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Effect of soil management on earthworm populations and soil hydraulic properties

GEO 511 Master's Thesis

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Abstract

Soil structure controls soil functional properties relevant to crop growth, such as hydraulic conductivity and water retention, which in turn affect water availability for crop systems. Soil management practices impact soil structure directly by loosening and compaction, and indirectly through management impacts on soil organic carbon content, earthworm abundance and activity, and root growth.

We assessed the impacts of soil management on soil structural quality, soil hydraulic properties, and earthworm abundance in a long-term field experiment (LTE) in Switzerland. The LTE had different treatment methods, including different levels of organic amendments, and tillage intensities. In-situ measurements and soil sampling were carried out in spring 2023, and later on during the year, the data was analysed.

Results from the LTE show that treatment management had an influence on soil structural quality (VESS). Hydraulic conductivities near saturation also changed slightly under different management, but we could not detect significant statistical differences.

Further results suggest a positive correlation between soil hydraulic conductivity near saturation and earthworm number and indicate that earthworm abundance was more strongly affected by the tillage system than by organic amendments. In this master's thesis, results from a Swiss LTE (FAST experiment) are shown, and we discuss the potential and limitations of agricultural soil management for climate change adaptation.

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1. Introduction

Agricultural soils and their long-term capability to produce food are essential for human civilization. Since recent decades, agricultural soil systems have been under threat and experienced growing stress due to several new challenges that have arisen

One reason for the growing soil stress is climate change. Especially the extreme weather events, which are thought to come along with increasing global air temperatures, and which have a strong influence on soil systems and their functions (Furtak and Wolińska, 2023). Namely, more frequent, more intense, and longer-lasting heat waves (Meehl and Tebaldi, 2004) as well as extreme precipitation events, which result from climate change (Myhre et al., 2019), are two major threats, agriculture is confronted with. The European Academies Science Advisory Council (2013) claims that natural extreme events increased by about 60% in Europe during the last three decades. The global trends report from the Centre for Research on the Epidemiology of Disasters (CRED) and the UN Office for Disaster Risk Reduction (UNDRR) from the year 2021 displays a global rise in disastrous environmental events. Within these disastrous events, the amount of rainfall during an extreme precipitation event and the increased duration of droughts, are the most severe changes compared to the beginning of the millennium, according to the CRED and UNDRR report (CRED and UNDRR, 2021; Furtak and Wolińska, 2023). Reasons for an elevated drought risk are seasonal differences in rainfall and higher evaporation rates due to rising global air temperatures (Calanca, 2007). Therefore, a higher evaporation rate can consequently lead to heavier precipitation events because the earth's hydrological cycle gets intensified with more water vapor available in the atmosphere, according to climate model analyses (Asadieh and Krakauer, 2017). This also increases the risk of occurring floods which can significantly damage agricultural soil systems. These two extremes in rainfall amount increase another risk with damageable potential for agricultural soil systems, the risk of soil erosion. Erosion is still considered one of the major menaces for agricultural soils and their environmental services (Montgomery, 2007). There are local differences when it comes to soil erosion rates and different soil management practices are thought to be able to mitigate the threat of soil erosion (Montgomery, 2007; Lal et al., 2012; Klein et al., 2014; Altieri, 2015; Blanchy et al., 2022; Blanchy et al., 2023).

According to Klein et al. (2014), the agricultural sector is one of the most sensitive economic sectors in regard to the changing global climatic conditions. The arising droughts and other extreme weather events, like floods, during the vegetational season are considered to be responsible for an increasing number of potentially unproductive years in yield in the future (Klein et al., 2014). Furthermore, the rising temperatures could result in a shift where favourable cropping conditions exist. European regions further north could become more of interest regarding agricultural production. In southern parts of Europe, however, the disadvantages of climate change will be of greater significance, based on Olesen and Bindi (2002). The enhanced possibility of droughts and other extreme weather events is a big risk considering harvestable yield. A higher yield variability and a decline in suitable agricultural areas for traditional cropping systems can be expected. This will lead to the fact that current farming systems need to adapt their management strategies to mitigate the impacts of the changing climatic conditions (Olesen and Bindi 2002).

One must also not forget that the steadily growing world population is also contributing more and more to the problem of sustainable food production in agricultural fields. The demand for nutritious-rich food is accelerating, as the human world population is growing too (Hobbs, 2007). Together with ongoing soil degradation, and the occurrence of extreme weather events, the increasing human population poses a serious threat to food security and agricultural production (Furtak and Wolińska, 2023).
The concept of soil structure is closely related to this challenge. An intact soil structure is crucial for sustainable food and fiber production (Bronick and Lal, 2005). The two researchers (Bronick and Lal, 2005) claim that humanity needs a more holistic approach to land use and land management. Mitigation practices to tackle the challenges arising from climate change are required to minimize the increasing pressure on soil systems and their resources while limiting harmful environmental impacts resulting from unfavourable agricultural practices (Bronick and Lal, 2005).

1.1 Rethinking agricultural management

“A nation which destroys its soils,
destroys itself”
(Franklin D. Roosevelt)

As early as the middle of the last century, the human population was already aware that they had to take care of their land and soil, and that it could not be exploited indefinitely. This is also shown by the above quote from former US President Franklin D. Roosevelt.
In the middle of the last century, it was recognised how conventional agriculture has the disadvantage of dramatically accelerating processes that are harmful to agricultural soil systems, like, for example, soil erosion. This led to studies investigating the influence of conservation tillage and no-till agriculture (Montgomery, 2007). Today, a lot of research is going on which focuses on adaptation and mitigation practices in agriculture. These practices are for example, crop rotation and appropriate soil management (e.g. Strudley et al., 2008; Klein et al., 2014; Altieri, 2015; Blanchy et al., 2023). The researchers mention a broad set of

potential mitigation practices with which the resilience of agricultural soils could be improved again, such as reducing tillage intensities or enhancing the soil organic carbon stocks in agricultural fields. These practices are thought to enhance soil resilience by improving soil structure and the overall health of the soil system and its inhabitants. Effective adaptation to climate change scenarios needs to make sure that soil systems have a well-developed and stable structure, meaning the ability to have a large infiltration capacity and to hold water long enough, so that plants can use it, also during dry periods (Blanchy et al., 2023).

According to Blanchy et al. (2023), beneficial effects, in terms of water regulation, can be seen if the use of organic amendments and the adoption of cropping systems are applied to agricultural fields. These are practices that maintain a continuous living cover. This, in turn, leads to an additional carbon input into the soil and therefore an increasing stimulation of biological processes in the system (Blanchy et al., 2023).

1.2 The importance of soil structure

So, we know that soil structure is a key factor when it comes to soil quality and the functioning of soil and that soil structure is sensitive to soil degradation (Mueller et al., 2012; Bronick and Lal, 2005). But what makes a good soil structure? This question is not that easy to answer because the concept of soil structure can be very complex (Peerlkamp, 1959).

Soil structure is thought to influence many processes that are happening in a soil system (Rabot et al., 2018). Following Rabot et al. (2018), soil structure controls important soil parameters such as water retention and infiltration, gaseous exchanges, soil organic matter and nutrient dynamics, root penetration, and susceptibility to erosion. Furthermore, it makes up the habitat for an enormous number of soil organisms and thus influences the diversity as well as the activity of soil organisms (Elliott and Coleman, 1988). Rabot et al. (2018) identified porosity, macroporosity, pore distances, and pore connectivity to be the most relevant factors regarding soil functioning, in their studies.

Together with the texture of the soil, soil structure shapes the pore space in the soil the most (Shanstrom, 2023). Together they influence how easily air, water, and roots can enter and move through a soil system. As mentioned by Shanstrom (2023), the soil texture (fraction of sand, silt, and clay) is often referred to be the main influence belowground. But in fact, the soil's structure is of equal importance as its texture. Shanstrom (2023) explains this as follows. Two soil systems can behave very differently despite having the same texture. A soil with a high clay content, for example, can have good permeability for air, water, and roots if a good soil structure is intact. On the other side, it can be almost locked for air, water, or roots to enter the soil system if the soil structure has been destroyed, for example by physical compaction due to the use of heavy machinery (Shanstrom, 2023).

The shape and size of soil aggregates, and how they are grouped together, do usually describe the state of the soil structure (Finch et al., 2014; Shanstrom, 2023). In contrast to the soil texture, the soil structure can be changed naturally. This can happen by pushing the soil particles physically closer together. In nature, this is forced by weathering, by freezing and thawing cycles, by wetting and drying of the soil, by roots pushing through the soil whilst growing, and not to forget by plant cultivations. Biological processes, like microbial or earthworm activity, can alter the soil structure too (Finch et al., 2014; Shanstrom, 2023).

An important method for recording the quality of soil systems is the so-called “VESS” method. VESS stands for “Visual Evaluation of Soil Structure” and is a visual assessment of soil structure (Ball et al., 2017). The VESS method is an advancement of the Peerlkamp spade test (Peerlkamp, 1959), according to Ball et al. (2017). Peerlkamp (1959) proposed an evaluation technique, where he looked at several key indicators that can be detected by the eye. These indicators are for example, the sizes and shapes of soil aggregates, the cohesion of soil particles, the porosity of soil aggregates as well as the porosity of the whole plough-layer, root development in the soil system, and the dispersion of the soil surface (Peerlkamp, 1959).

As explained by Mueller et al. (2012), the description and quantification of soil quality is fundamental regarding the fertility and productivity of soil systems. Thereby, the visual soil evaluation is an important instrument to assess the quality of agricultural soils (Mueller et al., 2013). Especially when soil systems are sensitive or exposed to soil degradation, the soil structure is of great importance (Mueller et al., 2012). This is the case because visual soil evaluation can give insights into soil indicators like soil structure, rooting depth, wetness, and slope. It is also suitable to recognise specific hazard indicators such as contamination or the risk of flooding (Mueller et al., 2012).

Another advantage of visual soil evaluation is that it can be inexpensively implemented at the farm level and therefore can help farmers in their decision making. The results can give fast and simple insights into the quality of their agricultural soils and can guide the farmers to develop appropriate soil management strategies for their agricultural fields (McKenzie, 2013; Guimarães et al., 2011).

In this master’s thesis, the focus only lies on the topsoil examination of the soil structure, and therefore the VESS method was used (Guimarães et al., 2011). As already mentioned above, assumptions about soil aggregates, porosity, rooting systems related to water storage and transport can be made with the help of the VESS method (Ball et al., 2017). Furthermore, this technique can help to identify compaction and waterlogging status, which can happen if the soils are not properly managed (Ball et al., 2017). The VESS technique helps to detect limiting (compacted) layers in the topsoil area and is crucial to implement improving soil management strategies and decisions (Ball et al., 2017). Moreover, Ball et al. (2017) indicate that the VESS method is suitable as an initial test for scientific research because first assumptions can be made only with visual observations. However, the visual method needs more actual measurement data of soil characteristics to support the initial results coming from the visual observation (Ball et al., 2017).

1.3 The influence of soil texture

The texture of soils can be named as one of the most important soil parameters (Weil and Brady, 2017: 152). It is linked to the retention of nutrients, as well as to the drainage capabilities in soil systems (Jaja, 2016). Drainage capability is an important determinant in the case of soil erosion risk because it describes how much water flows into the soil. A low drainage capability, and therefore a low infiltration rate, can cause the water to flow away as runoff. This can lead to the threat that water flows away without being available to plants and crops, and it can lead to the destruction of the uppermost soil layer due to water erosion (Weil and Brady, 2017: 846). Gaining knowledge about the proportions of different-sized soil particles (i.e., the soil texture) is necessary for understanding soil behaviour and soil management (Weil and Brady, 2017: 152 ff). From this information, say Weil and Brady (2017), a soil scientist is able to make many first assumptions about the functioning of a specific soil system.

There are three types of soil particles, so-called separates when it comes to soil texture. Particles, that are smaller than 2 mm but not below 0.05 mm in diameter, are called sand. The next smaller category of particles is named silt. Silt has a diameter smaller than 0.05 mm but larger than 0.002 mm. The smallest category is clay. The clay particles are all smaller than 0.002 mm. They have a very large specific surface area, which gives them the ability to adsorb huge amounts of water and other substances (Weil and Brady, 2017: 152 ff). The textural structure of a soil therefore determines to a large extent how a particular soil behaves under different (environmental) circumstances. For example, the water-holding capacity of clay soils is higher compared to soils with more sand particles present. Furthermore, soil organic matter levels are usually way higher in clay than they are in sand. On the other side, clay particles are more prone to compaction than sand because they can be pushed together more easily (Weil and Brady, 2017: 154 ff).

1.3.1 Texture and water flow

The risk of erosion, especially the risk of water erosion, is not the same everywhere around the world. The actual risk is depending on the topography, on the type of the soil, on the specific land use of the soil system, and the climatic conditions (McCool and Williams, 2008). Also, the influence of the weather conditions plays a major role in assessing this risk. Heavy rainfall events can wash out the topsoil layers and deposit them somewhere else, usually in locations downhill of the corresponding soil system (Weil and Brady, 2017: 847). Moreover, during the other extreme, when precipitation events are rare, the ability of soils to hold water becomes even more important. This ability is shown in soil water retention curves. Soil water retention curves describe how much water a specific type of soil can retain, and is, as said before, impacted by the texture and the type of soil, as well as the soil management (Lal et al. 2012; Weil and Brady, 2017: 227). The particle sizes also have an influence on the susceptibility to erosion. Larger particles in diameter are usually eroded more easily than smaller clay particles but this stability only remains if the clay particles are aggregated together in a stable environment (Weil and Brady, 2017: 156). Furthermore, larger particles make it more difficult for soils to retain water over a longer time. Larger particles let the water flow away more quickly compared to smaller particles (Stahr et al., 2008; Finch et al., 2014; Weil and Brady, 2017: 156).

Based on Weil and Brady (2017), the textural composition of soils also influences the hydraulic conductivity of a specific soil. The hydraulic conductivity describes how fast water flows through an area of a certain soil column. At high matric potential levels (high moisture content in the soil), the hydraulic conductivity in clay is lower compared to sand. At low matric potential levels (low moisture content in the soil) it is exactly the opposite, and clay particles contribute more to the water flow. This can be expected because sandy soils have many large pores, that are water-filled when the water potential in soils is high (soil is wet). On the contrary, most of these larger pores are empty when the soil dries out and therefore, the soil water potential decreases. Clay soils, however, have much more smaller pores (micropores) which are still filled with water at lower soil water potentials (drier soil conditions). These smaller pores are then still contributing to the water flow in unsaturated conditions. It is important to note that at or near zero potential (meaning the saturated flow region), the hydraulic conductivity can be thousands of times faster compared to lower potentials. Unsaturated flow is dominant when the water potential is lower than -1 kPa (-10 hPa), and thus most of the bigger pores are emptied (Weil and Brady, 2017: 230, 231).

There are also disadvantages that come with small clay particles. Smaller clay particles are more susceptible to compaction (Weil and Brady, 2017: 156). This can happen when heavy machines are used for soil management. On the other hand, it can also occur when clay particles dry out and shrink, especially during drought conditions. The shrinkage can lead to a natural cause of compaction. The compaction in turn can then cause rainfall to flow away directly, without reaching the lower levels of a soil system, and therefore, without reaching the root system of plants for instance (Artiola et al., 2019).

It can be said that a good mixture of soil particles and their sizes is needed for a soil system to function properly. Soils with a balanced size mixture of particles, like, for example, a sandy loam, have a better water-holding capacity than sandy soils while having a lower risk of compaction during dry periods (Weil and Brady, 2017: 156). Moreover, a good mixture makes it easier for plant roots to penetrate the soil deeper and absorb water compared to denser clay soils (Artiola et al., 2019). A good mixture is present in loams, for example. Loams are mixtures of sand, silt, and clay particles, where those separates exist in about equal proportions (Weil and Brady, 2017: 157). This does not mean that those proportions are perfectly balanced. A relatively small percentage of clay is sufficient to engender clayey properties in a soil system. Small amounts of silt and sand, on the other side, have a lower influence on how a soil is behaving (Weil and Brady, 2017: 157).

We have seen, how physical soil characteristics can shape the behaviour of a soil system. Therefore, soil management strategies have to take into account with which physical conditions they are confronted because they influence these strategies (Strudley et al., 2008). A specific soil management strategy can either be beneficial but also harmful for an agricultural soil system. The decisions on soil management practices are therefore crucial in mitigating the risk of future climate developments. Productivity and soil loss due to erosion are highly variable. They can change with climate scenarios, but they also depend on cropping practices and soil types (Strudley et al., 2008; Klein et al., 2014). According to Klein et al. (2014), this suggests that the possible negative influences of climate change could be minimized if an adequate soil management practice is chosen.

1.4 Intensive agricultural practices as a threat to soil resilience

One of the most important aspects of a soil system is how resilient the system is. Lehmann et al. (2015) highlight that resilient soil can cope with changes. Meaning it is possible for the soil system to adapt to new conditions, or to recover from stressful impacts, like extreme precipitation or droughts. Moreover, the soil system must have a healthy soil biota and an intact microbial community (Lehmann et al., 2015). As mentioned by Lehmann et al. (2015), a resilient and healthy soil system consists of five main functions in agriculture. These would be, the provision of nutrients, protection from harmful diseases, production of growth factors, availability of water, and reduction in susceptibility to soil erosion (Lehmann et al., 2015).

Bad decisions in soil management strategies and the enhanced occurrence of extreme weather events can further intensify the risk of soil erosion (Strudley et al., 2008; Klein et al., 2014).

Most of the agricultural land in Europe is used for intensive production. For an intense production, a lot of resources and external inputs into the soil are needed. The intensive use and application of tillage in agricultural soils have been common practices for most of modern history in the Western world (Weil and Brady, 2017: 175). These soil-exploiting management strategies can lead to an overall poorer soil health because a loss in soil biodiversity can be expected due to the strong human manipulation of soil systems (Tsiafouli et al., 2015). This is also true for the abundance of earthworms which can decrease in number and biomass when heavy machinery is used and the soil gets compacted (Capowiez et al., 2021).

The decrease in soil health can therefore lead to an even stronger amount of intensive soil management strategies. This means that, for example, higher agro-chemical inputs are applied on agricultural fields in order to sustain the food production levels and meet food security in the world (Hobbs, 2007; Panagos et al., 2012). This puts even more stress and pollution on current agricultural systems, and it is not thought to be sustainable over time (Panagos et al., 2012).

The implementation of sustainable management methods could therefore bring about a real improvement for arable soils and further damage through increased soil use must be reduced (Klein et al., 2014; Blanchy et al., 2023). With the help of an appropriate soil management strategy, an improvement in soil health and soil structure can be expected, and it is thought to strengthen the resilience of agricultural soils concerning external influences (like soil erosion) (Klein et al., 2014; Weil and Brady, 2017: 176).

In the following section, some soil management practices, influencing the soil's resilience, are introduced. It is, however, not a broad overview of all possible management strategies but only a brief explanation of the methods that were used in the field experiment of this master's thesis.

1.5 The influence of tillage practices

Most soils possess a stable enough surface structure to allow fast infiltration of water when they are covered with dense vegetation, and when no external disturbance occurs through trampling or tillage practices (Weil and Brady, 2017: 174). Tillage inverses the uppermost soil layer and has been in place for a long time in agricultural practices (Hobbs, 2007; Weil and Brady, 2017: 176). Tillage is mostly done by ploughing the agricultural field. Thereby the soil gets mechanically loosened and turned over. This is done to prepare the seedbed for the cultivation of the next crops in an agricultural field. Tillage practices temporarily suppress weeds, insert crop residues into deeper layers of a soil system, increase nutrient availability, loosen the soil, and break up clods (Weber et al., 2017; Weil and Brady, 2017: 176). On the other side, tillage practices can have serious detrimental effects. Most tillage practices leave the soil surface without any cover of plant litter, which could act as protection for the soil surface from sun, rain, and wind (Weil and Brady, 2017: 176). This increases the risk of soil erosion. Also, the compaction of soils, which disturbs the ecosystems in soils further, is a big problem when using conventional, intensive tillage practices (Weil and Brady, 2017: 176). Tillage practices disrupt the pore space created by roots and biological activity and therefore force a change in conditions in the existing ecosystem (e.g. earthworm abundance and activity) in a soil system (Hobbs, 2007; Blanchy et al., 2023).

Primary tillage usually occurs in a depth of 20 – 30 centimeters, meaning that this whole soil layer gets turned over inversely. Van Oost et al. (2006) state that among all soil types, decreasing tillage depth, substantially reduces tillage erosion rates and it is considered an effective conservation strategy.

In the last century, several new, less intrusive agricultural land-management practices have been developed. These practices minimize the need for soil tillage and the soil surface is kept covered by plant residues. This brings the advantages of maintaining soil's biological habitat, stabilizing soil structure, conserving soil organic matter, plus physical protection of the soil from drying sunlight, wind, and heavy rainfalls. These practices are called conservation tillage. Conservation tillage practices are defined as practices that leave at least 30% of the soil surface covered by plant residues, by the U.S. Department of Agriculture (Weil and Brady, 2017: 176). There also are other minimum-tillage strategies that permit reduced stirring of the soil (e.g. chisel ploughing), while still leaving a notable proportion of plant residues on the surface as a protection layer (Weil and Brady, 2017: 176, 860). For example, an approach that uses reduced tillage practices is soil cultivation in a shallower depth of the soil, where only the uppermost five centimeters get tilled. The disturbance is therefore limited to a smaller proportion of the soil and does not alter the soil composition in the same extensive way as it happens by ploughing. Yet another tillage system is when no-till operations are applied on an agricultural field. No-tillage practices include operations, where one crop is planted directly in the plant residues of the former crop and the disturbance of the soil is kept as minimal as possible (Weil and Brady, 2017: 176, 177). No-tillage systems try to make sure that a residue cover is always lying on the field in regard to cover and protect the uppermost soil layer from external impacts. This layer made of organic matter acts as mulch that facilitates water infiltration rates, which in turn decreases the risk of erosion caused by direct runoff (Montgomery, 2007). Moreover, these no-tillage systems reduce the costs of fuel, save time, and are less prone to the risk that the soil gets compacted while ploughing the field (Weil and Brady, 2017: 176, 177). Since they are non-invasive, these reduced tillage practices come with a set of notable advantages. Such advantages can be a decreased evaporation rate, more available water for plants (because of a better soil structure and a better water infiltration capacity), reductions in management costs, and higher outputs in yield (Weil and Brady, 2017: 176, 177). During a transition from conventional tillage to no-tillage, crop yields might decrease for several years, say Weil and Brady (2017: 862, 863).

Moreover, conservation tillage tends to increase earthworm populations and their activity compared to conventional management methods. Ploughing is thought to disrupt earthworm soil habitats, including the destruction of deep burrows, and ploughing exposes earthworms to the soil surface, which lead to a higher risk that they are getting eaten by predators, say Peigné et al. (2009). It must be noted that not always a clear relationship between tillage systems and earthworm abundance can be seen. Sometimes a reverse effect can be detected, meaning more earthworms are present in conventional tillage practices (Peigné et al., 2009). This master's thesis tries to give more insights into that question, and an evaluation of earthworm abundance was done.

Reduced tillage systems (and no-tillage systems) are not a miracle cure, as they are not entirely without disadvantages. Rather than a possible increase in yields, in fact, more yield penalties can be expected and potential, sustainable benefits of no-tillage methods are more limited than often assumed, based on the studies by Blanchy et al. (2023) and Pittelkow et al. (2015). Due to increased weed pressure and less available plant nutrients in reduced tillage systems, a higher proportion of herbicides, pesticides, and other synthetic fertilizers is applied compared to conventional tillage practices (Blanchy et al., 2023). Generally, greenhouse gas emissions are larger under no-tillage treatments and the risk of nitrates and pesticides leaching into groundwater could also increase (Blanchy et al., 2023). Additionally, several studies in different soils and climatic conditions have shown that the compaction of the untilled layer is larger with conservation tillage practices (Peigné et al., 2009).

All of this, of course, causes negative impacts on the environment and soil biodiversity. Nonetheless, a growing number of farmers prefer reduced tillage methods nowadays (Weil and Brady, 2017: 864), such as only stirring the soil with the help of a chisel plough for example.

1.6 Organic farming and treatment practices

Synthetic (or mineral) fertilizers do have a long tradition in crop cultivation. They can contain a huge quantity of phosphorus and nitrogen, which act as additional nutrient supply to agricultural fields and crops. In providing these important nutrients for crop plants, synthetic fertilizers enhance crop production rates and expectable yields (Yang et al., 2022). On the other side, they can lead to further soil degradation because they alter and affect the soil microbial biomass and fungal diversity in a soil system (Yang et al., 2022). Also, earthworm activity and diversity are affected by inorganic farming systems, but this relationship is not that clear and still needs further investigations and long-term research (Peigné et al., 2009).

A part of these negative effects can be reduced by using organic fertilizers instead of synthetic ones. Organic fertilizers are only made of natural resources. They can either stem from plant or animal residues, and they are thought to improve the overall soil quality (Shi et al., 2023). Synthetic fertilizers are often replaced with cattle slurry, manure, or compost in organic management treatments. Based on Shi et al. (2023), the additional importation of organic matter (together with mineral fertilizer) applied on agricultural fields can be beneficial for crop yields because additional nutrient inputs are implemented. Furthermore, the additional carbon input is thought to increase the organic carbon content, while promoting better aggregate stability and a better porosity of the soil system what can lead to an improved water-holding capacity (Shi et al., 2023).

In addition, the carbon input can lead to a stimulation of biological processes, such as earthworm activity because more nutrients are available for these burrowing creatures (Blanchy et al., 2023).

As mentioned by the USDA Natural Resources Conservation Service (2008), it is crucial that some important key points in soil management practices are considered when applying them. Practices that leave the soil covered and thereby protect the organic matter in the soil, or practices that result in the accumulation of organic matter are of great importance. The same is true for practices that maintain healthy plants and avoid soil compaction. This leads to an improved soil structure and an increasing number of existing macropores (Shanstrom, 2023).

Because of all these mentioned reasons, it is thus unavoidable that sustainable, considerate management practices, which ensure the sustainable functioning of soil systems, are getting involved in the agricultural management processes. Agricultural management practices have come more into the focus of policymakers and diverse stakeholders worldwide (Rivera-Ferre et al., 2013). In order to feed the growing human population and to address the upcoming challenges in agricultural production, a rethinking of current policy designs is needed (Rivera-Ferre et al., 2013). As mentioned before, such challenges can be related to climate change, like more frequent extreme weather events during cropping seasons (Klein et al., 2014), but also to the massive overuse of unsustainable energy sources in intensive agricultural food production, leading to biodiversity loss, scarcity of water, or other detrimental effects (Rivera-Ferre et al., 2013). A better understanding, accurate scientific information of soil dynamics and their interactions (Chandrasekhar et al., 2018), and an increased awareness of the social dimensions of agriculture, and how they are embedded in a certain society, are of the utmost importance to overcome and adapt to future challenges in farming (Rivera-Ferre et al., 2013).

1.7 Pore perspective

We have seen that soil structure can influence many processes in soil systems. Soil structure controls the magnitude of water retention and infiltration, gaseous exchanges from the soil to the atmosphere and vice versa, soil organic matter contents and nutrient dynamics, root penetration, and susceptibility to erosion (Rabot et al., 2008). Now, we also want to look at soil structure from a pore perspective. Pores in soils have an important function in regulating the water flow or in providing a habitat for soil organisms (e.g. earthworms). From this pore perspective, “the combination of different types of pores” is more informative, rather than only looking at “the shape, size and spatial arrangement of primary soil particles and aggregates” (Pagliai and Vignozzi, 2002: in Rabot et al., 2018: 122).

Total pore space in soils can vary greatly under different management practices. For example, a wide range of soil data indicates that intensive cultivation tends to decrease the total pore space compared to soils that are not cultivated. This decrease in pore space is associated with a reduction in organic matter contents, and a lowered biological activity, in intensively used soil systems (Weil and Brady, 2017: 190).

According to Weil and Brady (2017), soil pores come in a wide variety of sizes and shapes. They can be categorized into groups according to their diameter size. There are macropores, mesopores, and micropores. In this master’s thesis, we are particularly interested in macropores because they are thought to be linked with the abundance of earthworms. Macropores have a diameter larger than about 0.08 mm and allow the movement of air and the drainage of water. Moreover, this group of pores is big enough to act as a habitat for small animals, as well as a space for plant roots to grow (Weil and Brady, 2017: 191).

The balance between macropores and micropores in soils is influenced by soil structure and texture. Deeper down in the soil system, organic matter contents decrease while the amount of clay rises. This can cause a shift from macropores to more micropores (Weil and Brady, 2017: 191).

As said before and mentioned by Weil and Brady (2017), macropores are greatly influencing the movement of water through soils, and therefore also influencing the saturated hydraulic conductivity. Macropores are responsible for nearly all water flow in soils during saturated conditions. Sandy soils do usually have bigger saturated conductivities compared to finer-textured (i.e. clay) soils, because of the more macropores existing between larger (sand) particles. Also, stable structured soils conduct water in a faster way with the help of cracks and pores than soils with an unstable structure. Unstable soil structures can break down when being wetted and lose their ability to conduct water effectively. One must not forget, however, that air can be trapped in macropores when the soil is wetted rapidly. Thereby, the saturated hydraulic conductivity can be lowered significantly. A similar problem may arise when there are many non-interconnected pores in a soil. The interconnectedness plays an important role because if not connected to other pores, pores can act as “dead-end streets” to flowing water (Weil and Brady, 2017: 227).

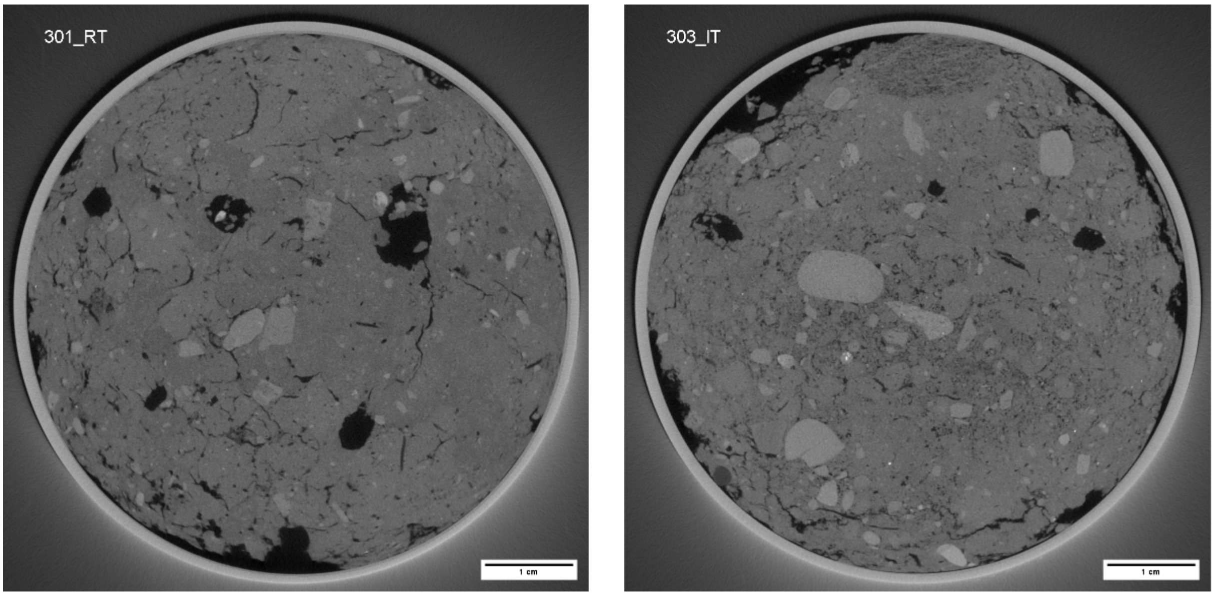
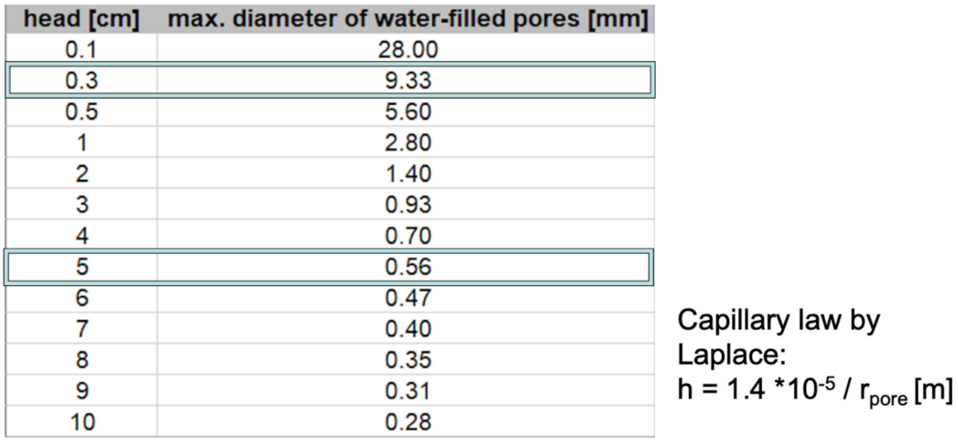


Figure 1: Two X-ray scans of two samples from our study site (FAST experiment). Left: Scan of a soil core from a reduced tillage treatment. Right: Scan of a soil core from a conventional tillage treatment. Source: Own scans.

Figure 1 shows a nice example of two of our own samples, where we did an X-ray scan to gain more insights about the pore space. On the left side, a sample stemming from a reduced tillage management practice is shown. On the right, we see a sample coming from a field that was intensively ploughed in the past. It is striking that there seem to be more pores present on the left side. This could be an indication for a less disturbed environment under reduced tillage approaches and that there are more earthworms present in these conservation agricultural treatments, which created these larger pores.

One of the most important kinds of macropores are biopores. Biopores are created by roots and earthworm activity (see Figure 1, left). Usually, this type of pore is tubular in shape, and they can be continuous with a length of a meter or even more. Root channels and earthworm burrows typically are larger in diameter than 1 mm (Weil and Brady, 2017: 227). Therefore, biopores are essential regarding saturated hydraulic conductivity for different soil horizons. Under different moisture contents, the maximal diameter of water-filled pores changes significantly (see Table 1 below). A network for stable biopores can be created by the existence of perennial vegetation. Tillage for the production of annual plants, on the other side, is thought to destroy the pore system and cut it off from the surface of the soil. The saturated hydraulic conductivity of perennial grasslands or forests is much larger, under normal circumstances, than it is in soils where crop plants are cultivated annually (Weil and Brady, 2017: 227). Furthermore, the conductivities measured in no-tillage management practices are normally higher compared to fields under conventional tillage methods (Weil and Brady, 2017: 227).

Table 1: *This table shows the maximal diameter of water-filled pores under a specific potential. Note that smaller numbers in the head [cm] are indicating a higher moisture content. The head in cm is equal to water potential in hPa (e.g. -5 cm = -5hPa). The two highlighted heads (potentials) are the moisture contents that were investigated in this master's thesis. The maximal diameter of pores filled with water under a specific water potential is calculated by using the capillary law of Laplace.*



head [cm]	max. diameter of water-filled pores [mm]
0.1	28.00
0.3	9.33
0.5	5.60
1	2.80
2	1.40
3	0.93
4	0.70
5	0.56
6	0.47
7	0.40
8	0.35
9	0.31
10	0.28

Capillary law by
Laplace:
$h = 1.4 * 10^{-5} / r_{pore}$ [m]

1.8 The role of earthworms

Earthworms can be called ecosystem engineers of the soil (Capowiez et al., 2021; Vidal et al., 2023). They shape and influence the soil habitat around them (Thomas et al., 2020). Earthworms eat detritus, decompose soil organic matter, plant litter, and microorganisms that they find. However, they do not eat living plants or the roots of such, so they are not a pest to crop systems (Weil and Brady, 2017: 495). Because they have major impacts on soil functions and on the surrounding ecosystem, earthworms can be called keystone species (Weil and Brady, 2017: 495; Huang et al., 2020) and they are increasingly thought to be important agents to improve soil structure (Vidal et al., 2023).

There are more than 7000 different species of earthworms in the world (Weil and Brady, 2017: 495). According to their habitat and their burrowing behavior, they can be grouped accordingly (Weil and Brady, 2017: 495; Capowiez et al., 2021). In this master's thesis, we investigated the occurrence of three different ecological functional groups of earthworms. Namely, epigeic, endogeic, and anecic earthworms (see an illustration of the three groups and their habitat in Figure 2).

Species that can be classified as epigeic are relatively small, and they live in the litter layer or near the soil surface where they can find an organic-rich environment. They improve and fasten the decomposition of litter without mixing it into the mineral soil further down.

Species that fall into the endogeic functional group, occur mainly in the upper 10 - 30 cm of mineral soils. There, they create shallow and mainly horizontal burrows (Weil and Brady, 2017: 495).

The third investigated group, the anecic earthworms, are much bigger compared to the former two groups. They form the longest and thickest burrows. These burrows are mostly vertical, and they can persist for a longer time (over years), while might being several meters deep.

Thus, anecic earthworms do have a huge potential to impact hydraulic conductivities near saturation conditions in soils (Briones and Schmidt, 2017; Weil and Brady, 2017: 495).
These burrow holes, which are left by earthworm activities, are an important factor considering plant productivity and soil development. That is because they can be beneficial in terms of increased aeration and drainage capacity in soil systems. The ability to mix the soils, performed by earthworms, can alleviate, or even reduce problems, like soil compaction, or prevent that an undesirable plough pan is formed, and thus enhance plant growth. Also, in case of a heavy rainfall event, earthworms can help to reduce its impact. The earthworm burrows may enhance the infiltration rates of water and thus bring a reduction in soil erosion risk in agricultural soil systems. As explained before, these beneficial effects are always dependent on the management practices that are in place in an agricultural field (Capowiez et al., 2009; Weil and Brady, 2017: 498; Vidal et al., 2023).

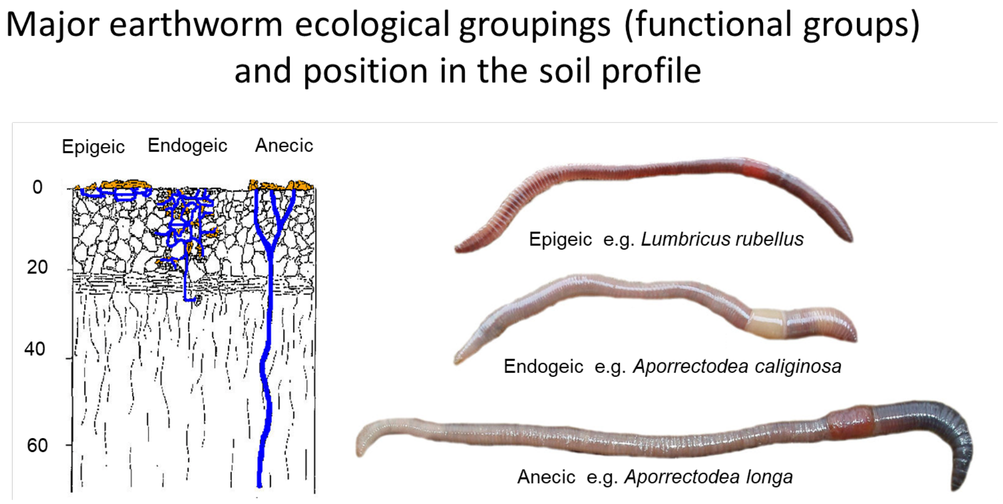


Figure 2: Illustration of the three major earthworm groups (epigeic, endogeic, and anecic) and their positioning in the soil system. Source: AgResearch (retrieved from: https://www.waikatoregion.govt.nz/community/whats-happening/news/media-releases/earthworms-improve-soil-health/).

With all this preliminary information in mind, the following research questions and hypotheses have been developed.

1.9 Research questions and hypotheses

Research questions

i) How do different cropping systems and tillage intensities influence soil hydraulic conductivity near saturation, in two separate depths?

ii) Can the difference in earthworm populations explain the differences in near-saturation hydraulic conductivity?

Hypotheses

H1: Tillage intensities have an influence on the near-saturation hydraulic conductivity (K_{sat}) in the top- and the subsoil.

H2: The observed differences are linked to the abundance of earthworms living in the soil system.

To answer these research questions, we measured the hydraulic conductivity at a water potential of h = -0.3 cm and at h = -5 cm, respectively (-0.3 hPa and -5 hPa), and compared them to the abundance of earthworm populations. A water potential of -0.3 hPa is close to saturated conditions in a soil. At this potential (-0.3 hPa), pores with a diameter up to 9.33 mm are water-filled and we are in the saturated range of the hydraulic conductivity (K_{sat}). For the potential of -5 hPa, only pores with a diameter up to 0.56 mm are water-filled and most macropores have no more or only very small flow rates (Jarvis and Larsbo, 2022).

The next two Figures (Figures 3 and 4), illustrate our thinking and research approach. We want to shed more insights on current knowledge gaps regarding soil hydraulic conductivity near saturation and the corresponding influence of earthworm abundance, and how they contribute to the functioning of a soil system. The already existing data and studies are not always consistent in results and many uncertainties still remain regarding the complex interactions within a soil system (Strudley et al. 2008). A better understanding of these interactions is needed in order to be adapted in the best possible way concerning future climatic and social challenges.

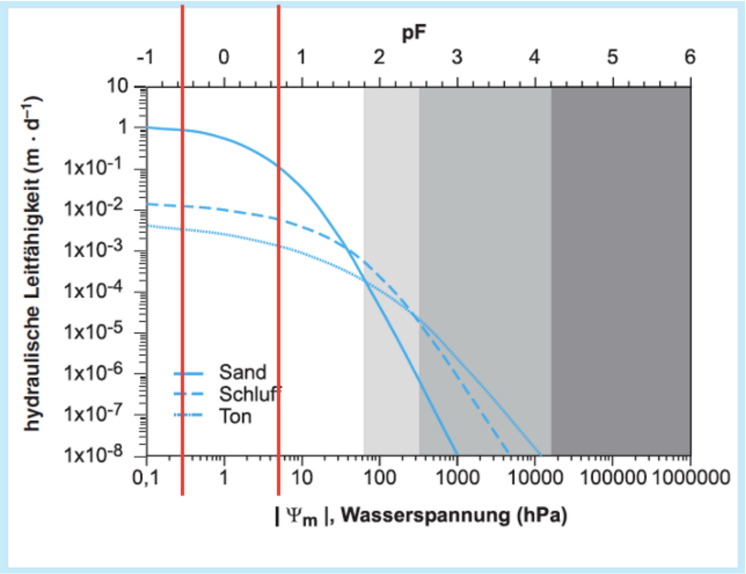
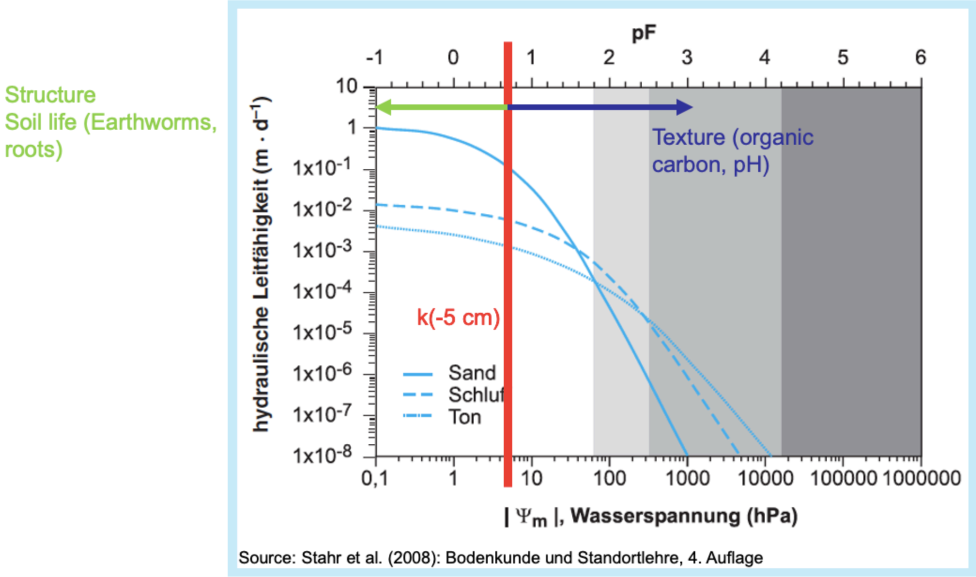


Figure 3: Generalized relationship between hydraulic conductivity and water potential for the three main soil types (sand, silt, and clay). The red lines are pointing out which water potential levels were measured in this thesis (e.g. -0.3 hPa and -5 hPa). Source: Stahr et al. (2008).



Source: Stahr et al. (2008): Bodenkunde und Standortlehre, 4. Auflage

Figure 4: Generalized relationship between hydraulic conductivity and water potential for the three main soil types (sand, silt, and clay). The red line is an indication of -5 hPa. We think that closer to saturated conditions (green arrow), soil structure is more influential (pore space), whereas drier conditions are shaped more by texture, and other physical and chemical impacts (blue arrow). Source: Stahr et al. (2008).

In the following chapter, it is explained how the sampling and the measurements of all investigated variables were performed and analysed.

2. Methods

The performed sampling campaign and the following measurement procedure are based on the “SoilX” sampling and measurement protocol from ten Damme et al. (2023).

2.1 Study site

The study site that was analysed for this master’s thesis is called the FAST experiment (Farming System and Tillage Experiment) and focuses on productivity and ecosystem services regarding organic and conventional farming, respectively. The FAST experiment is a *Long-term field experiment* (LTE) and has been running since 2009 in Rümlang, Altwi (Zürich, Switzerland). The annual precipitation of the location amounts to 1050 mm and the mean temperature around the year is 9.4 °C (at 485 m.a.s.l.). The soil in the FAST experiment can be categorized as a sandy loam (23% clay, 34% silt 43% sand) regarding its textural composition. According to the international soil classification system WRB (World Reference Base for Soil Resources), the soil in the FAST experiment can be classified as a calcaric Cambisol (called “Kalkbraunerde” in Switzerland, according to Heller et al. (2023)). This experiment managed by the Agroscope (Swiss Confederation's centre of excellence for research in the agriculture and food sector) includes four different agricultural treatments, namely conventional farming with and without ploughing (C-IT: conventional intensive tillage; C-NT: conventional no-tillage) and organic farming with ploughing and reduced tillage (O-IT: organic intensive tillage; O-RT: organic reduced tillage (shallow and non-turning: only the uppermost 10 cm of the soil get tilled and disturbed)). Organic farming consists of fertilization with cattle slurry and Biorga Quick whereas mineral fertilizers and synthetic plant-protection products are applied in the conventional farming method (information about the key data of the FAST experiment retrieved from Agroscope, FAST experiment: https://www.agroscope.admin.ch/agroscope/de/home/themen/umwelt-ressourcen/monitoring-analytik/langzeitversuche/fast.html). Each of the four agricultural treatments is replicated and measured four times, in this master’s thesis, which leads to 16 studied plots in total. Find a visualization of the experimental design in the following map below (Figure 5).

The different management measures in this long-term experiment are evaluated for how environmental impacts affect the quality of the soil under a specific management strategy for example, the susceptibility to soil erosion.

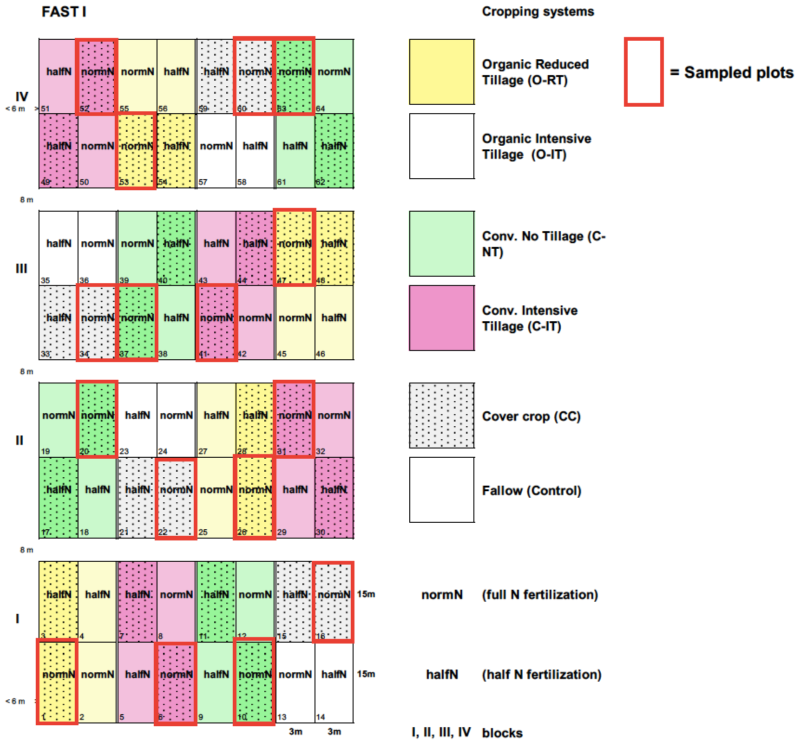


Figure 5: Visualization of the plots in the FAST I experiment at Agroscope, Reckenholz. The red rectangles are indicating the sampled plots (O-RT treatment in yellow: plot nr. 1, 26, 47, and 53; O-IT treatment in white: plot nr. 16, 22, 34, and 60; C-NT treatment in green: plot nr. 10, 20, 37, and 63; C-IT treatment in pink: plot nr. 6, 31, 41, and 52). Note: all investigated plots used cover cropping. Source: Agroscope.

The conventional farming methods were last fertilized on the 27th of May 2022 and a mineral fertilizer (Ammonium nitrate 25% N, 8% S, 2,5% Mg) was used manually. The applied fertilizer amounted to 40 kg N per hectare. The fields under an organic treatment (O-IT and O-RT), were organically fertilized through an organic fertilizer (Biorga Quick 12% N). The last time this happened was on the 29th of April 2022 and 60 kg N per hectare was used for fertilization.
Other interventions were also applied with the aim of protecting the crop, namely winter wheat at that time. For the conventional farming methods, this was lastly done on the 12th of April 2022 by using a weed herbicide spray (Othello) where 1.2 liters per hectare were applied on the C-IT and C-NT plots. The organic farming techniques (O-IT and O-RT), on the other hand, only underwent mechanical weed removal with a tine weeder on the 22nd of March 2022. By using a tine weeder, only very shallow areas of the soil get loosened and weeds will be unrooted. Additionally, when this agricultural implement is made use of, the covering of the surface with organic residues is only reduced by 5% (KTBL, 2020; Mohler et al., 2021). In our case, in the FAST experiment, the straws of the tine weeder loosened the uppermost 2 centimeters of the soil.

The last time the two intensive soil cultivation managements (C-IT and O-IT) were fully ploughed was on the 30th of September 2021. Used for that was a moldboard plough which tilled and turned the highest 20 cm of the respective plots. This technique is a so-called primary tillage process where the topsoil gets completely inverted. To be considered primary tillage, the tillage depth has to be 15 cm at least. After using the moldboard plough, only very little coverage with plant residues remains on the surface of the field (KTBL (2020)).

On the 20th of July 2022 the main crop, winter wheat, was harvested. After that, stubble cultivation was implied with the help of a tiller in the C-IT and the O-IT plots on the 3rd of August. Thereby, the top 8 centimeters were penetrated by the tiller and therefore a first soil preparation for the next crop was initiated. Meanwhile, on the same day, the C-NT and the O-RT treatments did undergo a seedbed preparation as well. This preparation, however, happened in a shallower zone of the soil, namely, down to 5 centimeters depth in the O-RT fields and down to 3 centimeters depth in the C-NT, respectively. Six days after this first preparation, on the 9th of August 2022, the C-IT and the O-IT plots also experienced a seedbed preparation but, in these plots, it was done by using a fine cultivator. This agricultural device loosens and mixes the soil with a non-inversion technique, meaning the soil does not get turned upside down during the process. The implementation of this device reduces the soil cover with organic residues by 20-40% (KTBL, 2020; NRCS, 2010). In the FAST experiment, this technique tilled the uppermost 10 centimeters in the C-IT and the O-IT.

Finally, on the same day (9th of August) as the seedbed was being prepared, also the cover crops were sowed via direct drill method using a no-till cereal seeder. Sowing the cover crop plants was the last management happening before the sampling campaign for this master's thesis started.

(All information regarding the different management interventions is based on personal communication with Raphaël Wittwer)

2.2 Sampling campaign

The sampling campaign in the FAST experiment started in March 2023, where over two weeks' time, all the necessary samples were collected and then brought to a cooling room at Agroscope for storage purposes afterwards. The following chapters will illustrate the sampling process in more detail.

2.2.1 Undisturbed soil core samples

The sampling of undisturbed soil cores, for further lab analyses, was conducted by using an "undisturbed core samplers" kit from the company *Royal Eijkelkamp*. This kit contains several devices which help to take the soil cores out of the soil system, like for example soil augers to drill holes into the soil, and core samplers which are used to push metallic sampling cylinder rings into the soil matrix. Each sampling cylinder ring is 5 cm in height and has a diameter of 8 cm, plus are they each marked with a unique number and will later contain one specific sample of an undisturbed soil core.

The undisturbed soil core samples were taken in two different depths in each of the 16 plots. One depth is located in the upper part of the soil (in 7.5 – 12.5 cm depth), and the other one in a lower part of the soil system (in 27.5 – 32.5 cm depth). Hence, the centre of the cylinder rings should always be at a depth of 10 cm, or a depth of 30 cm respectively. In order to measure the correct depth levels in the soil system, depth markings were attached to the soil auger and to the core sampler using yellow duct tape.

After the preparation of the sampling devices, a hole was drilled down to just above the required soil level using a soil auger from the *Royal Eijkelkamp* sampling kit. For the last few centimetres, we used a Riverside auger which reduces the volume of debris falling into the borehole. After the borehole was prepared, the core sampler must be made ready. A sampling cylinder ring is placed in the ring holder space of the core sampler. Then, the core sampler was cautiously pushed into the soil using a hammer. Thereby, the aim was to hammer the cylinder ring into the soil such that 1 cm of soil protrudes out of the upper end of the ring. By hammering the core sampler too far into the bottom of the borehole, the soil sample will get too compacted and compressed at its top. This should be avoided by all means to reduce the creation of artificial sampling artefacts.

Only the samples that were completely filled with soil, were used for further laboratory analyses. If the cylinder ring was not filled entirely, or if large stones protruded from the sample, the sample was taken again until a satisfactory sample was obtained. Satisfactory samples were then pre-trimmed as such that approximately one centimetre of soil protruded from each end of the sampling rings. We also used scissors and scalpels to cut roots that stuck out of the samples. Afterwards, the pre-trimmed samples were covered with a matching lid and put in a plastic bag to prevent that evaporation affects the soil core samples.

The last step of sampling the undisturbed soil cores was placing them carefully in a storage box (Figure 6) to ensure that the transport back to the laboratories of Agroscope did not damage the samples. Back at Agroscope, the soil core samples were put in a cooling room (3-6 °C) and stored until they were processed further (ten Damme et al., 2023).

These undisturbed cylinder ring samples were later used to perform the mini-disk infiltrometer measurements near saturation (measuring the so-called near-saturated hydraulic conductivity), but more about that in section 2.5.

As mentioned before, every agricultural management treatment is measured four times, which makes it 16 studied plots in total. Furthermore, three pseudo-repetitions per plot were taken to be able to analyse the samples in a statistically more robust way and to have more information per plot in general. It must be noted that four repetitions were conducted per plot, whenever it was possible. This was done because the FAST experiment partially lies on a glacial moraine with shallow soil and numerous stones present below ground which can affect the sample heavily. Thanks to four repetitions per plot, it was, therefore, possible to throw out unusable measurements and use the fourth repetition, the back-up sample, instead (more in section 2.5).

As a consequence, theoretically, there should be 96 soil core cylinder rings in total (16 plots x 2 depths x 3 repetitions = 96 measurements). Practically, we ended up with 93 soil core measurements because, in three plots, no back-up samples were sufficient enough to be used (namely two soil core samples in 10 cm depth in two plots of C-IT treatment (plot 16 and plot 34) and one soil core sample in 10 cm depth in one plot of O-RT treatment (plot 1)).

Figure 6: Left: Filled soil core sample ring. Right: Storage box for transportation filled with several soil core samples. Source: Own photos.

2.2.2 Composite samples

To be able to gain more information about the studied plots in the FAST experiment, also loose soil composite samples were carried out. With the help of the composite samples, it is possible to identify several important soil parameters later in a laboratory analysis. Composite sampling methods have a range of advantages. According to Patil (1995), fewer individual analyses are required because compositing several samples into one reduces the number of analyses which has to be done. Therefore, composite samples can reduce the costs of the laboratory analyses, while containing the same information that would otherwise require many more analyses (Patil, 1995).

In more detail, we wanted to analyse the different plots in the FAST experiment for texture (proportion of clay, silt, and sand) and for soil organic carbon content (SOC). The composite sample consists of five subsamples. The first one is centred in the middle of each plot and four cardinal subsamples that are approximately one meter away from the centre but not closer to one-third to the edge of the plot. In the end, there is one composite sample per plot and per depth, hence two composite samples per studied plot. The two depth levels which were measured, are at the same levels as the soil cores were taken from. Again, duct tape was used to mark the correct depth levels on the soil sampler. The five subsamples of one depth in a plot were stored in a labelled plastic bag so that it is clear from which plot (treatment) and from what depth the composite sample is originating from (see Figure 7). This was done for all studied plots and for both required depths, separately (ten Damme et al., 2023).

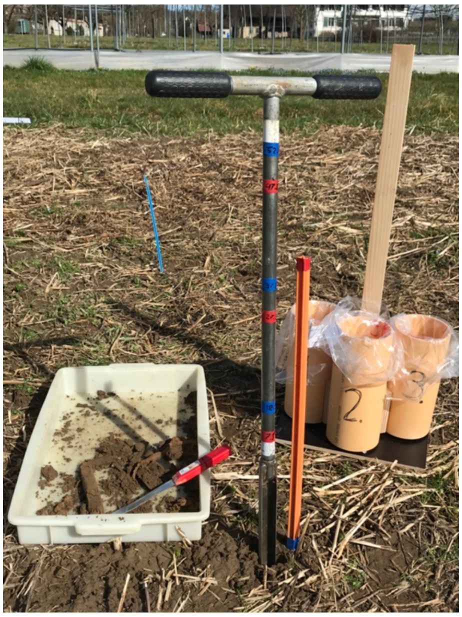


Figure 7: Setup for measuring the composite samples in the field. Source: Own photo.

After the sampling of the composite samples in the field, the labelled plastic bags, each filled with the five subsamples, were also stored in a cooling room until they were used again for further analysis.

The preparation of the composite samples for further analysis was done afterwards. This included the drying of the samples in an oven at 40°C until the weight of the samples reached a constant level. Afterwards, the samples were sieved with a mesh of 2 mm diameter. A small part of each sieved sample was also milled to very fine particles for the chemical analysis of the composite soil samples (ten Damme et al., 2023). The samples were milled for 60 seconds using a Mortar Grinder, called PULVERISETTE 2, from the company Fritsch GmbH. The prepared composite samples were then sent to the chemical laboratory of Agroscope and examined by the associated specialists.

2.3 VESS method

In the field, we implemented the VESS method as follows. A part of the topsoil was taken out of the field by using a spade. The part of the soil, which was taken out, and used for the visual evaluation, had the dimensions of 20 cm width * 20 cm length * 20 cm depth. Then, the excavated soil block was placed in a plastic box where it could be disassembled and visually analysed. The soil structure is detected by using the guidelines of the VESS score chart (the score chart can be found in the Appendix). The VESS score chart explains, how the different soil indicators (aggregates, roots, porosity) should be evaluated in a specific soil sample. According to the overall visible soil structure quality, every soil receives a score ranging from Sq. 1 to Sq. 5, where Sq. 1 is the best score possible, meaning a "good" structural quality exists. Sq. stands for topsoil quality (Ball et al., 2017). Score values from Sq. 1 to Sq. 3 are usually accepted as functioning soil systems, whereas higher scores (Sq.4 and Sq.5) suggest that a change in management strategies might be required.

(Information retrieved from the VESS score chart:
https://bbro.co.uk/media/50172/vess_score_chart-1.pdf).

The VESS method was done three times in each of the 16 studied plots. The calculated mean of these three subsamples was used for further interpretation. The soil blocks, which were used for the VESS method, and the soil pits dug for the VESS method, were used for the later following earthworm sampling (see next section 2.4).

2.4 Earthworm sampling

After completing the VESS method and evaluating the VESS score for each soil block, the same soil blocks were used for the earthworm sampling. Following the sampling protocol of ten Damme et al. (2023), the best time to sample earthworms is from March to May. That is because the minimum soil temperature should not be lower than 5°C for a minimum of three weeks after the winter. In addition, the soil temperature should not be over 10°C.

The previously excavated soil blocks, from the VESS score, can now be examined for earthworm occurrence. Remember that these soil blocks have the dimensions of 20 * 20 * 20 cm. The soil blocks were carefully crumbled apart in the plastic box to ensure that no earthworm was missed, and that no earthworm was harmed during the process.

Every earthworm that was found, was rinsed with cold water and then stored in a little container with cold water. Each container was marked with the matching number of the specific studied soil management plot.

Moreover, the soil pits were used to expel more earthworms from the soil. This was done by using a strong mustard powder. In this master's thesis, a brown mustard was used as an expelling agent. 20 grams of the brown mustard powder were diluted with two liters of water. Half a liter of the solution was then used for each soil pit. After the mustard solution was applied to the soil pit, we waited for 20 minutes and caught every earthworm that appeared on the surface. Every additional earthworm that came up, was immediately rinsed with cold water (to get rid of the mustard solution) and put into the correspondingly marked water container. Until the containers, filled with earthworms and water, were brought back to the cold storage room at Agroscope, we made sure that the earthworms were kept cool (4 – 15°C) and out of direct sunlight. Note that the earthworms can stay in the water containers until the next day if stored appropriately (4 – 10°C) (ten Damme et al., 2023).

Back at Agroscope, the measuring of the earthworm data was completed on the next day. Namely, the total number of earthworms and their biomass [g] were determined for each soil block. We also made sure that we differentiated the various earthworms according to ecological groups and age. We sorted them into groups of adults and juveniles, as well as into the three ecological earthworm groups that are examined in this master's thesis. The three ecological subgroups are epigeic, endogeic, and anecic (ten Damme et al., 2023).

Hence, we received the information of three subsamples in the form of three soil blocks per plot (the same as in the VESS method). Therefore, we had three pseudo-replicates per plot, and we could calculate the mean values for each of the studied plots. This helps to statistically evaluate the data later.

2.5 Measuring the hydraulic conductivity (k) in the lab with Mini Tension Disks Infiltrometer

Sample preparation

The next step was to measure the near-saturated hydraulic conductivity k of every sampled soil core cylinder ring from section 2.2.1. The hydraulic conductivity k near saturation was measured at -5 cm and at -0.3 cm suction tension (k (-5 cm) [cm/d]; k (-0.3 cm) [cm/d]) in the laboratory.

The before-hand sampled undisturbed soil core cylinders were taken out of the cold storing room and prepared for the measurement procedure. The preparation of the cylinder rings included the trimming of the bottom and the top of the cylinders. For this, we used sharp knives and scalpels. It was crucial to proceed with caution so that we did not affect and smear the sample. The presence and abundance of visible macropores (e.g. worm holes) were noted down to save as much information as possible. For the same reason, photos of every cylinder ring were taken, and each cylinder ring sample was weighed to gain information about the field moist water content in every single soil core sample. A Polyamide gauze was fixed to the bottom of every cylinder using a rubber band to ensure that the sample would not fall out.

After the preparation of the soil core samples, we decided which cylinder ring samples to use for the further measurement procedure. Decisive for that was the intactness of the samples and our comments from the field and from the preparation of the sample (i.e. we excluded a sample if there was an earthworm present in a soil core sample or if a big stone protruded from the sample). Remember that we took four repetitions (back-up sample) in each plot, whenever it was possible. If there was nothing wrong with repetitions 1 to 3, the fourth repetition, the back-up sample, was always thrown out. Reasons for not using a sample were, if a cylinder core was destroyed or broke apart, if there were too many stones present for a clean preparation, or if a living earthworm was still found in the sample (ten Damme et al., 2023).

Measurement of k (-5 hPa)

The infiltration rate of each cylinder ring sample was measured with a Mini tension disk infiltrometer (Mini TDI) with a 4.5 cm diameter porous steel disk. These Mini TDI stem from the company “METER Deutschland GmbH” in Germany.

Figure 8: Left: The empty apparatus for the hydraulic conductivity measurements with space for 10 Mini tension disk infiltrometers. Right: Apparatus with 10 soil core samples in place. Source: Own photos.

To fulfil the measurements of the hydraulic conductivity, we constructed an apparatus that made it possible to measure 10 samples at once (see Figure 8). It was important that the samples stood still and robust, and that the infiltrating water could move away from the sample at the bottom. For that, we used a measurement stand with a coarse rigid grid mounted above a water collection tray (see Figure 9 for an illustration).

The field moist soil core samples (ideally between -60 hPa and -100 hPa) were placed on the grid (see Figure 8: right, and Figure 9: right) in order to perform the measurements.

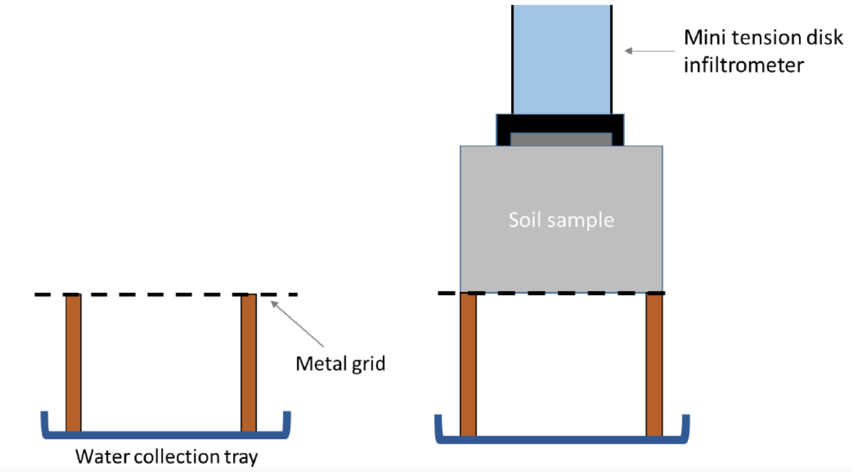


Figure 9: Left: Measurement stand in a tray for water collection. Right: Measurement stand combined with a soil core sample and Mini tension disk infiltrometer for carrying out the measurements (ten Damme et al., 2023).

The soil core samples placed on the grid were then nearly ready for the measurement procedure. There only had to be a patch of Polyamide gauze placed on top of the cylinder ring sample which was then covered with a thin layer of fine quartz sand (sand diameter: 0.1 – 0.3 mm). This was done to guarantee a plain surface exists, where the Mini tension disk infiltrometer could stand properly (see Figure 10). The Mini tension disk infiltrometer could then be placed directly in the middle of the gauze and the measurement could start (ten Damme et al., 2023).

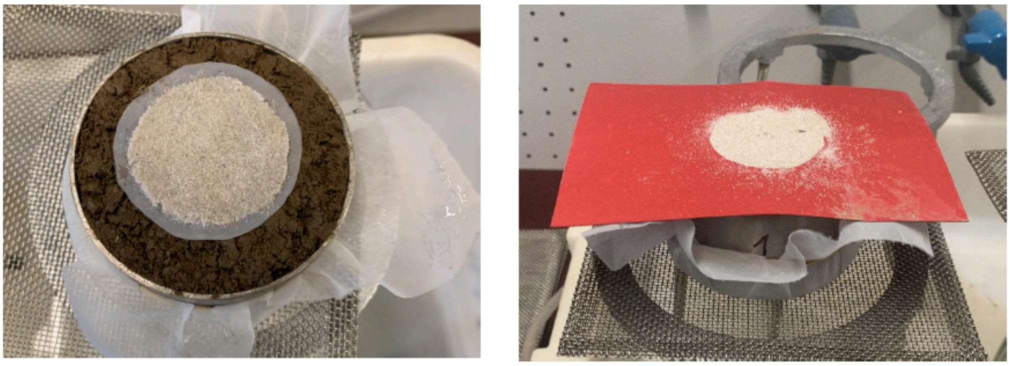


Figure 10: Left: Soil core sample with gauze and sand. Right: Soil core sample with red stencil. Source: Own photos.

The Mini tension disk infiltrometer was set to -5 cm and placed on the soil core sample. The water from the Mini tension disk infiltrometer should now be infiltrating into the soil core sample. The infiltration rate of each sample was recorded and saved in an Excel file. This was achieved by measuring the water level in the infiltrometer at regular time intervals (a minimum of 2 ml of discharge should have occurred between two intervals). The interval time is thus depending on the infiltration rate. A fast infiltration means that one has to check the water level in the Mini tension disk infiltrometer, in shorter intervals. If a constant infiltration has been reached, we call it a steady state and this infiltration rate is taken for further analysis. Note that a steady state can be reached after 10 – 30 minutes, but it can also take several hours if water infiltration is very low. We terminated the measurement after receiving at least five measurements at a steady state, or if the wetting front reached the bottom of the sample before a steady state could be detected. If the wetting front reached the bottom before a steady state was achieved, we placed the sample on a sand bed with -5 hPa suction to redo the measurement. This was done to prevent the filling of the sample with water (water flow would stop and infiltration would just fill up the soil core sample).

Preparation for the measurement of k (-0.3 hPa)

To prepare the samples for the measurements close to saturation (k (-0.3)), the cores had to be saturated completely. We took a Polyamide gauze and placed it over the top of the soil core sample with a rubber band. Then, the sample was saturated upside down for three days to make sure that every pore and crack was filled with water. After the saturation of the sample, the Polyamide gauze could be removed again, and the measurements of k (-0.3) could commence.

Measurement of k (-0.3 hPa)

The saturated soil core was placed on the grid again (upside up) in order to perform the measurements. Again, a gauze and sand were placed on top of the sample (the same as for the k (-5 cm) measurements). The gauze and sand were moisturized again with a water sprayer. The Mini tension disk infiltrometer was set to -0.3 cm and placed on the soil core sample, the same procedure as for k (-5 cm) but this time, the flow rates should be higher since more pores should be filled with water and contribute to the hydraulic conductivity. The measurement was terminated after at least five measurements at steady state were achieved. If no steady state was reached before the Mini tension disk infiltrometer runs empty, we refilled the infiltrometer and continued the measurement until a steady state could be achieved.

Record infiltration and calculate k(h)

We recorded the infiltration rates in an Excel sheet and evaluated the measurements accordingly. The formula of Sarkar et al., 2019 (a and b) was used to calculate the hydraulic conductivity k(h) of the soil core cylinders from the infiltration rate q(h). The formula is **k(h) = q(h) / f**. Where f is a factor depending on the size of the cylinder (diameter = 8 cm) and size of the infiltrometer disk (4.5 cm). In our case, for cores with an 8 cm diameter, we defined f as f = 0.7 (Sarkar et al., 2019a).

2.6 Laboratory analysis of the chemical and physical soil data

We received the chemical and physical data from our in-situ measurements back after some months, where they were analysed in the corresponding laboratory at Agroscope.

We calculated the mean (and standard error) for each of the four treatment practices, respectively. The four means from a specific treatment (four plots in total) of a certain soil variable were put together so that there was an overall mean for each separate treatment (e.g. soil organic carbon content for C-IT, C-NT, O-IT, and O-RT).

Note that for the texture analysis, we had to calculate the total texture (100%) out of the raw data. That is because the textural data comes with humus content in it. So, in order to get rid of the humus proportion, we had to cancel it out. For clay, for instance, this looked like this:

clay = clay [measured] / total texture * 100. Where the total texture is clay + silt + sand [measured].

2.7 Statistical approach

For the statistical analysis, we first performed an ANOVA. An analysis of variance (ANOVA) checks whether there are statistically significant differences between more than two groups (four groups in our case). For this purpose, the mean values of the respective groups are compared with each other (DATAtab Team, 2024). Because we do have more than two groups in our samples, performing an ANOVA makes sense to calculate differences in means, and to check whether there is a significant difference between numerous groups (between treatment methods in our case).

An ANOVA alone is not sufficient. We also need a post-hoc test to check where the potential differences between groups occur. With tests like an ANOVA, however, it remains unclear which differences are significant in detail. By using post hoc tests, we can examine different pairs as well as make group comparisons.

After using such a post-hoc test, it is possible to say, for example, not only that there are significant differences between the investigated groups, but also that the differences between groups A and B are significant, but those between groups B and C are not, for instance (Novustat, 2022). If two groups are significantly different from each other, different labels get attached to the specific group. In our case, this will be visualized in the boxplots with letters (a), (b), (c), (ab), (bc), and so on. The same letter for two groups means that there is no significant difference between them. Two different letters, however, indicate that difference exists indeed.

We decided to use the “Tukey post-hoc test” for that.

For both kinds of these tests (ANOVA and Tukey test) the confidence level was set to 0.95 (alpha = 0.05). For comparing a family of 4 estimates, in the Tukey method, the significance level used was alpha = 0.05, as well.

3. Results

This next chapter shows an overview of the most important findings and results of thee acquired data.

3.1 Description of the soil

Table 2: This table provides an overview of the measured physical and chemical soil parameters. The mean value of each parameter in each of the individual management treatments is shown per depth together with the corresponding standard error (se). C-IT: conventional intensive tillage; C-NT: conventional no-tillage; O-IT: organic intensive tillage; O-RT: organic reduced tillage. Furthermore, the F-value of the statistical analysis is shown for every parameter (ns = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). The attached letters (a) and (b) are indicating if a parameter is significantly different compared to the other treatments, according to the performed post-hoc Tukey test. Note: The VESS score was only measured in the topsoil (10 cm depth). SOC = Soil organic carbon.

Depth	Treatment	Clay [%]	Silt [%]	Sand [%]	VESS score	pH	SOC [mg C per g soil]
		mean se	mean se	mean se	mean se	mean se	mean se
10 cm	**C-IT**	20.5 ± 1.1 (a)	35.6 ± 2.0 (a)	43.9 ± 1.5 (a)	3.1 ± 0.1 (a)	6.9 ± 0.4 (a)	13.6 ± 0.5 (a)
	C-NT	22.5 ± 1.3 (a)	34.7 ± 2.3 (a)	42.7 ± 1.7 (a)	2.3 ± 0.2 (b)	7.0 ± 0.5 (a)	12.8 ± 1.3 (a)
	O-IT	22.5 ± 1.4 (a)	34.0 ± 1.6 (a)	43.5 ± 1.5 (a)	3.2 ± 0.1 (a)	7.0 ± 0.3 (a)	14.8 ± 0.7 (a)
	O-RT	20.6 ± 0.9 (a)	35.4 ± 1.0 (a)	44.0 ± 0.6 (a)	2.3 ± 0.0 (b)	7.0 ± 0.3 (a)	13.7 ± 1.5 (a)
	F value(3,9)	0.95 (ns)	0.5 (ns)	0.3 (ns)	14.6 (***)	0.003 (ns)	0.7 (ns)
		mean se	mean se	mean se		mean se	mean se
30 cm	**C-IT**	23.1 ± 1.0 (a)	24.5 ± 8.1 (a)	52.4 ± 7.3 (a)		7.4 ± 0.4 (a)	7.6 ± 1.2 (a)
	C-NT	23.5 ± 1.7 (a)	32.7 ± 3.1 (a)	43.9 ± 4.5 (a)	———	7.2 ± 0.5 (a)	6.8 ± 0.1 (a)
	O-IT	25.5 ± 2.0 (a)	30.6 ± 2.3 (a)	43.9 ± 2.7 (a)		7.1 ± 0.3 (a)	7.5 ± 0.4 (a)
	O-RT	23.7 ± 1.0 (a)	34.9 ± 1.8 (a)	41.5 ± 1.7 (a)		7.2 ± 0.4 (a)	6.3 ± 0.7 (a)
	F value(3,9)	0.7 (ns)	1.1 (ns)	1.5 (ns)		0.1 (ns)	0.7 (ns)

The results in Table 2 show that the only significant difference between treatments, of these investigated physical and chemical soil data, can be found in the VESS score. There, the statistical analysis calculated an F-value of 14.6, while the p-value was lower than 0.001. The letters of the Tukey test indicate that there are significant differences between the intensively tilled methods (C-IT and O-IT) and the conservation tillage methods (C-NT and O-RT) considering the VESS score, and therefore the soil structure quality.

All the other soil parameters showed no significant difference between the different treatments (ns = not significant).

Generally, it can be said that the proportion of clay in the soil slightly enhances with depth in all of the treatments. The amount of silt slightly reduces with depth in all treatments, seeing the biggest reduction in the C-IT treatment but the standard error is quite large with ±8.1. Also here, the Tukey test does not show any significant difference between the treatment methods. The proportion of sand seems to be more or less the same in both sampled depths. Except for the C-IT treatment, where the amount of sand increased with depth, but again no significant difference could be shown. In the O-RT treatment, the amount of sand reduced slightly in the deeper layer (30 cm).

The pH value seems to increase a bit in the lower depth in all treatments, whereas the SOC contents experienced a reduction in the deeper layer. Again, no significant difference could be found between the separate treatment methods. Although it would be interesting, the pH value and the soil organic carbon contents will not be discussed in much greater detail because it would be beyond the scope of this master's thesis. They primarily serve as additional information.

3.2 Results of the hydraulic conductivities k (-5 hPa) and k (-0.3 hPa) per treatment

This next section provides the results from the hydraulic conductivity measurements in the four different treatments that were investigated.

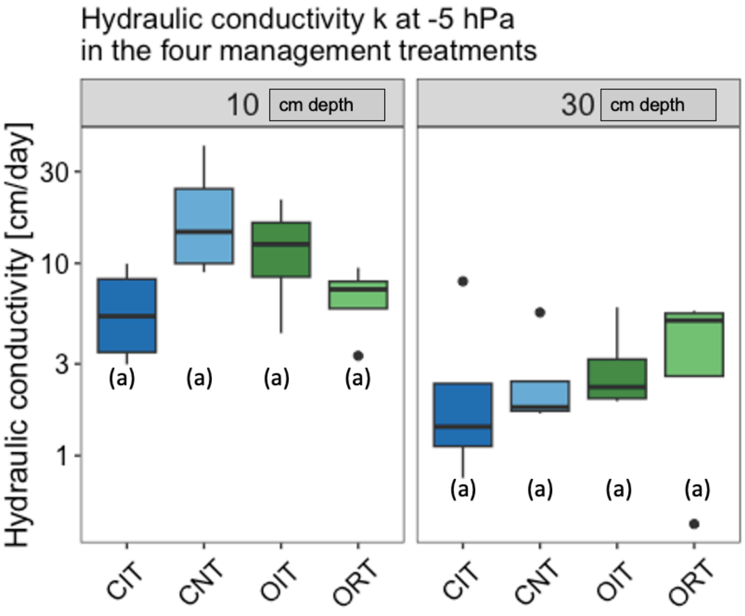


Figure 11: Boxplot of the results from the hydraulic conductivity measurements (in cm/day and visualized in a logarithmic scale) at a water potential of -5 hPa in the two separate depths. C-IT: conventional intensive tillage; C-NT: conventional no-tillage; O-IT: organic intensive tillage; O-RT: organic reduced tillage. The attached letters (a) are indicating if a specific hydraulic conductivity is significantly different compared to the other treatments, according to the performed post-hoc Tukey test. Note: the horizontal line within the boxes is the median and the black dots are considered outliers. The boxes represent the upper and lower quartiles of the data. The whiskers indicate the variability outside the upper and lower quartiles.

We can see that the hydraulic conductivity at -5hPa was the highest in the C-NT treatment with a mean of 20.2 cm/day in 10 cm depth (see Figure 11). The second highest conductivity was found in the O-IT method with a mean of 12.8 cm/day. The O-RT treatment resulted in a mean of 6.9 cm/day and the lowest conductivities were found in the C-IT plots with a mean hydraulic conductivity of 6.1 cm per day. However, the ANOVA and the post-hoc Tukey test did not calculate significant differences between the different management practices. Thus, all the treatments were attached with the same letter (a), indicating that the different treatments did not result in significantly different outcomes compared with each other. The used significance level for the statistical analysis was alpha = 0.05.

At 30 cm depth, though, the distribution of the hydraulic conductivities looked a bit different. Here, the highest conductivity was found in the O-RT treatment with a mean value of 4.1 cm/day. The second-highest hydraulic conductivity was produced in the O-IT plots. Here, the mean value was 3.1 cm per day. A mean of 2.9 cm/day was calculated for the C-IT treatments (outliers push the mean to a higher level). The C-NT plots produced a mean of 2.7 cm per day in hydraulic conductivity. The same as in 10 cm depth, no significant difference was calculated between the four different treatments, using a significance level of alpha = 0.05.
The lower depth produced smaller values of hydraulic conductivity compared to the conductivities in the topsoil (10 cm).

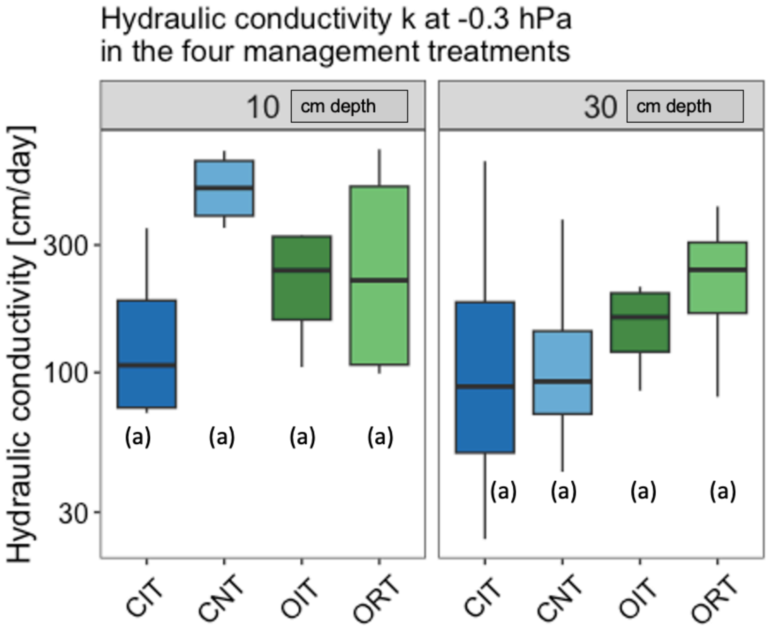


Figure 12: Boxplot of the results from the hydraulic conductivity measurements (in cm/day and visualized in a logarithmic scale) at a water potential of -0.3 hPa in the two separate depths. C-IT: conventional intensive tillage; C-NT: conventional no-tillage; O-IT: organic intensive tillage; O-RT: organic reduced tillage. The attached letters (a) are indicating if a specific hydraulic conductivity is significantly different compared to the other treatments, according to the performed post-hoc Tukey test. Note: the horizontal line within the boxes is the median and the black dots are considered outliers. The boxes represent the upper and lower quartiles of the data. The whiskers indicate the variability outside the upper and lower quartiles.

At a water potential of -0.3hPa (nearly completely saturated), the hydraulic conductivity was the highest in the C-NT treatment with a mean of 506.2 cm/day in 10 cm depth (see Figure 12). The second highest mean values in conductivity were found in the O-RT method with a mean of 335.0 cm/day. The O-IT treatment resulted in a mean of 233.1 cm/day and the lowest conductivities were found in the C-IT plots with a mean hydraulic conductivity of 160.9 cm per day. However, the ANOVA and the post-hoc Tukey test did not calculate significant differences in conductivity between the different management practices. Thus, all the treatments were attached with the same letter (a), indicating that the different treatments did not result in significantly different outcomes compared with each other. The used significance level was alpha = 0.05.

At 30 cm depth, though, the distribution of the hydraulic conductivities looked a bit different again, and the variances were large within the treatments. Here, the highest conductivity was found in the O-RT treatment with a mean value of 247.1 cm/day. The C-IT plots had a very large variance resulting in a mean of 207.0 cm per day. A mean of 155.8 cm/day was calculated for the O-IT treatments. The C-NT plots produced a mean of 150.6 cm per day in hydraulic conductivity, however, the median value of C-NT was close to the median from the C-IT plots. The same as in 10 cm depth, no significant difference could be calculated between the four different management treatments, using a significance level of alpha = 0.05.

Generally, the variances at a potential of k (-0.3 hPa), were much larger in both depths compared to the k (-5 hPa) measurements. Therefore, it is difficult to generate accurate assumptions.

3.3 Results of the Earthworm data

The next subchapter shows the results of the earthworm sampling.

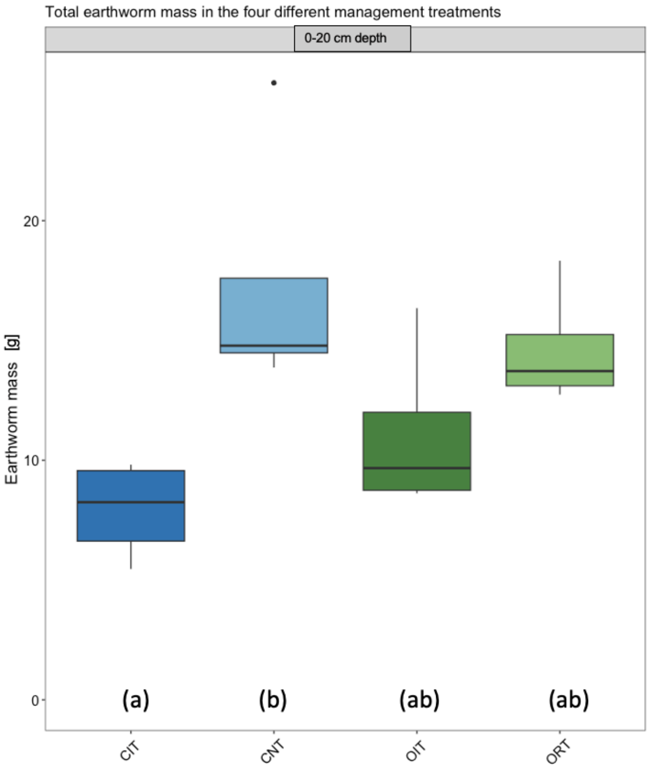


Figure 13: Boxplot of the total biomasses of all found earthworms (in g) in the four different management treatments in a 20 x 20 x 20 cm soil block. C-IT: conventional intensive tillage; C-NT: conventional no-tillage; O-IT: organic intensive tillage; O-RT: organic reduced tillage. The attached letters (a), (b), and (ab) are indicating if a specific amount of biomass is significantly different compared to the other treatments, according to the performed

post-hoc Tukey test. Note: the horizontal line within the boxes is the median and the black dots are considered outliers. The boxes represent the upper and lower quartiles of the data. The whiskers indicate the variability outside the upper and lower quartiles. The whiskers indicate the variability outside the upper and lower quartiles.

Figure 13 shows the distribution of the found earthworm biomasses in a boxplot. It is visible that the highest amount of biomass was found in the C-NT treatments. There, the mean was 17.3 g. In the O-RT plots, the calculated mean was 14.6 g which is close to the mean of the O-IT treatments (11.1 g). The smallest mean was calculated for the C-IT plots which was 7.9 g. The ANOVA and the post-hoc Tukey test calculated a significant difference in earthworm biomass between the C-IT and the C-NT treatment. This is indicating that indeed more earthworm biomass can be found in no-tillage treatments compared to intensively tilled management practices. Both organic treatment methods (O-IT and O-RT) were very similar to each other but not significantly different from any of the two conventional management practices (C-IT and C-NT). The used significance level was alpha = 0.05.

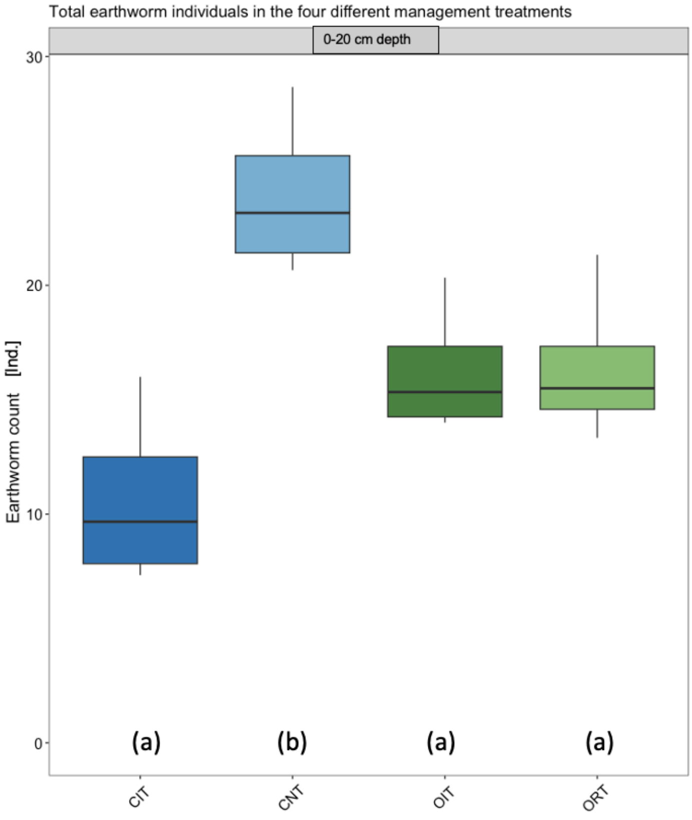


Figure 14: Boxplot of the total individuals of all found earthworms (in individuals) in the four different management treatments in a 20 x 20 x 20 cm soil block. C-IT: conventional intensive tillage; C-NT: conventional no-tillage; O-IT: organic intensive tillage; O-RT: organic reduced tillage. The attached letters (a) and (b) are indicating if a specific number of earthworm individuals is significantly different compared to the other treatments, according to the performed post-hoc Tukey test. Note: the horizontal line within the boxes is the median and the black dots are considered outliers. The boxes represent the upper and lower quartiles of the data. The whiskers indicate the variability outside the upper and lower quartiles. The whiskers indicate the variability outside the upper and lower quartiles.

Figure 14 visualizes the distribution of the found earthworm individuals in a boxplot. It is visible that the highest number of individuals was again found in the C-NT treatments. There, the mean was a count of 23.9 individuals. In the O-RT plots, the calculated mean was 16.4 individuals which is very close to the mean of the O-IT treatments (16.3 individuals). The smallest number (mean) was calculated for the C-IT plots which was 10.7 individuals. The ANOVA and the post-hoc Tukey test calculated a significant difference in earthworm count between the C-NT treatment and the three other treatments. This is indicating that indeed more earthworm individuals can be found in no-tillage treatments compared to intensively tilled management practices. Both organic treatment methods (O-IT and O-RT) were very similar to each other but not significantly different from the conventional management practice of C-IT. The used significance level was alpha = 0.05.

Furthermore, we wanted to have a look at how the situation is regarding the investigated ecological function groups of earthworms.

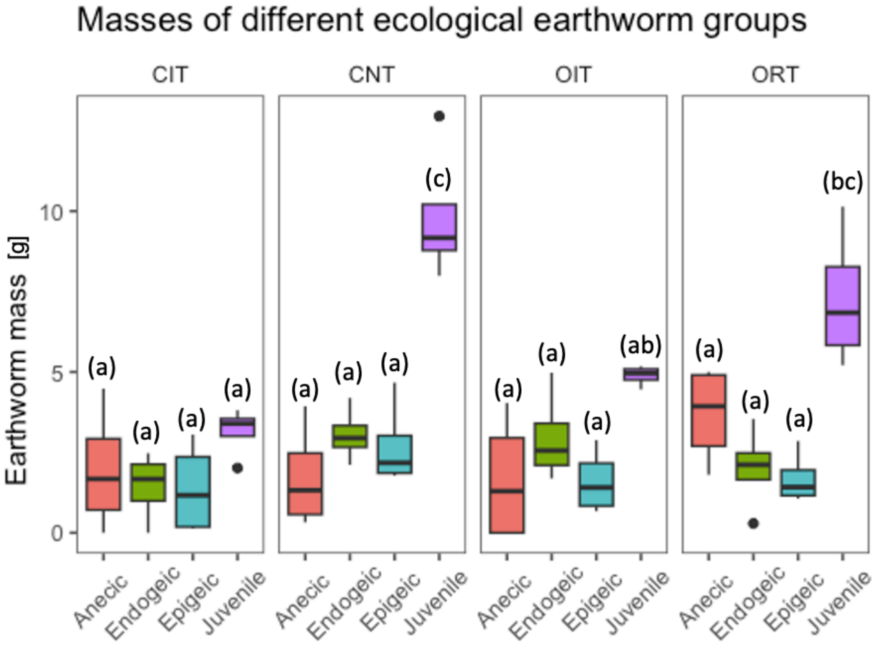


Figure 15: Boxplot of the biomasses (in g) of different ecological earthworm groups found in a 20 x 20 x 20cm soil block in the four different management treatments. C-IT: conventional intensive tillage; C-NT: conventional no-tillage; O-IT: organic intensive tillage; O-RT: organic reduced tillage. The attached letters (a), (ab), (bc), and (c) are indicating if the biomass of earthworms is significantly different between treatments within a functional group, according to the performed post-hoc Tukey test. Note: the horizontal line within the boxes is the median and the black dots are considered outliers. The boxes represent the upper and lower quartiles of the data. The whiskers indicate the variability outside the upper and lower quartiles. The whiskers indicate the variability outside the upper and lower quartiles.

The results of these boxplots (Figure 15) show that there are not many significant differences in earthworm biomass between treatments within an ecological earthworm group. The adult species (anecic, endogeic, and epigeic) showed no statistical difference throughout all four treatments within an ecological group. The biomass of juvenile earthworms in the C-NT treatment, however, was significantly larger compared to the C-IT and the O-IT treatments. Moreover, the biomass of juvenile earthworms in the O-RT plots was significantly higher than in the C-IT treatment. It seems that the management practices with reduced or no-tillage (O-RT and C-NT) enhanced the abundance of juvenile earthworms. The used significance level was alpha = 0.05.

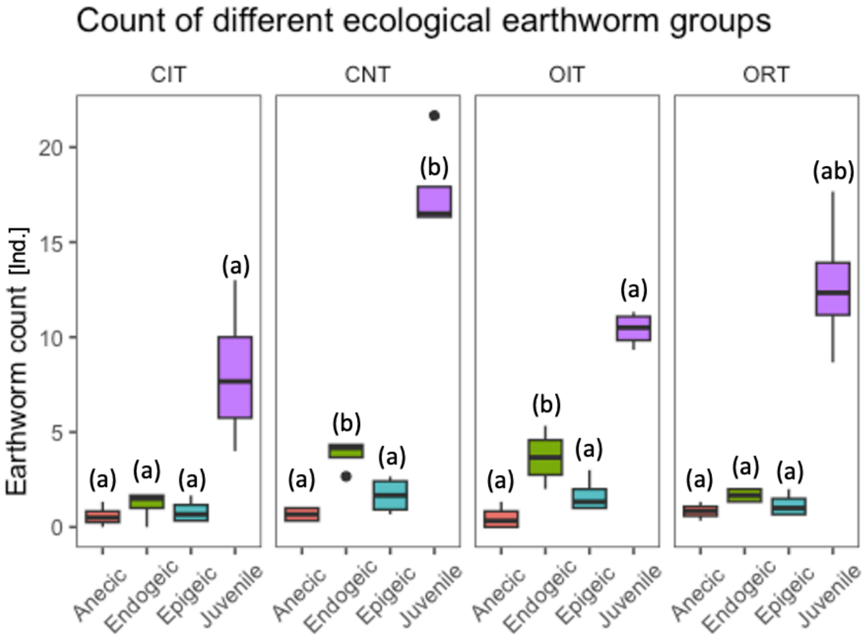


Figure 16: Boxplot of the number (in individuals) of different ecological earthworm groups found in a 20 x 20 x 20cm soil block in the four different management treatments. C-IT: conventional intensive tillage; C-NT: conventional no-tillage; O-IT: organic intensive tillage; O-RT: organic reduced tillage. The attached letters (a), (ab), and (b) are indicating if the number of earthworms is significantly different between treatments within a functional group, according to the performed post-hoc Tukey test. Note: the horizontal line within the boxes is the median and the black dots are considered outliers. The boxes represent the upper and lower quartiles of the data. The whiskers indicate the variability outside the upper and lower quartiles. The whiskers indicate the variability outside the upper and lower quartiles.

The results of these boxplots (Figure 16) show that there are, again, not many significant differences in earthworm count between treatments within an ecological earthworm group. The adult species (anecic, endogeic, and epigeic) only showed a statistical difference for the endogeic earthworms. The earthworm count of (adult) endogeic earthworms in the C-NT and O-IT management treatments was significantly bigger compared to the other two treatment practices (C-IT and O-RT).

The number of juvenile earthworms in the C-NT treatment was significantly larger compared to the other three treatment methods.

It seems that the management practice with no-tillage practices (C-NT) enhanced the abundance of juvenile earthworms, whereas the O-IT and C-NT treatments seem to have increased the number of existing (adult) endogeic earthworms in the soil. The used significance level was alpha = 0.05.

3.4 Regression models

The next section provides some of the most important and interesting relationships between two separate measured variables that were found in this master's thesis. For the comparison, linear regression models were performed and statistically evaluated.

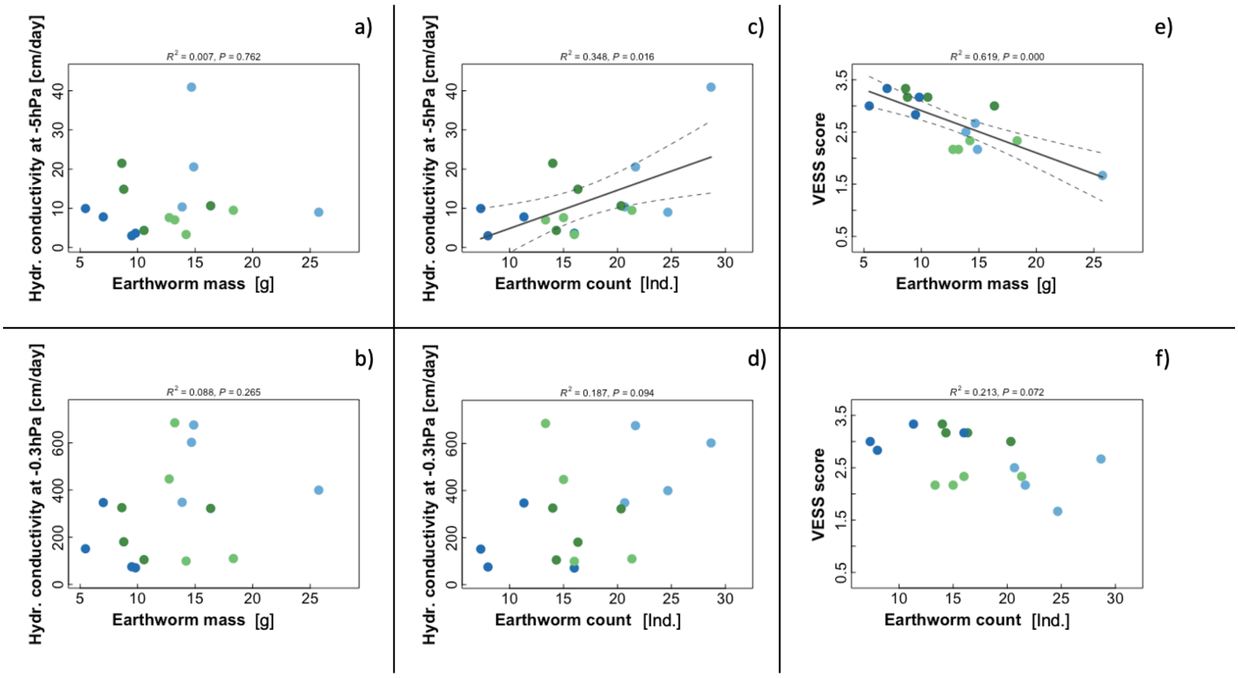


Figure 17: Regression models comparing the relationships between hydraulic conductivities in the topsoil (-5 hPa and -0.3 hPa) and earthworm measurements (a, b, c, and d). Plus, two regressions comparing the relationship between the VESS score and earthworm measurements (e and f). Dark blue dots: conventional intensive tillage; light blue dots: conventional no-tillage; dark green dots: organic intensive tillage; light green dots: organic reduced tillage. Note: the linear regression is only shown if there is a significant relationship between two measured variables ($p < 0.05$), plus only measurements from the topsoil (10 cm) were considered for these regression analyses.

The results of these boxplots show that there are not many significant dependencies between two separate variables in our data.

A significant positive correlation was calculated between earthworm count and hydraulic conductivity at k (-5 hPa) in the topsoil (Figure 17, c)). There, the p-value was 0.016 (lower than 0.05), and a higher number of earthworms seems to foster the hydraulic conductivity at a potential of -5 hPa. However, there could not be found a significant correlation between the earthworm biomass and the two hydraulic conductivities. As well as there was no dependency between earthworm count and hydraulic conductivity at -0.3 hPa registered.

In addition, we found a strong statistical dependency between the VESS score and earthworm biomass (p-value lower than 0.001) (see Figure 17, e)). The statistical dependency between the VESS score and earthworm biomass shows that a better soil structure quality seems to enhance the present biomass of earthworms (Note: a lower VESS score means a better soil structure). The same could not be said for the relationship between the VESS score and earthworm count, where no significant dependency could be detected (Figure 17, f)).

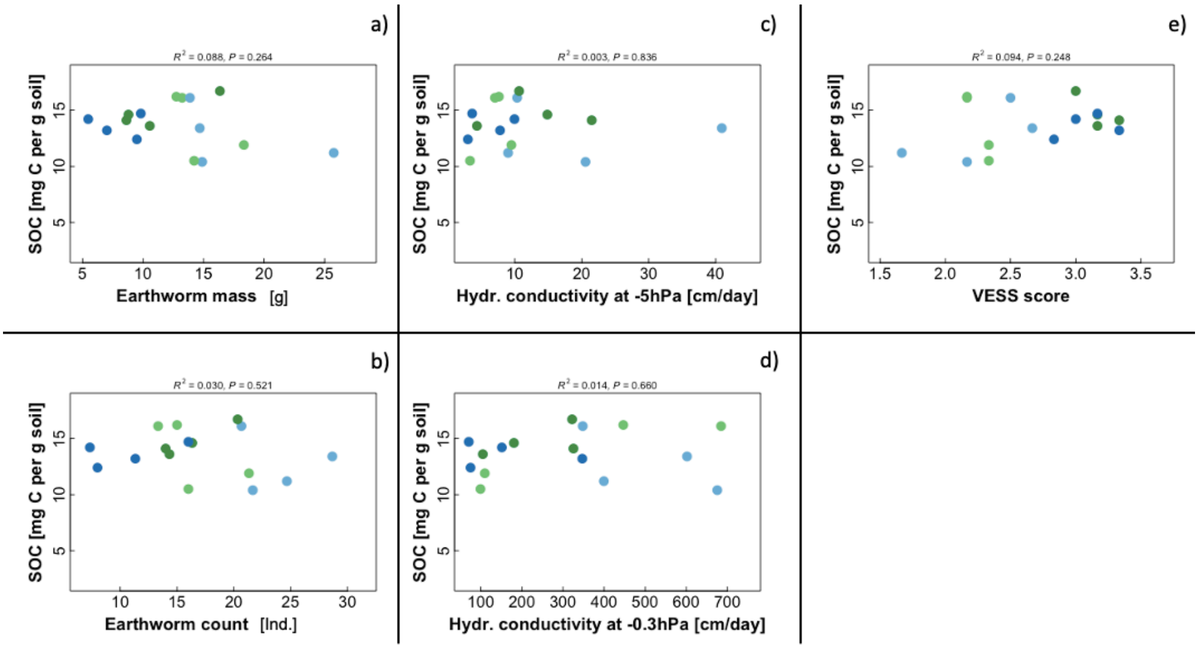


Figure 18: Regression models comparing the relationships between SOC (soil organic carbon) in the topsoil and earthworm measurements (a and b). Plus, two regressions comparing the relationship between SOC and hydraulic conductivities (c and d), and one regression comparing the SOC to the VESS score (e). Dark blue dots: conventional intensive tillage; light blue dots: conventional no-tillage; dark green dots: organic intensive tillage; light green dots: organic reduced tillage. Note: the linear regression is only shown if there is a significant relationship between two measured variables ($p < 0.05$), plus only measurements from the topsoil (10 cm) were considered for these regression analyses.

The results of these five regressions (Figure 18) indicate no significant correlation between SOC and the other soil variables. SOC seems to have no significant influence on earthworm abundance, hydraulic conductivities, or the VESS score. SOC data will not be further discussed in this thesis because it would be beyond the limits of this master’s thesis and no significant influence could be found in our data.

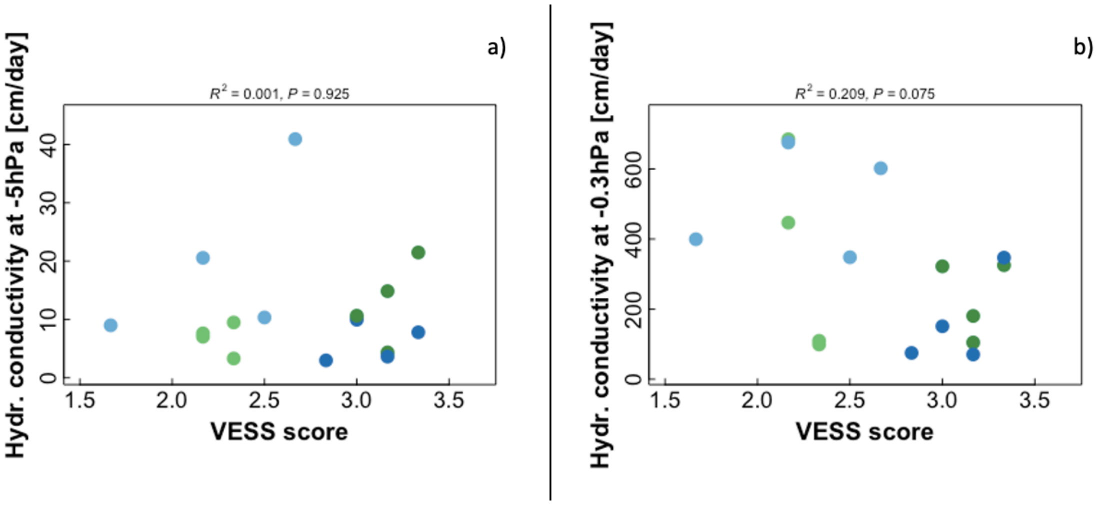


Figure 19: Regression models comparing the relationships between the VESS score and hydraulic conductivities (-5 hPa and -0.3 hPa) in the topsoil (a and b). Dark blue dots: conventional intensive tillage; light blue dots: conventional no-tillage; dark green dots: organic intensive tillage; light green dots: organic reduced tillage. Note: the linear regression is only shown if there is a significant relationship between two measured variables ($p < 0.05$), plus only measurements from the topsoil (10 cm) were considered for these regression analyses. (Note: a lower VESS score means a better soil structure).

The results of the VESS score compared to the measured hydraulic conductivity show no significant correlation (see Figure 19). Nonetheless, there seems to be a stronger influence of the VESS score on hydraulic conductivity at -0.3 hPa compared to the measurements at -5 hPa. This can be said because the p-value in Figure 19, b) is much smaller ($p = 0.075$) than the one in Figure 19, a) ($p = 0.925$). This could be another indication that soil structure is more influential in the near saturation zone, or in other words, has more influence on soil structure when the soil is wetter.

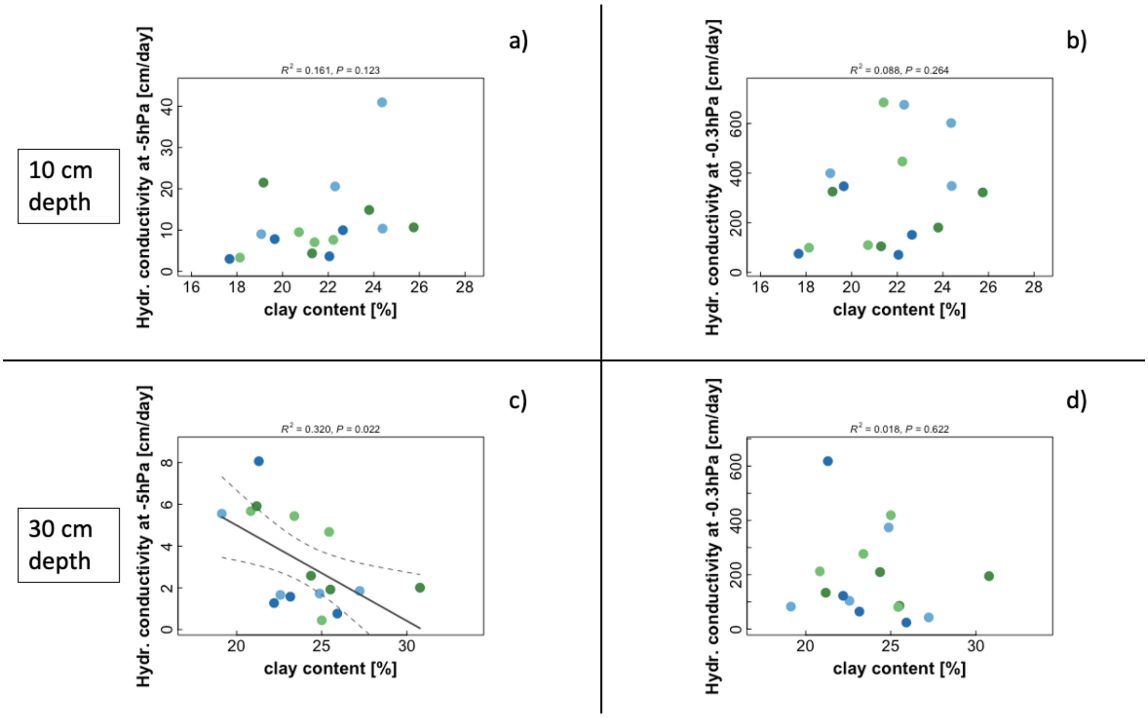


Figure 20: Regression models comparing the relationships between clay content and hydraulic conductivities (-5 hPa and -0.3 hPa) in the top- and subsoil. Dark blue dots: conventional intensive tillage; light blue dots: conventional no-tillage; dark green dots: organic intensive tillage; light green dots: organic reduced tillage. Note: the linear regression is only shown if there is a significant relationship between two measured variables ($p < 0.05$).

These four regressions in Figure 20 show the correlation between clay content and the hydraulic conductivities in both investigated depths. The only significant relationship was found in clay content and k (-5 hPa) at 30 cm depth. It seems that more clay content reduces the hydraulic conductivity at -5 hPa. Also, the conductivities at -0.3 hPa seem to decrease with more clay content but this relationship is not significant. On the other side, more clay content in the subsoil could also mean that the soil is structured more stably there, which can produce benefits for the soil system.

In the topsoil, the increasing clay content seems to favour the hydraulic conductivity (but not significantly). This could be because of the potentially better soil structure that comes with a stable and moderate amount of clay particles.

4. Discussion

4.1 Interpretation of results

4.1.1 Interpretation of the Soil description and important soil parameters

The results in Table 2 show that the only significant difference in the studied physical and chemical soil parameters between treatments was found in the VESS score. This finding corresponds with the study from Mondal and Chakraborty (2022), who also identified a better and more stable soil structure under no-tillage or reduced tillage management, in their global meta-analysis.

However, for the other parameters, no significant influence of tillage intensities was found in our data. Soil texture did not seem to be influenced significantly by tillage practices (see Table 2). This result makes sense because, according to Finch et al. (2014), only soil structure can be changed naturally or under the influence of external impacts, like tillage practices. The obtained proportions of sand, silt, and clay can indeed be classified as a sandy loam, based on the textural triangle (Weil and Brady, 2017: 157).

4.1.2 Findings about the hydraulic conductivity

The results of our hydraulic conductivity data did not indicate a significant influence of tillage intensities on the soil hydraulic conductivity near saturation in both investigated depths. There seem to be higher fluxes in the topsoil under no-tillage practices in general, but no statistically significant results could be detected in our data. So, our first hypothesis could not be approved with the obtained data. A global meta-analysis from Liao et al. (2022) also indicates that the conversion from conventional tillage methods to conservational tillage practices had no significant effects on the hydraulic conductivity near saturation in subsurface soil. Liao et al. (2022) point out that measurement techniques and the duration of the conversion period are strongly affecting the outcomes. Their results showed that conservation tillage type, soil texture type, and cropping system management had no significant effects on K_{sat}.

The relationship between different tillage practices and hydraulic conductivity are still debated and not always straightforward (Capowiez et al., 2009). Palm et al. (2014) and Strudley et al. (2008) found mixed results related to hydraulic conductivity and management practices in their studies. Palm et al. (2014) claim that no-tillage management reduced the porosity in the soil, and even a reduction in hydraulic conductivities, compared to conventional tillage methods, was detected by them. Still, these changes did not result in lower infiltration rates, but an increase in infiltration could be found instead. With an increased water infiltration, less direct surface runoff occurs which leads to a lower risk of soils being eroded. Palm et al. (2014) explain this effect with an enhanced soil organic matter content under no-tillage practices. Biological activity increases with a higher amount of surface residues left on the field under conservational tillage methods. This, in turn, favours increased stability of soil aggregates and greater macropore connectivity induced by greater macrofaunal activity.

Our results from the lower depth (30 cm) showed another distribution of the highest hydraulic conductivity rates compared to the measurements in the topsoil. There, no-tillage methods had about the same hydraulic conductivity levels as it was measured under intensive tillage (see Figures 11 and 12). Peigné et al. (2009) claim that ploughing can be helpful in preventing soil compaction in deeper soil layers. So, it might be possible that in our measurements in 30 cm depth, compaction was happening and thus the hydraulic conductivity decreased to similar levels as in the intensively ploughed fields due to the existence of a possible stow layer, which hinders the water from flowing rapidly.

However, Li et al. (2019) summarized that conservation tillage methods can also have other numerous positive effects on soil physical properties, like water availability or aggregate stability. They conclude that beneficial effects can be recognised even after a short time. A structural improvement of soils could be primarily found in the topsoil layer (0 – 10 cm). Medium-textured soils (like our sandy loam in the FAST experiment) are thought to experience the biggest benefits in subsurface layers when implementing no-tillage methods (Mondal and Chakraborty, 2022). However, we could not find a significant increase in hydraulic conductivity connected to a better soil structure in our data (see Figure 19).

Our findings are divergent from a study by Oquist et al. (2006), which resulted in higher saturated conductivities in the topsoil under conservational tillage practices than in conventional management approaches.

According to an experiment by Jarvis et al. (2013), saturated hydraulic conductivity was found to be only weakly related to soil texture. Their findings suggest that the hydraulic conductivity near saturation was influenced more strongly by bulk density, organic carbon content, and land use management. They also found a strong indication that clay soils have a smaller hydraulic conductivity in the soil matrix and that for this type of soil, the existence of macropores can contribute significantly to the hydraulic conductivity near saturation (Jarvis et al., 2013). In our data, we could find a significant decrease of k (-5 hPa) at 30 cm depth with more clay particles present (see Figure 20, c)). This could indicate that not many macropores were existing in this soil layer and thus the conductivity was decreasing (Jarvis and Larsbo, 2022). In the topsoil, on the other side, there seems to be a positive trend between clay content and hydraulic conductivity, but this was, however, not statistically significant. This could indicate a more stable soil structure in the topsoil, when more clay particles are present, which could lead to a higher hydraulic conductivity in turn.

The mixed results regarding soil management practices and hydraulic conductivities show that many complex interactions are going on and that further experiments are needed to better understand this relationship for an improved soil quality in agricultural crop systems.

4.1.3 The relationship between earthworm abundance and soil hydraulic conductivity

Our statistical analyses calculated a significant difference in earthworm biomass and number between the conventional tillage (C-IT) and the no-tillage (C-NT) treatment. The organic treatments, however, seemed to have a smaller influence on earthworm abundance (see Figures 13 and 14). This could be an indication that no-tillage enhances macropore connectivity and thus favours the habitat of earthworms and their activity in the soil system (Strudley et al., 2008). Ernst and Emmerling (2009) also found that earthworm biomass and species richness were generally larger in no-tillage systems. Furthermore, they claim that the observed effects were smaller in reduced tillage systems (i.e. O-RT management), which seems to approve our results concerning the found earthworms in our field experiment. Also, Johnson-Maynard et al. (2007) counted fewer earthworms, when chisel ploughing (reduced tillage) was used compared to no-tillage practices after an experiment of 3 years.

However, it is difficult to link these findings with the results of the hydraulic conductivity because we could not find any significant differences in hydraulic conductivity between different treatment strategies. So, also our second hypothesis could not be approved with the sampled data. At least, there seems to be one significantly positive correlation between earthworm number and hydraulic conductivity at k (-5 hPa) in the topsoil (see Figure 17, c)). For the earthworm number and hydraulic conductivity at k (-0.3 hPa), there seems to be a positive trend. However, this trend was not significant, when tested with $p < 0.05$ (the corresponding p-value was 0.094, see Figure 17, d)).

Another significant correlation was seen between the VESS score and earthworm biomass. This indicates beneficial conditions for earthworms when good structural soil quality is present. As explained by Ernst and Emmerling (2009), reduced tillage methods can change soil organic carbon distribution in topsoils and may positively affect earthworm biomass, even if we did not find any significant difference in soil organic carbon contents between management treatments. More continuous measurements of soil organic carbon contents throughout the soil profile could be helpful to better understand this relationship.

The same as before (with the hydraulic conductivity data), findings about earthworm biomass and abundance are not always consistent (Briones and Schmidt, 2017). Chan (2001) mentions that some researchers did not find any difference between different tillage systems. It even happened that the opposite effect could be detected, meaning more earthworms are present in conventional tillage. Based on Chan (2001), there are many complex interactions going on that can influence the outcome of the results. Soil types, crop rotation, soil organic carbon distribution, as well as the type, date, and intensity of tillage, are important factors that could explain differences in observed data. One possible explanation could be the fact that many studies showed increased compaction under conservational tillage in the topsoil, thus reducing the soils' porosity (Chan, 2001; Ernst and Emmerling, 2009).

Peigné et al. (2009) found more earthworms in the first years of a no-tillage approach compared to intensive tillage techniques which seemed to disturb the soil system more deeply. Similar results were also detected in studies and experiments that lasted over a longer time than just three years (Jordan et al., 2004; Pfiffner and Luka, 2007). Differences in earthworm abundance were less pronounced after shorter times of experimentation (Peigné et al., 2009; Briones and Schmidt, 2017). Based on a study by Wardak et al. (2022), earthworm populations experienced a significant increase under no-tillage management after 3 years. Similar to our results, they neither found a significant difference in saturated hydraulic conductivity (K_{sat}) over the same time.

As mentioned by researchers, earthworms cannot improve soil macroporosity in a short amount of time. They need time to transform their habitat in organic farming under conservation tillage, also in reduced tillage systems (Peigné et al., 2009; Wardak et al., 2022). This could be another indication why our results were less pronounced in the organic treatments (O-IT and O-RT) because they experienced an impact of tillage.

Additionally, considering ecological earthworm groups, we only found a significant difference in earthworm biomass between no-tillage and the intensive tillage methods (C-IT and O-IT) for juvenile earthworms. Plus, we could detect a significant difference between the organic reduced tillage approach (O-RT) and the conventional intensive tillage management (C-IT) in juvenile earthworm biomass (see Figure 15). Peigné et al. (2009) claim that juvenile species are thought to have a smaller impact on soil porosity than adult earthworms. Especially, the large anecic earthworms are thought to be important for altering the pore space in soils (Wardak et al., 2022). However, we did not find a significantly higher abundance of this ecological group in our measurements. These two reasons could be a possible explanation for our results in the hydraulic conductivity data, and why there was no significant difference found in hydraulic flow rates between the different management methods.

In the review of Briones and Schmidt (2017), it is noted that epigeic and anecic earthworms showed the strongest positive response to reduced tillage methods. We, on the contrary, counted a significantly larger number of endogeic adult earthworms in the no-tillage plots compared to the intensively ploughed fields. This indicates that their habitat (which primarily lies within the tillage zone) was less impacted and altered compared to plough-intensive management techniques.

It seems necessary to perform more studies regarding the influence of different ecological earthworm groups on the soil system functioning under the influence of different tillage intensities.

4.2 General limitations

This section explains which general limitations could be detected and are thought to have an influence on the results in this thesis.

In general, long-term field experiments (such as our field experiment) are a very useful method to detect changes that are going on under different soil management strategies. Researchers agree that site-specific and long-term experiments are the most suitable design to investigate the functioning of agricultural soil systems, and for the purpose of agricultural science (Strudley et al., 2008; Capowiez et al., 2009; Lal, 2020). The best results can be obtained by avoiding transient effects from recent management impacts, according to Johnson-Maynard et al. (2007).

However, there are limitations that come with the sampling of data and performing the measurements. Firstly, we only measured and collected the data in one specific time point. Therefore, we only know the information of a momentary snapshot during that specific time of sampling. Based on Strudley et al. (2008), there is a great complexity in spatial and temporal variability regarding the interactions in a soil system. For instance, Strudley et al. (2008) mention that the effects of tillage can diminish rapidly. In our case, the last time the conventional management practices experienced a ploughing process (down to 20 cm) was about one and a half years before the sampling campaign for this master’s thesis started. This could be enough time for potentially observable differences to become less pronounced. For more detailed and precise information, several sampling campaigns could be done throughout the year and during cropping cycles to gather more insights into the ongoing processes. However, this would not have been possible for this master’s thesis.

Furthermore, we only took point measurements which are limited in space. For instance, a biopore could just be missed while sampling, although it would be there (maybe right next to the sampling point). Moreover, some artificially created sampling artefacts can hardly be prevented. For instance, when pushing the soil core sampler a little bit too deep, the bulk density of the sample could be increased and compacted artificially by us. Of course, this was tried to be prevented. In addition, existing stones can always have an impact on the samples, and the problem is, that they cannot always be seen on the top of the sample. Figure 21 visualises this exact problem, where existing stones at the edge of the sample were pushed deeper into the soil sample and possibly changed the soil core matrix. Challenges in sampling and measuring will always remain but we tried to minimize them as best as possible.

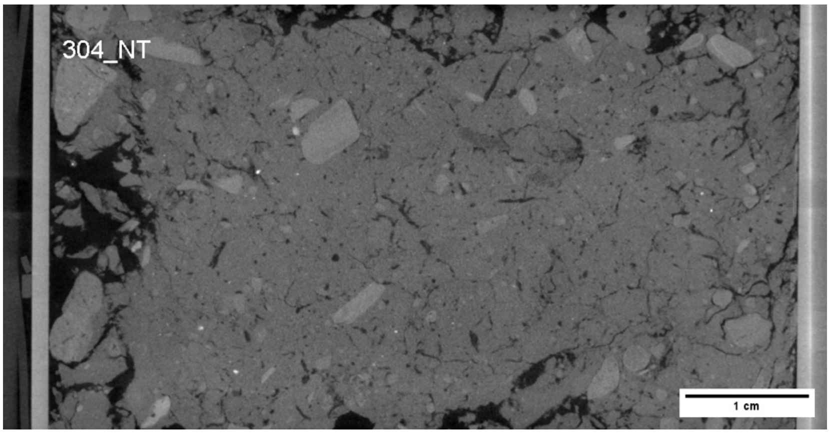


Figure 21: Side-view of an X-ray scan of a sampled soil core. On the left edge of the sample, it is visible that stones changed the soil matrix and artificial changes (cracks) were made while extracting the sample. Source: Own scans.

5. Conclusion

My master’s thesis indicates that there are considerable beneficial effects on soil quality when conservational management techniques are implemented in agricultural processes.

Nonetheless, there still are many processes and interactions within a soil system, which are not fully understood.

We investigated the impacts of soil management on soil structural quality, soil hydraulic properties, and earthworm abundance in a long-term field experiment, called the FAST experiment, in Switzerland. Our results showed that different tillage intensities had a considerable influence on the soil and improved soil structural quality (VESS). Hydraulic conductivities near saturation also changed slightly under different management strategies, but we could not detect significant statistical differences between the four treatments. Higher hydraulic conductivity rates were indeed found in the topsoil when no-tillage was applied, but again, these differences could not be called significant. In the lower soil region (30 cm depth), the distribution of hydraulic conductivity rates near saturation changed, and the highest rates were not found in the no-tillage method due to a possible formation of a stow layer.

Further results suggest a positive correlation between soil hydraulic conductivity near saturation (-5 hPa) and earthworm number, and indications were found that earthworm abundance was more strongly affected by the tillage system than by organic farming strategies. Since the difference in earthworm abundance was only significant between no-tillage (C-NT) and conventional intensive tillage (C-IT), the occurrence of earthworms can only partially explain the received differences for the soil structure (VESS score). Generally, the occurrence of earthworm populations seems to improve soil structural quality.

However, the existence of earthworms could not statistically explain the outcome of the hydraulic conductivity measurements near saturation.

This results in rejecting both of our hypotheses. Tillage intensities had no significant influence on the near-saturation hydraulic conductivity in both investigated depths. Consequently, the differences in earthworm populations could not explain the hydraulic conductivity in near-saturation conditions.

Further research is needed to fully grasp the complexity of interactions and functions happening in an agricultural soil system. For instance, one could investigate how the water infiltration rate in the field is coupled with the abundance of earthworm populations or soil organic carbon contents near the surface.

Researchers need to combine different management strategies and measurements when planning and implementing adaptation strategies for the future. Conditions and trade-offs can be hugely different depending on the investigated sites and places. Spatial heterogeneities and soil characteristics need to be taken into account at a regional level for the development of sustainable adaptation and mitigation strategies in agricultural management practices.

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7. Appendices

Raw data (soil core samples)

LTE_treat	treatment	block	plot_nr	depth_top	depth_bottom	replicate	Date_Core	Cond_5cm	Cond_3mm
FAST_CIT	CIT	A	6	27.5	32.5	4	21.03.23	8.472	1649.855
FAST_ORT	ORT	A	1	7.5	12.5	3	21.03.23	6.712	1320.526
FAST_ORT	ORT	C	47	27.5	32.5	3	22.03.23	0.285	1242.608
FAST_CNT	CNT	D	63	7.5	12.5	4	22.03.23	3.784	1133.147
FAST_CNT	CNT	C	37	7.5	12.5	1	22.03.23	32.199	1053.073
FAST_CNT	CNT	A	10	7.5	12.5	1	21.03.23	17.986	961.876
FAST_CNT	CNT	C	37	7.5	12.5	2	22.03.23	23.046	906.515
FAST_ORT	ORT	B	26	7.5	12.5	1	21.03.23	2.184	860.599
FAST_ORT	ORT	D	53	27.5	32.5	3	22.03.23	10.792	729.839
FAST_CNT	CNT	B	20	7.5	12.5	1	22.03.23	22.672	620.308
FAST_OIT	OIT	C	34	7.5	12.5	1	22.03.23	37.191	604.532
FAST_CNT	CNT	C	37	27.5	32.5	3	22.03.23	1.597	546.203
FAST_CNT	CNT	C	37	27.5	32.5	1	22.03.23	2.402	545.553
FAST_CIT	CIT	D	52	7.5	12.5	2	21.03.23	8.185	530.115
FAST_OIT	OIT	D	60	7.5	12.5	2	22.03.23	14.715	512.188
FAST_OIT	OIT	D	60	27.5	32.5	3	22.03.23	1.447	491.107
FAST_CIT	CIT	D	52	7.5	12.5	1	22.03.23	10.978	467.642
FAST_CNT	CNT	D	63	7.5	12.5	1	22.03.23	111.169	425.389
FAST_CNT	CNT	B	20	7.5	12.5	3	21.03.23	1.889	378.806
FAST_ORT	ORT	A	1	27.5	32.5	3	21.03.23	6.172	372.598
FAST_CIT	CIT	C	41	27.5	32.5	3	22.03.23	0.527	343.267
FAST_OIT	OIT	A	16	27.5	32.5	3	21.03.23	3.347	339.301
FAST_OIT	OIT	D	60	7.5	12.5	1	22.03.23	6.763	316.285
FAST_OIT	OIT	C	34	27.5	32.5	2	22.03.23	6.525	304.621
FAST_ORT	ORT	B	26	7.5	12.5	4	21.03.23	15.203	304.381
FAST_OIT	OIT	A	16	7.5	12.5	3	21.03.23	17.792	303.270
FAST_OIT	OIT	A	16	27.5	32.5	2	21.03.23	3.016	255.002
FAST_CNT	CNT	D	63	7.5	12.5	3	21.03.23	7.823	247.096
FAST_OIT	OIT	B	22	7.5	12.5	2	21.03.23	4.739	237.612
FAST_CIT	CIT	A	6	7.5	12.5	1	21.03.23	9.448	234.268
FAST_OIT	OIT	B	22	27.5	32.5	1	22.03.23	1.872	217.125
FAST_CIT	CIT	A	6	7.5	12.5	2	21.03.23	19.290	213.162
FAST_CNT	CNT	B	20	7.5	12.5	2	21.03.23	2.404	199.166
FAST_ORT	ORT	C	47	7.5	12.5	2	22.03.23	2.425	193.659
FAST_CIT	CIT	C	41	7.5	12.5	2	22.03.23	3.770	184.551
FAST_ORT	ORT	D	53	7.5	12.5	3	22.03.23	3.069	184.165
FAST_CNT	CNT	B	20	27.5	32.5	4	21.03.23	1.921	182.965
FAST_ORT	ORT	B	26	7.5	12.5	3	21.03.23	5.457	175.215
FAST_CNT	CNT	A	10	27.5	32.5	1	21.03.23	2.851	154.385
FAST_ORT	ORT	A	1	27.5	32.5	4	21.03.23	8.129	149.085
FAST_CIT	CIT	B	31	7.5	12.5	3	21.03.23	5.130	144.504
FAST_OIT	OIT	D	60	7.5	12.5	4	22.03.23	10.434	137.793
FAST_ORT	ORT	A	1	27.5	32.5	2	21.03.23	2.720	114.946
FAST_CIT	CIT	A	6	27.5	32.5	1	21.03.23	2.507	114.275
FAST_ORT	ORT	B	26	27.5	32.5	1	21.03.23	10.093	105.728
FAST_ORT	ORT	C	47	7.5	12.5	3	22.03.23	3.870	103.676
FAST_CNT	CNT	D	63	27.5	32.5	3	21.03.23	2.046	101.077
FAST_ORT	ORT	B	26	27.5	32.5	3	21.03.23	1.805	95.378
FAST_CNT	CNT	B	20	27.5	32.5	3	21.03.23	1.391	94.686
FAST_CIT	CIT	A	6	27.5	32.5	3	21.03.23	13.215	89.435
FAST_ORT	ORT	D	53	7.5	12.5	1	22.03.23	2.660	69.407
FAST_CNT	CNT	C	37	7.5	12.5	1	22.03.23	6.433	66.849
FAST_CIT	CIT	D	52	27.5	32.5	3	21.03.23	1.657	66.522
FAST_CIT	CIT	D	52	27.5	32.5	1	22.03.23	2.046	63.497
FAST_CIT	CIT	D	52	27.5	32.5	4	22.03.23	1.023	62.414
FAST_OIT	OIT	C	34	27.5	32.5	3	22.03.23	4.383	58.464
FAST_OIT	OIT	A	16	7.5	12.5	1	21.03.23	11.913	57.692
FAST_CNT	CNT	A	10	27.5	32.5	3	21.03.23	11.452	55.342
FAST_OIT	OIT	B	22	7.5	12.5	3	21.03.23	2.209	52.993
FAST_ORT	ORT	D	53	27.5	32.5	4	22.03.23	1.075	50.259
FAST_ORT	ORT	D	53	27.5	32.5	1	22.03.23	4.436	49.489
FAST_ORT	ORT	A	1	7.5	12.5	2	21.03.23	7.347	48.963
FAST_CNT	CNT	A	10	7.5	12.5	3	21.03.23	9.175	48.824
FAST_OIT	OIT	D	60	27.5	32.5	1	22.03.23	2.399	46.625
FAST_OIT	OIT	C	34	7.5	12.5	3	22.03.23	5.773	46.141
FAST_OIT	OIT	D	60	27.5	32.5	2	22.03.23	2.167	45.960
FAST_ORT	ORT	D	53	7.5	12.5	2	22.03.23	4.184	43.696
FAST_CIT	CIT	D	52	7.5	12.5	3	21.03.23	4.220	42.915
FAST_CIT	CIT	B	31	7.5	12.5	2	21.03.23	1.825	42.245
FAST_ORT	ORT	B	26	27.5	32.5	4	21.03.23	2.130	42.021
FAST_CNT	CNT	A	10	27.5	32.5	2	21.03.23	2.350	37.881
FAST_OIT	OIT	C	34	27.5	32.5	4	22.03.23	6.821	37.596
FAST_CIT	CIT	B	31	27.5	32.5	1	21.03.23	0.682	35.781
FAST_OIT	OIT	A	16	27.5	32.5	1	21.03.23	1.364	34.312
FAST_CNT	CNT	B	20	27.5	32.5	2	21.03.23	1.663	33.439
FAST_CNT	CNT	A	10	7.5	12.5	2	21.03.23	3.854	33.254
FAST_CIT	CIT	C	41	7.5	12.5	1	22.03.23	3.850	31.473
FAST_ORT	ORT	C	47	7.5	12.5	1	22.03.23	22.159	31.446
FAST_CNT	CNT	C	37	27.5	32.5	2	22.03.23	1.171	29.417
FAST_CIT	CIT	B	31	7.5	12.5	4	21.03.23	3.900	24.917
FAST_OIT	OIT	B	22	7.5	12.5	1	22.03.23	6.061	23.648
FAST_CIT	CIT	B	31	27.5	32.5	2	21.03.23	0.724	22.004
FAST_OIT	OIT	B	22	27.5	32.5	4	22.03.23	2.033	21.150
FAST_OIT	OIT	B	22	27.5	32.5	2	21.03.23	1.842	18.166
FAST_CNT	CNT	D	63	27.5	32.5	1	22.03.23	2.046	17.498
FAST_CIT	CIT	C	41	27.5	32.5	1	22.03.23	0.550	13.720
FAST_CIT	CIT	B	31	27.5	32.5	3	21.03.23	0.888	13.603
FAST_ORT	ORT	C	47	27.5	32.5	2	22.03.23	0.517	10.092
FAST_CIT	CIT	C	41	27.5	32.5	2	22.03.23	2.728	9.859
FAST_CNT	CNT	D	63	27.5	32.5	2	21.03.23	1.457	8.942
FAST_CIT	CIT	C	41	7.5	12.5	3	22.03.23	1.318	8.792
FAST_CIT	CIT	A	6	7.5	12.5	3	21.03.23	1.098	5.822
FAST_ORT	ORT	C	47	27.5	32.5	1	22.03.23	0.521	3.523

Raw data (VESS score)

LTE_treat	treatment	block	plot_nr	replicate	Date_VESS	VESS
FAST_CIT	CIT	A	6	1	23.03.23	3
FAST_CIT	CIT	A	6	2	23.03.23	2.5
FAST_CIT	CIT	A	6	3	23.03.23	3.5
FAST_CNT	CNT	A	10	1	23.03.23	3
FAST_CNT	CNT	A	10	2	23.03.23	2.5
FAST_CNT	CNT	A	10	3	23.03.23	2
FAST_OIT	OIT	A	16	1	23.03.23	3
FAST_OIT	OIT	A	16	2	23.03.23	3
FAST_OIT	OIT	A	16	3	23.03.23	3.5
FAST_CNT	CNT	B	20	1	23.03.23	2
FAST_CNT	CNT	B	20	2	23.03.23	1.5
FAST_CNT	CNT	B	20	3	23.03.23	1.5
FAST_OIT	OIT	B	22	1	23.03.23	3
FAST_OIT	OIT	B	22	2	23.03.23	3.5
FAST_OIT	OIT	B	22	3	23.03.23	3
FAST_ORT	ORT	B	26	1	23.03.23	2
FAST_ORT	ORT	B	26	2	23.03.23	2
FAST_ORT	ORT	B	26	3	23.03.23	2.5
FAST_CIT	CIT	B	31	1	23.03.23	3
FAST_CIT	CIT	B	31	2	23.03.23	3.5
FAST_CIT	CIT	B	31	3	23.03.23	3
FAST_OIT	OIT	C	34	1	23.03.23	3.5
FAST_OIT	OIT	C	34	2	23.03.23	3.5
FAST_OIT	OIT	C	34	3	23.03.23	3
FAST_CNT	CNT	C	37	1	23.03.23	2.5
FAST_CNT	CNT	C	37	2	23.03.23	2
FAST_CNT	CNT	C	37	3	23.03.23	2
FAST_CIT	CIT	C	41	1	23.03.23	3
FAST_CIT	CIT	C	41	2	23.03.23	2.5
FAST_CIT	CIT	C	41	3	23.03.23	3
FAST_ORT	ORT	C	47	1	23.03.23	2.5
FAST_ORT	ORT	C	47	2	23.03.23	2.5
FAST_ORT	ORT	C	47	3	23.03.23	2
FAST_CIT	CIT	D	52	1	23.03.23	3
FAST_CIT	CIT	D	52	2	23.03.23	3.5
FAST_CIT	CIT	D	52	3	23.03.23	3.5
FAST_ORT	ORT	D	53	1	23.03.23	2.5
FAST_ORT	ORT	D	53	2	23.03.23	2.5
FAST_ORT	ORT	D	53	3	23.03.23	2
FAST_OIT	OIT	D	60	1	23.03.23	2.5
FAST_OIT	OIT	D	60	2	23.03.23	3
FAST_OIT	OIT	D	60	3	23.03.23	3.5
FAST_CNT	CNT	D	63	1	23.03.23	2.5
FAST_CNT	CNT	D	63	2	23.03.23	2.5
FAST_CNT	CNT	D	63	3	23.03.23	3
FAST_ORT	ORT	A	1	1	23.03.23	2
FAST_ORT	ORT	A	1	2	23.03.23	2.5
FAST_ORT	ORT	A	1	3	23.03.23	2

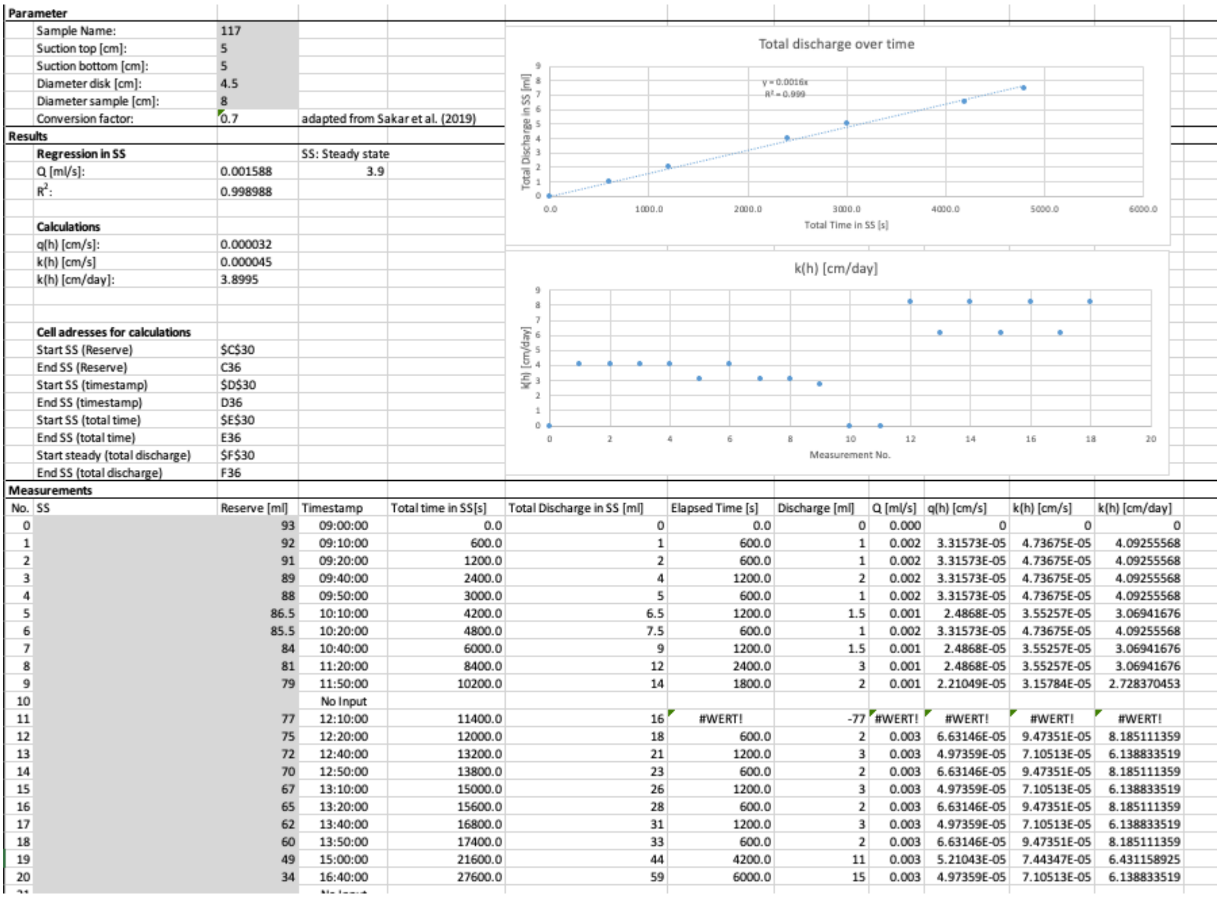
Raw data (composite samples)

LTE_treat	treatment	block	plot_nr	depth_top	depth_bottom	replicate	Date_Chemistry	SOC	pH_H2O	clay	silt	sand
FAST_ORT	ORT	A	1	7.5	12.5	1	20.03.23	16.1	7.34	20.8	33.3	43.1
FAST_ORT	ORT	A	1	27.5	32.5	1	20.03.23	6.2	7.68	20.6	34.9	43.4
FAST_CIT	CIT	A	6	7.5	12.5	1	20.03.23	14.2	7.71	22.1	28.9	46.6
FAST_CIT	CIT	A	6	27.5	32.5	1	20.03.23	11.1	7.9	20.9	27.7	49.5
FAST_CNT	CNT	A	10	7.5	12.5	1	20.03.23	16.1	7.73	23.7	27.3	46.2
FAST_CNT	CNT	A	10	27.5	32.5	1	20.03.23	6.8	8.05	18.9	23.5	56.4
FAST_OIT	OIT	A	16	7.5	12.5	1	20.03.23	14.6	7.15	23.2	29.3	45.0
FAST_OIT	OIT	A	16	27.5	32.5	1	20.03.23	8.7	7.38	24.0	26.0	48.5
FAST_CNT	CNT	B	20	7.5	12.5	1	20.03.23	11.2	6.33	18.7	37.4	42.0
FAST_CNT	CNT	B	20	27.5	32.5	1	20.03.23	7	6.32	22.3	37.4	39.1
FAST_OIT	OIT	B	22	7.5	12.5	1	20.03.23	13.6	6.59	20.8	32.8	44.1
FAST_OIT	OIT	B	22	27.5	32.5	1	20.03.23	6.8	6.78	25.2	27.3	46.3
FAST_ORT	ORT	B	26	27.5	32.5	1	20.03.23	7.7	7.88	25.1	29.3	44.3
FAST_ORT	ORT	B	26	7.5	12.5	1	20.03.23	16.2	7.76	21.6	32.1	43.5
FAST_CIT	CIT	B	31	7.5	12.5	1	20.03.23	14.7	7.53	21.5	36.4	39.6
FAST_CIT	CIT	B	31	27.5	32.5	1	20.03.23	7.2	7.81	25.6	0.6	72.6
FAST_OIT	OIT	C	34	27.5	32.5	1	20.03.23	7.8	6.49	20.9	35.9	41.9
FAST_OIT	OIT	C	34	7.5	12.5	1	20.03.23	14.1	6.37	18.7	36.7	42.2
FAST_CNT	CNT	C	37	7.5	12.5	1	20.03.23	10.4	5.92	21.9	36.0	40.3
FAST_CNT	CNT	C	37	27.5	32.5	1	20.03.23	6.4	6.46	24.6	32.6	41.7
FAST_CIT	CIT	C	41	7.5	12.5	1	20.03.23	12.4	5.94	17.3	37.6	43.0
FAST_CIT	CIT	C	41	27.5	32.5	1	20.03.23	5.5	6.36	22.0	32.6	44.5
FAST_ORT	ORT	C	47	27.5	32.5	1	20.03.23	6.8	6.79	24.7	36.6	37.5
FAST_ORT	ORT	C	47	7.5	12.5	1	20.03.23	11.9	6.66	20.3	36.2	41.5
FAST_CIT	CIT	D	52	7.5	12.5	1	20.03.23	13.2	6.58	19.2	36.3	42.2
FAST_CIT	CIT	D	52	27.5	32.5	1	20.03.23	6.4	7.47	22.9	35.8	40.2
FAST_ORT	ORT	D	53	27.5	32.5	1	20.03.23	4.6	6.27	23.2	37.2	38.8
FAST_ORT	ORT	D	53	7.5	12.5	1	20.03.23	10.5	6.19	17.8	36.6	43.8
FAST_OIT	OIT	D	60	27.5	32.5	1	20.03.23	6.7	7.82	30.4	31.8	36.6
FAST_OIT	OIT	D	60	7.5	12.5	1	20.03.23	16.7	7.77	25.0	33.8	38.3
FAST_CNT	CNT	D	63	27.5	32.5	1	20.03.23	7	8	26.9	35.6	36.3
FAST_CNT	CNT	D	63	7.5	12.5	1	20.03.23	13.4	7.86	23.8	35.2	38.7

Raw data (earthworms)

LTE_treat	treatment	block	plot_nr	replicate	Total_Ind	Total_mass	Total_Ind_Juv	Total_mass_Juv	Juv_Endo_number	Juv_Endo_mass	Juv_Epig_number	Juv_Epig_mass	Juv_Lumbricus_number	Juv_Lumbricus_mass	Ad_Endo_number	Ad_Endo_mass	Ad_Anecic_number	Ad_Anecic_mass	Ad_Epig_number	Ad_Epig_mass
FAST_O-RT	ORT	A	1	1	11	8.39	10	7.27	2	0.4	3	1.54	5	5.33	0	0	1	1.12	0	0
FAST_O-RT	ORT	A	1	2	18	21.41	7	5.16	5	3.6	2	1.56	0	0	4	0.87	1	6.82	6	8.56
FAST_O-RT	ORT	A	1	3	11	9.88	9	3.2	4	1.03	5	2.17	0	0	0	0	2	6.68	0	0
FAST_C-IT	CIT	A	6	1	8	9.87	5	3.48	3	1.27	1	0.63	1	1.58	0	0	0	0	3	6.39
FAST_C-IT	CIT	A	6	2	5	1.22	5	1.22	4	0.7	1	0.52	0	0	0	0	0	0	0	0
FAST_C-IT	CIT	A	6	3	9	5.3	9	5.3	5	0.82	0	0	4	4.48	0	0	0	0	0	0
FAST_C-NT	CNT	A	10	1	25	15.68	21	12.4	13	2.97	3	2.79	5	6.64	3	2.49	1	0.79	0	0
FAST_C-NT	CNT	A	10	2	23	18.99	19	9.81	13	2.53	4	4.06	2	3.22	1	1.97	2	5.18	1	2.03
FAST_C-NT	CNT	A	10	3	14	6.94	9	1.76	9	1.76	0	0	0	0	4	1.88	0	0	1	3.3
FAST_O-IT	OIT	A	16	1	18	6.33	11	2.74	10	2.24	1	0.5	0	0	6	1.72	0	0	1	1.87
FAST_O-IT	OIT	A	16	2	11	8.26	9	7.4	7	3.12	1	1.49	1	2.79	2	0.86	0	0	0	0
FAST_O-IT	OIT	A	16	3	20	11.78	13	5.39	12	4.44	1	0.95	0	0	5	2.49	0	0	2	3.9
FAST_C-NT	CNT	B	20	1	15	8.52	11	4.82	11	4.82	0	0	0	0	3	2.1	0	0	1	1.6
FAST_C-NT	CNT	B	20	2	26	27.13	19	17.28	12	3.77	4	6.66	3	6.85	4	5.03	1	1.75	2	3.07
FAST_C-NT	CNT	B	20	3	33	41.6	20	16.76	13	7.15	4	4.66	3	4.95	6	5.45	2	10.05	5	9.34
FAST_O-IT	OIT	B	22	1	14	8.34	10	4.52	6	1.68	0	0	4	2.84	1	0.26	2	3.31	1	0.25
FAST_O-IT	OIT	B	22	2	13	11.72	10	5.21	0	0	8	1.56	2	3.65	1	2.06	2	4.45	0	0
FAST_O-IT	OIT	B	22	3	16	11.6	10	5.45	7	3.63	2	0.78	1	1.04	4	4.39	0	0	2	1.76
FAST_O-RT	ORT	B	26	1	13	15.98	11	7.94	8	1.8	2	1.65	1	4.49	0	0	1	5.41	1	2.63
FAST_O-RT	ORT	B	26	2	12	8.56	10	5.08	8	3.43	2	1.65	0	0	2	3.48	0	0	0	0
FAST_O-RT	ORT	B	26	3	20	13.69	15	9.92	13	7.67	1	1.1	1	1.15	4	2.83	0	0	1	0.94
FAST_C-IT	CIT	B	31	1	18	5.92	18	5.92	14	2.94	1	0.77	3	2.21	0	0	0	0	0	
FAST_C-IT	CIT	B	31	2	17	16.93	11	2.97	10	2.3	0	0	1	0.67	2	2.99	3	10.37	1	0.6
FAST_C-IT	CIT	B	31	3	13	6.59	10	2.54	10	2.54	0	0	0	0	2	0.98	1	3.07	0	0
FAST_O-IT	OIT	C	34	1	5	2.67	4	0.94	3	0.65	1	0.29	0	0	1	1.73	0	0	0	0
FAST_O-IT	OIT	C	34	2	19	13.88	15	10.73	10	3.6	1	1.67	4	5.46	4	3.15	0	0	0	0
FAST_O-IT	OIT	C	34	3	18	9.32	9	2.89	8	2.29	1	0.6	0	0	4	3.75	0	0	5	2.68
FAST_C-NT	CNT	C	37	1	21	12.08	12	2.29	12	2.29	0	0	0	0	7	4.67	1	1.95	1	3.17
FAST_C-NT	CNT	C	37	2	19	12.86	16	11.63	11	2.98	3	4.08	2	4.57	3	1.23	0	0	0	0
FAST_C-NT	CNT	C	37	3	25	19.69	21	13.97	15	4.84	2	2.48	4	6.65	2	3.24	0	0	2	2.48
FAST_C-IT	CIT	C	41	1	7	9.45	3	0.8	3	0.8	0	0	0	0	1	0.77	1	3.69	2	4.19
FAST_C-IT	CIT	C	41	2	6	4.22	3	1.23	3	1.23	0	0	0	0	3	2.99	0	0	0	0
FAST_C-IT	CIT	C	41	3	11	14.79	6	4.01	4	0.47	0	0	2	3.54	1	2.29	1	3.52	3	4.97
FAST_O-RT	ORT	C	47	1	35	32.12	30	14.81	23	6.87	4	2.91	3	5.03	2	2.38	2	13.08	1	1.85
FAST_O-RT	ORT	C	47	2	17	12.73	15	8.73	13	4.38	0	0	2	4.35	2	4	0	0	0	0
FAST_O-RT	ORT	C	47	3	12	10.13	8	6.88	6	2.45	1	1.81	1	2.62	0	0	1	1.92	3	1.33
FAST_C-IT	CIT	D	52	1	12	9.79	7	2.37	5	1.26	0	0	2	1.11	5	7.42	0	0	0	0
FAST_C-IT	CIT	D	52	2	12	8.97	10	5.74	3	0.51	4	1.65	3	3.58	0	0	1	2.84	1	0.39
FAST_C-IT	CIT	D	52	3	10	2.27	10	2.27	10	2.27	0	0	0	0	0	0	0	0	0	0
FAST_O-RT	ORT	D	53	1	15	13.73	12	8.53	6	1.72	5	2.06	1	4.75	2	3.76	0	0	1	1.44
FAST_O-RT	ORT	D	53	2	19	20.02	15	7.06	12	2.71	1	1.19	2	3.16	1	0.47	2	8.98	1	3.51
FAST_O-RT	ORT	D	53	3	14	8.9	11	2.52	9	2.01	1	0.13	1	0.38	3	6.38	0	0	0	0
FAST_O-IT	OIT	D	60	1	13	13.3	8	2.26	8	2.26	0	0	0	0	3	2.11	1	8.4	1	0.53
FAST_O-IT	OIT	D	60	2	19	13.76	8	2.67	5	1.27	2	1.01	1	0.39	8	7.18	0	0	3	3.91
FAST_O-IT	OIT	D	60	3	29	21.98	18	8.44	3	3.29	15	5.15	0	0	5	5.64	1	3.7	5	4.2
FAST_C-NT	CNT	D	63	1	29	13.32	22	8.01	15	2.77	5	3.15	2	2.09	4	3.07	0	0	3	2.24
FAST_C-NT	CNT	D	63	2	23	14.33	20	9.17	18	5.59	0	0	2	3.58	1	0.57	0	0	2	4.59
FAST_C-NT	CNT	D	63	3	34	16.4	23	9.95	15	1.92	5	3.35	3	4.68	8	4.89	1	0.98	2	0.58

Example of an Excel sheet to note down and calculate infiltration rate and hydraulic conductivity

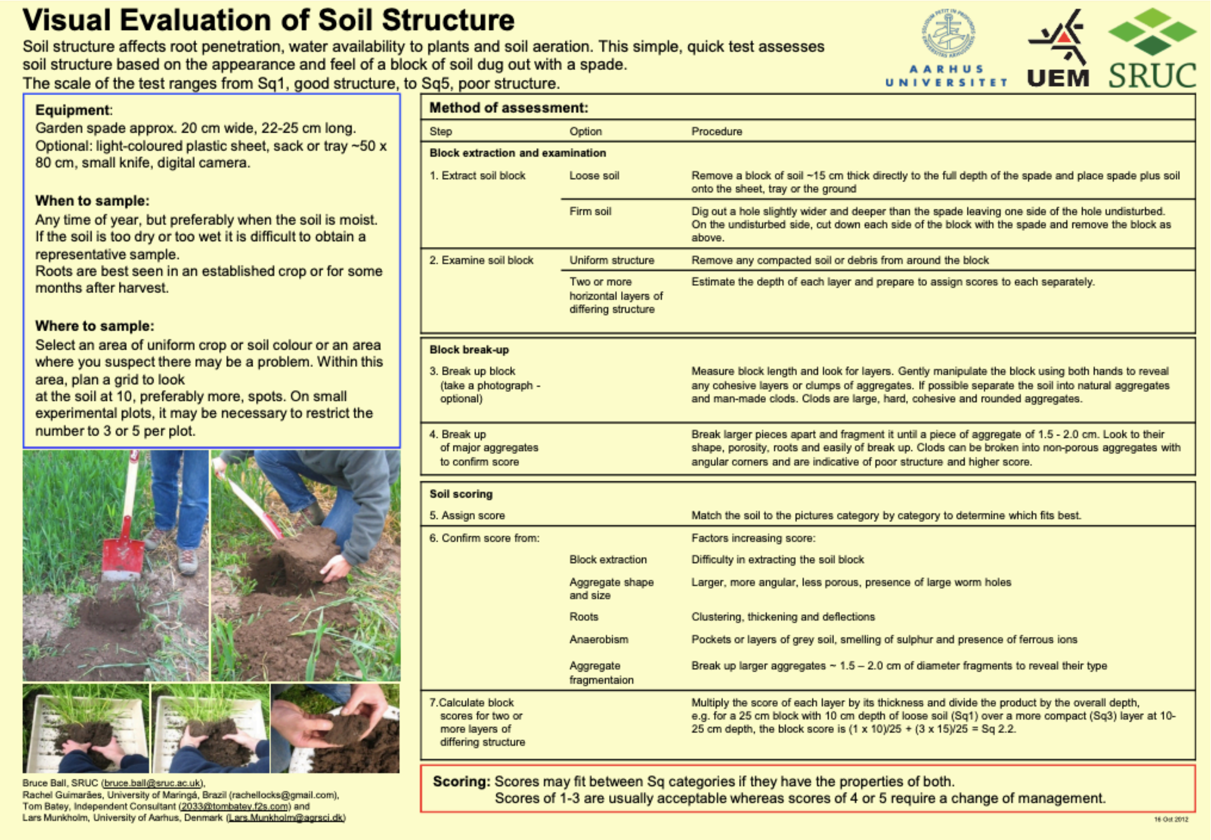


Parameter		
Sample Name:	117	
Suction top [cm]:	5	
Suction bottom [cm]:	5	
Diameter disk [cm]:	4.5	
Diameter sample [cm]:	8	
Conversion factor:	0.7	adapted from Sakar et al. (2019)
Results		
Regression in SS		SS: Steady state
Q [ml/s]:	0.001588	3.9
R^2:	0.998988	
Calculations		
q(h) [cm/s]:	0.000032	
k(h) [cm/s]	0.000045	
k(h) [cm/day]:	3.8995	
Cell adresses for calculations		
Start SS (Reserve)	C30	
End SS (Reserve)	C36	
Start SS (timestamp)	D30	
End SS (timestamp)	D36	
Start SS (total time)	E30	
End SS (total time)	E36	
Start steady (total discharge)	F30	
End SS (total discharge)	F36	

Measurements

No.	SS	Reserve [ml]	Timestamp	Total time in SS[s]	Total Discharge in SS [ml]	Elapsed Time [s]	Discharge [ml]	Q [ml/s]	q(h) [cm/s]	k(h) [cm/s]	k(h) [cm/day]
0		93	09:00:00	0.0	0	0.0	0	0.000	0	0	0
1		92	09:10:00	600.0	1	600.0	1	0.002	3.31573E-05	4.73675E-05	4.09255568
2		91	09:20:00	1200.0	2	600.0	1	0.002	3.31573E-05	4.73675E-05	4.09255568
3		89	09:40:00	2400.0	4	1200.0	2	0.002	3.31573E-05	4.73675E-05	4.09255568
4		88	09:50:00	3000.0	5	600.0	1	0.002	3.31573E-05	4.73675E-05	4.09255568
5		86.5	10:10:00	4200.0	6.5	1200.0	1.5	0.001	2.4868E-05	3.55257E-05	3.06941676
6		85.5	10:20:00	4800.0	7.5	600.0	1	0.002	3.31573E-05	4.73675E-05	4.09255568
7		84	10:40:00	6000.0	9	1200.0	1.5	0.001	2.4868E-05	3.55257E-05	3.06941676
8		81	11:20:00	8400.0	12	2400.0	3	0.001	2.4868E-05	3.55257E-05	3.06941676
9		79	11:50:00	10200.0	14	1800.0	2	0.001	2.21049E-05	3.15784E-05	2.728370453
10			No Input								
11		77	12:10:00	11400.0	16	#WERT!	-77	#WERT!	#WERT!	#WERT!	#WERT!
12		75	12:20:00	12000.0	18	600.0	2	0.003	6.63146E-05	9.47351E-05	8.185111359
13		72	12:40:00	13200.0	21	1200.0	3	0.003	4.97359E-05	7.10513E-05	6.138833519
14		70	12:50:00	13800.0	23	600.0	2	0.003	6.63146E-05	9.47351E-05	8.185111359
15		67	13:10:00	15000.0	26	1200.0	3	0.003	4.97359E-05	7.10513E-05	6.138833519
16		65	13:20:00	15600.0	28	600.0	2	0.003	6.63146E-05	9.47351E-05	8.185111359
17		62	13:40:00	16800.0	31	1200.0	3	0.003	4.97359E-05	7.10513E-05	6.138833519
18		60	13:50:00	17400.0	33	600.0	2	0.003	6.63146E-05	9.47351E-05	8.185111359
19		49	15:00:00	21600.0	44	4200.0	11	0.003	5.21043E-05	7.44347E-05	6.431158925
20		34	16:40:00	27600.0	59	6000.0	15	0.003	4.97359E-05	7.10513E-05	6.138833519

Guidelines for VESS score and its evaluation



Visual Evaluation of Soil Structure

Soil structure affects root penetration, water availability to plants and soil aeration. This simple, quick test assesses soil structure based on the appearance and feel of a block of soil dug out with a spade.
The scale of the test ranges from Sq1, good structure, to Sq5, poor structure.

Equipment:
Garden spade approx. 20 cm wide, 22-25 cm long.
Optional: light-coloured plastic sheet, sack or tray ~50 x 80 cm, small knife, digital camera.

When to sample:
Any time of year, but preferably when the soil is moist. If the soil is too dry or too wet it is difficult to obtain a representative sample.
Roots are best seen in an established crop or for some months after harvest.

Where to sample:
Select an area of uniform crop or soil colour or an area where you suspect there may be a problem. Within this area, plan a grid to look at the soil at 10, preferably more, spots. On small experimental plots, it may be necessary to restrict the number to 3 or 5 per plot.

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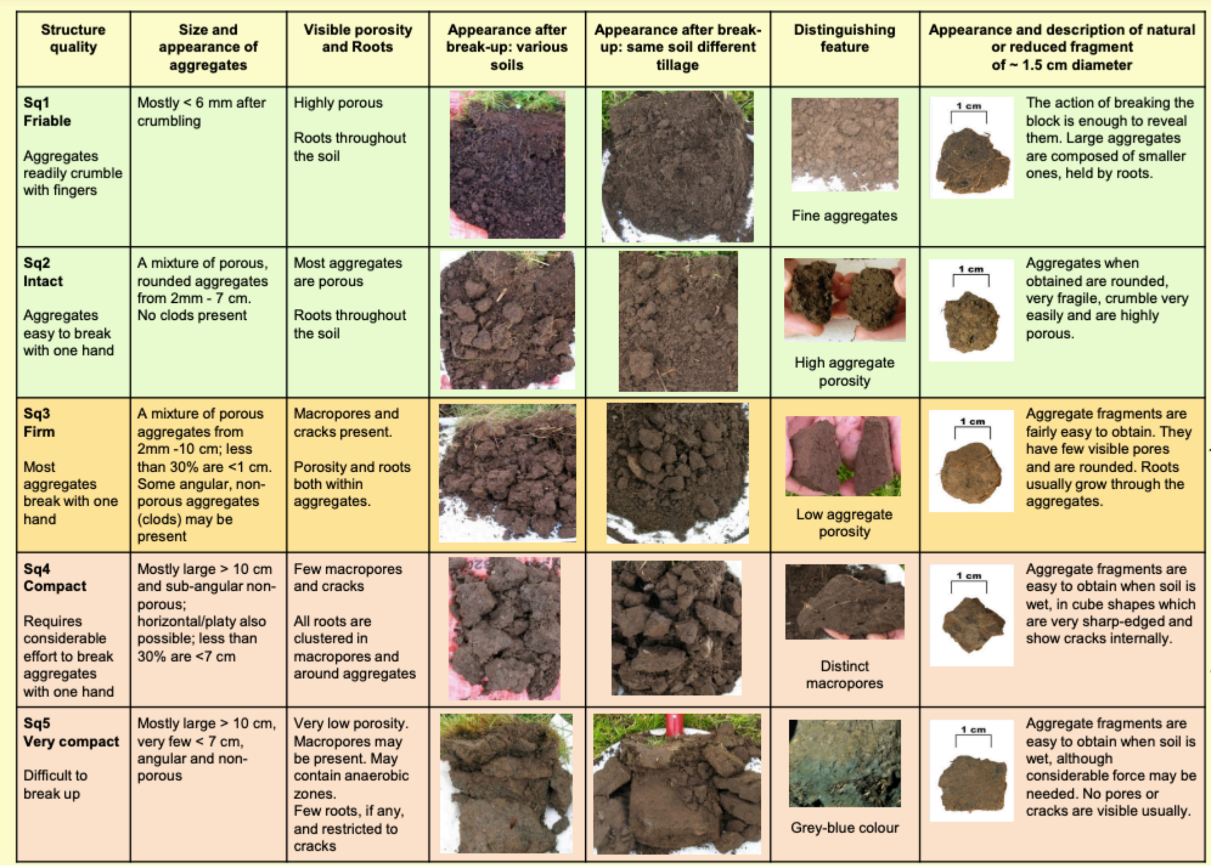
Method of assessment:

Step	Option	Procedure
Block extraction and examination		
1. Extract soil block	Loose soil	Remove a block of soil ~15 cm thick directly to the full depth of the spade and place spade plus soil onto the sheet, tray or the ground
	Firm soil	Dig out a hole slightly wider and deeper than the spade leaving one side of the hole undisturbed. On the undisturbed side, cut down each side of the block with the spade and remove the block as above.
2. Examine soil block	Uniform structure	Remove any compacted soil or debris from around the block
	Two or more horizontal layers of differing structure	Estimate the depth of each layer and prepare to assign scores to each separately.
Block break-up		
3. Break up block (take a photograph - optional)		Measure block length and look for layers. Gently manipulate the block using both hands to reveal any cohesive layers or clumps of aggregates. If possible separate the soil into natural aggregates and man-made clods. Clods are large, hard, cohesive and rounded aggregates.
4. Break up of major aggregates to confirm score		Break larger pieces apart and fragment it until a piece of aggregate of 1.5 - 2.0 cm. Look to their shape, porosity, roots and easily of break up. Clods can be broken into non-porous aggregates with angular corners and are indicative of poor structure and higher score.
Soil scoring		
5. Assign score		Match the soil to the pictures category by category to determine which fits best.
6. Confirm score from:		Factors increasing score:
	Block extraction	Difficulty in extracting the soil block
	Aggregate shape and size	Larger, more angular, less porous, presence of large worm holes
	Roots	Clustering, thickening and deflections
	Anaerobism	Pockets or layers of grey soil, smelling of sulphur and presence of ferrous ions
	Aggregate fragmentaion	Break up larger aggregates ~ 1.5 – 2.0 cm of diameter fragments to reveal their type
7.Calculate block scores for two or more layers of differing structure		Multiply the score of each layer by its thickness and divide the product by the overall depth, e.g. for a 25 cm block with 10 cm depth of loose soil (Sq1) over a more compact (Sq3) layer at 10-25 cm depth, the block score is (1 x 10)/25 + (3 x 15)/25 = Sq 2.2.

Scoring: Scores may fit between Sq categories if they have the properties of both.
Scores of 1-3 are usually acceptable whereas scores of 4 or 5 require a change of management.

16 Oct 2012



Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 **Friable** Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous Roots throughout the soil			Fine aggregates	The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots.
Sq2 **Intact** Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present	Most aggregates are porous Roots throughout the soil			High aggregate porosity	Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous.
Sq3 **Firm** Most aggregates break with one hand	A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots both within aggregates.			Low aggregate porosity	Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates.
Sq4 **Compact** Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks All roots are clustered in macropores and around aggregates			Distinct macropores	Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally.
Sq5 **Very compact** Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			Grey-blue colour	Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

8. Personal declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

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