-60 minutes. Afterwards, the soil had mainly deposited to the bottom and 15 ml of each replicates' supernatant were filtered into a control bottle and frozen.

The remaining 3 replicates were instead flushed with N_2 gas to enable anaerobic conditions before being incubated at 40 degrees Celsius in a climate chamber for 7 days. After the incubation, the mixtures also had 25 ml 4M KCl added to them before being shaken for two hours and settling for 30-60 minutes. Twenty-five ml of the 3 mixtures were then filtered into 3 bottles before freezing.

Finally, all the samples were sent for analysis of ammonium.

2.5 Visible and Near Infrared Reflectance

Soil samples from the three different top soil locations (good bad and representative) and the subsoil samples from the representative place were dried and sieved to 2 mm before being used for the visible and near infrared reflectance (vis-NIR) measurements. The samples were measured using a vis-NIR spectrophotometer (FieldSpec Pro FR scanning instrument, Malvern Panalytical). To get a representative result, each sample was measured, stirred and then measured again. This was done to make sure a larger portion of the sample was included in the measurement. The results were saved in the computer for further analysis.

The vis-NIR spectrophotometer is a device used to analyse samples both quantitively and qualitatively, and the later was used for this thesis. The instrument measures the range of the electromagnetic spectrum from 350 to 2500 nanometre. The light reflected by the sample is measured to create a spectrum which holds information of sample's properties. The NIRS automatically recalculates the reflection to absorbance and presents the raw data in graphs (Figure 8). The raw data graphs are good for seeing the water peaks around 1400 and 1900 nanometre.

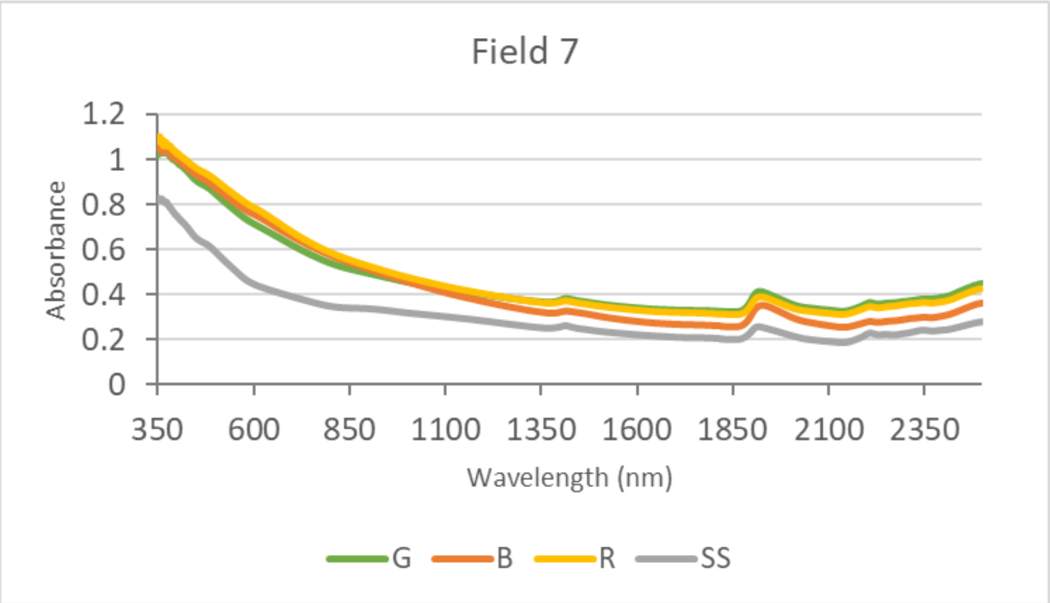

Figure 8. An example of how the raw data NIR spectra looks. It presents the absorbance in relation to the electromagnetic spectrum. G, B, and R stands for the good, bad and representative top soil measurements. SS stands for the subsoil measurement.

The point of the graph is to see how the different lines differ from each other. What is not interesting is their different starting points and other disturbances. This is dealt with by deriving the results, making them look more like Figure 9. Here, it is clearer that the subsoil sample differs more from the other samples, especially in the beginning of the spectra where information related to SOM is usually found.

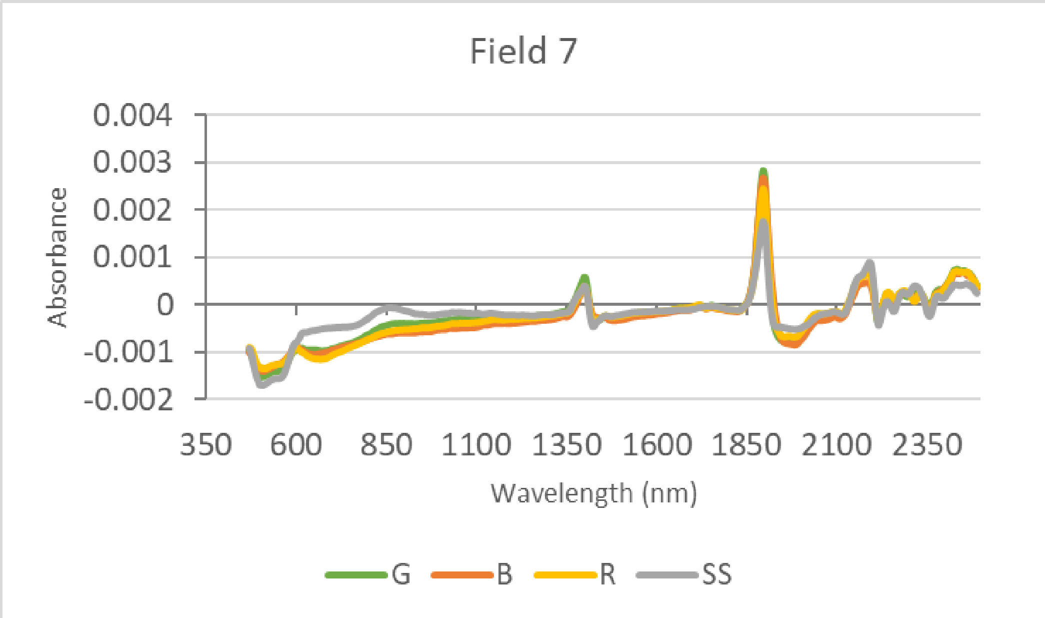

Figure 9. An example of how the spectra looks after derivation. G, B, and R stands for the good, bad and representative top soil measurements. SS stands for the subsoil measurement.

The different spectrums that were the results of the measurements varies due to the different samples ability to absorb energy (Stenberg et al. 2010). The major causes for differences in the spectrums are typically SOM and clay content. A principal component analysis (PCA) was conducted after finishing all the measurements, which is explained more thoroughly in the *Statistics* section.

2.6 Plant Nutrients and Soil pH

Some measurements were previously analysed within the CONSTRAINTS-project and the results that were used in this master thesis were for soil pH, plant nutrients and clay content.

Soil samples were taken at the depth 0-20 cm in the fall 2021, shortly after the sowing of the winter wheat crop. They were sent for analysis to obtain their chemical composition including the following elements: pH (1:2.5, H2O), available potassium (K-AL) and phosphorus (P-AL), as well as the 'storage' of P and K using the HCl-extractable method (Egnér et al. 1960).The AL method represents the plant-available nutrients whereas the HCl-extractable method gives an indication of the pool which is less available.

The P-AL classes are as follows; class I < 2, class II 2-4, class III 4-8, class IVA 8-12, class IVB 12-16 and class V > 16 (mg P/100g soil) (Jordbruksverket 2022). The K-AL classes are class I < 4, class II 4-8, class III 8-16, class IV 16-32, class V > 32 (mg K/100 g soil). The different classes are commonly used as a way of indicating the need for fertilisation. A high class suggests that there is little to no need for fertilisation and that there might instead be a risk of leakage. A low class could instead indicate the need for more fertiliser containing the specific nutrient. Class III is generally the class to aim for, indicating that the need for fertilising with the nutrient is equal to what is removed by the yield.

The HCl method gives an indication on the long-term supply of the nutrient (Jordbruksverket 2022). The values are more commonly considered for K, whereas it less common to consider P-HCl in the practical fertilisation planning. The P-HCl classes are divided as follows; class I <20, class II 20-40, class III 41-60, class IV 61-80, and class V >80. The K-HCl classes are class I <50, class II 50-100, class III 101-200, class IV 201-400, and class V >400. The different K-HCl classes indicate how stable the K-AL-classes might be, and with a low K-HCl class, there might be reason to fertilise with the nutrient even with a sufficient K-AL class. K-HCl is typically strongly correlated with the clay content of Swedish soil since they are rich in potassium. A value for the clay content at the representative place was selected by using the digital soil map in *Markdata.se*.

2.7 Farmer Management Interviews

The farmer management of the fields were assessed through interviews by telephone. The interviews were semi-structured, where the questions and their order were predetermined but the farmers were free to elaborate on what they found the most interesting. The main aim of the interviews was to learn how the farmer had managed the preceding crop (ley) and the winter wheat crop. The questionnaire is presented in Appendix 1.

An interesting aspect for the discussion regarding soil health was the varying amount of nitrogen fertilisation applied by the farmer. The idea was to investigate the links between good soil health and a high yield. However, a low amount of nitrogen applied can “hide” positive effects of a good soil health since the fields with high fertilisation will most likely have the highest yields. To avoid bias in the results, the analysis of soil indicators was based on the unfertilised yield. The management indicators were instead correlated to the yield obtained with the farmer’s practices, including fertilisation.

2.8 Crop Yield

To compare the crop yield, the yield of the unfertilised, representative area of the field as well as the yield of the area with the farmers own practice was measured. Four replicated were made for both treatments, cutting the crop by hand in a 50*100 cm area. The harvested crop was then sorted by hand to divide into straw and ears. The purpose was to have data on both kernels and total biomass. For this master thesis, only the grain yield (kg/ha) was used.

2.9 Combined Soil Health

Most of the individual results of the indicators were combined as a simplified scoring of the soil health. The idea was to see how many "good aspects" each field had from the measurements. For the BD indicator, a relation between the value of the representative and good place was used (R/G). A lower value than 100 indicates that the representative place was less compacted than the good place, and therefore considered a good aspect of the soil. The PCA from the vis-NIR was used to analyse if the representative topsoil samples had high or low SOM content. A higher content than the average of the fields was selected as a good aspect. For the P-AL, classes III-IVA were used as the good aspect, and for K-AL, classes III or above were used based on the recommendations of Jordbruksverket (2022). It is difficult to say what is better or worse regarding the clay content, since it depends a lot on management. However, for the sake of this master thesis, a clay content of 25-45 % making it a heavy clay was chosen as the good aspect of soil. This was chosen since a high clay content is commonly connected to high yields in Sweden, especially for winter wheat (Weidow 2018). The unfertilised yield was in this case used as an indicator of its own, for the nitrogen availability in the soil. A higher unfertilised yield indicates a higher nitrogen availability in the soil, and the average of the studied fields was used as the threshold for considering it a good aspect. The number of good aspects for each field was finally summarised.

2.10 Statistics

Simple descriptive statistics were used to gain knowledge of standard errors, means and variation of most data. To identify factors correlating to crop yield, multivariate statistical analyses based on partial least squares (PLS) were carried out. Yield data for both the unfertilised plots and farmer practices were used. All analyses were carried out using R software (*R Core Team* 2022). PLS regression is a statistical method based on covariance. It is often used in the case where the number of explanatory variables is high, and where it is likely that the explanatory variables are correlated. This method reduces the explanatory variables to a smaller set of predictors. These predictors are then used to perform a regression. One way of interpreting the results of the regression is to use Variable Importance in Projection (VIP) scores. These are meant to estimate the importance of each variable in the projection used in a PLS model. The VIP score can then be used for selecting explanatory variables most related to the response variable (in this case "winter wheat yield"). A variable with a VIP Score close to or greater than 1 can be considered important in the PLS model (Martens & Naes 2004).

For the vis-NIR measurements, a PCA was used. A PCA is a way to enable an analyse of data with many variables (Esbensen et al. 2018). The aim is to reduce the many variables to a few principal components (PC). The PCs describe the importance of different variables by ordering them starting from 1. The first and second variables thus being the most important. It can be difficult to interpret what variables correlates to the different PC's. This makes it hard to analyse the results without other measurement or prior knowledge of the sampling site. The PCA and PLS are similar techniques, but where the PLS explain the predictors to the yield (in this study), the PCA explains the whole variation in data (for the vis-NIR measurements).

3. Results

The results are here presented, divided by indicator. In the end of this section, the results are finally collected to present a soil health scoring and two case study fields in an attempt to visualise the assembled soil health, management and yield data of the fields.

3.1 Bulk Density

The results from the BD measurements are visualised in Figure 10. It shows that the BD varies between 1.2-1.7 in the fields. The detailed results for each field as a table are presented in Appendix 2.

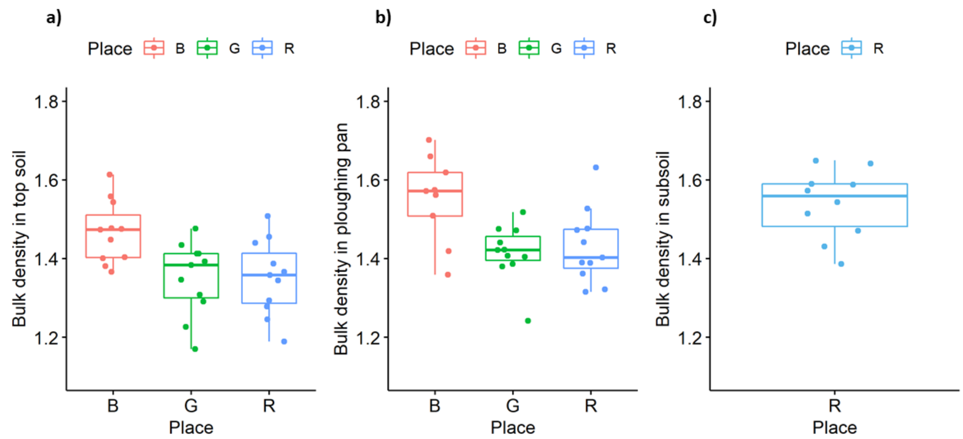

Figure 10. The fields' BD (g/cm^3) results representing the topsoil samples (a), the ploughing pan samples (b), and the subsoil samples (c). The good (G) and bad (B), sites are visualised in addition to the representative (R) site in graph a and b. The box plots show the spread of the measurements along the vertical line, the box includes the measurements between the 25th and 75th percentile. The median of the measurements is visualised as the thick horizontal line.

There is a substantial variance within each site and depth, but there are some general differences visible. The bad place is the site which has the highest bulk density in both the topsoil and the ploughing pan. It is important to remember that the site was chosen with an aim to find a highly compacted place in the field. The good place, which was chosen with a vegetation biomass index does not seem to have a lower bulk density than the representative place. The ploughing pan has a slightly higher BD than the topsoil, no matter the location in the field and the subsoil also has high values.

3.2 Potential Mineralisation of Nitrogen

The results from the potential mineralisation would have displayed the amount of ammonium present in the solutions that had previously been prepared in the lab. Unfortunately, due to unknown reasons, an unexpected turbidity was found in the extracts after thawing, and they were deemed unsuitable for analysis.

3.3 Visible and Near Infrared Reflectance

The results from the vis-NIR measurements were used to perform a PCA (Figure 11). The two axes represent the two aspects that effect the results the most. It is not set what these two aspects are, but they are closely related to the SOM and clay content. In PC1 (axis x), a high SOM content (and a lower clay content) seem to be indicated to the left in the graph and a higher clay content (and lower SOM) to the right. In PC2 (axis y), a high clay content seem to be represented higher in the graph. The graph (Figure 11) presents all the different measurements in the same colour as their field. There are four measurements per field, the topsoil of the good, bad, and representative place as well as the subsoil measurement. When studying the graph, it is most common for the dots to either be relatively close together or for three of the measurement to be close and one to be further away.

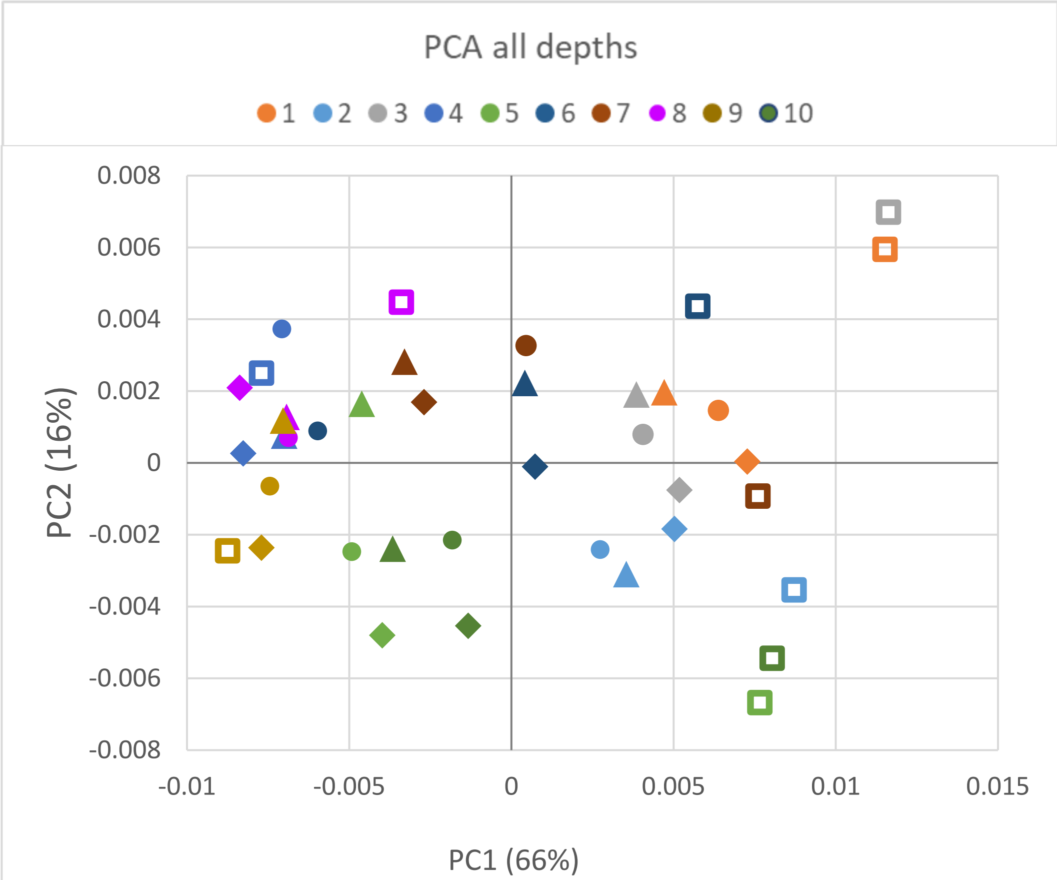

Figure 11. PCA of the vis-NIR measurements for the good place (circle), the bad place (triangle), representative place (rhomb), and the subsoil (hollow square).

It shows that the measurement that differs the most from the others is the subsoil sample. Some subsoil samples, from field 4, 8 and 9, seem to be high in SOM and field 1, 2 and 3 are the fields which have the highest clay content in the topsoils.

3.4 Plant Nutrients and Soil pH

The result for the plant nutrients, soil pH and clay content are shown in Tables 2, 3 and 4. Table 2 presents the P-AL, K-AL, and their corresponding classes for each field. The P-AL classes for the fields varies between I and IVA with a majority in the desired class III. There is only one field above class III and one field below class II. K-AL classes only varies between II and III with a majority of the fields in the slightly low class II.

Table 2. The P-AL, K-AL, and the P-AL- and K-AL classes for each field.

Field	P-AL (mg P/ 100 g soil)	P-AL class	K-AL (mg K/ 100 g soil)	K-AL class

1	3.6	II	16	III
2	5.3	III	8	II
3	3.7	II	10	III
4	9.5	IVA	6.6	II
5	4.5	III	4.5	II
6	4.8	III	6.2	II
7	7.3	III	6.6	II
8	3.1	II	5.3	II
9	1.9	I	4.5	II
10	4.8	III	9.5	III

Table 3 displays the P-HCl, K-HCl and the corresponding classes. The P-HCl classes for the fields varies between III and V, i.e. commonly being high. The K-HCl classes varies between I and V, stretching over all classes. The K-HCl can be linked to the clay content of the fields (Table 3)

Table 3. The P-HCl, K-HCl and the P-HCl- and K-HCl classes for each field.

Field	P-HCl (mg P/ 100 g soil)	P-HCl class	K-HCl (mg K/ 100 g soil)	K-HCl class
1	57	III	420	V
2	61	IV	210	IV
3	65	IV	330	IV
4	110	V	130	III
5	58	III	49	I
6	45	III	140	III
7	74	IV	120	III
8	60	III	200	III
9	72	IV	78	III
10	59	III	63	II

Finally, the pH and clay content are presented in Table 4. The pH varies within a reasonable span, were optimum is 5.5-7.5 (Oshunsanya 2019). The pH of the different field's lays within that span and the only possible outlier would be field 4 with pH 7.4. The field with the lowest soil pH values are field 5 and 7 with a pH of 6.1.

The clay content shows higher values in field 1, 2 and 3, whereas the lower values are in field 4, 5, 7 and 10. As stated previously, the clay content are values taken from a map and not values measured from the collected soil samples. The USDA texture triangle (USDA 2008) was used to classify the soils as loams, loamy soils, clays or heavy clays. The majority of the studied fields had a lower clay content, making them loams.

Table 4. The pH, clay content and the clay classification for each field.

Field	pH	Clay content (%)	Clay classes [1]
1	6.6	38	Clay
2	6.5	27	Clay
3	6.6	41	Heavy clay
4	7.4	14	Loamy soil
5	6.1	7	Loamy soil
6	6.5	17	Loam
7	6.1	15	Loam
8	6.5	18	Loam
9	6.6	16	Loam
10	6.6	15	Loam

[1] Clay classes based on the USDA texture triangle.

3.5 Farmer Management Interviews

The interviews have been compiled into the results presented in Figure 13. The different groupings of the results are made in relation to the ranges of results of this study, not considering other fields or practices. As an example, the first aspect of how long the ley as pre crop was grown before the winter wheat is categorised in 1-2, 3-4 and 5-6 years, not considering that some leys on other farms can be grown well over 10 years. Some results from the interviewing questions (Appendix 1) were included in the background information of the fields (see section *The Fields)* and are therefore not presented in the table. Other results were used in the CONSTRAINTS-project and outside of the scope of this thesis.

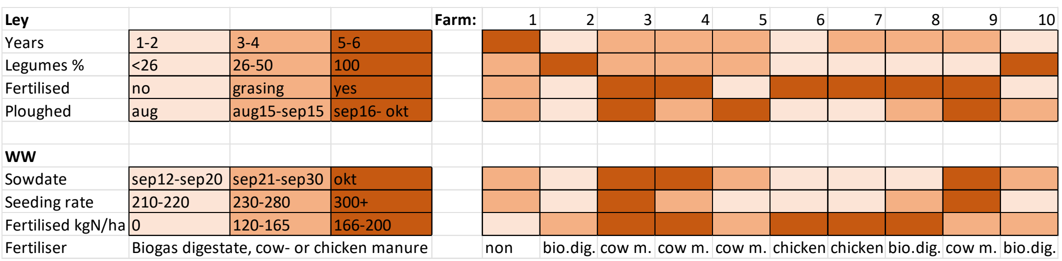

Figure 12. A visualisation of the variance in management between the selected fields on ten farms. The figure displays a group of the asked questions and are divided into two main categories, ley and winter wheat (WW) management.

The results from the interviews show the main differences between the farms and their management of organic fields. Some variables are usually correlated, such as the number of years the ley was grown, and the proportion of legumes. The fields with only one year ley had 100 % legumes since they had a clover seed ley. Whereas the leys grown for more years had a mixed ley with legumes and grasses. Another aspect that typically correlated was the sowing date and seeding rate. The farmers explained how the difficult weather conditions in autumn 2021 (high precipitation) caused a late sowing date. To make up for the late sowing, they often compensated with a high seeding rate.

The fertilisation typically varies between 120-200 kg N/ha with only one field (field 1) were the farmer chose to not fertilise their field. The different types of fertiliser used were biogas digestate, cow manure or chicken manure.

3.6 Crop Yield and its Relation to Indicators

The yields are presented in Table 5. It varies between 2500 – 8100 kg/ha in the unfertilised plot, and between 2400 – 10500 kg/ha in the farmer practice plot. Some fields (1, 4, 5, and 8) does not have big differences between the two yields and few of those fields (4, 8) also seems to have a higher yield in the unfertilised plot. However, the standard error of the yields was typically high and a direct comparison might be misleading.

Table 5. The mean yield of the unfertilised plot (N0) and the yield of the farmer practice plot (FP) for each field, as well as the standard error of each field and treatment.

Field	Yield N0 (kg/ha)	Standard error N0 (kg/ha)	Yield FP (kg/ha)	Standard error FP (kg/ha)
1	2 500	500	2 400	400
2	4 300	1 100	10 500	1 100
3	8 100	700	9 700	1 700
4	7 900	1 200	7 500	1 500
5	5 500	600	5 700	600
6	3 100	200	4 300	1 200
7	2 700	500	4 300	700
8	7 500	1 000	7 300	1 400
9	5 600	600	7 100	700
10	4 600	400	6 900	500

To be able to answer the research question, "*Which indicators correlate the most to crop yield?*" the different indicators were put in relation to the yield of the field. This was done using VIP scores (Figures 14 and 15) from the PLS (Appendix 3). In Figure 14, the measured or collected soil indicators were correlated to the unfertilised yield. According to the diagram, the pH and PC1 from the vis-NIR measurement are the indicators most related to the yield (N0). The pH in the fields vary from 6.1 to 7.4 (Table 3.) The PC1 from the vis-NIR measurements is driven by SOM and clay content.

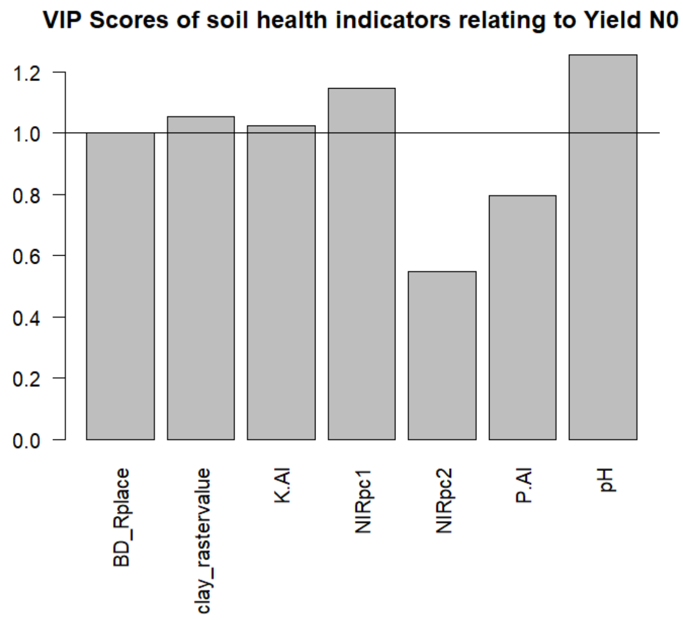

Figure 13. Some of the most important soil indicators related to the unfertilised yield. A higher value indicates a higher correlation of the indicator to the yield.

In Figure 15, some of the management aspects of the fields were correlated to the yield from the farmer practice plots. The diagram shows that the length of the preceding ley (Ley_years), the proportion of legumes sown in the ley (Ley_legumes) and the fertilisation of the field (Total_N_kgha) is what affected the yield the most. The VIP scores do not say anything about how the indicators relate to yield, but simply that they are strongly correlated.

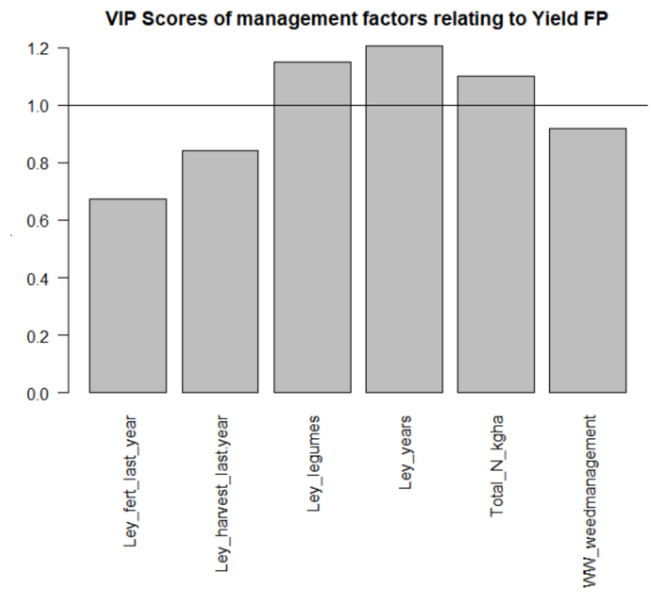

Figure 14. Some of the most important management indicators related to the farmer practice's yield. A higher value indicates a higher correlation of the indicator to the yield.

3.7 Combined Soil Health

The results are here summarised in an attempt to provide an overall picture of the measured indicators. The indicators are marked in a darker green if they are deemed to be "good aspects" of the soil in the studied fields. From this attempted characterisation method, field 1, 3, 4, 5, 8 and 10 have a high number (4-5) of good aspects and therefore a good soil health.

Table 6. The summarised results of the some of the soil health indicators. The indicators marked in darker green are the indicators which can be classified as "good aspects" of the fields.

Field	BD topsoil (R/G)	vis-NIR SOM content	P-AL class	K-AL class	pH	Clay classes	Yield N0 (kg/ha)	Number of good aspects
1	97	Low	II	III	6.6	Clay	2 500	4
2	104	Low	III	II	6.5	Clay	4 300	3
3	94	Low	II	III	6.6	Heavy clay	8 100	5
4	102	High	IVA	II	7.4	Loamy soil	7 900	4
5	100	High	III	II	6.1	Loamy soil	5 500	4
6	107	Low	III	II	6.5	Loam	3 100	2
7	101	High	III	II	6.1	Loam	2 700	3
8	90	High	II	II	6.5	Loam	7 500	4
9	104	High	I	II	6.6	Loam	5 600	3
10	95	High	III	III	6.6	Loam	4 600	5

As an attempt to combine the biological, chemical, and physical components of soil health and put them into context of the farmer management, case studies of two fields (1 and 10) were made and are presented in Table 6.

Table 7. Soil health and management indicators for fields 1 and 10.

	1	10
SOM	Low	High
Ley (years)	6	3
Clay content (%)	38	16
BD	Low variation	High variation
BD - comment	Old ley, no fertilisation/ driving	Bad place selected was very compacted
P-AL (class)	Low (II)	Very low (I)
K-AL (class)	Good (III)	Low (II)
pH	6,6	6,6
Management	No fertilisation, using "pre-crop" effect Otherwise, standard management	Ploughed the ley late, resulting in a late sowing date for the WW Compensation with high seeding rate
Yield FP (kg/ha)	Very low (2400)	High (7100)
Yield N0 (kg/ha)	Low (2500)	Average (5600)

Both farm 1 and 10 have livestock and the fields studied lay close to the farm centre. The main underlying conditions is the difference in clay content and SOM. A high clay content can as previously mentioned typically be connected to high yields but be subject to soil compaction if not managed properly. A high SOM content is beneficial to biodiversity and soil fertility.

The farmer of field 1 chose to grow a 6 year pasture on their clayey field. They also chose to use standard methods (in the context of the group of farms studied in this thesis) to manage the ley and winter wheat with one exception. The field was not fertilised for either the pasture or the ley, but the ley was used as a pasture for cattle grazing. The farmer of field 1 decided to let winter wheat be left unfertilised and rely on the nitrogen and nutrients were left in the soil to sustain its growth. This led to the lowest yield for farmers practices among the fields in this study, since all the other farmers fertilised their fields. It also had one of the lowest yields when comparing the unfertilised yields across the fields. It is difficult to point out one single aspect to why this is, but the low SOM content and the old ley are factors that indicate a low nitrogen delivery.

Farm 10 chose to plough the ley very late in the autumn, resulting in a late sowing date for the winter wheat. To compensate this, the farmer chose a high seeding rate in hope to get some of it to germinate. The farmer stated in the interview that they expected a good yield since it seemed like the winter wheat had established well. Something to be noted in field 10 is that the P-AL class was only I, indicating a high need for fertilisation including P. The yield in the farmer's plot for this field was high anyway, possibly due to the added cow manure. The yield in the unfertilised plot was lower, which is to be expected without addition of N and P.

The bulk density (Figure 16) of the fields shows that field 1 had little variation between measurements and generally low values. A reasonable explanation is that the long laying ley and reduction of heavy traffic due to not fertilising the field has had a positive effect on the soil structure. The bulk density of field 10 was lower, except for the considerably higher BD in the 'bad place'. The place selected was however particularly compacted and located in the tracks of the main entrance. A place the farmer noted, where they barely bothered to till.

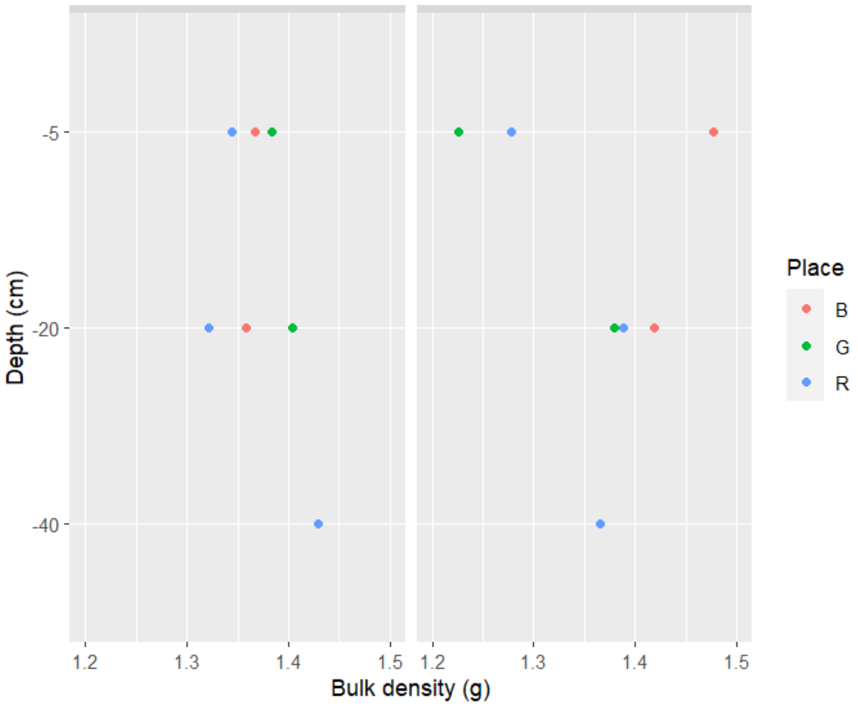

Figure 15. The bulk density for field 1 to the left and 10 to the right. The values are presented for the three depths, 5, 20 and 40 cm. The good (G), bad, (B) and representative place (R) are also visualised.

4. Discussion

In this section, the indicators will be discussed and an attempt at answering the two research questions "*How does the soil health and management vary between fields on organic farms in Västra Götaland?*" and "*Which indicators correlate the most to crop yield?*" will be done. Future research or applications related to soil health will also be suggested.

4.1 Discussion of the Soil Health Indicators

The BD results mainly indicated what had been expected, with higher values in the ploughing pan and the 'bad place'. The fact that the BD results did not show any particular differences between the representative and good place could indicate that the higher biomass (which was used to select the good place) was not due to a better soil structure. Another possibility could be that the field was not compacted in general, but that conclusion is hard to motivate using only this data. The fact that the ploughing pan was compacted was also expected since all farmers typically tilled the soil to a depth of about 20 cm. That the subsoil has the highest BD values can be explained by the fact that the subsoil typically contain more clay and less SOM than the topsoil. Clay can be heavier than other soil textures if compacted (USDA 2008 see Arshad et al. 1997), and soil particles are heavier than SOM, which raises the BD.

The mineralised nitrogen would have served as an indicator of biological activity in the soil, however, no results could be obtained for this indicator. This aspect would have been valuable to include in the discussion on how representative our choice of indicators to estimate soil health were. Hypothetically, a large amount of ammonium measured would have pointed towards a soil where the microorganisms had been able to mineralise nitrogen when confined in the climate chamber in the lab. The healthier the community of soil microorganisms, the more nitrogen can be potentially mineralised, but the results would also have been affected by the amount of SOM. This is an important aspect of soil health since the plants need plant available nutrients to grow and develop.

The vis-NIR measurements can be used to understand some of the variance within the fields. The subsoil sample was typically the one which stood out from the rest. That is probably because the subsoil naturally contains less SOM as well as more clay than the topsoil. The fields which had high SOM content (4, 8 and 9) can be connected to the management interviews where the farmer of field 8 stated to have a deep topsoil layer which might mean that the subsoil sample taken contains more SOM if they did not reach the actual subsoil depth of this field. The farmer of 9 discussed the field having a high SOM content, which was confirmed by the vis-NIR measurements. In the case for field 4, the farmer did not give any additional explanation about his soil. That field 1, 2 and 3 seemed to have the highest clay content correlates well with the clay content value in the section *Plant nutrients and Soil pH*. The clay content value was taken through *Markdata.se* and is not measured in the samples which were used for the vis-NIR measurements.

From the interviews, not all results were presented. As an example, the farmers shared their perception of the variability within their field in order to help us choose the different sampling locations. They also shared their view of different soil quality aspects that were helpful in the analysis. As previously mentioned, the farmer of field 9 stated to have a soil with high SOM content, something which was confirmed by the vis-NIR results.

4.2 Limitations of the Chosen Indicators

The method used for the bulk density in this master thesis is commonly used but it can be difficult to provide credible results since the soil density is very variable. There were several repetitions made for each measurement which were executed by the same two people. What can be noted is that the measurements were conducted in fields with varying weather and disturbances. Some of the bulk density soil samples were also difficult to collect due to rocks, compacted clay or even too porous soil which could fall out. This means that some of the BD are not as precise as desired.

The potential mineralisation of nitrogen was measured through a method which also involved soil samples. These soil samples were however easier obtained than the BD soil samples. The sources of error might instead be found in the lab process, where exact volumes of the different solutions were somewhat difficult to obtain. This should however not affect the result too much.

The vis-NIR-measurements began with sieving the previously dried BD soil samples. The dry soils were sometimes challenging to sieve completely, resulting in sieved samples that might not be entirely representative. The final analysis of the vis-NIR-results used in this study was qualitative, which can be open for interpretation. The vis-NIR was a necessary analysis since the SOM and clay content were not measured individually, something that might been preferably.

The soil analyses from the CONSTRAINTS-project were used to complement the main results of this master thesis. It can be argued that the measurements were done a half year before the rest and therefore not as relevant but then again, the pH and nutrients (K, P) measured would probably not vary much over the span of a half year. A common guideline in Sweden is that a farmer should redo their nutrient analysis every 5-15 year (Jordbruksverket 2022).

A common critique to interviews such as the one performed in this master thesis is that the answers will be too subjective. This might have been the case unless the purpose of these interviews was to simply learn how each farmer managed their own farm and put it into context with the other results from the measurements. There is no underlying purpose to claim that these farms are representative for organic farmers in Sweden or even Västra Götaland, nonetheless the sample of farms shows a high variation in characteristics (size, production, management practices) which was useful to the study.

The combination of the soil health indicators was a simplified version of a scoring. Typically, scorings of the soil health is done by weighing how the indicators proportionally affect the soil. This would however have been difficult to develop within the scope of this master thesis. An alternative could have been to use an already developed score/index of soil health, probably including a different group of indicators.

4.3 Variation in Soil Health and Management Practices

The first research question for this thesis was: "*How does the soil health and management vary between fields on organic farms in Västra Götaland?*". This was investigated by dividing the term "soil health" into three main categories that were to be studied. The main categories were soil biology, soil chemistry and soil physics. To study the soil biology in the fields, potential mineralisation was measured, which was used as an indicator of one of the functions microorganisms can have in the soil. The most commonly used soil biological indicator, SOM or soil carbon, was unfortunately not available to use in this study. However, vis-NIR measurements containing information about organic matter as well as other soil properties were used. Soil chemistry was mainly investigated through analysing the amount of plant available and less easily available pools of the plant macro nutrients P and K as well as the pH. Soil physics was studied by looking at the bulk density at separate locations in the field.

As seen in the results section, there is a variation both within and between fields. The variations within a field can partly be explained by the farmers' management. When looking at the 'bad place' in the bulk density measurements, which was usually taken at the entrance/exit of the field where the machines will pass many times, it is typically the most compacted place. However, some differences within a field can be explained by differences in soil texture and/or SOM, as seen in the vis-NIR results. Figure 17 shows the dried and sieved soil samples of two different fields. The soil samples on the left of the figure that were taken from the same field had noticeably different colours as well as different textures when handling them. This can give an indication that when comparing results within the field, differences might be due to already existing differences in the soil. When compared to the soil samples to the right in the figure where the soil samples had the same colour and texture, one can assume that the differences in such a field is more likely to be due to farmer management.

Figure 16. Two sets of soil samples. The three samples to the left are the samples from field 5 and the three samples to the right are from field 3. It shows the topsoil samples from the good place on top, the subsoil samples in the middle and the topsoil samples from the bad place furthest down.

Since there were some differences found within the fields, there might be some hesitations regarding the comparisons done between the fields. It is important to take into consideration that the actual representativeness of the representative place will have an influence of how characteristic the results are of the field.

The management of the fields varied as well, as seen in Table 1 and Figure 13. Some key factors did not vary that much though, the tillage of the fields was somewhat similar since all the farmers chose to plough the field in preparation of the winter wheat. Some chose to cultivate the soil directly after the ley, but all ploughed the soil at some point. The plough is arguably the most important method of tillage (Jordbruksverket 2009) and whether the farmers then chose to cultivate or harrow the field does not change the soil as much in comparison.

The combination of the indicators was done as an attempt to provide an overall picture of the indicators and give some reasonable guesses of the soil health of the fields. The method used for this was very simple and did not take into account how different indicators proportionally affect the soil health differently. The summary also gives an indication that a few of the farms have a better soil health than the others. Chahal et al. (2021) discusses how different additions to the soil can have different impact depending on the tillage system of the field. I think that the soil health of a farm might be better compared on the same field over a timespan, rather than with another field. A score or index like the Cornell Soil Health Assessment is a well-developed way of measuring the soil health on a field that should be tested in Sweden.

The case studies were done in order to connect most soil health indicators of two farms to their management and try to describe the soil health at those fields. However, it is difficult to determine the soil health of a field based on a few indicators and the crop yield for only one year and crop.

4.4 Soil Health Indicators in Relation to Crop Yield

The second research question: "*Which indicators correlate the most to crop yield?*" is a bit more difficult to answer. To begin the discussion, I will explain our reasoning of the chosen indicators. One could argue that since all three categories of soil health (biology, chemistry and physics) in some way were examined, it should be enough to determine the soil health of the fields. Lehman et al. (2015) lists a few soil quality areas that are usually measured in soil health research. This list included BD, potential mineralisation of nitrogen, SOM, pH, and N, P and K which are also studied in this thesis in some way. The list did however include several aspects that are not brought up in this thesis, such as water holding capacity and soil enzyme activity. This could mean that the aspects covered are a good start for examining soil health, but it could possibly be too little to represent the complex idea that soil health is.

Lehmann et al. (2020) discusses how the typical classification into biological, chemical, and physical aspect of soil health might not be as easy as one might assume. Most aspects of the soil do not only affect one of the categories but rather two or all three. As an example, the nutrients in the soil are mainly a chemical aspect but they are often affected by biological processes in the soil. Another example is the SOM which can affect and be affected by biological, physical, and chemical aspect of the soil. Therefore, the question might arise, whether this thesis does indeed cover the three typical categories of soil health.

Since the following definition soil health was chosen; *"…'the state of the soil being in sound physical, chemical, and biological condition, having the capability to sustain the growth and development of land plants.'"* (Idowu et al. 2019), the aim of this thesis was focused on finding representative indicators for physical, chemical, and biological soil aspects and relating them to the crop growth. I would argue that we have covered all three aspects in a way that should give an indication of the soil health. By correlating them to the yield, we were able to study which indicators were the most closely related to crop growth. The indicators studied and the analyses made were of course limited by time and resources, and without limitations, the study could have been even more developed.

The indicators most closely correlated to the crop yield were the pH and the PC1 from the vis-NIR measurement (including information on SOM and clay content) for the soil indicators, and the age of the ley, percentage of legumes sown in the ley, and fertilisation for the management indicators. All five of these indicators are core aspects of the soil and expected yield. Since the management aspects were correlated to the farmer practice yield, it was a consistent pattern that the indicators typically connected to N content added. It is important to point out that the yield might not be the best indicator for soil health and that the fertilisation can hide other patterns. It would however not make sense to correlate management practises of the winter wheat to the unfertilised plot because of the differences in fertilisation.

The PC1 from the vis-NIR measurements, to a large extent, represents SOM and clay content as one combined principal component. Soil organic matter can be a source of nutrients, food and habitats for soil organisms and improve soil structure and water holding capacity. It makes sense that it is an aspect which strongly affects the crop yield. Combined with clay content which also has a strong impact on soil structure, nutrient and water holding capacity, as well as K content, it was expected to correlate to the crop yield. It would however have been interesting to have the aspects separated as measured values for the soil samples collected. This could have helped in distinguishing if one or the other aspect had more of an effect on the yield.

Since the pH in the fields did not differ much, it would be good to study the pH and yield of the fields for several years in order to confirm the correlation. However, the pH of a field is an important aspect of soil health since it affects many other components in the soil, such as nutrient availability.

The VIP scores (see section *Crop Yield and its Relation to Indicators*) for the management highlights the importance of the age and species composition of the ley as the preceding crop. A one year old ley typically has a higher amount of legumes than a three year old ley. These can enable a higher amount of nitrogen left in the soil for the main crop (in this case winter wheat) to take up. In contrast, an older ley, established for several years on the field, can have a positive effect on soil structure and SOM content in the soil. These two aspects were mostly opposing in the studied fields since the short-lived leys were the ones containing the most legumes (clover seed leys).

The unfertilised yield was used to verify the soil health in the statistical analyses. Another way of using it is to simply include it as an indicator as it was used in the summary of the results. It then gives a value of the nitrogen delivery of the field and says something of the function of the microorganisms, which was missing from the potential mineralisation of nitrogen results.

Even if I think the aspects we have researched should be enough to correlate to soil health, there are several other measurements I think would have been able to provide an even clearer interpretation. The CEC is a typical aspect which indicates a soil's capacity to have nutrients available for the plants to take up (Sonon et al. 2022). Other aspects which might have been interesting are the ones connected to the water in the soil. To measure water infiltration or water holding capacity of the soil could also have given valuable insight in the soil health and limitations. This was included in the original plan for the thesis but which unfortunately had to be excluded due to a time shortage.

Whereas I think the methods used in this thesis are enough to examine soil health as the chosen definition states, other definitions usually include resilience and ecosystem services of the soil. These are two aspects that were not considered. To study resilience of a soil, I think that it would require following fields over several years, with different management practices or conditions. This was not prioritised for this thesis.

Finally, two of the most important aspects, SOM and clay content were separately estimated and/or taken from a soil map which might not capture the variation within the field precisely. If this study was repeated, more means should be invested in the analyses of the SOM and clay content directly in the field, not using estimations.

4.5 Further Research

The soil health at specific fields can always be interesting for the individual farmer since it can be used as a tool for planning fertilisation, crop rotation and management. What currently is included in the farm soil mapping that farmers do, could be developed to consider more aspects to give a more holistic view of the farm. This could help farmers make management choices to enable a long term sustainable cultivation system.

The Farm to Fork strategy (2020) is a part of The European Green Deal as a way of working towards a climate-neutral continent. The Farm to Fork strategy has a focus on sustainable food systems and links the production and consumers. It is stated that European food already has a high-quality standard, but there is a need for ensuring a high food production sustainability. This could be done by increasing organic farming and regaining biodiversity within farming.

Organic farming is typically linked to lower yields when compared to conventional farming. The yield of organic fields has been found to be ca 20 % lower than the yield of conventional fields (Ponisio et al. 2015). To increase organic farming and the interest of biodiversity and soil health, I think there are several things that could be done. If soil health tests were developed and made accessible to farmers, they could more easily investigate the soil health on their own farm. A good soil health will increase yield and supposedly decrease the need for other inputs. I think that soil health will continue to be an important topic in the future and its definition will continue to be discussed depending on the actors involved.

Lehmann et al. (2020) describes how the versatility of the soil health concept is what is making it an important term which is accessible in many different areas. It is a term open for interpretation which can be used for a variety of purposes, which will keep contributing to knowledge and an interest about and for soil. Since some of the previous soil health case studies I have read focused on various aspects, I would imagine that it instead could be helpful in the future if the concept of soil health were to have a clearer definition. This could enable more accurate meta-analyses and comparisons between different studies.

4.6 Conclusion

The soil health of a field is not easily measured and there are many factors contributing to it. The underlying conditions of the soil, like the texture and the weather conditions that the field is being subject to are aspects that cannot be changed. Management is one thing that can help in developing a healthier soil. This can be done by avoiding soil compaction, adding the right amounts of nutrients and organic material as well as keeping the field well drained. The yield is not a complete image of the soil health since it only represents the results of the crop production for one year. It is important to follow a field for several years and with different crops and possibly management practises in order to properly assess the soil health.

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Popular science summary

This paper covers the subject of soil health. Soil health is a term that covers several aspects of the soil and its capability to sustain the plants grown there. The biological aspects of soil health typically include the microorganisms living in the soil and their functions. The chemical aspects are about the nutrients that are necessary for the plants, and the physical aspects of soil health is usually focused on soil structure. Soil structure is important because a poor structure can be difficult for the plants to grow in.

Soil health is an important concept since it can be a way of measuring sustainability. One way of working towards a good soil health and more sustainable agriculture is through organic farming. Organic farming is preferable since it usually adds more organic matter to the fields, it uses less chemical input (such as pesticides) and usually has a more diverse crop rotation.

To study soil health, ten organic fields were chosen, and different measurements were made. The soil health measurements in this thesis were chosen to give a representation of the three main categories of soil health. The different aspects were then compared to the yield of the field and the farmer management, which was discussed in interviews with the different farmers.

The result was presented as a visualisation of the variation of soil health aspects between fields. There was also an attempt made to extinguish which measurement was the closest related to the yield. The yield was used in many analyses since it was chosen to measure the soil health. A high yield would in theory mean a good soil health at the field, which enhances the plants grown there.

When looking at the statistical analyses made, it seemed like the pH, clay content and SOM content were indicators in the soil that affected the yield most. The management the farmers used on the fields also played a part in affecting the yield. The aspects of management that were most connected to yield were the fertilisation the farmer had used on the field. A high amount of added nitrogen has a positive effect on the yield. The nitrogen can be added through manure or other fertilisers, or the farmer could use a good crop rotation to add nitrogen. This is usually done by sowing a crop with legumes as the preceding crop. Legumes has an ability to bind nitrogen from the air into the soil, which can then be used by the next crop grown there.

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Appendix 1

Farmer Interview 2022

Preceding crop – Ley
How many years was the ley grown?
Which proportion of legumes was sown?
Was the ley fertilised? With what, when and how much?
How many times was the ley harvested last year?
When was the ley ploughed?
Main crop – Winter wheat
How was the soil tilled before the winter wheat?
Is that how the soil is typically tilled?
When was the winter wheat sown?
Which was the variety of winter wheat?
What seeding rate did you sow?
Has there been any weed treatment done? How and when?
Did you fertilise the winter wheat? With what, when and how much?
Do you have any plans for the usage of the harvested winter wheat?
What is your expected yield?
Other questions
How big is your farm?
How big is the specific field?
What is your crop rotation? (If the ley was shorter than three years)
What production do you have on the farm?
For how long has the farm been organic?
What is your image of the field? Do you have any good or bad aspects?
Is there anything you would want to know regarding your field?
Have you used biogas digestate before? What are your opinions/thoughts about it?

Appendix 2

The bulk density results. The values are an average of the three replicas at each site. The results are presented for each separate field and their good, bad, and representative place as well as the different depths, topsoil at 5 cm, ploughing pan at 20 cm and subsoil at 40 cm.

Table. Bulk density results presented for each field. The different depths include topsoil (5 cm), ploughing pan (20 cm) and subsoil (40 cm). The subsoil is usually only taken at the representative place.

Field	Depth (cm)	BD – Good place (g/cm^3)	BD – Bad place (g/cm^3)	BD – Representative Place (g/cm^3)
1	5	1.38	1.37	1.34
1	20	1.40	1.36	1.32
1	40			1.43
2	5	1.41	1.40	1.46
2	20	1.41	1.51	1.48
2	40			1.59
3	5	1.48	1.61	1.39
3	20	1.52	1.57	1.53
3	40			1.47
4	5	1.31	1.47	1.44
4	20	1.42	1.57	1.47
4	40			1.64
5	5	1.17	1.40	1.19
5	20	1.24	*	1.32
5	40			1.39
6	5	1.29	1.38	1.29
6	20	1.39	1.56	1.44
6	40			1.57
7	5	1.41	1.56	1.51
7	20	1.47	1.70	1.63
7	40			1.54
8	5	1.35	1.48	1.37
8	20	1.48	1.62	1.40

8	40			1.59
9	5	1.39	1.44	1.25
9	20	1.44	**	1.36
9	40			1.51
10	5	1.23	1.48	1.28
10	20	1.38	1.42	1.39
10	40	1.37		
11	5	1.43	1.54	1.36
11	20	1.42	1.66 ***	1.39
11	40			1.65

** The ploughing pan of field 5 had too many rocks to enable a measurement without compromising the tools. ** The ploughing pan of field 9 was too compacted to collect. *** Only one sample.*

Appendix 3

Here are the results from the PLS model of which soil health indicators affect the unfertilised yield:

```
data.pls
<-subset(SHnum, select=c("P.Al", "K.Al", "pH", "NIRpc2",
"clay_rastervalue", "NIRpc1", "BD_Rplace","yield_N0"))

pls.fit2 <- plsr(yield_N0 ~ ., data = data.pls, ncomp =
7, na.action = na.omit, scale = TRUE,  validation =
"LOO")
```

```
> summary(pls.fit2)
Data:   X dimension: 30 7
        Y dimension: 30 1
Fit method: kernelpls
Number of components considered: 7

VALIDATION: RMSEP
Cross-validated using 30 leave-one-out segments.
       (Intercept)  1 comps  2 comps  3 comps  4 comps  5 comps  6 comps  7 comps
CV            2084     1825     1703     1549     1406     1246     1206     1114
adjCV         2084     1823     1697     1544     1403     1242     1185     1109

TRAINING: % variance explained
          1 comps  2 comps  3 comps  4 comps  5 comps  6 comps  7 comps
X           31.11    51.46    69.27    81.18    86.25    88.73   100.00
yield_N0    36.88    54.08    62.92    69.11    76.64    82.17    82.74
```

Figure 17. Results from the PLS model of soil health indicators related to the unfertilised yield.

And here are the results from the PLS model of which management factors affect the yield of the farmer practice plots.

```
data.pls<-
subset(SHnum,select=c("Ley_years","Ley_baljvaxter_sown"
,"Ley_fert_last_year","Ley_harvest_last.year","WW_weedm
anagement", "Total_N_kgha","yield_FP"))

pls.fit2 <- plsr(yield_FP ~ ., data = data.pls, ncomp =
6, na.action = na.omit, scale = TRUE,  validation =
"LOO")
```

```
> summary(pls.fit2)
Data:    X dimension: 30 6
         Y dimension: 30 1
Fit method: kernelpls
Number of components considered: 6

VALIDATION: RMSEP
Cross-validated using 30 leave-one-out segments.
       (Intercept)  1 comps  2 comps  3 comps  4 comps  5 comps  6 comps
CV            2434     1927     1748     1239     1169     1152     1129
adjCV         2434     1924     1749     1229     1159     1148     1125

TRAINING: % variance explained
          1 comps  2 comps  3 comps  4 comps  5 comps  6 comps
X           40.72    77.34    82.26    88.43    96.06   100.00
yield_FP    45.05    54.40    80.50    83.00    84.11    84.43
```

Figure 18. Results from the PLS model of farmer management practices related to the yield of the farmer practice plots.

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