Potential of boreholes combined with deep-rooted cover crops to ameliorate subsoil compaction

Results from 2021-2022

Authors | Isabella Selin Norén, Stefan van Gestel, Vera Velt, Derk van Balen

Report WPR-OT 999

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Summary: Due to climate change longer periods of drought and high precipitation in short periods of time will become more common. Subsoil compaction causes cropland to be less resilient to such changes due to worse root growth, water infiltration and less capillary rise of water. There is a lack of measures to ameliorate subsoil compaction. Two experiments were performed where the potential of different types of boreholes were compared to deep subsoiling and an untreated reference. Effects on soil structure and crop productivity were analysed.

Keywords: subsoil compaction, boreholes, deep subsoiling, cover crops, rooting

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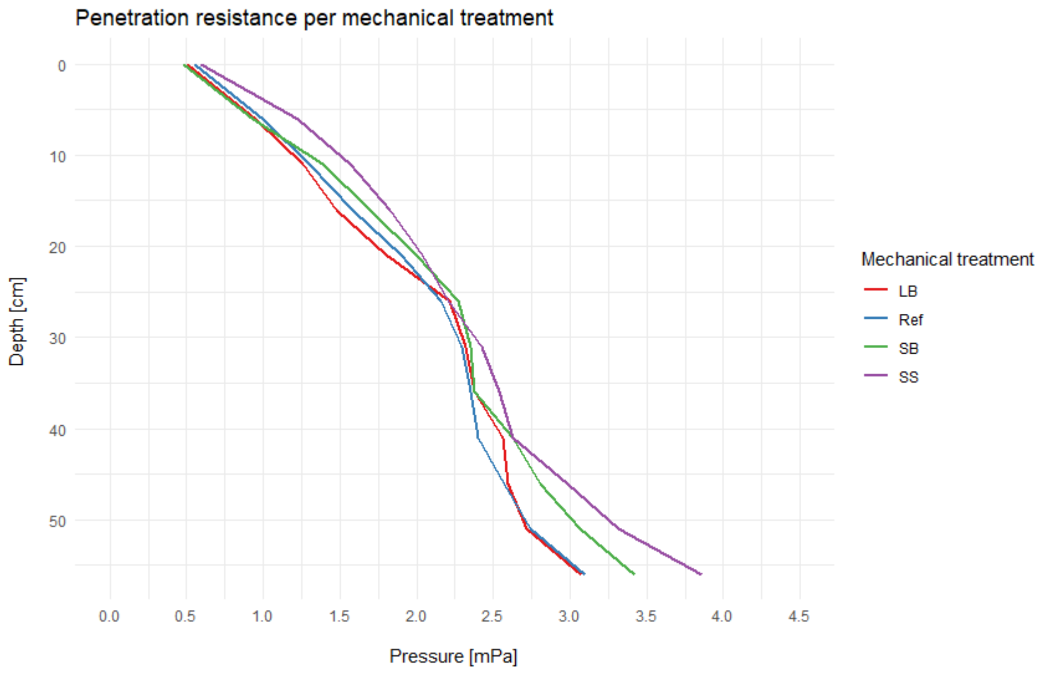
Summary

Climate change is expected to bring higher temperatures and changing precipitation patterns, leading to more frequent droughts and heavy rainfall events. This poses significant challenges for agriculture, with soil quality playing a crucial role in mitigating these effects. In the Netherlands, there's a concerning trend of soil compaction which the consequences may be worsened by the changing climate. Subsoil compaction, often caused during land preparation or harvest in wet conditions, not only affects soil water management but also reduces crop yields.

There are a number of measures to ameliorate subsoil compaction. Mechanical methods like deep subsoiling with a chisel plough or deep ploughing are commonly used but require a lot of energy and there is a risk of re-compaction and deterioration of soil stability. Less known methods such as the drilling of holes can create pores for plant roots and improve soil porosity, but the effectiveness seems to vary and there is also a risk of re-compaction. Planting deep-rooted crops can stabilize the subsoil after such mechanical treatment but may vary in performance. In this study, experiments were conducted on a sandy soil in Vredepeel and a clay soil in Lelystad to compare the effectiveness of methods for long-term amelioration of subsoil compaction while minimizing soil disturbance. Drilling of small boreholes as well as drilling of large boreholes stabilized with a substrate were compared with deep subsoiling and an untreated reference. In addition, three cover crop treatments with different rooting patterns were tested at each location.

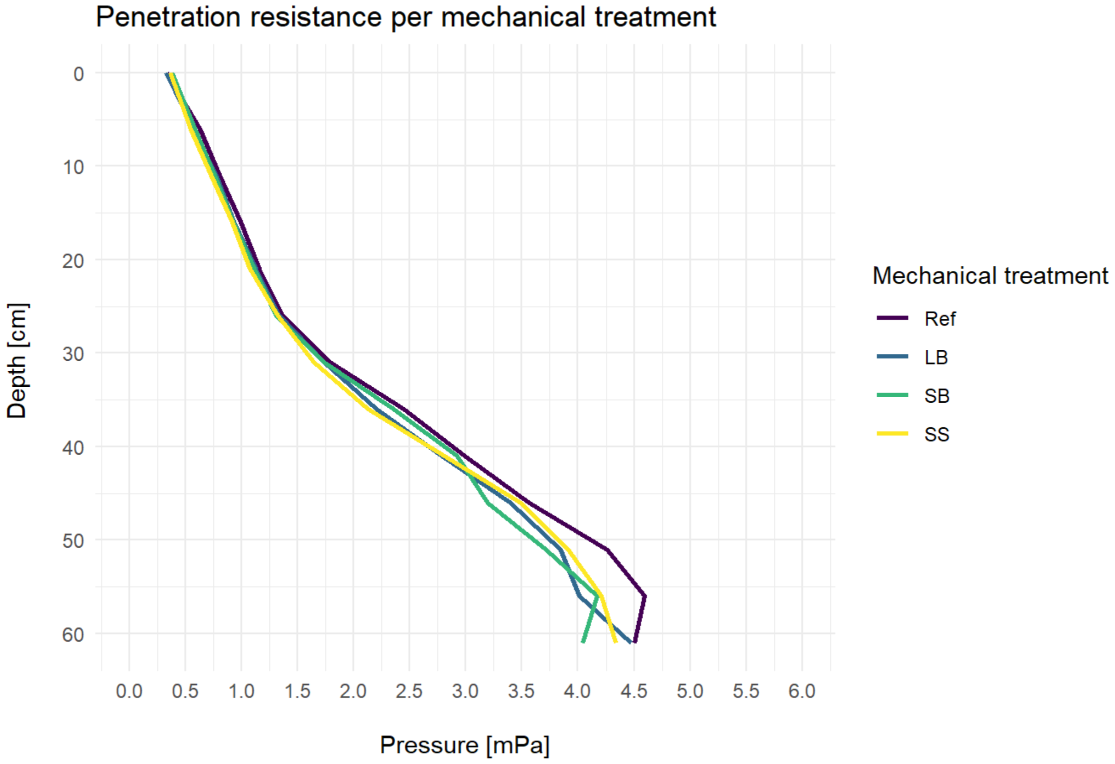
The results from the experiment conducted in Lelystad indicated that the treatments generally had minor effects and did not significantly impact crop yield or the development of cover crop biomass. While there were some significant effects observed in the cover crop treatments, particularly regarding the reduction of penetration resistance in the taproot treatment, these effects were deemed minor in practical terms. Moreover, the mechanical treatments, whether small or large boreholes or traditional deep subsoiling, did not show meaningful effects on penetration resistance immediately after treatment or two years afterwards (see figure



Lelystad: *Penetration resistance in 2021-2022 per mechanical treatment averaged over the cover crop treatments in MPa in the layer of 0-80 cm based on means per 5 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. Compaction causes problems from around >2.5 MPa.* <u>*N.B.: There were no replications of these mechanical treatments.*</u>

Lelystad). Additionally, there were no indications of changes in bulk density or soil moisture. Note that there were no replications of these mechanical treatments in Lelystad, these results are only indications.

In Vredepeel, the outcomes were quite similar. Mechanical treatments did not significantly affect crop yield or cover crop biomass development. Notably, the cover crop treatment did show significant differences in silage maize yield between tall fescue and black oats, although the underlying reasons for this discrepancy could not be explained by other known factors. Nitrate leaching was influenced by some treatments, but a solid hypothesis to account for this observation was lacking. Penetration resistance was reduced in the deep subsoiling and large borehole treatments, albeit only in the year of treatment, and these differences became insignificant in subsequent years (see figure Vredepeel). Similarly, the treatments showed minor and non-significant differences in bulk density and soil moisture. It was observed that deep subsoiling had a relatively large loosening effect on the soil in the extra treatments, but this effect also diminished in later years.



Vredepeel: *Penetration resistance in 2021-2022 across the soil profile 0-65 cm for the replicated treatments based on means per 5 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. Compaction causes problems from around >2.5 MPa.*

The lack of measured effects at both locations might be attributed to various reasons. The field in Lelystad was compacted when it was selected but was faced with dry summers after the start of the experiment leading to better soil conditions and limited hindrance to crop growth and, subsequently, yielding no effects from the treatments. This can occur due to natural processes such as frost, soil shrinking/drying, or swelling during the experiment. In Vredepeel the soil may also have not been compacted enough in order to see effects from the treatment in the crops.

Another possible reason for lack of effects is the limitation in the methods used for measuring soil compaction and the effects of it. Bulk density and penetration resistance provide localized measures of soil compactness, and the borehole treatments only influenced the immediate vicinity of the drilled area which may cause that no effects are measured. Alternative methods for assessing soil compaction are currently lacking and methods for investigating soil moisture are inaccurate or labour intensive.

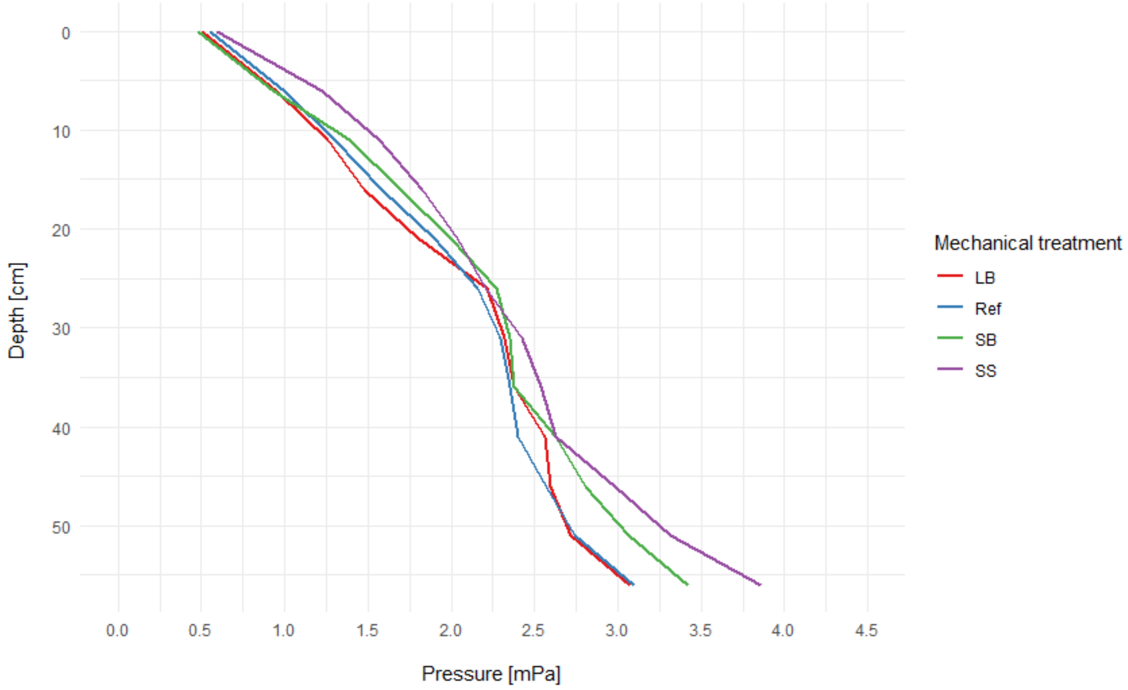
To summarize, the results indicated that these measures had minor effects on crop yields and soil structure parameters. However, due to various complexities, including a lack of homogeneously compacted soil to perform the experiment on and uncertainties regarding measurement methods, it is not possible to definitively draw conclusions on the potential of these measures in addressing subsoil compaction. We recommended further research of the borehole and cover crop methods to gain a better understanding of the efficacy of these measures. This means that the new measures to ameliorate subsoil compaction that were tested in these experiments, didn’t provide solutions for today’s farmers' practice. Even if the method of drilling of boreholes would have been shown effective, it would be very costly and time-consuming to implement with the current techniques which means that the method would require further development. Farmers are aware of measures to prevent soil compaction, however the wet weather conditions during harvests often make it unavoidable to not cause (sub)soil compaction. Natural processes can help to restore the soil structure but are dependent on soil type and climate conditions. Since the available methods for amelioration of subsoil compaction aren’t effective and sustainable, the prevention of subsoil compaction should remain a high priority.

Samenvatting

Klimaatverandering gaat naar verwachting leiden tot hogere temperaturen en veranderde neerslagpatronen, waardoor droogte en hevige neerslag vaker gaan voorkomen. Dit stelt de landbouw voor grote uitdagingen, waarbij de bodemkwaliteit een cruciale rol speelt bij het beperken van de effecten. Ook problemen met ondergrondverdichting zouden kunnen verergeren door het veranderende klimaat. Ondergrondverdichting wordt vaak veroorzaakt bij bodembewerking of oogst onder natte omstandigheden en beïnvloedt niet alleen de waterhuishouding in de bodem maar vermindert ook de gewasopbrengsten.

Er zijn een aantal maatregelen beschikbaar om ondergrondverdichting op te heffen. Mechanische methoden zoals woelen en diepploegen worden vaak gebruikt, maar kosten veel brandstof en er bestaat een risico op herverdichting en verslechtering van de bodemstabiliteit en draagkracht. Minder bekende methoden zoals het boren van gaten zouden poriën kunnen creëren voor plantenwortels om in te groeien en de porositeit van de bodem verhogen voor een betere waterhuishouding. Uit onderzoek blijkt dat de effectiviteit van het boren van gaten varieert en er is ook een risico op herverdichting. Het telen van diepwortelende gewassen zou de bodem kunnen stabiliseren na dit soort mechanische behandelingen. In deze studie werden experimenten uitgevoerd op een zandgrond in Vredepeel en een kleigrond in Lelystad waarbij methodes voor het duurzaam opheffen van ondergrondverdichting met minimale verstoring van de bodem vergeleken werden. Kleine boorgaten en grote boorgaten gestabiliseerd met een substraat werd vergeleken met woelen en een onbehandelde referentie. Deze behandelingen werden gecombineerd met drie verschillende diepwortelende groenbemesters met verschillende bewortelingspatronen.

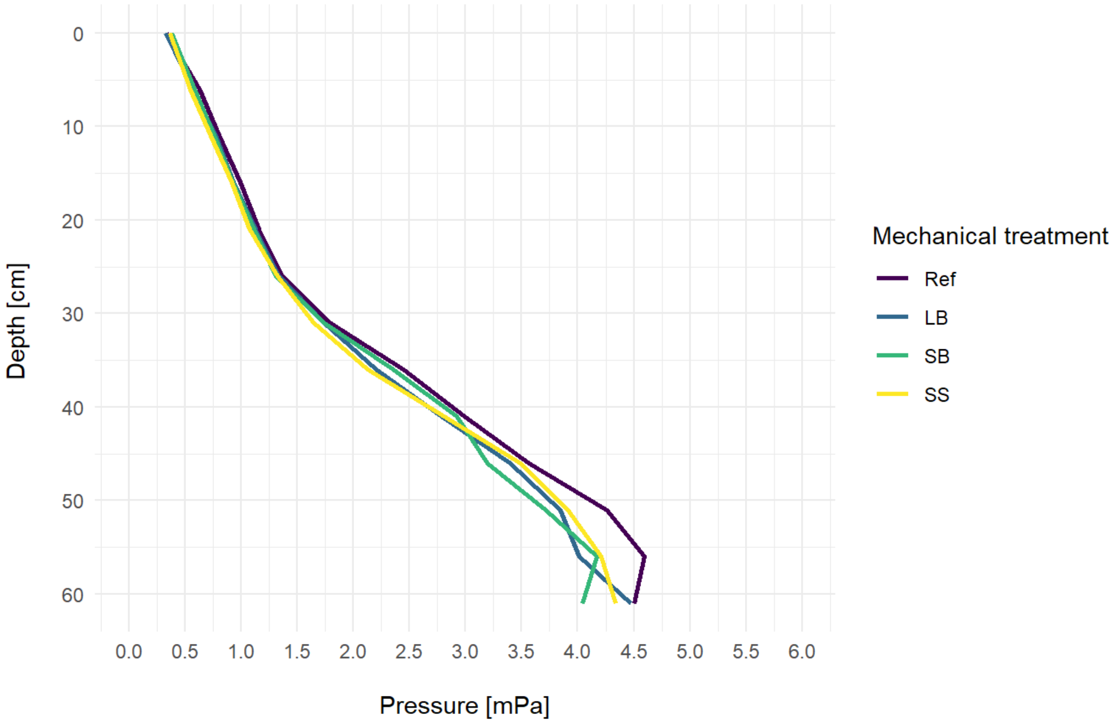
De resultaten van het experiment in Lelystad tonen over het algemeen kleine effecten van de behandelingen en er was geen statistisch significant effect op de gewasopbrengst of de ontwikkeling van de groenbemester. De groenbemesterbehandeling met diepe penwortel, de bladrammenas, toonde een significant lagere indringingsweerstand, maar in praktische termen was dit verschil gering.



Lelystad: *Indringingsweerstand in MPa in 2021-2022 per mechanische behandeling gemiddeld over de groenbemesterbehandelingen, in de laag van 0-80 cm op basis van gemiddelden per 5 cm. Ref = Onbehandeld, LB = Grote boorgaten, SB = Kleine boorgaten, SS= Woelen. Bodemverdichting veroorzaakt problemen vanaf ongeveer >2,5 MPa. N.B.: Er waren geen herhalingen van deze mechanische behandelingen.*

Geen van de mechanische behandelingen toonde effecten ten opzichte van de onbehandelde referentie, na het uitvoeren van de behandeling of in de jaren daarna (zie figuur Lelystad). Er waren verder geen statistisch significante effecten op de bulkdichtheid of het bodemvocht. Let op: er waren geen herhalingen van deze mechanische behandelingen in Lelystad, deze resultaten zijn dus slechts te beschouwen als indicaties.

In Vredepeel waren de resultaten vergelijkbaar. De mechanische behandelingen hadden geen significante effecten op de gewasopbrengst of groei van de groenbemester. Er waren wel significante verschillen in de opbrengst van de snijmaïs tussen rietzwenkgras en Japanse haver, hoewel een verklaring hiervoor ontbreekt. De nitraatuitspoeling verschilde significant tussen enkele behandelingen, maar een duidelijke hypothese om deze effecten te verklaren ontbreekt. De indringingsweerstand was significant lager in de behandelingen met woelen en grote boorgaten in het jaar van de behandeling, echter in de daaropvolgende jaren waren deze verschillen niet meer statistisch significant (zie figuur Vredepeel). Verder waren er kleine en niet-significante verschillen in bulkdichtheid en bodemvocht tussen de behandelingen. Diep woelen had een relatief groot losmakend effect in de extra plots (niet herhaald), maar dit effect nam ook af in latere jaren.



Vredepeel: *Indringingsweerstand in MPa in 2021-2022 over het bodemprofiel 0-65 cm voor de behandelingen in herhalingen, gebaseerd op gemiddelden per 5 cm. Ref = Onbehandeld, LB = Grote boorgaten, SB = Kleine boorgaten, SS= Woelen. Bodemverdichting veroorzaakt problemen vanaf ongeveer >2,5 MPa.*

Het ontbreken van duidelijke effecten van de behandelingen op beide locaties kan verschillende oorzaken hebben. Het perceel in Lelystad was verdicht toen het werd geselecteerd, maar kreeg na de start van het experiment te maken met droge zomers waardoor de bodemcondities verbeterden en de gewasgroei minder werd gehinderd. Hierdoor hadden de behandelingen mogelijk geen effect. Dit kan het gevolg zijn geweest van natuurlijke processen zoals vorst, krimp of zwelling van de bodem. Ook in Vredepeel is de bodem mogelijk niet voldoende verdicht geweest, bij aanvang van het experiment, om effecten van de behandelingen in de gewasgroei terug te zien.

Een andere mogelijke reden voor het uitblijven van effecten is de beperking in de gebruikte methodieken voor het meten van bodemverdichting en de bijbehorende effecten. Het meten van bulkdichtheid en indringingsweerstand geeft erg lokaal aan hoe verdicht de bodem is, en de behandelingen met boorgaten beïnvloedden waarschijnlijk alleen de directe omgeving van de geboorde gaten, wat ertoe kan leiden dat er geen effecten worden gemeten bij het meten van het hele perceel. Alternatieve methoden voor het beoordelen van bodemverdichting ontbreken momenteel en methoden voor het onderzoeken van de waterhuishouding zijn over het algemeen onnauwkeurig of erg arbeidsintensief.

Samenvattend tonen de resultaten dat de maatregelen beperkt effect hadden op gewasopbrengsten en bodemstructuur. Vanwege verschillende redenen, waaronder een gebrek aan goed verdichte grond om het experiment op uit te voeren en onzekerheden met betrekking tot de meetmethoden, is het echter niet mogelijk om definitieve conclusies te trekken over het potentieel van deze maatregelen om ondergrondverdichting op te heffen. Er is meer onderzoek nodig naar het boren van gaten en diepwortelende groenbemesters om de effectiviteit van deze maatregelen goed in beeld te brengen. Deze maatregelen bieden dus op dit moment geen perspectieven voor de huidige landbouwpraktijk. Als het boren van gaten wel effectief was gebleken, zou het nog steeds een erg kostbaar en tijdrovend methode zijn om uit te voeren met de huidige technieken en zou doorontwikkeling van de methode nodig zijn geweest. Boeren zijn zich goed bewust van maatregelen om bodemverdichting te voorkomen, maar door de natte weersomstandigheden tijdens de oogst is het veroorzaken van bodemverdichting vaak onvermijdelijk. Natuurlijke processen kunnen helpen om de bodemstructuur te herstellen, maar zijn afhankelijk van bodemtype en klimaatomstandigheden. Aangezien de beschikbare methoden voor het opheffen van ondergrondverdichting niet effectief of duurzaam zijn, verdient het voorkomen van ondergrondverdichting de hoogste prioriteit.

1 Introduction

1.1 Problem description

Due to climate change higher average temperatures and changing precipitation patterns are expected. Longer periods of drought and high precipitation in short periods of time will become more common (KNMI, n.d.). This has major implications for agriculture. In some time periods it will be a challenge to ensure sufficient irrigation water of suitable quality while in other periods there is a risk of crop damage due to flooding. The quality of the soil on which crops are grown and the method and amount of irrigation are crucial factors. The soil has to retain the water sufficiently on the one hand, but must also be able to infiltrate the water quickly into the subsoil if there is too much water. There is currently a negative trend in soil quality in the Netherlands. Insufficient soil quality and more specifically soil subsidence, subsoil compaction and low (active) levels of soil organic matter, gives higher risks of insufficient moisture supply to the crop and poor infiltration of excess water. Subsoil compaction is a major and growing problem (van den Akker et al., 2008; van den Akker et al., 2013) and refers to soil compaction below the tillage depth, usually >30 cm. Due to the natural weather conditions subsoil compaction is unavoidable during land preparation or harvest. It is be caused by driving into the furrow when ploughing (plough sole), or by excessive machine load when driving on the soil. Specifically, it is the wet conditions during crop harvest that is a main cause of subsoil compaction. In addition to negatively influencing the water management of the soil, it also causes decreases in yield (Schneider et al., 2017; Yang, 2022a). The presence of compaction can be shown by measuring the bulk density of the soil. There are known limits for the soil densities for reduced and obstructed root growth (Table 1).

Table 1. Bulk density limits in g/cm^3 for root growth on clay and sand soil (Bakema et al., 2023a).

	Reduced root growth	**Obstructed root growth limit**
Clay	1.39-1.49	1.47-1.58
Sand	1.69	1.85

1.2 Measures for subsoil compaction amelioration

In order for a measure aimed at amelioration of subsoil compaction to be interesting for a farmer, it needs to show results in the short term. Stimulating anecic earthworms (*Lumbricus Terrestris*) and soil life in general can help ameliorate subsoil compaction but effects are slow to show up. For faster amelioration of subsoil compaction mechanical methods and amelioration by crop rooting might have a better potential.

A common agricultural practice is **deep subsoiling** with a chisel plough, which can break up and eliminate deep compacted layers up to a depth of 70 cm. This method is mainly used after the harvesting of root crops in order to eliminate the compaction caused by the traffic. A lot of energy is required for this method and it has to be done during dry conditions in order to prevent smearing of the subsoil. Additionally, the carrying capacity of the soil is reduced and because of this the risk of re-compaction is high (Geel et al., 2009; Schneider et al., 2017) unless tillage techniques are adapted to avoid it such as on-land ploughing and light traffic (Munkholm et al., 2005). The compaction caused by a subsoiler is even more difficult to eliminate, due to the large depth. An experiment with different techniques on sandy loam soil showed only a slight improvement in the following year (van Geel at al., 2009). A combination of subsoiling and application of manure can help to restore the soil. It resulted in an increase in a.o. >0.25 mm soil aggregates, soil organic carbon, soil microbial mass and soil enzyme activity (Yang et al., 2022).

Another method is the sporadic use of **deep digging or deep ploughing** (up to 100 cm depth) which causes an intensive disturbance of the soil. The tilled soil layer is mainly turned or mixed, making this method only suitable for soils with a relatively homogenous soil profile. Turning the soil upside down can improve workability in case of a clay topsoil by mixing it with the lighter subsoil. However, by changing the soil composition and reducing the carrying capacity, this soil is more susceptible to re-compaction and the risk of soil-borne pests (free-living nematodes) is larger (Van Balen, 2008).

Digging trenches with a chain digger which is usually used for installation of drainage pipes can also break through deeper compacted soil layers. In order to have sufficient effect, these trenches will have to be at shorter distances from each other than is common for the laying of drainage. This method is highly disruptive to the soil and may affect its stability. Before the soil in the trenches has settled and stabilized, such soil is more susceptible to compaction.

Additional methods with potential are the drilling of smaller or bigger holes through the compacted soil layers which could help to creates pores in which plant roots can grow and water can infiltrate. Advantage of this system is the minimizing of soil disturbance and by this preservation of soil bearing capacity. The anecic *Lumbricus Terrestris* earthworm, is capable of digging vertical burrows up to 100 cm deep. In the process, this earthworm can also burrow through compacted soil layers. Plant roots use these worms' burrows to grow into deeper layers, and the excretions of the earthworms along the walls of the burrows can serve as plant nutrients. The function of the anecic earthworm can be replicated mechanically by **small boreholes** in the soil. Previous research on this showed slightly increased soil porosity and air-filled porosity (Zhai and Horn, 2017). The soil also seemed less susceptible for compaction. In Switzerland, experiments have been conducted in which holes with a 1.25 mm diameter were pierced in compacted soil, up to a depth of 20-30 cm below ground level (Colombi et al., 2017). Plant roots used these artificial macro pores because of a reduced resistance to root penetration and an improvement in air permeability. Other studies show no indication that roots make use of the smaller boreholes (Yang, 2022b).

A final option for the mechanical amelioration of subsoil compaction is to **large boreholes stabilized with substrate**. The drilling of holes allows plants to root deeper and to stabilize the soil. However, there is a chance of re-compaction over time as the old soil layer "sinks back”. The combination of deep loosening of the soil and placement of nutrients with the substrate can enhance root growth (Schulte, 1993). By replacing the compacted soil layer in the drilled holes with a substrate (for example manure, compost, potting soil or a mixture of these), the old soil layer cannot sink back and the substrate can be used by the plants. However, under extremely wet soil conditions, there is a danger that a carbon-rich substrate can have a net-negative effect. If dewatering is the main objective for ameliorating subsoil compaction, coarse sand (drainage sand) can be chosen to fill a part of the borehole. However, sand will not be attractive for plant roots to grow in and it will not stimulate root growth to deeper soil layers. Previous research on large boreholes on sandy loam soil resulted in the highest yield. Although roots grow preferably in bore-holes, no significant difference was found in root weight (Yang, 2022b).

After mechanically treating soil compaction, it is important to stabilize the subsoil for example by growing of **deep-rooted crops**. Plant roots contribute to the cohesion of soil aggregates and stimulate fungal networks and excretions of soil microbes. When space becomes available in the subsoil, due to tillage or, for example, shrinkage in clay soils, plant roots can utilize this space and occupy the subsoil with roots. To ensure that a tilled subsoil is stabilized after deep tillage, a fast colonization with plant roots is essential. A combination of crops with different types of rooting can occupy a larger portion of the fertile layer and thereby contribute to soil stability and carrying capacity.

The degree to which plant roots can grow through compact soil layers varies (Bakema et al, 2023b). For example, sorghum is known to have a strong rooting and can penetrate even slightly compacted soil (Yang et al., 2022). Taproots are able to penetrate deeper soil layers and create bio pores (with lower penetration resistance) in which roots of succeeding crops can grow, also known as bio-drilling (Chen and Weil, 2010). Dicotyledonous plants have in general a better ability to penetrate compacted soil than monocotyledonous crops. The difference is probably related to the ability of dicotyledonous crops to increase in root diameter when there is an increase on root pressure (Cresswell and Kirkegaard, 1995). Hence the roots of a crop like forage radish (*Raphanus raphanistrum subsp sativus)* is more capable of penetrating compacted layers then the roots of rye (*Secale cereale*). It's not only the diameter of roots but also the design of the root system. Both forage radish and rapeseed (*Brassica napus subsp napus*) have a taproot, but tillage radish has one taproot with thick branches and rapeseed has several tap roots and side roots (Chen and Weil, 2010).

1.3 Research questions

Two experiments were conducted in order to test measures for durable amelioration of subsoil compaction. Measures were chosen that have potential to ameliorate subsoil compaction in the long term while minimizing soil disturbance. In the experiment the effect of small boreholes and large boreholes stabilized with substrate were compared with deep subsoiling and an untreated reference. Additionally, different deep-rooting cover crops were tested for their influence on stabilizing and further improving the soil properties after the mechanical treatments. For these experiments, three research questions were formulated:

1. What is the influence of the drilling of small boreholes or large boreholes filled with a substrate on soil physical properties and crop yields on soils with subsoil compaction?
2. What is the influence of deep-rooted cover crops on stabilizing the soil physical properties after the mechanical treatments?
3. What is the influence of different rooting traits of deep rooting cover crops on the soil physical properties on soils with subsoil compaction?

It is expected that the reference treatment will have the most compacted soil and poor soil structure and that the deep subsoiling reference will show improvements on soil structure, compaction and yield in the short term and then recompact. The boreholes are expected to decrease the average compactness of the soil. Moisture conditions are expected to improve for the borehole treatments during droughts and excess moisture. Small boreholes might close up faster than large boreholes which would decrease the relative effects. Furthermore, the yields of the cover crop and main crops may increase for the treatments that decrease the compaction the most. These major soil interventions may also influence nitrogen dynamics in the soil profile which in turn influence yields and nitrogen losses.

2 Materials and methods

To evaluate the measures for amelioration of subsoil compaction, two experiments were conducted, one on a clay soil in Lelystad and one on a sandy soil in Vredepeel, The Netherlands. The experimental designs are described in 2.1, the measurement protocols in 2.2. and the statistical analysis in 2.3.

2.1 Experimental setup

Two different experimental layouts were used for the locations (Figure 1**,** Figure 2). The experiments had three mechanical treatments combined with three cover crop treatments (**Table 2**). A reference with no mechanical treatment for each of the three cover crops gives in total of 12 treatments. The experiment in Vredepeel had five additional treatments but these do not have the same number of replications and were not randomized and are therefore intended to be indicative. The cover crop species were selected based on suitability for the region and characteristics such as perennialism and rooting type and the main crops were common crops in the region of the experiment (**Table 3**). On clay a very diverse mixture was sown with the expectation of a large variety in rooting patterns. Due the risk of nematodes, a mixture treatment was not included on a sandy soil. Drawings of rooting patterns of some of the included species are available in **annex 5.2**.

Table 2. Overview of experimental treatments. The cover crops differ per location and are described in detail in Table 3. The extra treatments were only tested in Vredepeel and were not included for statistical comparison as they were not scientifically replicated and randomized.

Treatment code	Mechanical treatment	Cover crop Lelystad	Cover crop Vredepeel
1a	Deep subsoiling (SS)	Diverse perennial mixture	Annual taproot
1b	Deep subsoiling (SS)	Perennial with fibrous roots	Annual with fibrous roots
1c	Deep subsoiling (SS)	Perennial with tap root	Perennial with fibrous roots
2a	Small boreholes (SB)	Diverse perennial mixture	Annual taproot
2b	Small boreholes (SB)	Perennial with fibrous roots	Annual with fibrous roots
2c	Small boreholes (SB)	Perennial with tap root	Perennial with fibrous roots
3a	Large boreholes with substrate (LB)	Diverse perennial mixture	Annual taproot
3b	Large boreholes with substrate (LB)	Perennial with fibrous roots	Annual with fibrous roots
3c	Large boreholes with substrate (LB)	Perennial with tap root	Perennial with fibrous roots
4a	Untreated (Ref)	Diverse perennial mixture	Annual taproot
4b	Untreated (Ref)	Perennial with fibrous roots	Annual with fibrous roots
4c	Untreated (Ref)	Perennial with tap root	Perennial with fibrous roots
Extra treatments Vredepeel (outside experiment) (see 2.1.1)			
LBS	Large boreholes with substrate (LB Sand)	-	Annual with tap root
LBExt	Large boreholes with substrate (LB Extensive)		
Comp	Compost		
SSC	Subsoiling with caterpillar (SS Caterpillar)		
Ref	Untreated (Ref)		

In the reference treatment, the soil was ploughed to a depth of 25 cm. This is also the type of tillage that was historically applied at the experimental sites. The deep subsoiling was done with a rigid tine cultivator with 75 cm between the tines to a depth of 60 cm on sand and 40 cm on clay. For the borehole treatments a machine was built with a fuel engine with four hydraulic-powered auger drill mounted on a frame. The tractor used for the treatments was equipped with an automatic start-stop system with 75 cm between the stops. The width was suited for crop beds of 3 m (225 cm machine width). Large holes were drilled in a grid of 75 x 75 cm (Ǿ 10 cm) until 60 cm depth and the bottom half was filled with substrate and the top half with drilled soil. The small holes were drilled using ten stone drill bits in a grid of 25 x 25 cm (Ǿ 2 cm) until 60 cm depth and were not filled with substrate (Figure 3). A short film of this technique can be found on: https://www.youtube.com/watch?v=Xk-RX33Nbvo

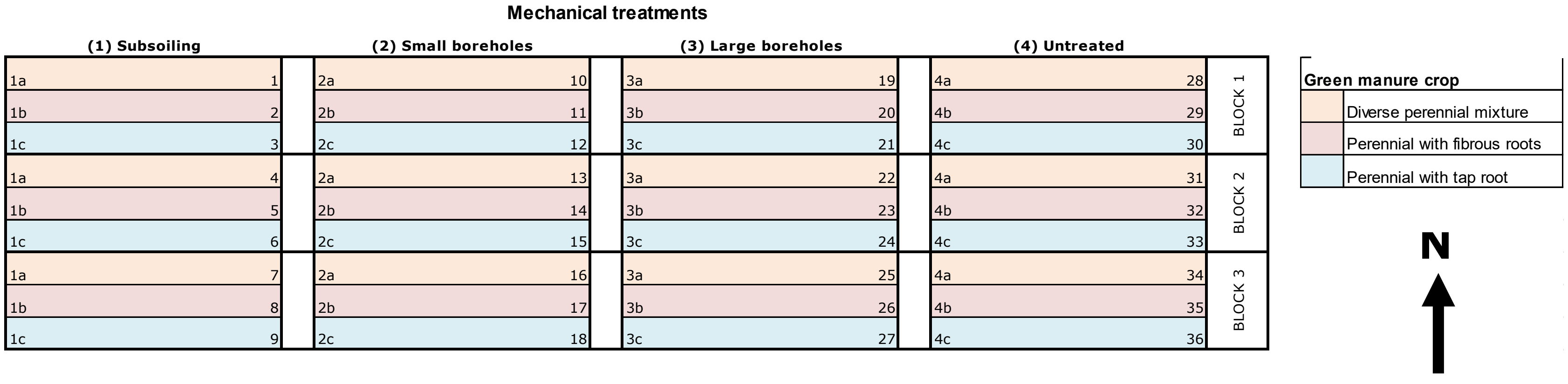


Figure 1. Experimental setup of subsoil compaction amelioration experiment, location Lelystad. 1= subsoiling (SS), 2=small boreholes (SB), 3=large boreholes (LB), 4=untreated reference (Ref). a= diverse perennial mixture, b= perennial with fibrous roots, c= perennial with taproot.

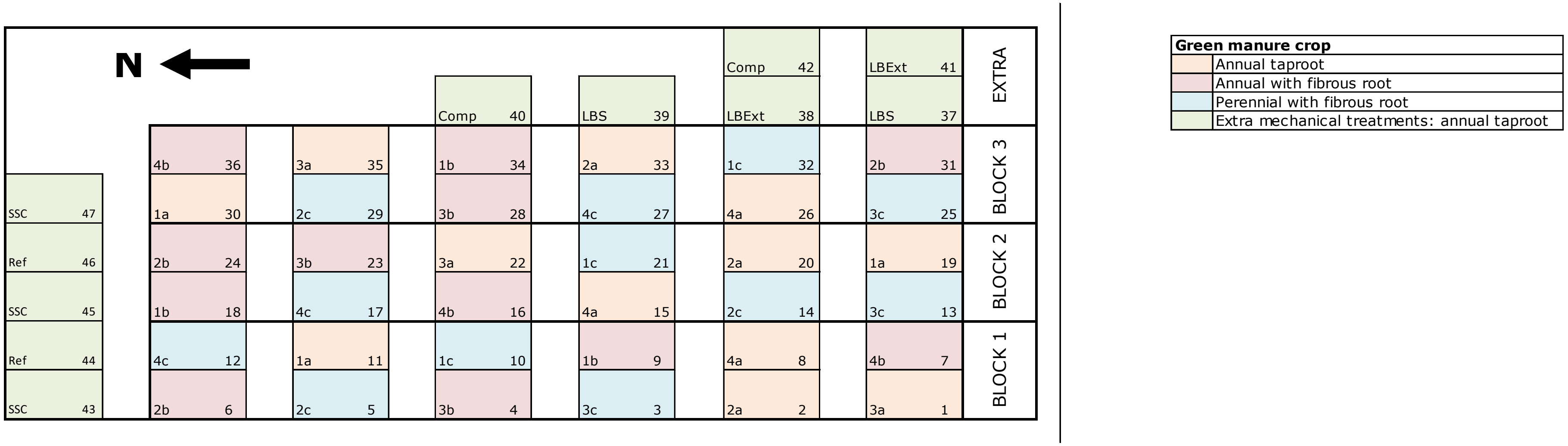


Figure 2. Experimental setup of subsoil compaction amelioration experiment, location Vredepeel. 1= subsoiling (SS), 2=small boreholes (SB), 3=large boreholes (LB), 4=untreated reference (Ref), SSC=Subsoiling with caterpillar, Comp = Compost, LBS = Large boreholes with sand, LBExt = Large boreholes extensive, a=annual taproot, b= annual with fibrous root, c= perennial with fibrous root.

Table 3. Overview of main crops and cover crops before and during each year of the experiments. Bold=main experimental cover crop treatments.

Location	Treatment	2019		2020		2021		2022	
		Main crop	Cover crop	Main crop	Cover crop	Main crop	Cover crop	Main crop	Cover crop
Lelystad	A	Spring wheat	Annual mixture *	Spring barley	**Perennial mixture 2 ****			Potato	-
	B		Sudangrass ***		**Tall fescue**				
	C		Fodder radish		**Lucerne + Berseem clover**				
Vredepeel	A				**Fodder radish**	Silage maize	Tall fescue (undersown)		Fodder radish + Black oats
	B				**Black oats**				
	C				**Tall fescue + English ryegrass**				

* Annual mixture: Solarigol TR: Flax, Black oats, niger, vetch, Egyptian clover, fodder radish, camelina, peas, Persian clover

** Perennial mixture: Italian ryegrass, tall fescue, meadow fescue, lucerne, black oats, sweet yellow clover, white clover, red clover, crimson clover.

*** Crop unsuccessful, with very low biomass

Figure 3. Top: Large borehole drill (left) with potting soil as stabilizing substrate(right). Bottom: Small borehole drills.

2.1.1 Lelystad

The experimental field was located on the former Waiboerhoeve at the Wisentweg in Lelystad. Part of the plot has had problems with waterlogging in the past. This probably occurred because the plot was leased to third parties for an extended period of time where the proportion of root crops was high causing the soil structure to deteriorate and the soil to become compacted. Pre-treatment measurements with penetrometer showed a gradient from east-west with an increase towards the west.

The experiment started in late 2019 when the first round of mechanical treatments was executed. The plots in the experiment had a size of 3 x 20 m. The mechanical treatments do not have statistically randomized replication while the cover crop treatments have three repetitions, however they are not randomized (Figure 1). In 2019 the borehole machine as described in 2.1.0 was not yet available and the drilling was performed manually on ¼ of the plot area. It was very difficult to push the metal rods into the ground even when a tractor was used. Because of this, the final mechanical treatments were done with a different technique in 2020 using the special developed machine at another area of the plot. Large boreholes were filled with potting soil in the small plots (3 x 6 m) of 2019 and coarse sand in 2020. The fields of 2020 were 3 x 12 m and because of the size more suitable for soil sampling. Therefore data is only used from 2020 onwards, while the cover crops sown in 2019 also must be seen as a part of the treatment as these were sown on the whole plots. The cover crop sown in 2020 stood the whole season of 2021 and was mown. Seeding densities were 62 kg/ha for the perennial mixture, 20 kg/ha for the tall fescue (mixed with a low amount of English ryegrass) and 25+5 kg/ha for the lucerne and Berseem clover, respectively.

2.1.2 Vredepeel

At the Vredepeel site a plot was chosen that was known to have a compacted subsoil. In general, the transition from the humic upper layer to a sandy subsoil is abrupt which can be disruptive to root growth but also to water infiltration and capillary rise.

The experiment started in the late summer of 2020. The fields have a size of 6 x 12 m in and are divided in three blocks making three replications (Figure 2). To the east of the experiment, there is a tree line which causes a light shade on that part of the field were the extra objects of the experiment are located. There is a gradient in the A-horizon from southwest to northeast in this field. The treatments are the same as in the experiment on clay soil in Lelystad with the exception of the large boreholes being stabilized with compost instead of coarse sand (2020). Since there was space left on the field of the experiment, a number of additional research objects were added:

- LB Sand (LBS): large boreholes stabilized in the bottom half with coarse sand and rest with drilled soil, to be compared to the filling with compost.
- LB extensive (LBExt): large boreholes in grid 150 x 75 cm stabilized in the bottom half with compost and the top layer with drilled soil. To be compared with the LB treatment to see if one can achieve the same effects with less holes which would save time when applied.
- Compost (Comp): 100 ton of compost/ha ploughed into a depth of 25 cm as a reference of general improvement of soil conditions.
- Deep subsoiling with caterpillar(SSC): Comparable to deep subsoiling but deeper and more destabilizing. The treatment was done to a depth of 85 cm with three tines.
- Untreated (Ref): Same as in replicated part of the experiment.

These extra plots had fodder radish as cover crop treatment. The cover crops in 2020 were sown in the following densities; 20 kg for fodder radish (variety Angus), 80 kg for black oats and 10 kg of tall fescue mixed with 20 kg of English ryegrass.

2.2 Methods

2.2.1 Lelystad

- Before the leaf termination **potato** biomass and yield was determined in 2022 by machine harvesting of two rows of 8 m.

- Aboveground biomass of the **cover crop** was cut at soil level in an area of 50 by 50 cm in November in 2020 and 2021. In this area six root samples were taken with an auger until 30 cm depth, three in the row and three between the rows. Roots were cleaned from soil by rinsing with water. Cover crop aboveground biomass was mowed an additional two times (May and September) during the growing season in 2021 with a Haldrup harvester (6 x 1.50 m). Biomass data was only recorded for the mowing in September.
- **Bulk density** was sampled in 2020-2022 at 5-10 and 20-25 cm depth by using one Kopecky ring for each layer in each plot. Sampling was done in December, November and September, respectively over these years. From the same rings also the moisture content of the soil was retrieved.
- **Penetration resistance** was measured in 2020 (during cover crop treatment) and 2022, in December and September, respectively. Six measurements were done per plot to a depth of 80 cm using a penetrometer from Eijkelkamp with a cone size of 1 cm^2/60 deg., with a penetration speed of 2 cm/s.
- **Soil moisture** was measured in Lelystad in a subset of plots in 2020 (30 cm) and 2021 (15 and 30 cm). In 2020 the measurements were done between May and until end of August and in 2021 between half June and end of November.
- **Soil profile inspection** was performed in February 2023. A pit of 50 cm depth was dug for each plot and a score between 1-10 was given for 0-25 cm and 25-50 cm for the general structure, visual soil life, rooting and water regulation.
- In the potato crop in 2022 there was a visible difference in the leaf greenness and production between the cover crop treatments. In order to explain these differences a possible effect from **nitrogen** fixation or "catching/retention" of cover crops on the nitrogen uptake by the potato plants was investigated. For this, three plants per plot were harvested at the end of the growing season. Leaves were cut at soil level and tubers and stolons were manually harvested. The nitrogen content of the leaves, tubers and stolons was determined as well as the mineral nitrogen content of the soil in the 0-60 cm layer with an auger.

2.2.2 Vredepeel

- After harvest of spring barley, the different treatments were applied on the field. The crops for 2021 and 2022 were silage maize and potato, respectively. Silage maize is a common crop for the region and potato fitted well with the crop in the experiment in Lelystad with was potato as well in 2021.
- The yield determination of **silage maize** in 2021 was done by harvesting two rows of 11 m length. Fresh yield and dry matter yield was determined as well as quality parameters.
- Before the **potato** leaf termination in 2022 the yield and quality characteristics were determined by machine harvesting two rows of 10,5 m.
- Aboveground biomass of **cover crops** was sampled and analysed as is described for Lelystad. The sampling of the cover crops was done in November in 2020 and 2022, and in September in 2021. The year 2020 was analysed separately for effects of the mechanical treatments because the cover crop treatment was still undergoing.
- **Bulk density** was sampled in December in 2021 and September in 2022 as is described for the experiment in Lelystad. From the same rings also the moisture content of the soil was retrieved.
- The **penetration resistance** of the soil was measured each autumn during 2020-2022, in the month December (2020), November (2021) and September (2022). The same protocol was used as in Lelystad. In the potato (2022) half of the measurements were done between the ridges and half within the same ridges. The year 2020 was analysed separately for effects of the mechanical treatments because the cover crop treatment was still undergoing. Baseline measurements of the penetration resistance are missing.
- **Soil moisture** was measured in 2021 and 2022 to a depth of 30 cm using a Sensoterra moisture meter. It was measured during July in 2021 and 3rd of May to 20th September in 2022 in six different plots with the cover crop mixture of tall fescue and English ryegrass (C). In 2021 data from other months than July is missing. In 2022 there were broken sensors which caused gaps in the dataset at multiple different dates. Two plots each for the mechanical treatments Deep subsoiling(SS) and Large boreholes(LB), one plot each for the Untreated(Ref) and the plots with Small boreholes(SB). Due to not working sensors, the Untreated (Ref) data was lacking. In each plot two moisture meters were placed, one between the rows or ridge and one in the row or ridge.
- **Soil profile inspection** was performed in February 2023. See description for Lelystad.

- The **nitrate concentration of the groundwater** was measured in 2021-2023 in January, February and March (only in 2022). Monitoring wells were placed in each plot and samples were taken one day later after emptying the well. The analysis of the water was done by using a Nitrachek reflectometer. This variable was not measured in the experiment in Lelystad because nitrate leaching is not a big issue on clay soils whereas it is a great concern at the location of the Vredepeel experiment.

The results from the moisture sensors are presented in the appendix 5.4 and not in the main results section due to the unreliability of the measurement which made interpretation of the data difficult. Our experiences with the sensors will be discussed in the chapter 4 Discussion and conclusion.

2.3 Statistical analysis

All data analysis and visualisation was done in R (R Core Team, 2021) and the output is made available as HTML files. Response variables were checked for outliers and type of distribution using boxplots and histograms. Ln-transformations were performed for nitrate concentration in the groundwater, potato yield losses and <70 mm sized potato for Vredepeel. All variables had orthogonal data with four repetitions. For all variables a linear model was fit and an ANOVA was performed. Variable selection was done using the Akaike information criterion (AIC) using the function stepAIC from the package MASS (Venables & Ripley, 2002) with the full tested model containing the mechanical treatment and the cover crop treatment including their interaction, the blocking factor, the row in the experimental setup and year. The interaction term between the treatments was excluded if not statistically significant. In some cases an ANOVA III was used for comparing two models. For nitrate concentration in the groundwater, the moment of sampling and depth of groundwater were also tested for inclusion into the model. Pairwise comparisons were made using the emmeans package (Lenth, 2021). Penetration resistance was analysed per 5 cm of depth. All figures in the results section in were made with ggplot2 (Wickham, 2016). The full data analysis and statistical output is available at this link. Throughout the results section there will be links referring to this site with the HTML file name indicated.

3 Results

3.1 Lelystad

Due to the lack of replications of the mechanical treatments, statistical analysis was only performed to compare the cover crop treatments. It is important to note that the cover crop treatments were not randomized over the fields which could cause errors in the interpretation in case an unknown gradient was present.

3.1.1 Crop yield and quality – Potato 2022

There were no significant differences between the cover crop treatments on the net- and gross yield or the product tare of potato (Figure 4; Table 4). The blocks, which overlap with the mechanical treatment, appear to show a gradient in yield effects which makes it difficult to interpret the results (see year report 2022) (LS 2022 Potato yield). This gradient is corresponding to the gradient in penetration resistance before the mechanical treatment.

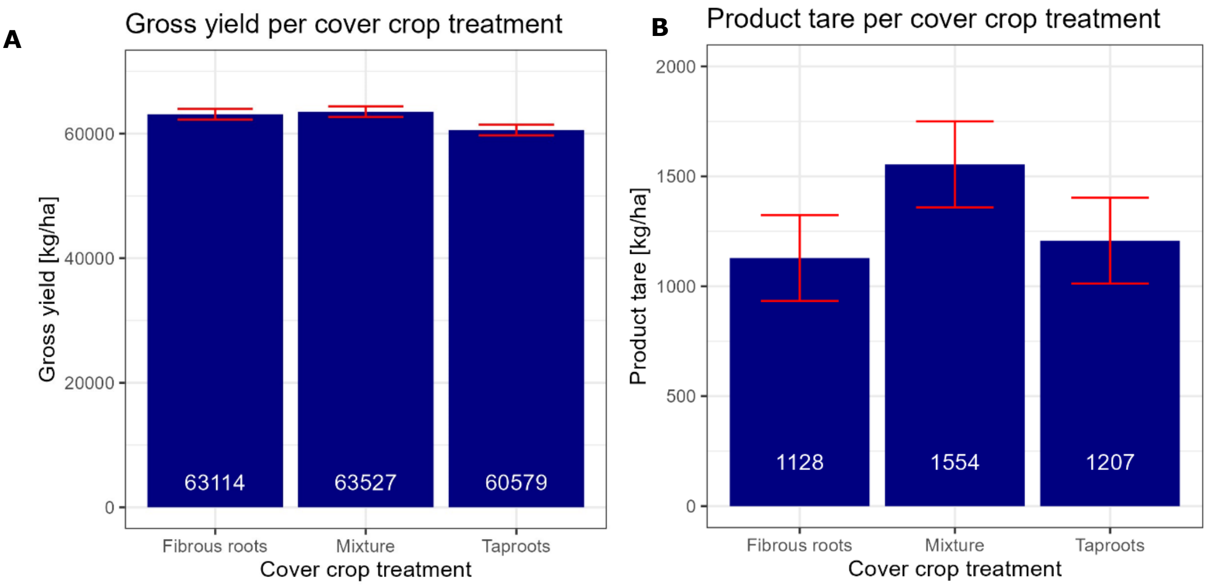


Figure 4. (A) Gross potato yield in kg/ha averaged for all mechanical treatments based on estimated marginal means (EMM) with the standard error in the error bars. (B) Potato product tare in kg/ha based on estimated marginal means (EMM) with the standard error in the error bars. There were no statistically significant differences. A= Mixture, B=Fibrous roots, C=Taproots.

Table 4. Overview of mean results on potato crop variables in kg/ha for all treatments. NB: Mechanical treatments do not have any replications. The different colours do not indicate statistical differences but indicate relative differences between the values of that column.

Mechanical treatment	**Cover crop treatment**	**Gross yield [kg/ha]**	**Net yield [kg/ha]**	**Product tare [kg/ha]**	**<35 mm [kg/ha]**	**35-60 mm [kg/ha]**	**>60 mm [kg/ha]**
Reference	Mixture	64050	61591	2459	945	18433	42213
Reference	Fibrous roots	62674	60603	2071	1105	20928	38570
Reference	Taproots	62742	60889	1852	1198	20077	39614
Large boreholes	Mixture	65631	64001	1630	943	19276	43782
Large boreholes	Fibrous roots	64455	63569	886	1011	22090	40468
Large boreholes	Taproots	63305	61874	1431	948	17846	43080

Small boreholes	Mixture	62847	61951	895	951	18304	42697
Small boreholes	Fibrous roots	64407	63583	823	1169	22788	39627
Small boreholes	Taproots	60751	59972	778	1079	18912	39981
Deep subsoiling	Mixture	61579	60346	1233	1066	17608	41673
Deep subsoiling	Fibrous roots	60920	60187	733	918	19273	39996
Deep subsoiling	Taproots	55519	54751	768	1030	18786	34935

3.1.2 Cover crop biomass 2021

In 2021 cover crop biomass was measured in order to see possible effects from the mechanical treatments. In 2020 the cover crop treatment was just sown and in 2022 there was no cover crop due to the late harvest of the potato. Because of this only year 2021 is included. No notable effects from the mechanical treatments were seen on above- or belowground biomass (LS_2021_Cover_crop). These measurements also give an impression of the possible impact of the cover crop on the soil due to its growth. The mixture accumulated a larger amount of biomass, followed by the taproots and fibrous roots treatment (Figure 5, Figure 6). It is therefore likely to expect larger effects from the taproots and mixture than from the fibrous roots. No statistical tests were performed. The lower biomass for subsoiling in the taproots treatment corresponds with the lower potato yield in 2022 (n.s.). Aboveground biomass was sampled an additional time earlier in the year of 2021, here the same pattern can be seen as in Figure 5 (LS_2021_Cover_crop).

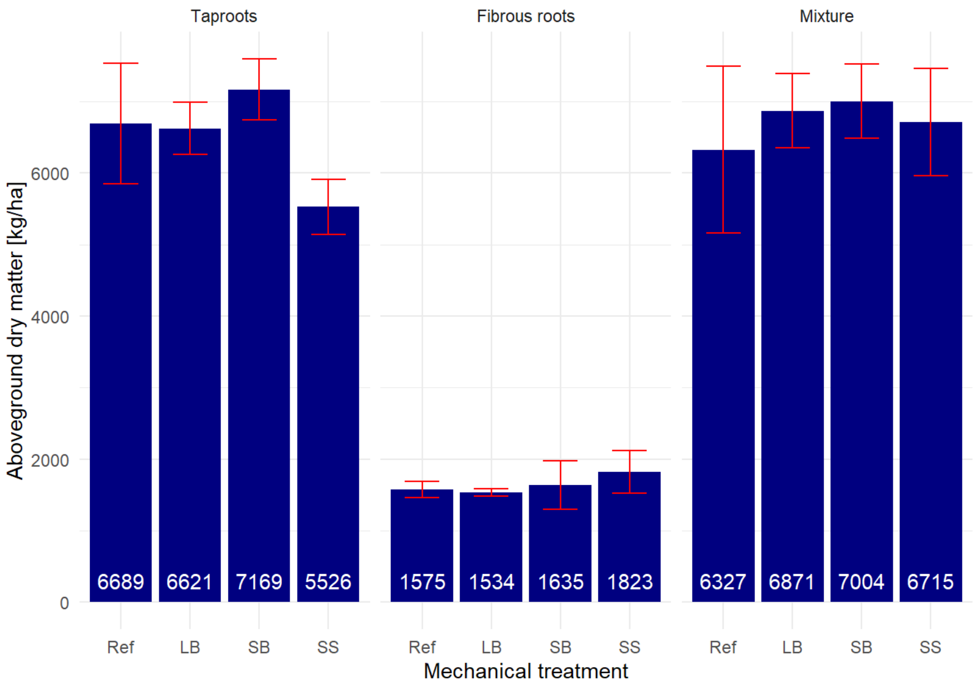


Figure 5. Dry aboveground mass of cover crop treatments [kg/ha] in November based on estimated marginal means (EMM) with the standard error in the error bars. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. There were no statistically significant differences.

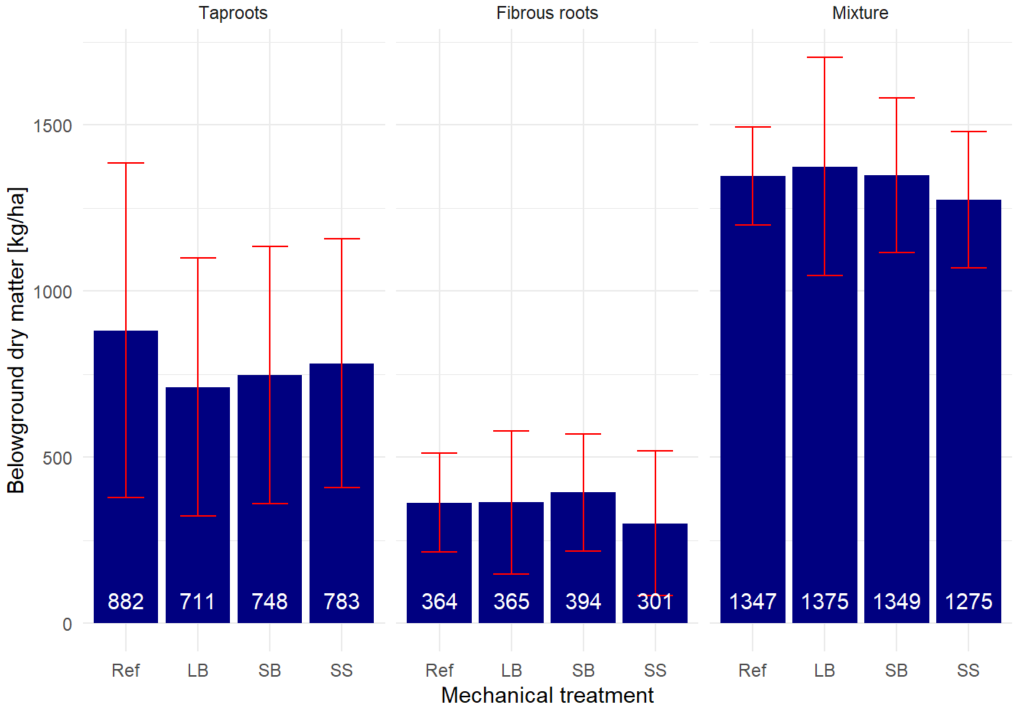


Figure 6. Dry belowground mass of cover crop treatments [kg/ha] based on estimated marginal means (EMM) with the standard error in the error bars. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Deep subsoiling. There were no statistically significant differences.

3.1.3 Nitrogen content in potato and soil

Nitrogen was sampled in the potato crop and the soil due to visible differences in the aboveground biomass. Statistical analysis shows a significant lower nitrogen (ca. 40 kg/ha) in the fibrous roots treatment (grasses) compared to the other two cover crop treatments ($p<0.01$) (Figure 7) (LS 2022 Nitrogen). Possible explanation for this difference is nitrogen fixation of the leguminous cover crops (Taproots and Mixture). These differences in nitrogen did however result in differences in potato yield (Figure 4). Averaging the data for the mechanical treatments show some differences between the borehole treatments and the reference treatment however these cannot be statistically substantiated (Table 5).

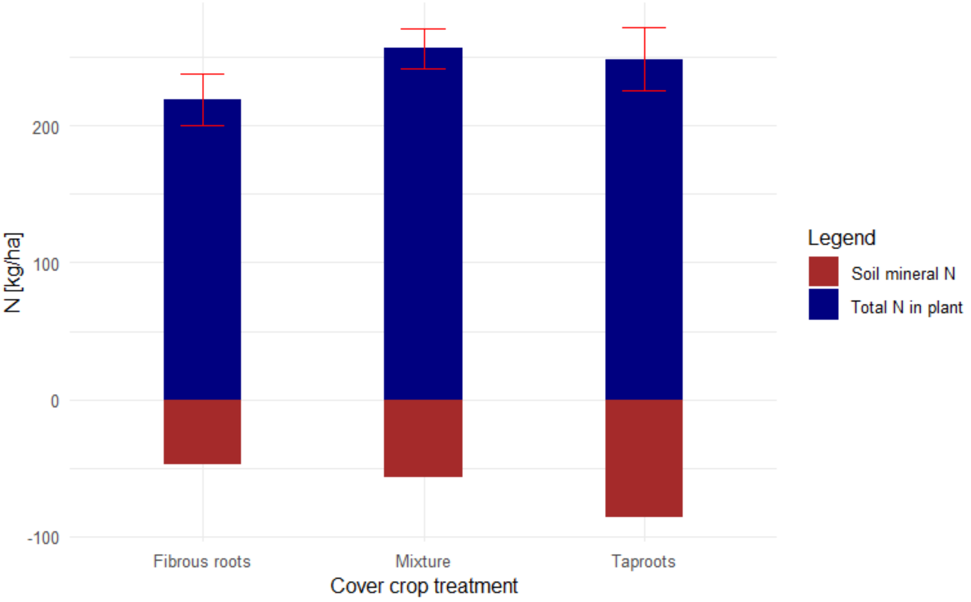


Figure 7. Mean total nitrogen in potato plants [kg/ha] (blue) and mineral soil nitrogen at 0-30 cm depth (brown), with standard deviation in the error bar. For mineral soil nitrogen there were no repetitions hence no error bars.

Table 5. Overview of mean mineral soil nitrogen 0-30 cm and total nitrogen in potato plants [kg/ha]. The different colours do not indicate statistical differences or judgement but indicate relative differences between the values of that column.

Mechanical treatment	Cover crop treatment	N in soil [kg/ha]	N in potato plant [kg/ha]
LB	Fibrous roots	43	222
LB	Mixture	55	260
LB	Taproots	89	269
Ref	Fibrous roots	47	223
Ref	Mixture	59	266
Ref	Taproots	76	252
SB	Fibrous roots	51	213
SB	Mixture	58	259
SB	Taproots	100	258
SS	Fibrous roots	49	219
SS	Mixture	56	240
SS	Taproots	80	214

3.1.4 Penetration resistance

Compaction (>2.5 Mpa) was reached at around 60 cm depth. Statistical analysis was done per 5 cm and showed that in several layers the fibrous roots had a significantly higher resistance than both or one of the other two treatments ($p<0.01$) (Figure 8) (LS 2021 2022 Penetration resistance). These significant differences are in the range of 0.1-0.2 MPa which is agronomically a minor difference. The slightly higher compaction in the fibrous roots treatment could be due to the lower growth of this crop, as seen in the amount of root biomass produced (see 3.1.2.).

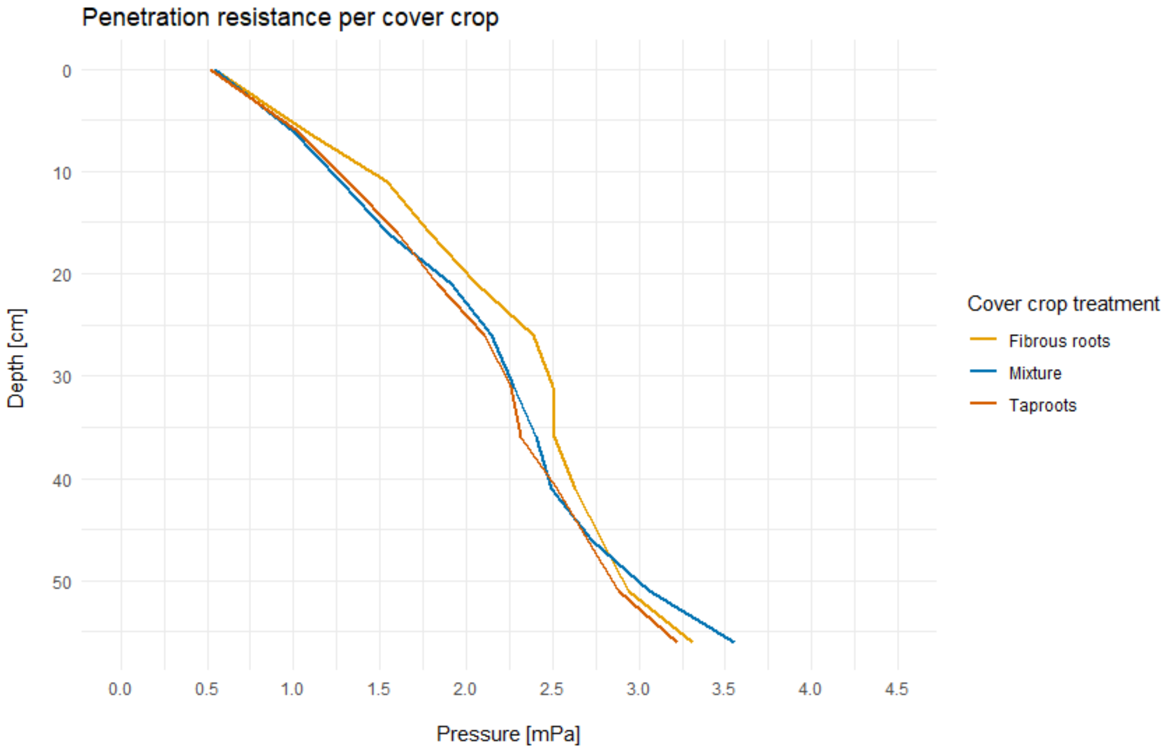


Figure 8. Penetration resistance 2021-2022 per cover crop treatment averaged over the mechanical treatments in MPa in the layer of 0-80 cm based on means per 5 cm.

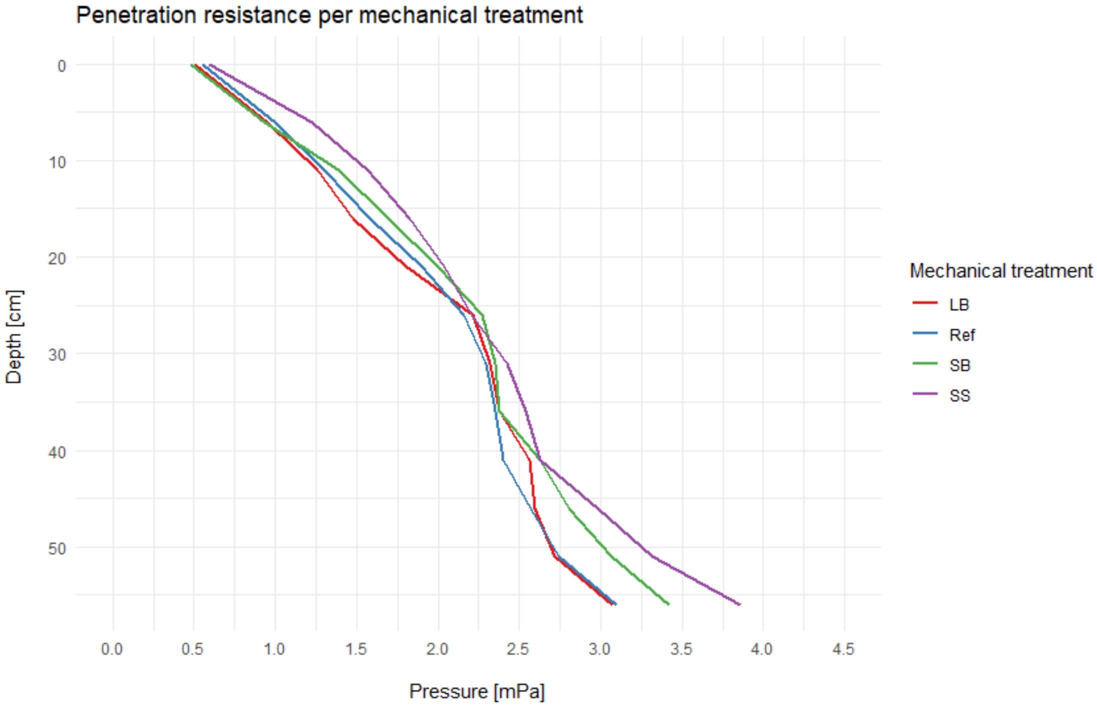


Figure 9. Penetration resistance in 2021-2022 per mechanical treatment averaged over the cover crop treatments in MPa in the layer of 0-80 cm based on means per 5 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

The mechanical treatments, despite lacking repetitions, do not show major differences between the treatments (Figure 9). The reference (Ref) and large boreholes treatment (LB) generally have a lower resistance from around 45 cm and below. Comparing the figure 9 and figure 10 we can see that there were also no major differences in penetration resistance at the beginning of the experiment shortly after the treatments (Figure 10) (LS_2020_Penetration_resistance).

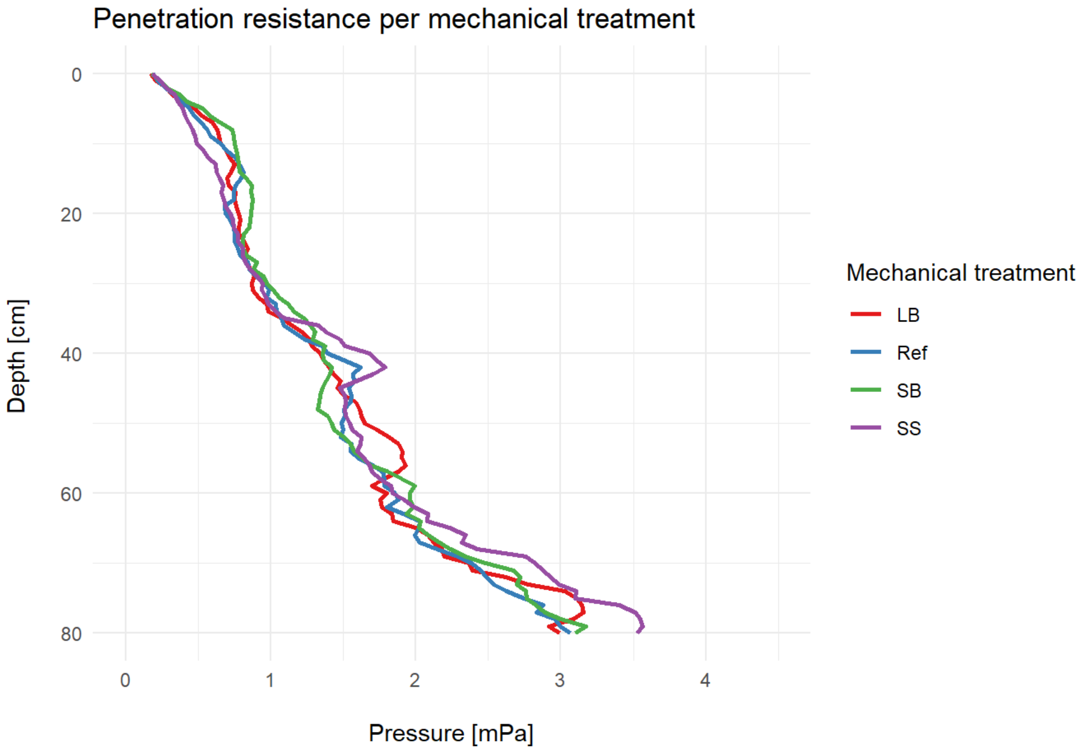


Figure 8. Penetration resistance in 2020 per mechanical treatment averaged over the cover crop treatments in MPa in the layer of 0-80 cm based on means per 1 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

3.1.5 Dry bulk density

In 2020, a few months after the mechanical treatments were executed, the soil had a low bulk density in both soil layers. In 2021 and 2022 the soil was slightly more compact (ca.+0.2 g/cm^3) however on average not in the compacted range for clay soils which is >1.46 g/cm^3. Differences between the years are likely due to the natural variation related to weather as well as the crop and its related management and are difficult to explain. Comparing the mean measured values in 2020 it is observed that the mechanical treatments all have a higher bulk density than the reference (Figure 11) and differences between the treatments were generally small in all years (0.02-0.1 g/cm3). The difference between the reference and the treatments in 2020 cannot however be confirmed statistically. This difference also does not follow the hypotheses that the treatments will have a lower dry bulk density compared to an untreated reference[1]. In both 2021 and 2022 there were also no statistically significant differences between the cover crop treatments (LS_2021_2022_Bulk_density, Table 6).

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[1] Discussion: It is likely that this difference is caused by already-present variation in the field. The dry bulk density of the treatments recovers better than the reference at 30 cm except for the subsoiling treatment. The increase in bulk density in 2021 is probably caused by the non-ploughing of the field because of the overwintering of the cover crops.

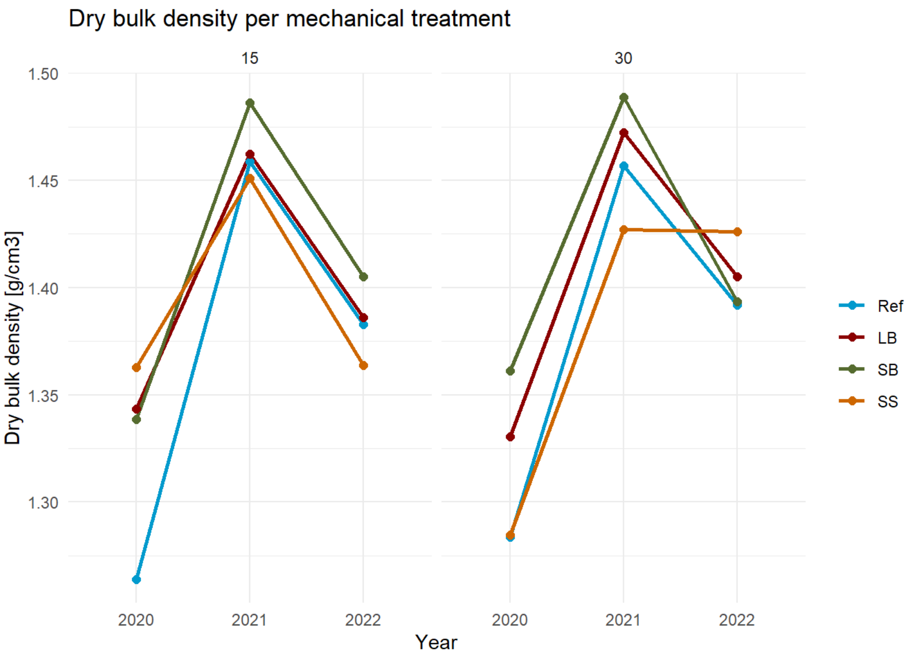

Figure 9. Dry soil bulk density [g/cm3] for the mechanical treatments at depth 15 and 30 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling (LS_202102022_Bulk_density).

Table 6. Mean bulk density in g/cm^3 in 2020-2022 on the soil depths 15 cm and 30 cm. The different colours do not indicate statistical differences but indicate relative differences between the values of that year. Root growth is reduced from 1.39 g/cm^3 and severely obstructed from 1.47 g/cm^3 and higher. Green = <1.39 g/cm^3. Yellow = 1.39-1.47 g/cm^3, Red = 1.47 g/cm^3.

Soil depth	Mechanical treatment	Cover crop treatment	2020	2021	2022
15 cm	Reference	Mixture	1.26	1.45	1.41
	Reference	Fibrous roots	1.30	1.48	1.34
	Reference	Taproots	1.23	1.45	1.40
	Large boreholes	Mixture	1.36	1.44	1.41
	Large boreholes	Fibrous roots	1.37	1.45	1.40
	Large boreholes	Taproots	1.30	1.50	1.35
	Small boreholes	Mixture	1.32	1.46	1.35
	Small boreholes	Fibrous roots	1.34	1.52	1.41
	Small boreholes	Taproots	1.35	1.48	1.45
	Deep subsoiling	Mixture	1.36	1.45	1.36
	Deep subsoiling	Fibrous roots	1.37	1.46	1.41
	Deep subsoiling	Taproots	1.36	1.44	1.33
30 cm	Reference	Mixture	1.26	1.43	1.38
	Reference	Fibrous roots	1.34	1.53	1.37
	Reference	Taproots	1.24	1.41	1.43
	Large boreholes	Mixture	1.36	1.44	1.42
	Large boreholes	Fibrous roots	1.28	1.47	1.42
	Large boreholes	Taproots	1.35	1.50	1.38
	Small boreholes	Mixture	1.38	1.52	1.40
	Small boreholes	Fibrous roots	1.36	1.46	1.37
	Small boreholes	Taproots	1.34	1.48	1.41
	Deep subsoiling	Mixture	1.31	1.42	1.38
	Deep subsoiling	Fibrous roots	1.28	1.42	1.40
	Deep subsoiling	Taproots	1.27	1.44	1.50

3.1.6 Soil moisture

In general, differences between plots in soil moisture at the moment of bulk density sampling were minor within each year (< 1-2%) (Table 7). An agronomically relevant difference would have to be at least approximately 4% (expert estimation). In both 2021 and 2022 there was no statistically significant differences between the cover crop treatments (LS_2021_2022_Moisture_rings).

Table 7. Mean soil moisture fraction in 2020-2022 on the soil depths 15 cm and 30 cm. The different colours do not indicate statistical differences but indicate relative differences between the values of that year. There is no value judgement of the moisture levels in this range of data.

Soil depth	Mechanical treatment	Cover crop treatment	2020	2021	2022
15 cm	Reference	Mixture	0.24	0.21	0.20
	Reference	Fibrous roots	0.24	0.22	0.21
	Reference	Taproots	0.24	0.22	0.21
	Large boreholes	Mixture	0.23	0.22	0.21
	Large boreholes	Fibrous roots	0.23	0.22	0.21
	Large boreholes	Taproots	0.23	0.22	0.21
	Small boreholes	Mixture	0.22	0.21	0.21
	Small boreholes	Fibrous roots	0.23	0.21	0.21
	Small boreholes	Taproots	0.23	0.21	0.20
	Deep subsoiling	Mixture	0.23	0.21	0.21
	Deep subsoiling	Fibrous roots	0.23	0.22	0.21
	Deep subsoiling	Taproots	0.23	0.22	0.22
30 cm	Reference	Mixture	0.24	0.22	0.23
	Reference	Fibrous roots	0.24	0.21	0.22
	Reference	Taproots	0.24	0.22	0.21
	Large boreholes	Mixture	0.23	0.22	0.22
	Large boreholes	Fibrous roots	0.24	0.22	0.22
	Large boreholes	Taproots	0.24	0.21	0.22
	Small boreholes	Mixture	0.23	0.21	0.21
	Small boreholes	Fibrous roots	0.23	0.23	0.21
	Small boreholes	Taproots	0.24	0.22	0.22
	Deep subsoiling	Mixture	0.24	0.23	0.23
	Deep subsoiling	Fibrous roots	0.24	0.22	0.23
	Deep subsoiling	Taproots	0.24	0.22	0.20

3.1.7 Visual soil assessment

From the treatment repetitions, means were calculated for each of six aspects (**annex 5.3**). Thereafter a mean for all scores were calculated (Table 8). Differences between treatments were generally within 1.0 which can be considered small. The largest difference was between the subsoiling treatment and the reference in the 0-25 cm layer for structure and soil life. This difference corresponds to the differences seen in penetration resistance and bulk density between these treatments where the untreated plots were less compact. This difference may have been established before the start of the experiment, therefore we cannot draw any conclusions. There were no remarkable differences between the cover crops.

Table 8. The mean score for the treatments in the visual soil assessment. The different colours do not indicate statistical differences but indicate relative differences between the values.

Mechanical treatment	**Cover crop treatment**	**Mean score**
Deep subsoiling	Diverse perennial treatment	6.3
Deep subsoiling	Perennial with fibrous roots	5.6
Deep subsoiling	Perennial with taproot	5.8
Small boreholes	Diverse perennial treatment	6.3
Small boreholes	Perennial with fibrous roots	6.3
Small boreholes	Perennial with taproot	5.8
Large boreholes	Diverse perennial treatment	6.4
Large boreholes	Perennial with fibrous roots	6.3
Large boreholes	Perennial with taproot	6.5
Untreated	Diverse perennial treatment	6.8
Untreated	Perennial with fibrous roots	6.3
Untreated	Perennial with taproot	6.5
Means for mechanical treatments		
Deep subsoiling		5.9
Small boreholes		6.1
Large boreholes		6.4
Untreated		6.5
Means for cover crop treatment		
Diverse perennial treatment		6.5
Perennial with fibrous roots		6.1
Perennial with taproot		6.2

3.2 Vredepeel

3.2.1 Crop yield and quality – Potato 2022

There were no significant effects from the experimental treatments on the gross yield (Figure 12) or net yield or the yield in the size classes <40 mm, 40-70 mm and >70 mm. The experimental treatments also showed no significant effects on the product tare. The four extra treatments show similar results as the experimental treatments (see year report) (VP_2022_Potato_yield).

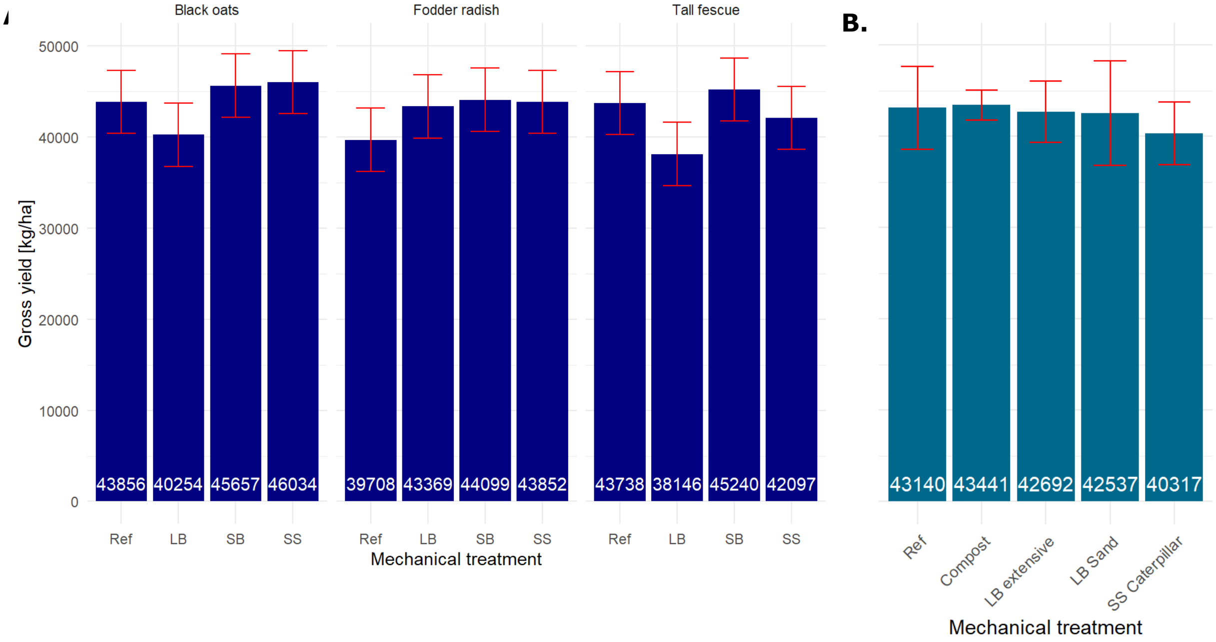

Figure 12.. (A) Gross potato yield [kg/ha] based on estimated marginal means (EMM) with the standard error in the error bars. There were no statistically significant differences. (B) Gross potato yield with standard deviation in the error bars. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

3.2.2 Crop yield and quality– Silage maize 2021

Mechanical treatments showed a trend in the statistical model (p=0.07) and the cover crop showed a significant effect (p=0.03) in which the treatments with black oats (51388 kg/ha), on average, shows a significantly lower fresh yield of ca. 2 tonnes per ha than the treatments with tall fescue (53445 kg/ha) (p=0.04). Pairwise comparisons showed no significant differences between any of the treatments in fresh or dry matter yield (Figure 13). The quality parameters dry matter concentration, sugar concentration, neutral detergent fibre and VEM (Voeder Eenheid Melk) showed no significant effects of the treatments (VP_2021_Silage_maize_yield). Silage maize yield and quality was not measured for the extra treatments.

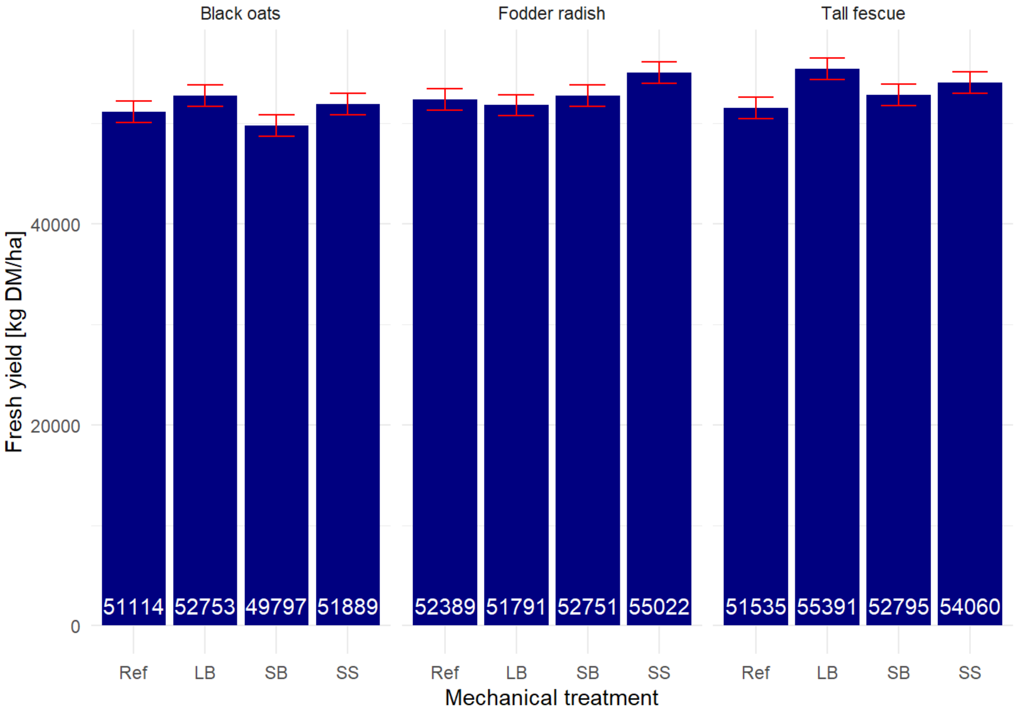

Figure 10. Fresh yield [kg/ha] based on estimated marginal means (EMM) with the standard error in the error bars. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

3.2.3 Cover crop biomass

Analysis of cover crop biomass was done separately for the year 2020 as the cover crop in this year was part of the treatment and gives an indication of how impactful the cover crop treatment was. In this year, it might however be possible to see some effects of the mechanical treatments. The years 2021-2022 were analysed together. Aboveground cover crop biomass seems to be a bit lower for the small and large borehole treatment

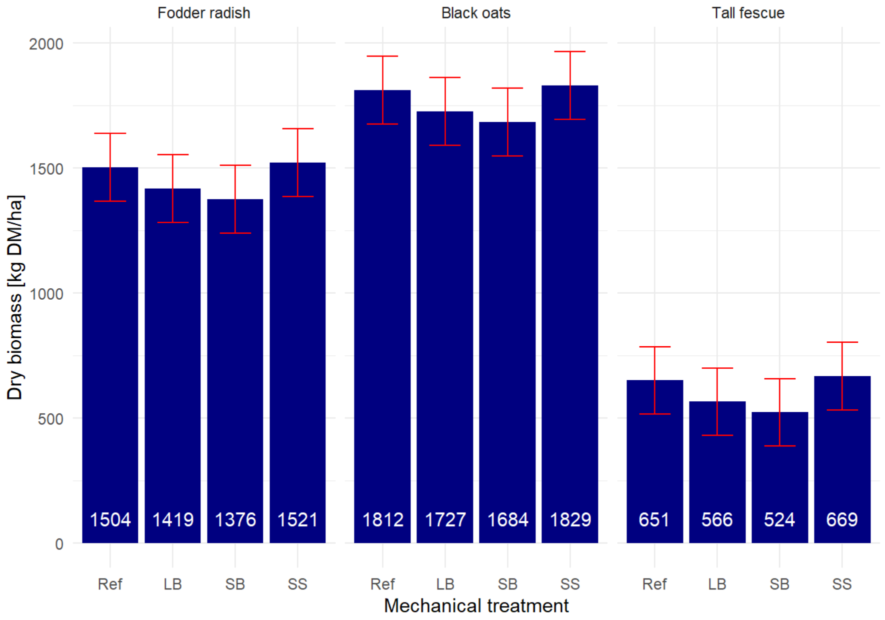

Figure 14. Dry aboveground mass of cover crop treatments [kg/ha] in 2020 based on estimated marginal means (EMM) with the standard error in the error bars. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. There were no statistically significant differences.

compared to subsoiling and the reference (Figure 14). It’s different for the belowground biomass where the small boreholes seem to perform better and large boreholes and subsoiling lower compared to the reference (Figure 15).

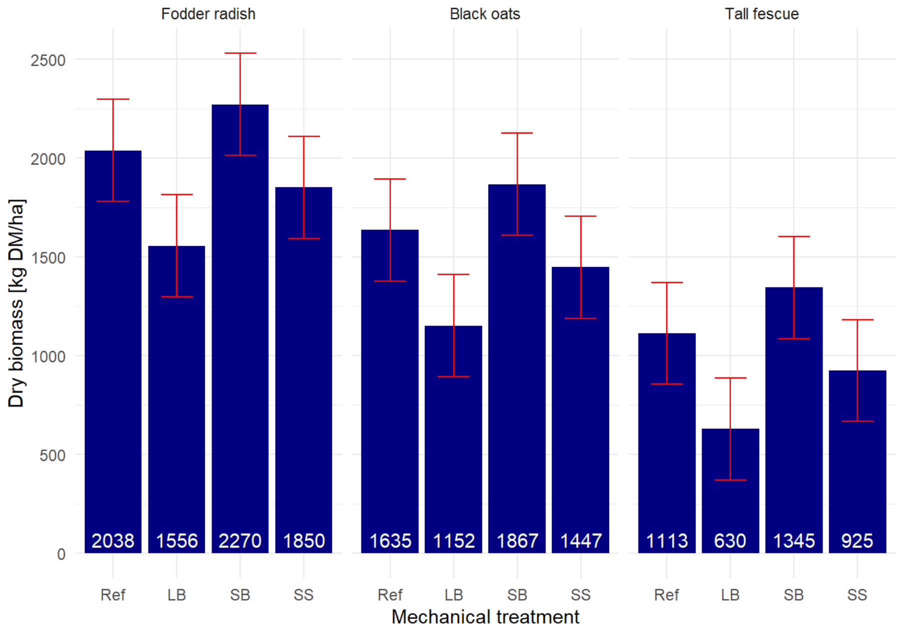

Figure 15. Dry belowground mass of cover crop treatments [kg/ha] in 2020 based on estimated marginal means (EMM) with the standard error in the error bars. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. There were no statistically significant differences.

In 2020 there were no significant effects from the mechanical treatments (Above: p=0.76, Below: p=0.12) (VP_2020_2022_Cover_crop). The tall fescue produced significantly less biomass (Above: 594 kg/ha, Below: 1003 kg/ha, Total: 1597 kg/ha) than the other cover crop treatments, followed by black oats (1763 kg/ha, Below: 1525 kg/ha, Total: 3288 kg/ha) and fodder radish (1428 kg/ha, Below: 1929 kg/ha, Total: 3357 kg/ha) (Figure 14, Figure 15, next page). Based on this, we expect the effects of the treatments to be the largest for fodder radish and black oats, although the specific rooting patterns of the species can influence the compounded effect. For both above- and belowground biomass there are repeating patterns which seems related to the mechanical treatment, although this is not statistically proven.

In the years 2021-2022 there were no significant effects of treatments in the above- and belowground biomass of the cover crops. In both years the belowground biomass of the treatment with large boreholes is higher than in the reference, and the small boreholes and subsoiling lower than in the reference treatment (n.s.). This is another pattern than is observed than in the year 2020 (Figure 16, Figure 17). Black oats has a slightly higher yield than the other crops (n.s.), which corresponds with the observed effect on increased maize yield from black oats in 2021. A possible cause of this is a reduction in the population of the plant-parasitic nematode *P. penetrans* due to the black oats compared to the other cover crops, however no measurements were made of this.

The extra fields showed no interesting effects from the mechanical treatments in 2021-2022 (VP_2020_2022_Cover_crop, year report 2022).

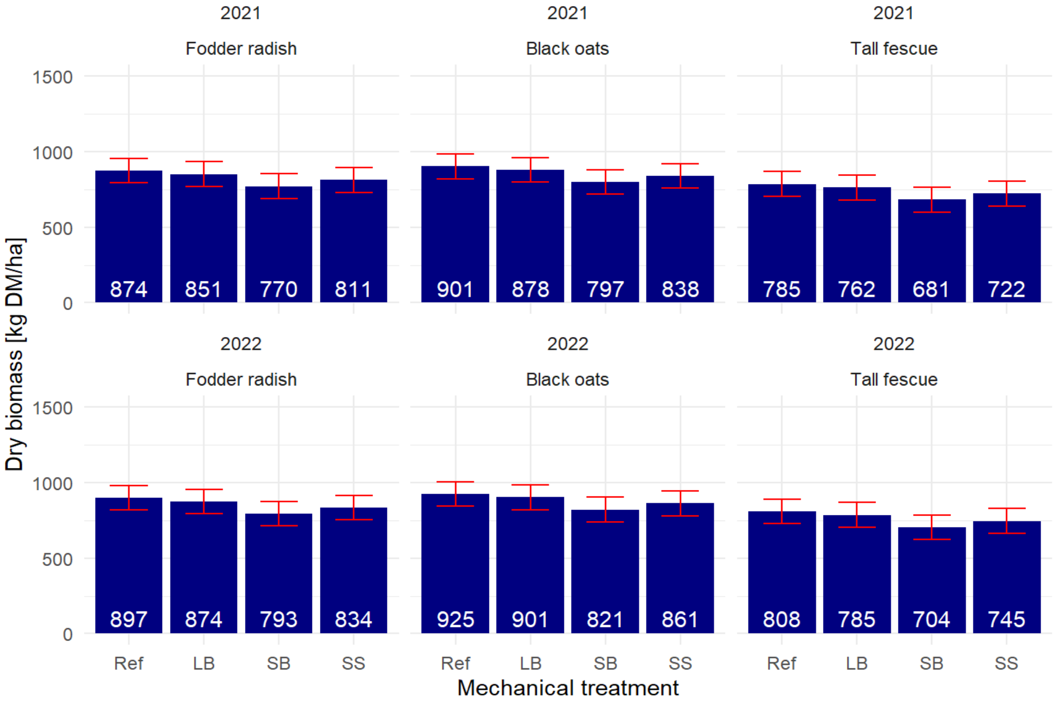

Figure 16. Dry aboveground mass of cover crop treatments [kg/ha] based on estimated marginal means (EMM) with the standard error in the error bars. In 2021 the cover crop was tall fescue and in 2022 it was fodder radish + black oats. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. There were no statistically significant differences.

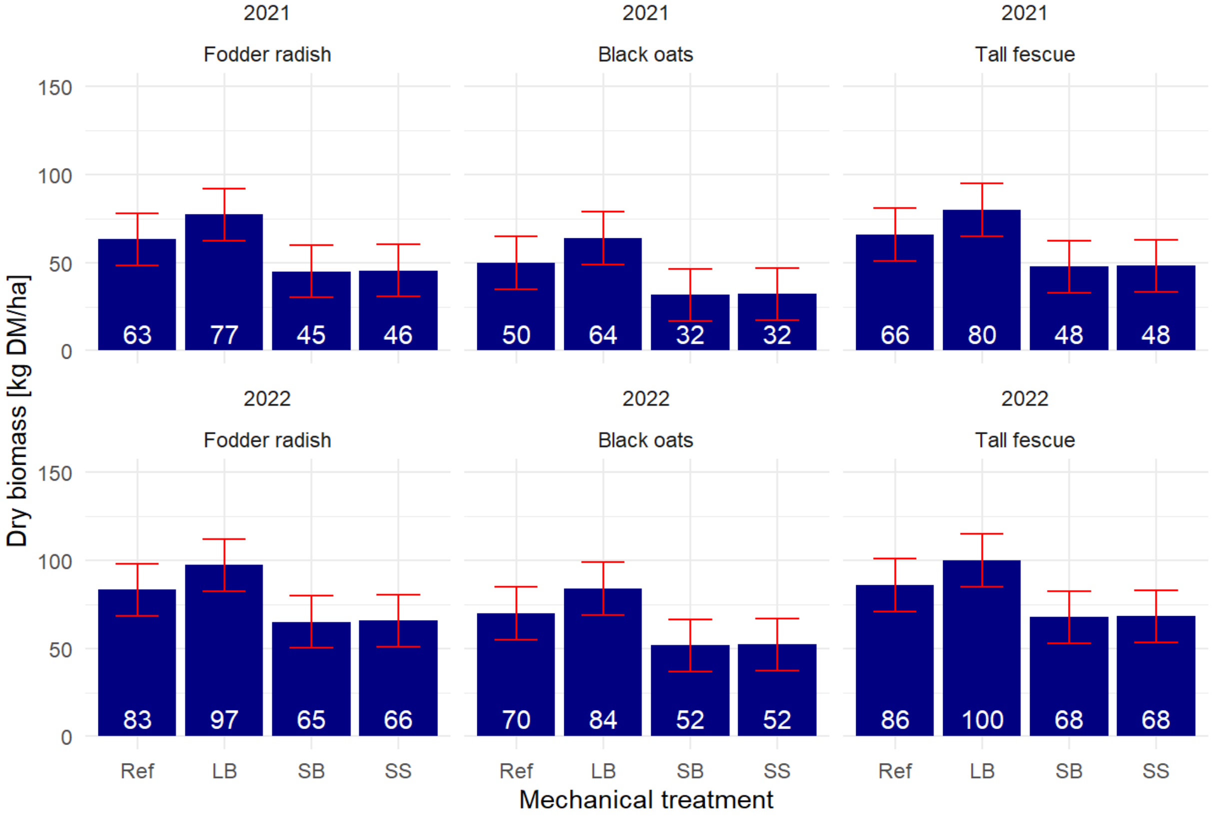

Figure 17. Dry belowground mass of cover crop treatments [kg/ha] based on estimated marginal means (EMM) with the standard error in the error bars. In 2021 the cover crop was tall fescue and in 2022 it was fodder radish + black oats. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. There were no statistically significant differences.

3.2.4 Nitrate concentration in groundwater

Nitrate levels were measured in three years: 2021-2022. Nitrate leaching levels were on average very high (>100 mg NO_3/L) for all the treatments in all the years (Figure 18) (VP_2021_2022_Nitrate_leaching). The year effect as well as the interaction between the mechanical and cover crop treatments was significant ($p<0.01$). Across the years, the fodder radish in the subsoiling treatment had a significantly lower concentration than the large boreholes treatment of fodder radish as well as the subsoiling treatment with black oats and tall fescue (all $p<0.05$) (Figure 18). This means the subsoiling treatment shows contrasting effects for the different cover crops. This is difficult to explain since these are measurements from the years after the cover crops themselves were grown and because fodder radish creates macro pores with their taproots which hypothetically could lead to more nitrogen leaching through these pores.

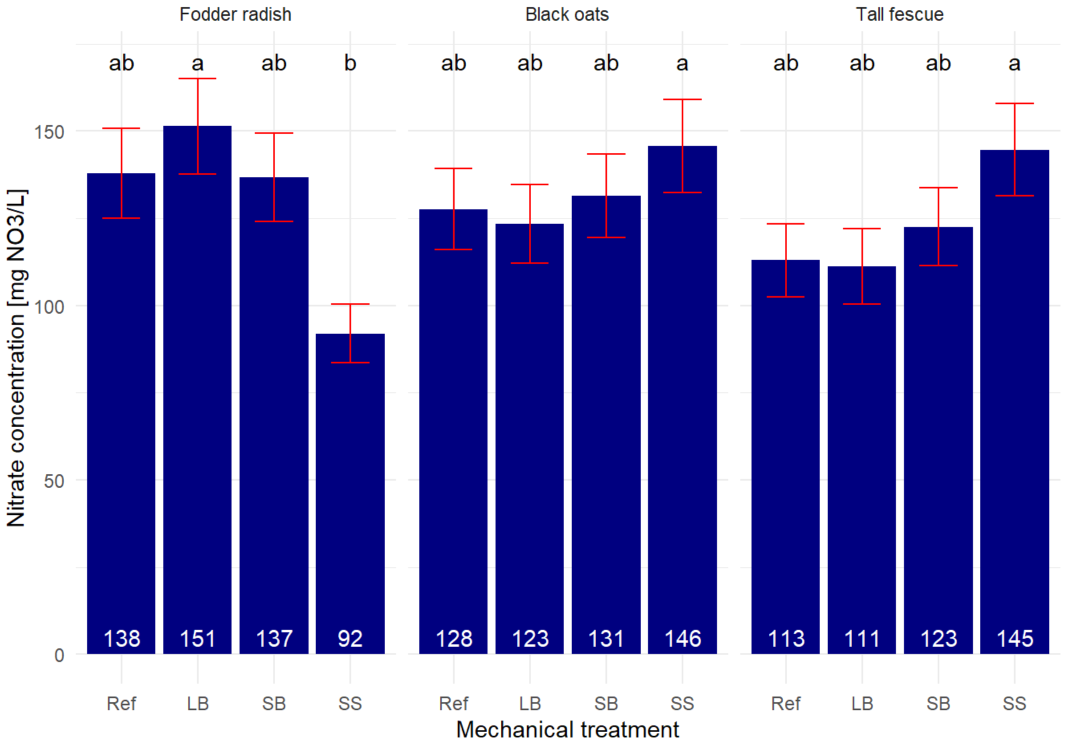

Figure 11. Nitrate concentration in groundwater 2021-2023 based on estimated marginal means (EMM) with the standard error in the error bars. Statistically significant differences between treatments are indicated with different letters. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

Effects in nitrate concentration in groundwater from the cover crop are expected in the year 2021 due to uptake of nitrogen from the cover crop treatment. In this year a larger leaching is observed for tall fescue although not significant, corresponding with the lower biomass accumulated by this crop in 2020. In 2022-2023 effects could be seen based on influence on structure, as nitrogen effects are likely to be smaller in these years. It is also expected that these structure-effects are similar in both these years.

3.2.5 Penetration resistance

Analysis of the penetration resistance was done separately for the year 2020 as this measurement was done during the cover treatment. For this data, the effect on the mechanical treatment can still be evaluated. The years 2021-2022 were analysed together.

In 2020 there were significant differences between the subsoiling treatment and the other treatments between 6-40 cm depth ($p<0.001$). From 26-35 cm depth there was also a significant difference between the reference and the large boreholes treatment ($p<0.01$) (Figure 19) (VP_2020_Penetration_resistance). As expected, the cover crop as a factor did not have a significant effect in 2020. A significant lowering effect of subsoiling on the penetration resistance in the months just after the treatment is expected. Also the relative differences between the boreholes and the reference are in line with the expectations.

In the period 2021-2022 the resistance profile has changed significantly with a smaller difference between the mechanical treatments. There were no significant effects from the mechanical treatment or the cover crop treatments (Figure 20, Figure 21) (VP_2021_2022_Penetration_resistance).

Over the whole duration of the experiment the extra treatments showed that subsoiling with caterpillar had a lower resistance than the other treatments (Figure 22) which was also seen in the replicated treatments in 2020.

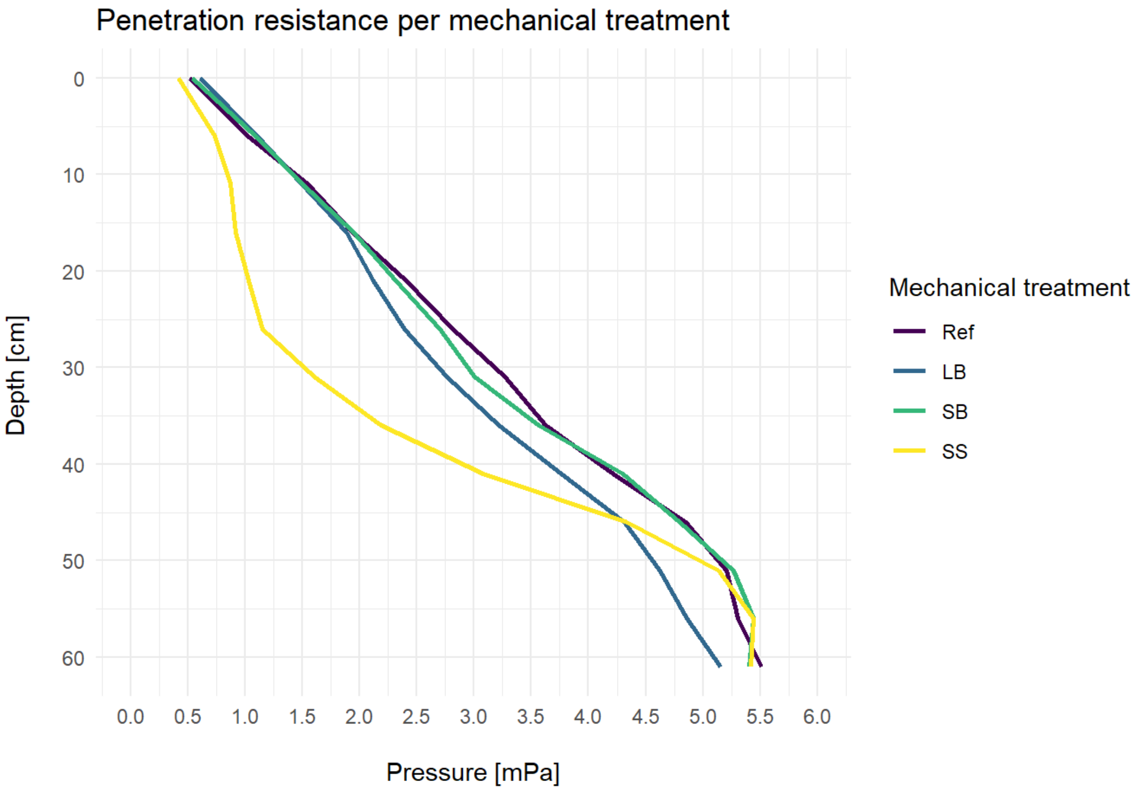

Figure 19. Mean penetration resistance in 2020 across the soil profile 0-65 cm for the replicated treatments, per 5 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

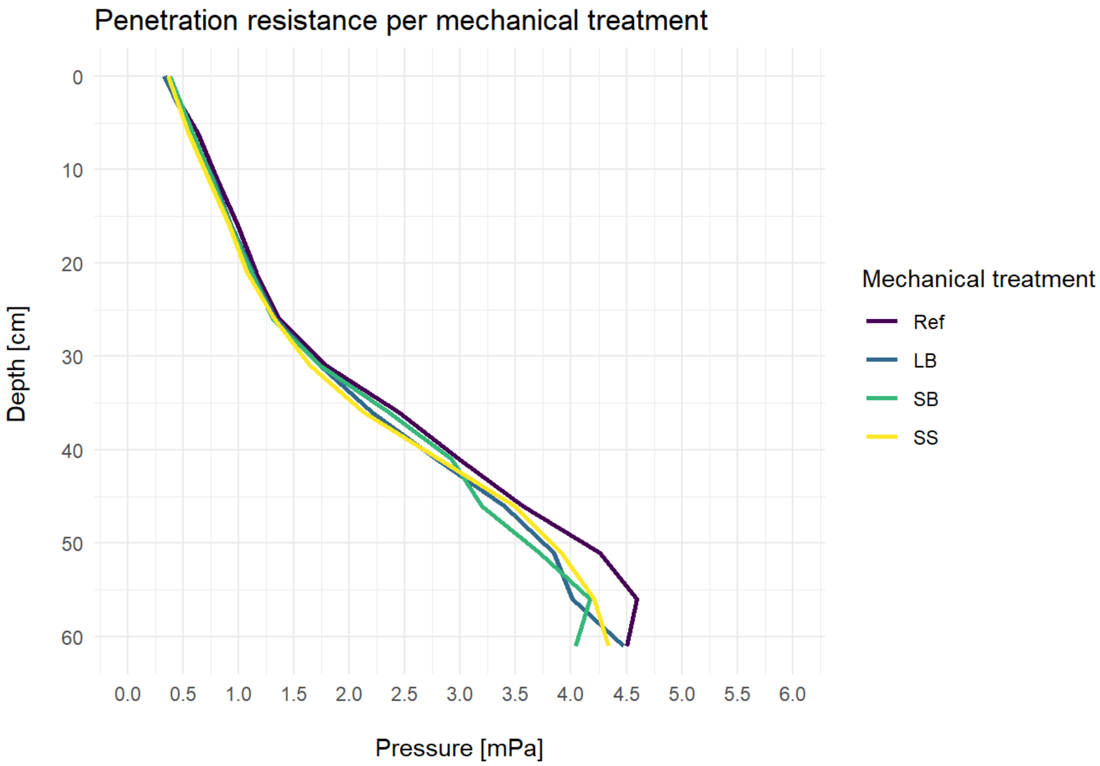

Figure 12. Mean penetration resistance in 2021-2022 across the soil profile 0-65 cm for the replicated treatments, per 5 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

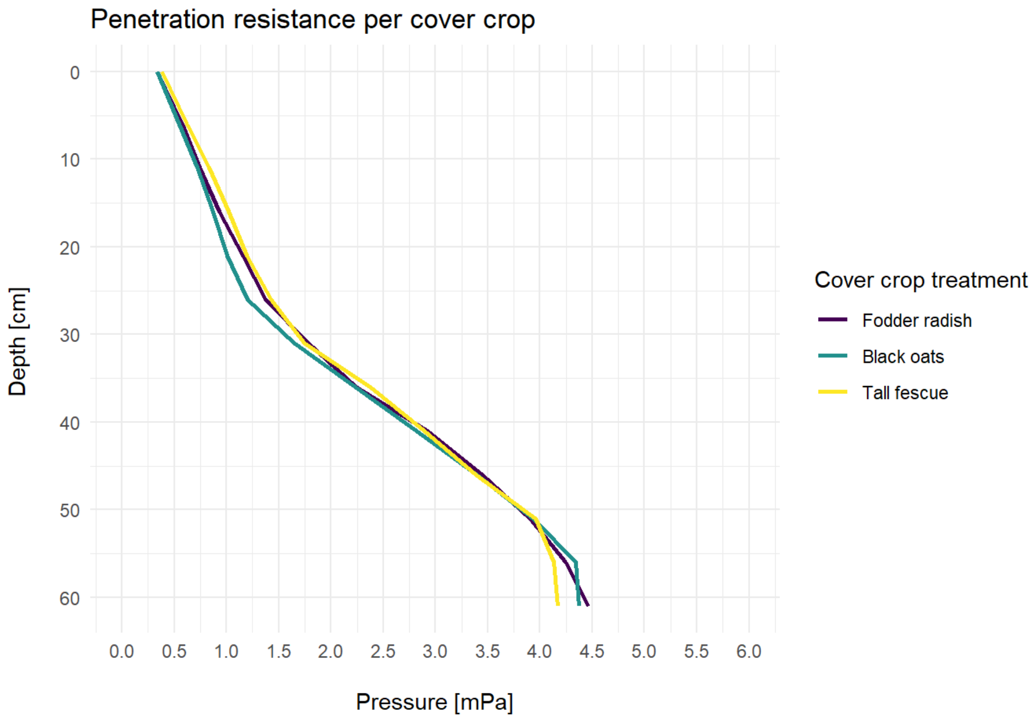

Figure 21. Mean penetration resistance in 2021-2022 across the soil profile 0-65 cm for the replicated treatments, per 5 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling.

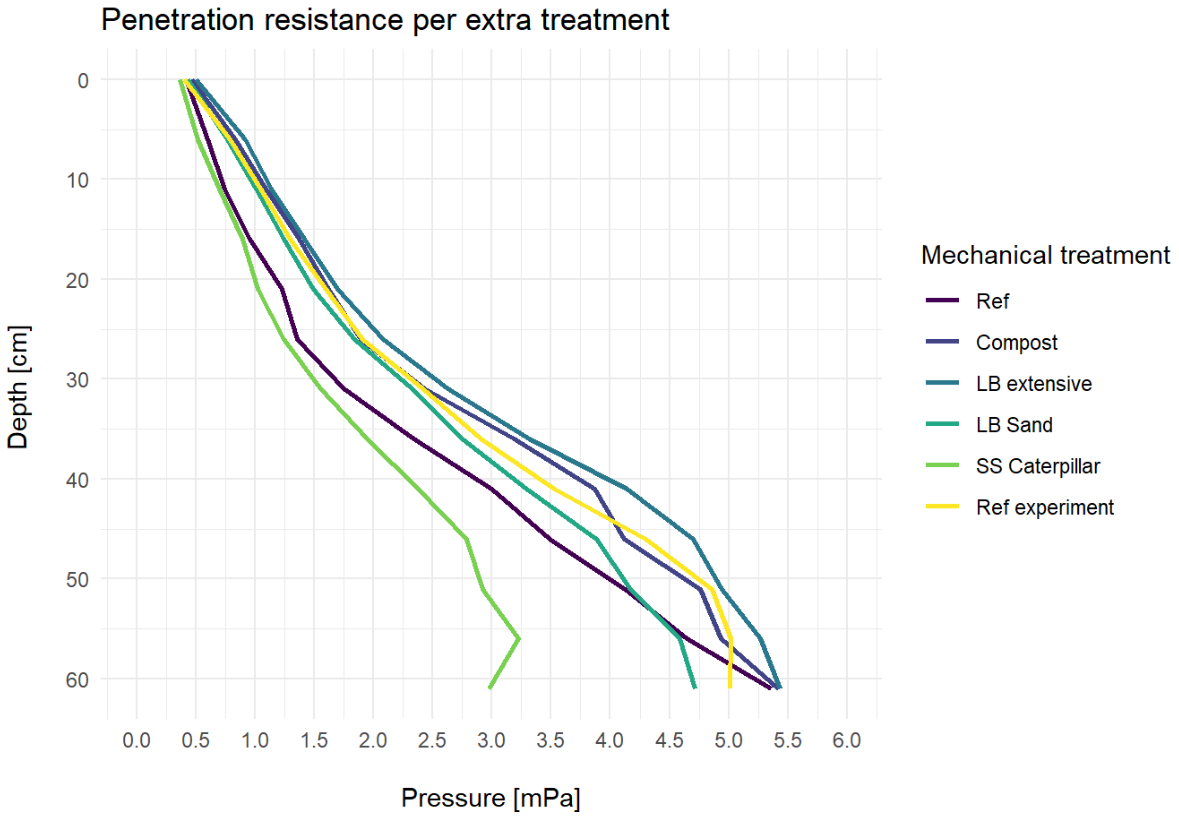

Figure 13. Mean penetration resistance in 2020-2022 across the soil profile 0-65 cm for the extra treatments, per 5 cm. Ref = No treatment, LB = Large Boreholes, SB = Small Boreholes, SS= Subsoiling. "Ref experiment" is the reference treatment within the experiment, available in randomized replications.

3.2.6 Dry bulk density

There were no significant effects from the experimental treatments on the dry bulk density at 5-10 cm and 20-25 cm depth (Table 9) (VP_2021_2022_Bulk_density).

Table 9. Mean dry bulk density in g/cm^3 2021-2022 on the soil depths 5-10 cm and 20-25 cm. There were no statistically significant differences. Root growth is reduced from 1.69 g/cm^3 and severely obstructed from 1.85 g/cm^3 and higher. The data is below this range.

Mechanical treatment	**Cover crop**	**5-10 cm (n.s.)**	**20-25 cm (n.s.)**
Reference	Fodder radish	1.38	1.36
Reference	Black oats	1.35	1.38
Reference	Tall fescue	1.34	1.36
Large boreholes	Fodder radish	1.37	1.35
Large boreholes	Black oats	1.35	1.37
Large boreholes	Tall fescue	1.39	1.38
Small boreholes	Fodder radish	1.35	1.36
Small boreholes	Black oats	1.34	1.41
Small boreholes	Tall fescue	1.36	1.34
Deep subsoiling	Fodder radish	1.37	1.39
Deep subsoiling	Black oats	1.36	1.40
Deep subsoiling	Tall fescue	1.35	1.35
Extra treatments (outside experiment)			
Ref	Fodder radish	1.33	1.37
Compost	Fodder radish	1.34	1.35
LB extensive	Fodder radish	1.35	1.36
LB Sand	Fodder radish	1.34	1.38
SS Caterpillar	Fodder radish	1.32	1.39

3.2.7 Soil moisture

In the layer 5-10 cm there was a significant difference in soil moisture between black oats (17%) and tall fescue (22%) in the reference treatment ($p<0.02$), and between the black oats in the reference treatment and small boreholes treatment (22%) ($p<0.01$) (Table 10) (VP_2021_2022_Moisture_rings). A difference of 5% is relatively large. These results are difficult to interpret due to the differing effects of black oats for the two treatments. It might be an indication of a better capillary rise of water in the small borehole treatment and the tall fescue.

Table 10. Soil moisture fraction in 2021-2022 based on estimated marginal means (EMM) on the soil depths 5-10 cm and 20-25 cm. Significant differences are indicated with different letters. Significant differences were only found on 5-10 cm depth.

Mechanical treatment	**Cover crop**	**5-10 cm**	**Stat. significance**	**20-25 cm (n.s.)**
Reference	Fodder radish	0.21	ab	0.20
Reference	Black oats	0.17	b	0.18
Reference	Tall fescue	0.22	a	0.22
Large boreholes	Fodder radish	0.19	ab	0.18
Large boreholes	Black oats	0.20	ab	0.20
Large boreholes	Tall fescue	0.20	ab	0.19
Small boreholes	Fodder radish	0.21	ab	0.19
Small boreholes	Black oats	0.22	b	0.20
Small boreholes	Tall fescue	0.20	ab	0.20
Deep subsoiling	Fodder radish	0.21	ab	0.22
Deep subsoiling	Black oats	0.19	ab	0.20
Deep subsoiling	Tall fescue	0.20	ab	0.21
Extra treatments (outside experiment)				
Ref	Fodder radish	0.19		0.18
Compost	Fodder radish	0.18	Not tested	0.16
Large boreholes extensive	Fodder radish	0.18		0.17
Large boreholes Sand	Fodder radish	0.19		0.18
Subsoiling Caterpillar	Fodder radish	0.19		0.18

3.2.8 Visual soil assessment

From the treatment repetitions, means were calculated for each of six aspects (annex 5.3). Thereafter a mean for all scores were calculated. From the treatment repetitions, means were calculated for each of six aspects (annex 5.3). Thereafter a mean for all scores were calculated. Differences between treatments were generally within 1.0 which can be considered small. The largest difference was between the subsoiling treatment and the reference in the 0-25 cm layer for structure and soil life. This difference corresponds to the differences seen in penetration resistance and bulk density between these treatments where the untreated plots were less compact. This difference may have been established before the start of the experiment, therefore we cannot draw any conclusions. There were no remarkable differences between the cover crops. The extra treatments show larger differences but these plots were also located at different places making it difficult to interpret.

Table 11. *The mean score for the treatments in the visual soil assessment. The different colours do not indicate statistical differences but indicate relative differences between the values.*

Mechanical treatment	**Cover crop treatment**	**Mean score**
Reference	Annual with tap root	7.3
Reference	Annual with fibrous root	6.8
Reference	Perennial with fibrous root	7.1
Deep subsoiling	Annual with tap root	6.9
Deep subsoiling	Annual with fibrous root	7.2
Deep subsoiling	Perennial with fibrous root	7.1
Large boreholes	Annual with tap root	6.8
Large boreholes	Annual with fibrous root	6.7
Large boreholes	Perennial with fibrous root	6.7
Small boreholes	Annual with tap root	7.0
Small boreholes	Annual with fibrous root	6.8
Small boreholes	Perennial with fibrous root	6.9
Mechanical treatment		
Reference		7.1
Deep subsoiling		7.1
Large boreholes		6.7
Small boreholes		6.9
Cover crop treatment		
Annual with tap root		7.0
Annual with fibrous root		6.9
Perennial with fibrous root		6.9
Extra mechanical treatments (outside experiment)		
Large boreholes Sand		6.7
Large boreholes Extensive		7.4
Compost		7.5
Subsoiling Caterpillar		6.9
Reference		6.5

4 Discussion and conclusion

4.1 Synthesis of experiments

In **Lelystad** the effects of the treatments were generally minor and did not result in effects on crop yield or cover crop biomass development. There were significant effects from the cover crop treatments, with the taproot treatment having the lowest penetration resistance. However, in practical terms these effects were minor. Although no replications were available to draw strong conclusions, the mechanical treatments showed no indications of meaningful effects on the penetration resistance directly after treatment as well as after two years after the treatment. Furthermore, no significant effects of cover crop treatments were seen on bulk density or soil moisture and the mechanical treatments indicated a negligible influence. Effects from the cover crops grown in 2019 need to be included in the interpretation of effects from cover crops in 2020, which makes it more difficult to draw relationships between specific cover crops and rooting patterns and effects on variables.

In **Vredepeel** there were also no effects on crop yield or cover crop biomass development from the mechanical treatments. The cover crop treatment showed differences in silage maize yield between the tall fescue and black oats which lacks explanation. The extra treatments did not show any interesting indications of effects on these variables. Nitrate leaching was influenced by some of the treatments although a good hypothesis for explaining this is lacking. The penetration resistance showed lower resistance in the subsoiling treatment and large boreholes treatment, however only in the year of the treatment. Also deep subsoiling, in the extra treatments, showed a relatively large loosening effect on the soil. Differences between the treatments in later years returned to insignificant differences between the treatments. Furthermore, similarly as to the other variables differences in bulk density and soil moisture were very minor and not significant.

4.2 Discussion

Even though there was a lack of repetitions of mechanical treatments in Lelystad it can be concluded that there were no indications of meaningful effects from the large boreholes or small boreholes treatments at any of the two sites. The lack of measured effects can be due to several reasons and the reasons are difficult to pinpoint. That the treatments did not result in effects on yields may have to do with the soil conditions of the experimental field, these were not compacted to the extent that it hindered crop growth and caused decreases in yield at the beginning of the experiments. This may be due to the fact soil physical characteristics in general show a lot of variation in space but also dependent on the prevailing weather at short term and long term. The level of compaction of the soil may hence have decreased by natural means such as frost, shrinking/drying and swelling before or at an early phase of the experiments. The statistical analysis of Vredepeel showed block as a significant factor for many variables and sometimes also the additional factor of row. This indicates the presence of large spatial variation in the experimental field which is undesired, however it doesn't not affect the ability to draw conclusions from the experiment. This also shows the challenge in finding homogeneously compacted plots for experiments due to compaction which is a very local phenomenon. An interesting option to explore is purposely compacting the experimental field before the start of the experiment by driving with heavy vehicles under wet conditions like in the experiment as described by Håkansson (1985). This can have a high impact on soil quality of the experimental field over longer time.

Another possible reason for lack of effects is that they are difficult to bring into picture with the measurements used and the measurements generally available. Bulk density and penetration resistance provide a very local measure of the compactness of the soil while the boreholes treatments tested also only influences the very local area where the drill enters the soil. Alternative methods to determine soil compactness are however lacking. In this context, it is also worth mentioning the lack of methods and difficulty to research physical soil properties in general. Due to the large variability in soil physical properties, it requires a lot of measurements in order to be able to establish effects from treatments rather than effects from the weather or field variability.

The true effectivity in reducing the effects from subsoil compaction, should also be evaluated in situations of extremes in water availability (minimum-maximum) which is when soil compaction is a major issue. Such research would be weather dependent with large variations between the years, complicating the research further, unless simulations of drought and flooding can be implemented. During the three growing seasons of this experiment there were only extremely dry periods but no extremely wet periods which limits the scope of the experiment. Soil moisture was measured in these years using sensors, although not in sufficient repetitions in order to statistically analyse it. Next to this, the soil sensors have proved to be very challenging to use in research. The sensors break easily, suddenly stop working in periods without the researchers being aware of this, they lose contact with the soil due to changing weather conditions (mainly clay soils), cannot communicate with the ground station or they are not sufficiently calibrated. These are causes why the data from the soil moisture meters is considered unreliable and is not used for drawing conclusions (see 5.4). Other methods to investigate soil water management are for example infiltration rate measurements although this is expensive and time consuming. In case of extremely wet periods, observations of water levels or waterlogging would also provide interesting data on the effect of the treatments.

A combination of mechanical measures and cover crops was expected to have a large impact on soil compaction. Belowground biomass of cover crops was measured up to 30 cm deep and visual rooting was recorded up to 50 cm deep. The potential of deep-rooted crops should be investigated better by sampling up to 70-80 cm. Unfortunately, the existing mechanical equipment for taking soil probes is not suited for these depths.

The combination of difficulty in doing research on soil compaction in homogeneously compacted soil and the lack of suitable measurement methods might be a reason why effects have not been found. Due to the mentioned difficulties, it is not possible at this stage to conclude whether drilling of large or small holes has a potential to ameliorate (effects of) subsoil compaction.

Based on the above discussion a few recommendations can be made:

- Severe soil compaction needs to be established on the experimental plot well-before the start of the experiment for a period of more than one year in order to be able to research subsoil compaction. This compaction needs to be as homogenous as possible.
- Investigate soil moisture effects from the measures against soil compaction using other methods or protocols. A simple option is to take soil samples of a fixed volume and to calculate the volumetric moisture content after drying the sample, or using a handheld soil moisture sensor.

4.3 Conclusions

Subsoil compaction is a growing and serious problem in industrialized farming areas due to use of heavy machinery under poor moisture conditions. This is causing decreases in yields due to difficulties for crops to grow roots and because it limits the flow of water through the compacted soil layer in both directions. In this experiment we investigated whether the drilling of small boreholes and large boreholes filled with substrate in combination with cover crops can ameliorate subsoil compaction.

The drilling of boreholes to ameliorate subsoil compaction showed only minor effects on crop yields and soil structure parameters. However, from this experiment we cannot definitively conclude what the potential is of the drilling of boreholes to ameliorate subsoil compaction due to lack of homogeneously compacted soil in the experiments, natural restoration of the soil and uncertainty whether the methods were able to measure possible effects. Therefore, it is recommended that the potential of these measures to ameliorate subsoil compaction are further investigated.

This means that the new measures to ameliorate subsoil compaction that were tested in these experiments, didn’t provide solutions for today’s farmers' practice. Even if the method of drilling of boreholes would have been shown effective, it would be very costly and time-consuming to implement with the current techniques which means that the method would require further development. Farmers are aware of the measures to prevent soil compaction, however the wet weather conditions during harvests often make it unavoidable to cause (sub)soil compaction. Natural processes can help to restore the soil structure but are dependent on soil type and climate conditions. Since the available methods for amelioration of subsoil compaction aren’t effective and sustainable, the prevention of subsoil compaction should remain a high priority.

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5 Annexes

5.1 Baseline penetration resistance Lelystad

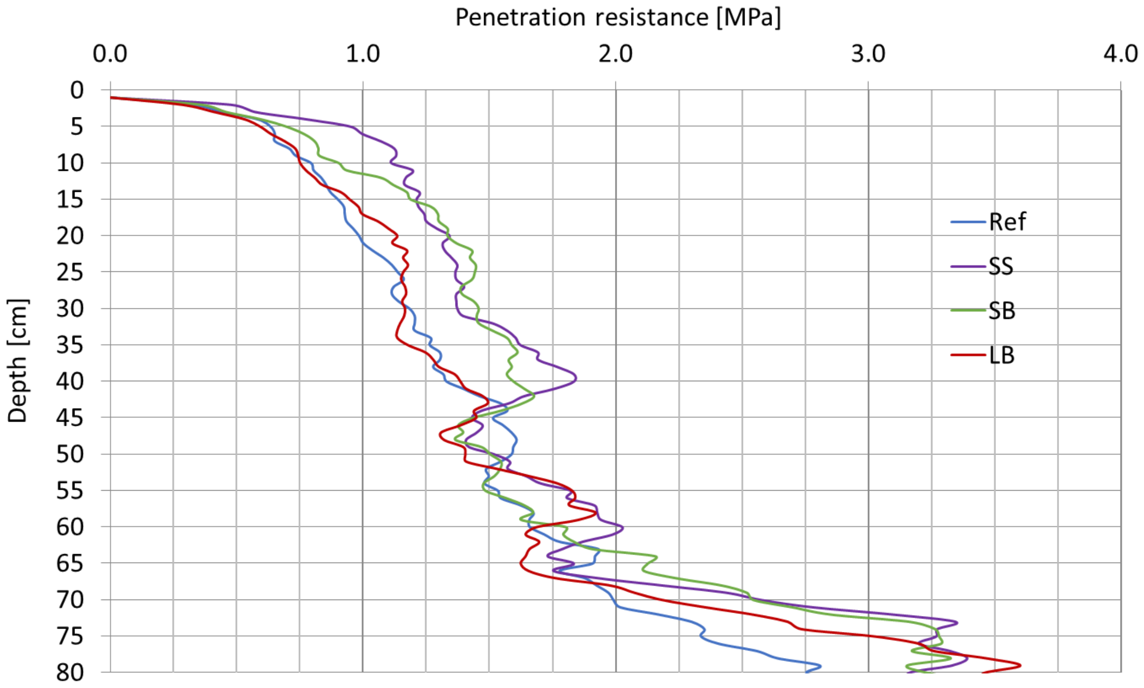
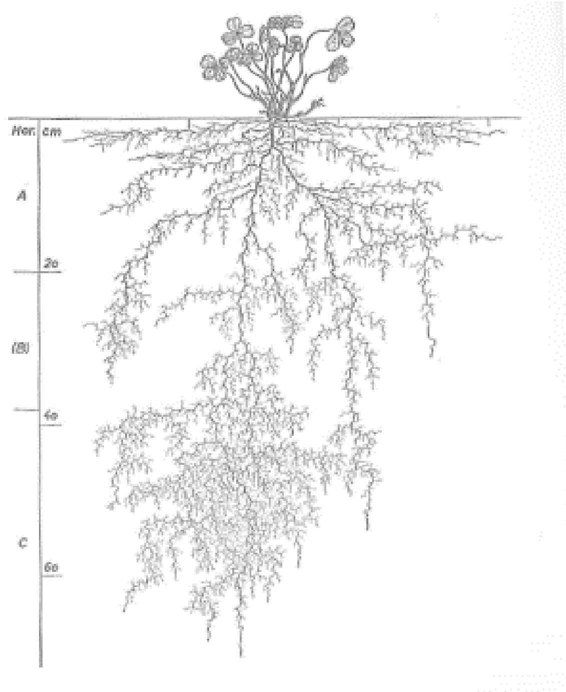


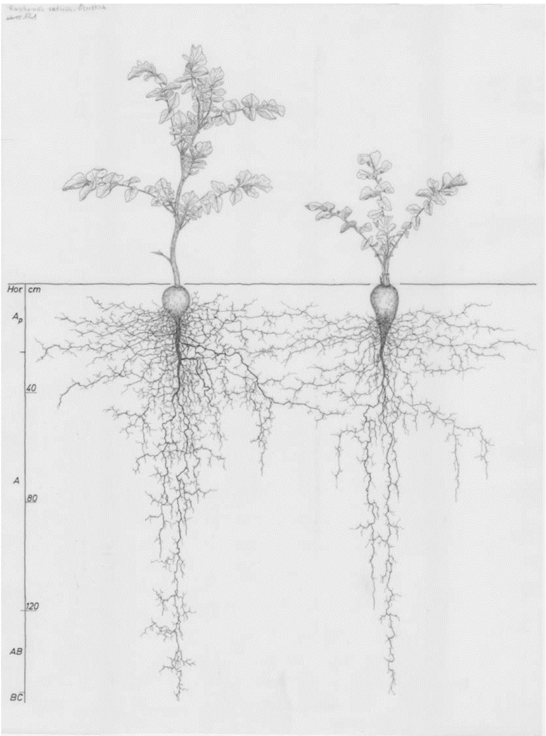
Figure 14. Baseline penetration resistance in MPa at the experimental plot in Lelystad in 2019.

5.2 Crop root system

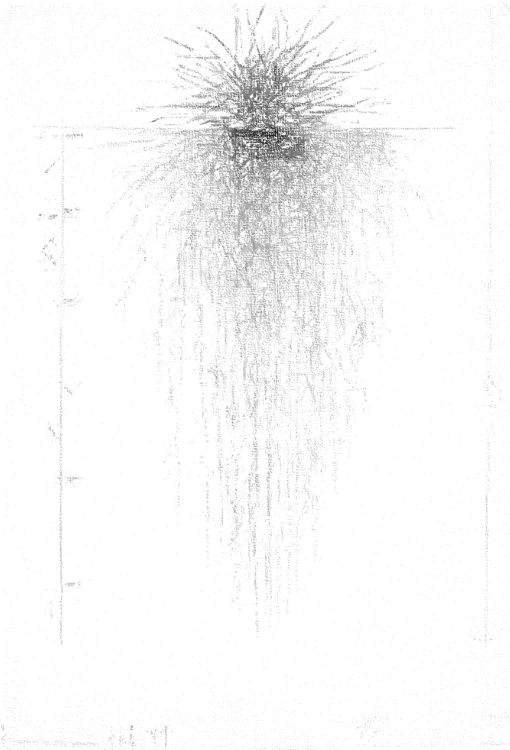
White clover (*Trifolium repens*)



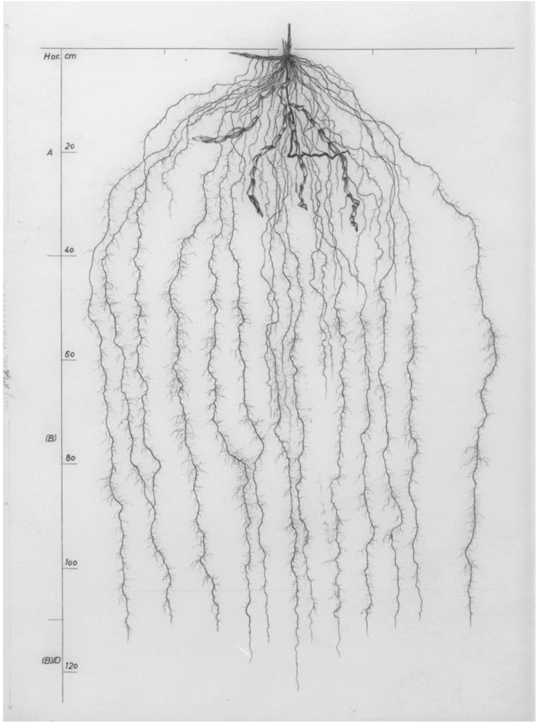
Fodder radish (*Raphanus sativus*)



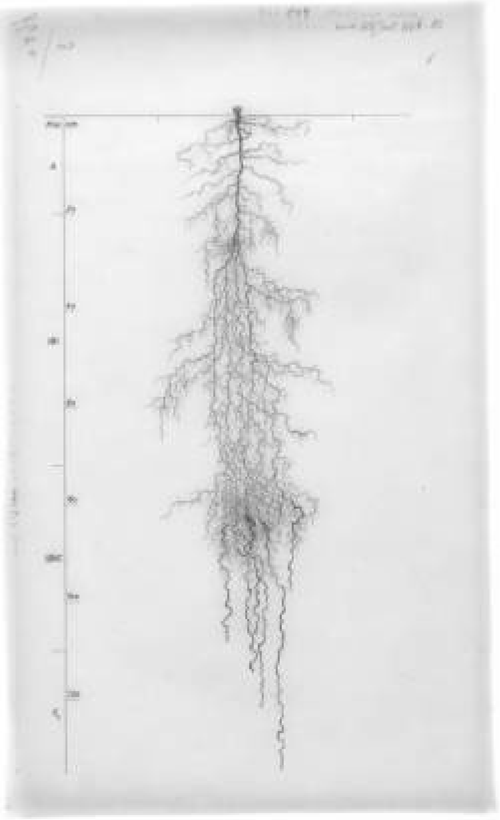
Tall fescue (*Festuca arundinacea*)



Sorghum *(Sorghum halepense)*



Lucerne (*Medicago sativa*)



5.3 Visual soil assessment results

5.3.1 Lelystad

Table 12. Results from the visual soil assessment in Lelystad in 2022. Each number is based on four repetitions.

Mechanical treatment	Cover crop treatment	Structure 0-25 cm	Structure 25-50 cm	Soil life 0-25 cm	Rooting 0-25 cm	Rooting 25-50 cm	Water regulation 0-50 cm	Average score	Min	Max
Deep subsoiling	Diverse perennial treatment	5.0	7.0	5.3	6.0	6.7	7.8	6.3	5.0	7.8
Deep subsoiling	Perennial with fibrous roots	5.7	5.3	4.7	5.5	5.5	7.0	5.6	4.7	7.0
Deep subsoiling	Perennial with taproot	4.7	7.0	4.7	6.2	6.0	6.5	5.8	4.7	7.0
Small boreholes	Diverse perennial treatment	5.7	6.5	5.7	6.3	6.7	7.3	6.3	5.7	7.3
Small boreholes	Perennial with fibrous roots	5.3	7.0	6.3	5.7	5.7	7.5	6.3	5.3	7.5
Small boreholes	Perennial with taproot	5.0	6.0	6.0	5.3	5.3	7.0	5.8	5.0	7.0
Large boreholes	Diverse perennial treatment	5.7	7.3	5.3	5.3	6.7	7.8	6.4	5.3	7.8
Large boreholes	Perennial with fibrous roots	6.3	6.7	5.7	6.0	5.3	7.5	6.3	5.3	7.5
Large boreholes	Perennial with taproot	5.7	6.7	7.0	5.7	6.7	7.2	6.5	5.7	7.2
Untreated	Diverse perennial treatment	6.7	6.7	6.0	6.5	7.5	7.7	6.8	6.0	7.7
Untreated	Perennial with fibrous roots	6.3	5.3	6.3	5.7	6.5	7.5	6.3	5.3	7.5
Untreated	Perennial with taproot	7.0	6.0	7.0	5.0	6.3	7.8	6.5	5.0	7.8
Mechanical treatment										
Deep subsoiling		5.1	6.4	4.9	5.9	6.1	7.1	5.9	4.9	7.1
Small boreholes		5.3	6.5	6.0	5.8	5.9	7.2	6.1	5.3	7.2
Large boreholes		5.9	6.9	6.0	5.7	6.2	7.5	6.4	5.7	7.5
Untreated		6.7	6.0	6.4	5.6	6.7	7.7	6.5	5.6	7.7
Cover crop treatment										
Diverse perennial treatment		5.8	6.9	5.7	6.1	6.8	7.7	6.5	5.7	7.7
Perennial with fibrous roots		6.0	6.1	5.8	5.7	5.7	7.4	6.1	5.7	7.4
Perennial with taproot		5.7	6.3	6.2	5.7	6.2	7.2	6.2	5.7	7.2

5.3.2 Vredepeel

Table 13. Results from the visual soil assessment in Vredepeel in 2022. Each number is based on four repetitions.

Mechanical treatment	**Cover crop treatment**	**Structure 0-25 cm**	**Structure 25-50 cm**	**Soil life 0-25 cm**	**Rooting 0-25 cm**	**Rooting 25-50 cm**	**Water regulation 0-50 cm**	**Average score**	**Min**	**Max**
Reference	Annual with tap root	7.5	7.7	5.3	8.3	6.7	8.0	7.3	5.3	8.3
Reference	Annual with fibrous root	7.7	7.7	4.0	8.0	5.7	8.0	6.8	4.0	8.0
Reference	Perennial with fibrous root	8.3	8.0	4.0	8.3	6.0	8.0	7.1	4.0	8.3
Deep subsoiling	Annual with tap root	7.7	6.5	5.0	8.3	6.0	8.0	6.9	5.0	8.3
Deep subsoiling	Annual with fibrous root	8.7	7.2	4.0	8.7	6.7	8.0	7.2	4.0	8.7
Deep subsoiling	Perennial with fibrous root	9.0	6.7	4.0	8.5	6.7	8.0	7.1	4.0	9.0
Large boreholes	Annual with tap root	7.7	7.0	4.0	7.7	6.5	8.0	6.8	4.0	8.0
Large boreholes	Annual with fibrous root	7.0	7.0	4.0	7.7	6.5	8.0	6.7	4.0	8.0
Large boreholes	Perennial with fibrous root	7.3	6.7	4.0	8.0	6.0	8.0	6.7	4.0	8.0
Small boreholes	Annual with tap root	8.2	7.3	4.0	8.3	6.3	8.0	7.0	4.0	8.3
Small boreholes	Annual with fibrous root	8.0	7.0	4.0	7.7	6.3	7.7	6.8	4.0	8.0
Small boreholes	Perennial with fibrous root	7.3	6.5	4.0	8.7	6.8	8.0	6.9	4.0	8.7
Mechanical treatment										
Reference		7.8	7.8	4.4	8.2	6.1	8.0	7.1	4.4	8.2
Deep subsoiling		8.4	6.9	4.3	8.6	6.5	8.0	7.1	4.3	8.6
Large boreholes		7.4	6.9	4.0	7.9	6.2	8.0	6.7	4.0	8.0
Small boreholes		7.8	6.9	4.0	8.2	6.5	7.9	6.9	4.0	8.2
Cover crop treatment										
Annual with tap root		7.7	7.2	4.6	8.2	6.4	8.0	7.0	4.6	8.2
Annual with fibrous root		7.8	7.2	4.0	8.0	6.3	7.9	6.9	4.0	8.0
Perennial with fibrous root		8.0	6.9	4.0	8.4	6.4	8.0	6.9	4.0	8.4
Extra mechanical treatments										
LBS		6.75	7.5	4	7.5	6.5	8	6.7	4.0	8.0
LBExt		8.25	7.3	6	8	7	8	7.4	6.0	8.3
Comp		8.25	8.5	4	8	8.5	8	7.5	4.0	8.5
SSC		7.5	6.8	4	8	7	8	6.9	4.0	8.0
Ref		7.25	6.3	4	8	6.25	7.5	6.5	4.0	8.0

5.4 Soil moisture sensors

5.4.1 Vredepeel

2021

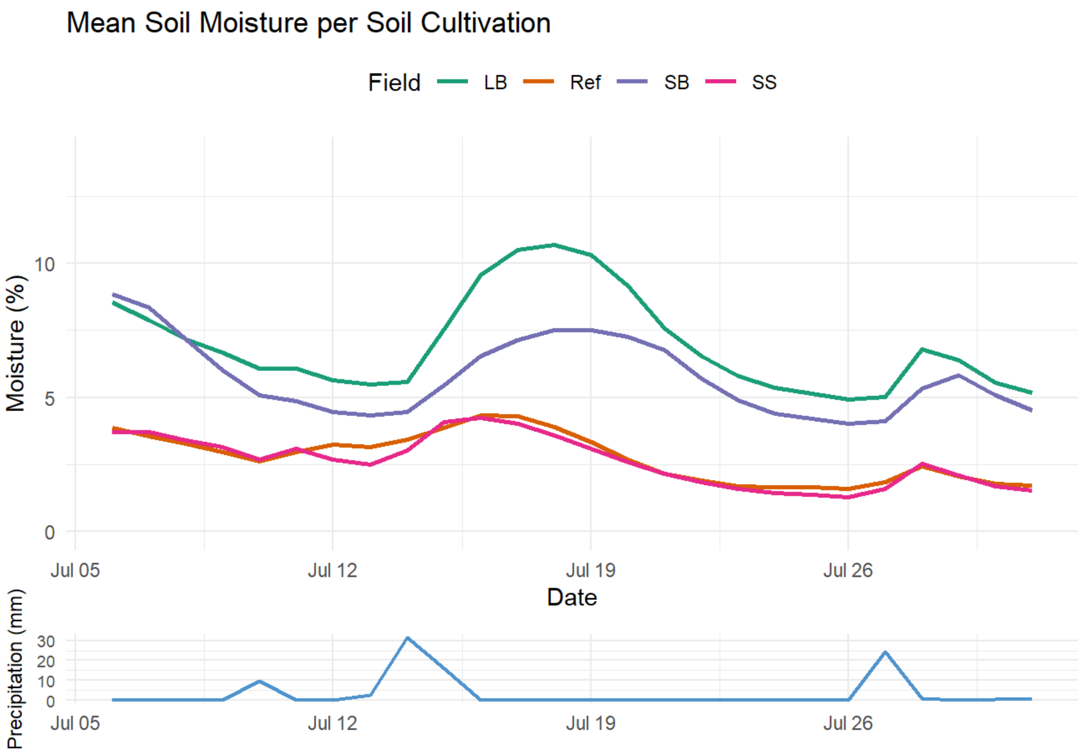


Figure 15. The moisture percentage in July of 2021 during the maize crop, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period.

2022

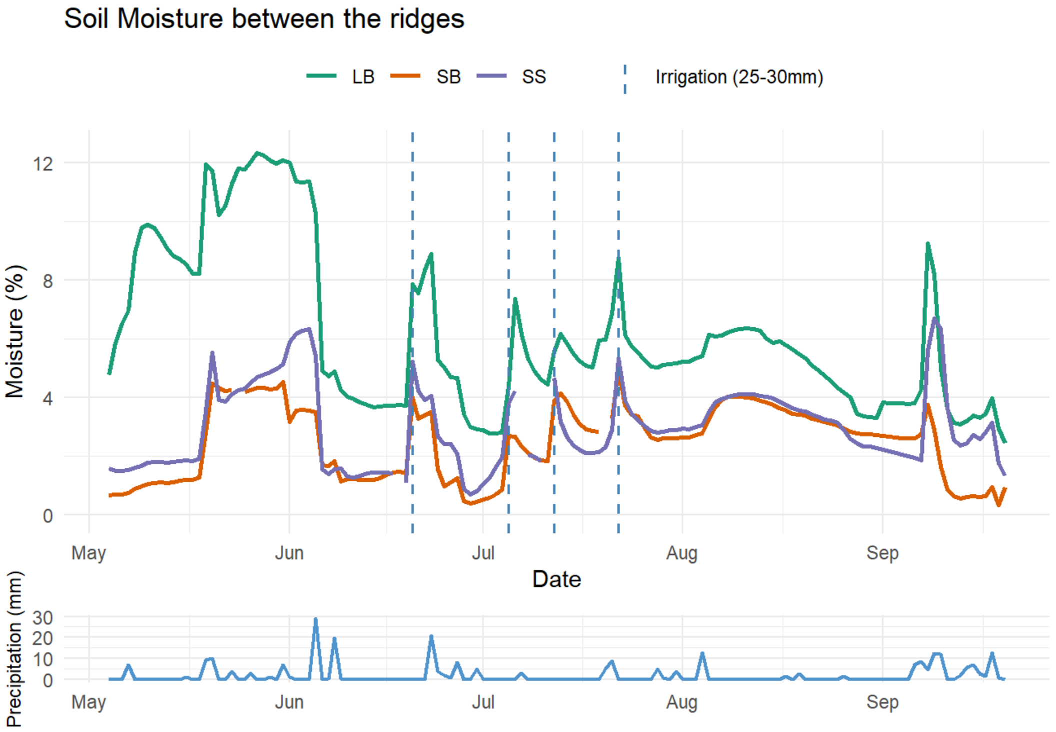


Figure 16. The moisture percentage in 2022 between the potato crop ridges, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period and the vertical dashed lines to irrigation events.

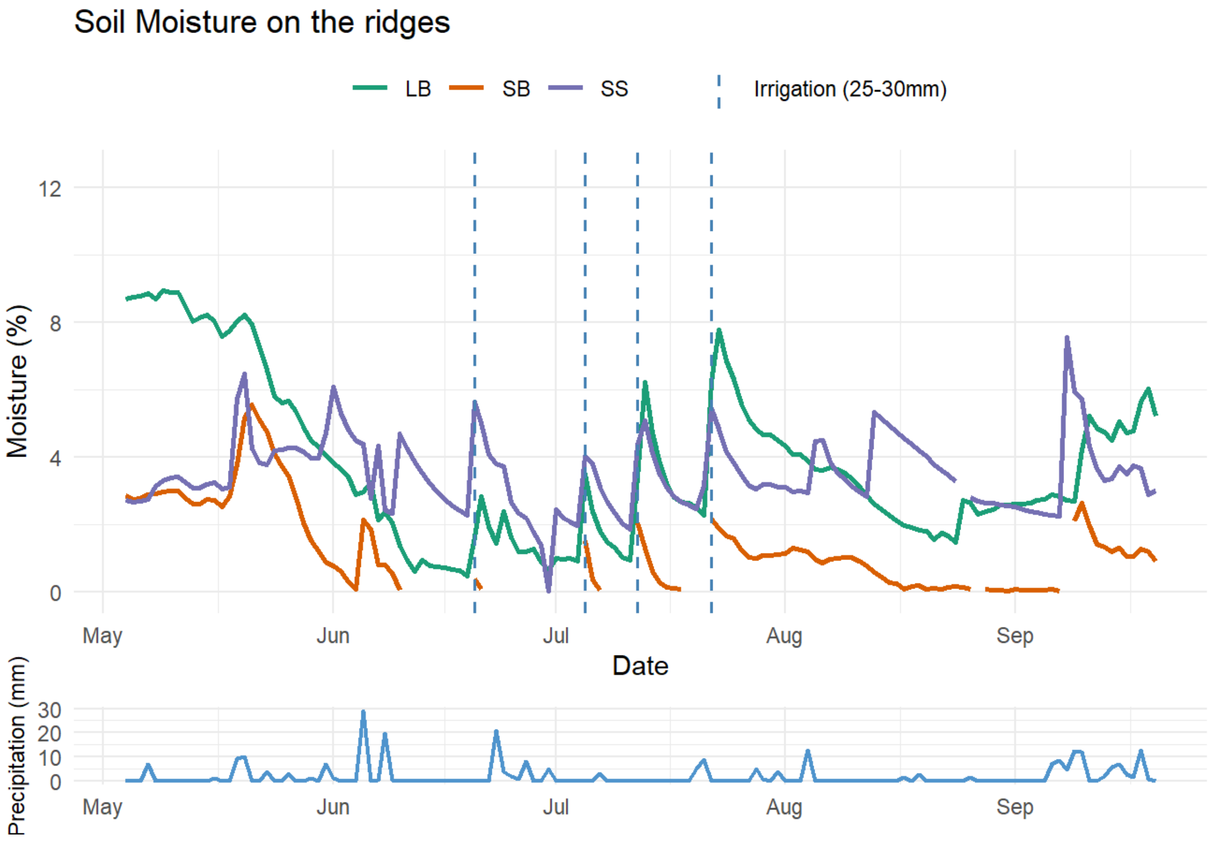


Figure 17. The moisture percentage in 2022 in the potato crop ridges, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period and the vertical dashed lines to irrigation events.

5.4.2 Lelystad

2020

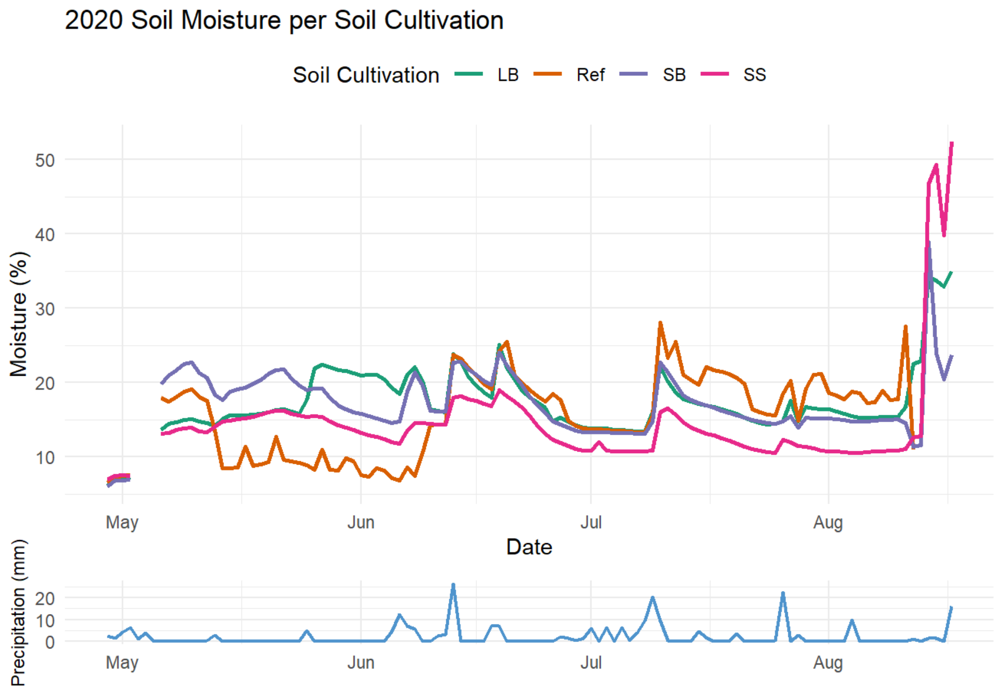


Figure 18. The moisture percentage in 2020 at 30 cm depth during the spring barley and later the cover crop, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period.

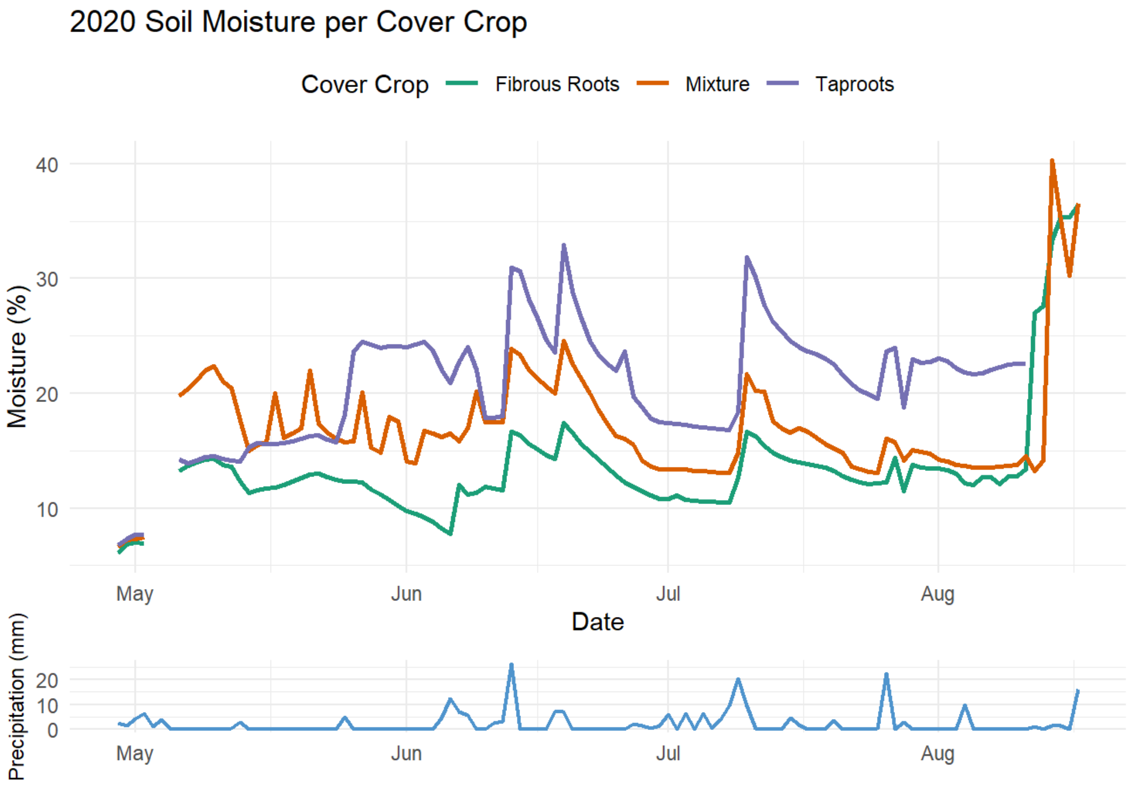


Figure 19. The moisture percentage in 2020 at 30 cm depth during the spring barley and later the cover crop, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period.

2021

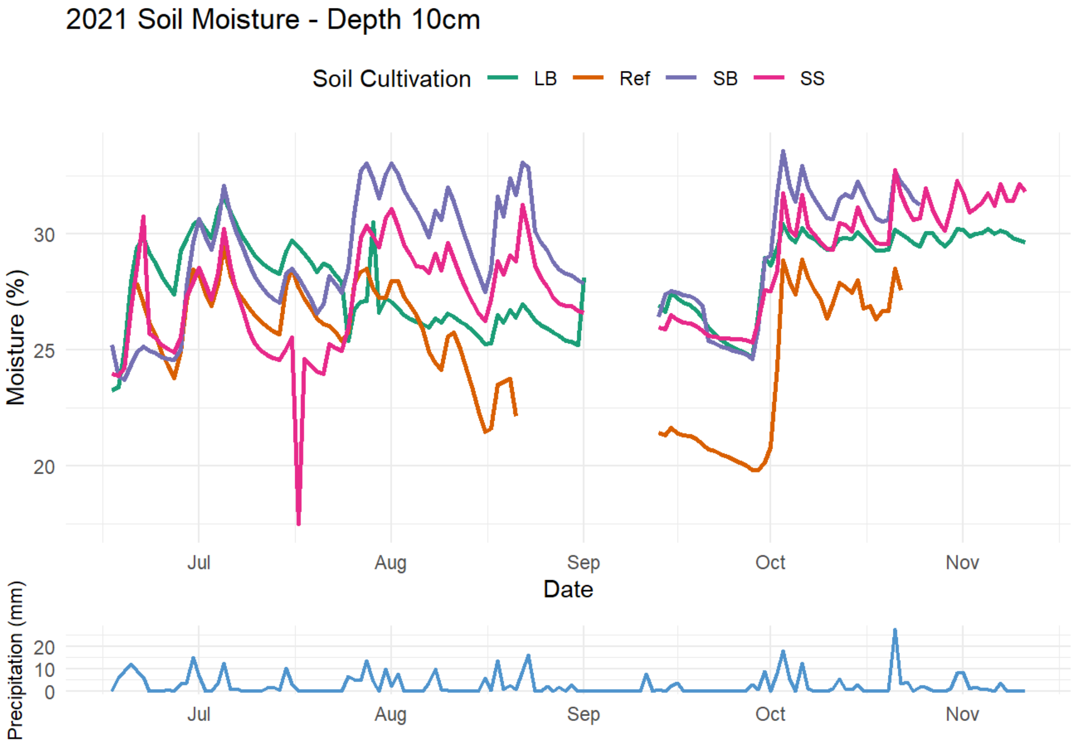


Figure 21. The moisture percentage in 2021 at 10 cm depth during the cover crop, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period.

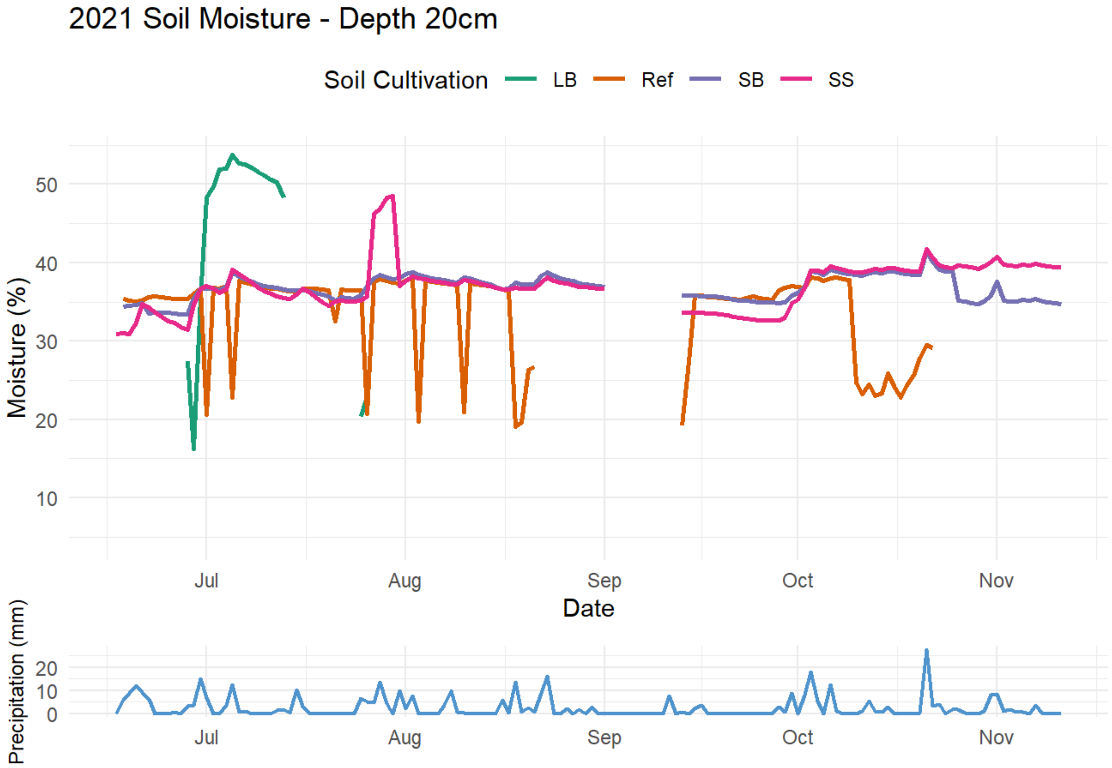


Figure 20. The moisture percentage in 2021 at 10 cm depth during the cover crop, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period.

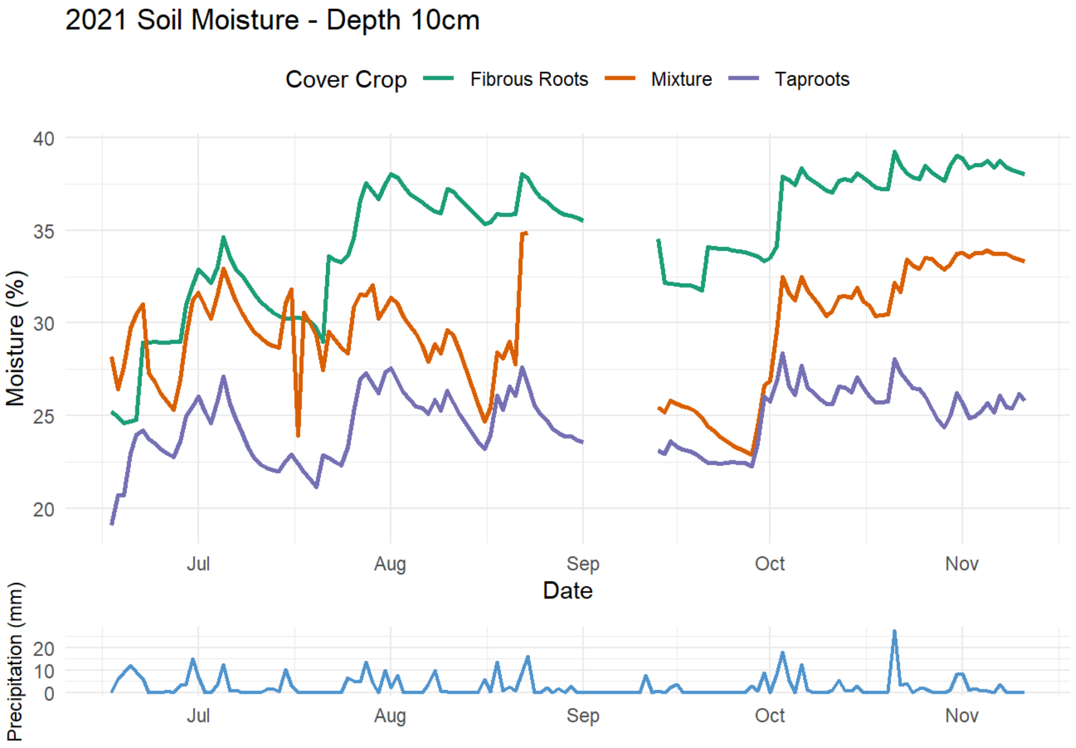


Figure 22. The moisture percentage in 2021 at 20 cm depth during the cover crop, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period.

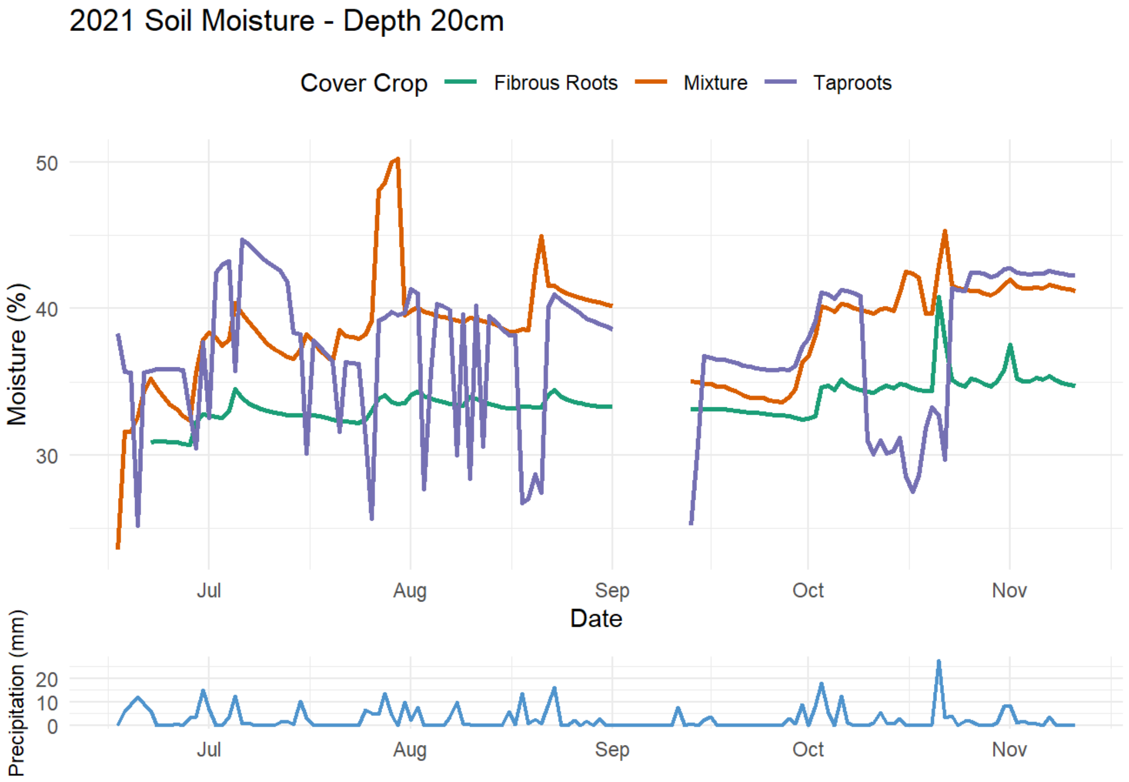


Figure 23. The moisture percentage in 2021 at 20 cm depth during the cover crop, measured with the soil moisture sensors. The lower graph refers to the precipitation in mm during this period.

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