Effects of reduced tillage on (cash) crop yields, soil quality and other ecosystem services

Results from 2009 till 2022 of the long term experiment BASIS, the Netherlands

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The Dutch Ministry of Agriculture aims to manage agricultural soils in a sustainable way by 2030. Reduced tillage is proposed, offering a positive effect on multiple ecosystem services like improved soil quality, but with possible drawbacks such as compaction and yield reduction. The Dutch BASIS long term experiment (established by Wageningen University in 2009) assesses reduced tillage combined with controlled traffic farming on sandy loam soil for common Dutch crop rotations in a conventional and organic system. Three tillage systems (conventional and reduced with and without sub-soiling) are studied. The BASIS experiment shows that reduced tillage is a viable option for most of the Dutch crops and indicates a trend towards improved soil quality.

Keywords: long term experiment, reduced soil tillage, marketable yield, yield quality, root crops, small seeded crops, ecosystem services, soil quality

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Cover page picture: WUR OT – frozen cover crop in the winter on reduced tillage, besides a plough field of conventional tillage.

Content

Preface

Worldwide, reduced soil tillage systems are being implemented without ploughing (inverting) the soil. This approach has mainly been applied with rotations consisting solely of cereal and legume crops (such as grains, rapeseed, soybeans, etc.). The key considerations for implementing this system are fuel savings and reduced risk of wind and water erosion. Its widespread adoption takes place primarily in North and South America and Australia. A significant eye-opener regarding the disadvantages of conventional tillage were the enormous "dust bowls" in the Great Plains of North America in 1930. In Europe, the adoption of non-inversion tillage systems is much lower with the Netherlands even lagging behind in the European context. In the Netherlands, the system is mandatory in a small area on slopes in South Limburg due to reduced erosion risks. Prior to 2010, non-inversion tillage was rarely applied elsewhere in the country.

However, the plough has been used for a reason for the past 5000 years. The main reasons for ploughing are the removal of organic residues from the surface, weed control, and loosening the soil. This process creates a soil environment suitable for sowing or planting, allowing crops to face fewer challenges from weeds and crop residues during their initial development. The loosened soil enables proper root growth and uptake of water and nutrients by the crops.

The rapid global adoption of various forms of reduced tillage proves that cereal and legume crops can be successfully grown without ploughing. In addition to the described advantages of fuel savings and reduced erosion risks, benefits such as improved soil quality, enhanced water infiltration, and reduced organic matter decomposition are often mentioned. These advantages may play an even stronger role amid increasing climate change.
The question is, do these mentioned benefits also apply to arable farming in the Netherlands? The situation here differs significantly from the vast plains of the Americas and Australia in terms of soil type, precipitation, climate and crop types. Will our small-seeded crops like carrots and onions still perform well without ploughing? Will omitting ploughing still have an effect when we extensively cultivate the soil to create ridges for potatoes or carrots? Will we achieve a desirable soil structure on our clay and loamy soils if the soil no longer freezes in winter, as with ploughed soil? Can we still effectively control weeds on our sandy soils if we no longer bury the seeds deeply through ploughing each year? Will we be able to eliminate soil compaction caused by heavy machinery if we stop ploughing? Summarizing: Do the mentioned benefits manifest themselves under Dutch conditions, and do they outweigh any potential disadvantages?

Questions from the organic sector regarding the advantages and disadvantages of reduced tillage under Dutch conditions led us to explore literature and practices from both domestic and international sources. We visited pioneers and experiments in Europe and gained valuable knowledge through our contacts with the European Conservation Agriculture Federation (ECAF). Based on this, Derk van Balen, Wiepie Haagsma, and I designed experiments for the loamy soils of Flevoland in 2008. These experiments, called BASIS, included variations under conventional and organic conditions, reflecting the typical cropping systems in the area. The experiments were conducted on a sufficiently large scale and for a long enough duration, since changes in soil quality occur very slowly. Above all, we aimed to consistently apply Controlled Traffic Farming, with the idea that if the soil is no longer randomly compacted by heavy machinery, there would be no need to loosen it with ploughing. These experiments were established in 2009, and I am pleased to present our results from the preceding period in this report. Is 14 years sufficient to make conclusive statements about the effects of non-inversion tillage under these conditions? Perhaps not. It might require even more time to accurately measure the changes. Some trends can be observed, but they may not be statistically significant. It would be beneficial to continue these experiments for at least the same 14-year period. Usually, soil quality changes very slowly and pays little attention to our desire for quick results. In the meantime, partly due to the public exposure of the BASIS experiments and the discussions around it, the application of reduced tillage as shallow ploughing and non-inversion tillage, often in combination with increasing use of cover crops, has significantly increased in the Netherlands.

Wijnand Sukkel, July 2023

Acknowledgements

There was a lot to figure out at the start of this experiment. Reduced tillage on sandy loam soil and controlled traffic farming were new areas of research. The late manager, Henk Oosterhuis†, worked together with colleagues of the experimental farm and interested arable farmers on a cultivation system that is broadly used to this day. This cultivation system has been refined over the years by current farm manager Joost Rijk and his enthusiastic and committed team. The input from the sounding board group and guidance committee of the PPP Bettersoilmanagement has helped with this and provided a connection with practice in addition to excursions and open days at the trial location. Jan Tolhoek played an important role in collecting and classifying data. Support for the statistical analysis of these data was provided by Sabine Schnabel. The collection of crop, soil and weed data was possible thanks to the efforts of all experimental field and laboratory staff at the experimental station in Lelystad. Since 2009, BASIS has been used by students for internships or research. In addition, colleagues from within and outside WUR made use of the experiment. Most of the data they collected is included in the database and serves as the basis for this report.

Summary

Decreasing soil quality, worsened by climate change-related weather extremes, is prompting the Dutch Ministry of Agriculture's aim for sustainable management of all agricultural soils by 2030. One proposed practice for this goal is reduced tillage, which offers potential benefits such as improved soil structure and reduced greenhouse gas emissions. However reduced tillage comes with potential drawbacks such as topsoil compaction and yield reduction. While global meta-analyses mainly focus on effects of reduced tillage in North and South American cash crops, like grains, maize and soy, this long-term Dutch farming systems experiment called BASIS is unique in its focus on Dutch small seeded, root and tuber crops.

The BASIS experiment, established in 2009 by Wageningen University and Research in Lelystad, consists of three organic and two conventional fields with common Dutch crop rotations. In BASIS we experiment with three tillage systems: conventional tillage with mouldboard plough (CT), reduced tillage with sub-soiling (RTS), and reduced tillage without sub-soiling (RT). Reduced tillage with shallow ploughing was added (RT/SPL) later in the experiment. The experiment employs controlled traffic farming (CTF) and is a randomized complete block design with four replicates per tillage system and field. In the BASIS experiment a system approach is used; this allowed for the experiment to be optimized during the project period. Effects of reduced tillage on ecosystems services such as yield, yield quality and soil quality were investigated.

Overall, reduced tillage systems showed comparable or higher marketable yield for most crops, except for fine-seeded crops like carrots and onions. The Twinrotor tiller seems a viable option in reduced tillage systems to create a finer seedbed and reduce the yield gap of carrots between reduced and conventional tillage. The influence of extreme weather conditions on reduced tillage effects varied, with yields sometimes higher and sometimes lower compared to conventional tillage. Over time the differences in marketable yield between reduced and conventional tillage showed no increasing or decreasing trend.

For yield quality, the difference between gross yield and marketable product, there were no significant differences nor discernible trends between the tillage systems; with the expedition of carrots which showed a lower yield quality under reduced tillage, with larger-sized and deformed carrots. This was likely caused by cover crop residue and soil aggregate size. The impact of reduced soil tillage on crop quality parameters such as sugar content (sugar beet) and thousand grain weight (cereal crops) showed no significant differences between the tillage systems.

Bulk density showed no differences in the upper 0-10 cm layer, but significantly higher values were observed in the deeper 10-20 cm layer for reduced tillage. Soil moisture was generally higher for reduced tillage in the upper 0-10 cm layer, while conventional tillage exhibited higher moisture in the lower 10-20 cm layer. Penetration resistance was consistently greater for reduced tillage, particularly in the 10-30 cm layer. Despite these soil property differences, there was no substantial evidence of decreased yields or root limitations. The increased compaction under reduced tillage could potentially enhance soil bearing capacity.

Reduced tillage leads to higher soil organic matter and carbon content in the upper 0-15 cm layer compared to conventional tillage. However, in lower layers no significant difference were found. Reduced tillage shows minimal impact on soil pH. Total nitrogen content is higher in the upper 0-15 cm layer for reduced tillage. Other nutrient availabilities are not strongly influenced by tillage systems. Mineral nitrogen levels in the soil are very low in this experiment and differences between tillage systems are small. Overall, reduced tillage increases soil organic matter, carbon, and nitrogen in the upper layer (0-15 cm), with a trend towards higher values in the 0-30 cm layer.

To summarize, the BASIS experiment shows that reduced tillage is a viable option for most of the Dutch crops and indicates a trend towards improved soil quality.

Samenvatting

Het verminderen van de kwaliteit van de bodem, verergerd door klimaatverandering-gerelateerde weersextremen, dwingt het Nederlandse Ministerie van Landbouw om te streven naar duurzaam beheer van alle landbouwgronden tegen 2030. Een voorgestelde maatregel voor dit doel is gereduceerde grondbewerking. Dit biet potentiële voordelen zoals verbeterde bodemstructuur en verminderde uitstoot van broeikasgassen. Echter, gereduceerde grondbewerking brengt ook potentiële nadelen met zich mee, zoals verdichting van toplaag van de bodem en opbrengstverlies. Terwijl wereldwijde meta-analyses zich voornamelijk richten op de effecten van gereduceerde grondbewerking in Noord- en Zuid-Amerikaanse gewassen, zoals granen, maïs en soja, is dit lange termijn experiment, genaamd BASIS, uniek in zijn focus op Nederlandse fijnzadige akkerbouwgewassen en rooigewassen.

Het BASIS-experiment, opgericht in 2009 door Wageningen University and Research in Lelystad, bestaat uit drie biologische en twee gangbare percelen met typische Nederlandse gewasrotaties. In dit experiment worden drie grondbewerkingssystemen onderzocht: conventionele grondbewerking met ploegen (CT), gereduceerde grondbewerking met woelen (RTS) en gereduceerde grondbewerking zonder woelen (RT). Later in het experiment werd gereduceerde grondbewerking met ondiep ploegen toegevoegd (RT/SPL). Het experiment maakt gebruik van vaste rijpaden (CTF) en is opgezet als een gerandomiseerd compleet blokontwerp met vier herhalingen per bewerkingssysteem en veld. In het BASIS-experiment wordt een systeemaanpak gehanteerd, waardoor het experiment geoptimaliseerd kon worden tijdens de projectperiode. De effecten van verminderde grondbewerking op ecosysteemdiensten zoals opbrengst en opbrengst- en bodemkwaliteit werden onderzocht.

Over het algemeen lieten gereduceerde grondbewerkingssystemen vergelijkbare of hogere marktbare opbrengsten zien voor de meeste gewassen, behalve voor fijnzadige gewassen zoals wortels en uien. De Twinrotor-cultivator lijkt een goede optie bij gereduceerde grondbewerking om een fijner zaadbed te creëren en het opbrengstverschil van wortels tussen gereduceerde en conventionele grondbewerking te verminderen. De invloed van extreme weersomstandigheden op de effecten van gereduceerde grondbewerking varieerde, waarbij de opbrengsten soms hoger en soms lager waren in vergelijking met conventionele grondbewerking. In de loop van de tijd vertoonden de verschillen in marktbare opbrengst tussen gereduceerde en conventionele grondbewerking geen stijgende of dalende trend.

Wat betreft de opbrengstkwaliteit, het verschil tussen bruto en marktbare opbrengst, waren er geen significante verschillen of waarneembare trends tussen de grondbewerkingssystemen, met uitzondering van wortels, die een lagere opbrengstkwaliteit vertoonden onder gereduceerde grondbewerking, met grotere en misvormde wortels. Dit werd waarschijnlijk veroorzaakt door groenbemester gewasresten en bodemaggregaat grootte. Het effect van gereduceerde grondbewerking op gewaskwaliteitsparameters zoals suikergehalte en duizendkorrelgewicht vertoonde geen significante verschillen tussen de grondbewerkingssystemen.

De bulkdichtheid vertoonde geen verschillen in de bovenste 0-10 cm laag, maar significant hogere waarden werden waargenomen in de diepere 10-20 cm laag voor verminderde bodembewerking. De bodemvochtigheid was over het algemeen hoger voor verminderde bodembewerking in de bovenste 0-10 cm laag, terwijl conventionele bodembewerking hogere vochtigheid vertoonde in de onderste 10-20 cm laag. De penetratieweerstand was consequent groter voor verminderde bodembewerking, vooral in de 10-30 cm laag. Ondanks deze verschillen in bodemeigenschappen was er geen substantieel bewijs van verminderde opbrengsten of wortelbeperkingen, met uitzondering van wortels. De toegenomen verdichting onder verminderde bodembewerking kan mogelijk de draagkracht van de bodem verbeteren.

Gereduceerde grondbewerking leidt tot een hoger organische stof en koolstof gehalte in de bovenste 0-15 cm laag in vergelijking met conventionele grondbewerking. In de diepere lagen werden geen significante verschillen gevonden. Gereduceerde grondbewerking heeft minimaal effect op de pH van de bodem. Het totale stikstofgehalte is hoger in de bovenste 0-15 cm laag voor gereduceerde grondbewerking. Andere nutriënten worden niet sterk beïnvloed door grondbewerkingssystemen. Het gehalte aan minerale stikstof in de bodem is zeer laag in dit experiment en de verschillen tussen grondbewerkingssystemen zijn klein. Over het algemeen verhoogt gereduceerd grondbewerking het organische stof, koolstof en stikstof gehalte in de bovenste laag (0-15 cm), met een trend naar hogere waarden in de 0-30 cm laag.

In het BASIS-experiment vinden we dat gereduceerde grondbewerking een goede optie is voor de meeste Nederlandse gewassen en dat er een trend is richting verbeterde bodemkwaliteit.

List of abbreviations

Abbreviation	Definition
RT	Reduced Tillage without sub-soiling
RT/SPL	Reduced Tillage with occasional Shallow Ploughing
RTS	Reduced Tillage with Sub-soiling
CT	Conventional Tillage (mouldboard plough, 23-25 cm depth)
CTF	Controlled Traffic Farming with GPS
BASIS	Broekemahoeve Applied Soil Innovation Systems
PPP	Public Private Partnership
CBAV	Commissie Bemesting Akkerbouw en Vollegrondsgroente teelt
OM	Organic Matter
AMF	Arbuscular Mycorrhizal Fungi

1 Introduction

Note: For the introduction of this report, some of the text from Van Balen et al. (2023) is adapted.

1.1 Impetus

Soil quality is decreasing. Problems with decreasing soil quality become even more urgent with the increased frequency of weather extremes, such as droughts and heavy rainfall, due to climate change (Podmanicky et al., 2011). To counter this, the Dutch ministry of agriculture, nature and food quality has expressed the goal that all Dutch agricultural soils should be managed sustainably by 2030 (Bodemstrategie 2018, LNV). Therefore it is necessary to determine what sustainable management of agricultural soils contains and which practices fit within sustainable management. One of the practices that is mentioned as a contribution to sustainable soil management is reducing the intensity of soil tillage by using shallow or non-inversion tillage methods, often with fewer tillage operations per year. Reduced tillage can potentially serve multiple ecosystem services, including better soil structure (Draghmeh et al., 2009), reduced erosion risk (Hoogmoed et al., 1999), increased soil biological activity (D'Hose et al., 2018), reduced greenhouse gas emissions (Tian et al., 2013), increased soil carbon stocks (Palm et al., 2014; Cooper et al., 2016) and enhanced soil water holding capacity and water infiltration (Tebrügge & Düring, 1999). However, potential disadvantages have also been found, like increased topsoil compaction, insufficient control of weeds and lower crop productivity (Gruber et al., 2012; Soane et al., 2012; Bijttebier et al., 2018). Reduced tillage in different forms is being adopted around the world. Meta-analyses summarizes the global findings on this topic (e.g. Van den Putte et al., 2010; Pittelkow et al., 2015; Cooper et al., 2016). However, the focus of these studies is mainly on North and South American cash crops, like maize, wheat and soybean. There are fewer studies on Dutch soils, concerning crops in a Dutch cropping system, such as small seeded, root and tuber cash crops like potato, sugar beet, carrot and seed onion. To investigate the effects of reduced tillage within a Dutch setting on a sandy loam soil, a long term farming systems experiment was established in 2009 by Wageningen University and Research in Lelystad at the test site Broekemahoeve, called BASIS (Broekemahoeve Applied Soil Innovation Systems). In this experiment multiple intensities of reduced tillage, from non-inversion tillage to shallow ploughing, are compared with standard mouldboard ploughing within a system with controlled traffic farming (CTF). The combination with CTF was chosen to show the full potential of reduced tillage in the untrodden beds. CTF can increase the yield (Van Wijk, 2011), soil biological activity (Vermeulen et al. 2010) and water infiltration and decrease the use of fossil energy and the risk of erosion. In the BASIS experiment a system approach is used, this means that the system can be optimized during the project period (Vereijken, 1997). During the seasons, the research team was in close contact with the farm manager Joost Rijk. Although the research team was often found in the field, Joost was the daily manager of the crops. His experience with the system was taken into account when writing the discussing and conclusion of this report.

1.2 Purpose and research questions

The purpose of this report is to share the gained insight in the effects of reduced soil tillage in combination CTF on a wide range of agronomical and ecological aspects. Effects on yield, yield quality and soil quality within a conventional and organic farming system are reported. Physical, chemical and biological soil aspects are investigated. Since the experiment under consideration was established in 2009, 14 years of data (2009-2022) are available. Parts of the results have already been published in separate reports, scientific papers and agricultural journals. In this reported the full range of the available data will be analysed for the first time and per subject the relevant references to earlier published results will be given.

The research questions are divided in five topics: yield, yield quality and physical, chemical and biological soil aspects. Beside these main topics some extra research was done, for example by PhD or master students. Their collected data is used in our data analysis, to answer other research questions.

1.2.1 Yield

For farmers, the possible negative effects of reduced tillage on crop productivity, form a potential hurdle to adopt reduced tillage practices. Therefore, many studies have been conducted to quantify the effect of reduced tillage on crop yield. The results of these studies have been synthesized in extensive meta-analyses in the quest to determine whether yield outcomes are affected by decreasing tillage intensity (Van den Putte et al., 2010, Pittelkow et al., 2015, Cooper et al., 2016). These meta-analyses show that the effect of reduced tillage on crop yield depends on many factors, particularly crop type and local environmental conditions (soil and climate), and that this effect is not necessarily negative. For example, Cooper et al. (2016) found that, compared to deep inversion tillage, reduced tillage in organic systems resulted in yield losses of 8% in the humid continental zone (16 studies), but that yield losses were negligible in the humid oceanic zone (<−1%, 3 studies). In terms of crop-specific effects, Pittelkow et al. (2015) meta-analysis of conventional tillage versus no-till systems found that yields were reduced in no-till wheat (2.6%), rice (7.5%) and maize (7.6%), but that yields of oil seed, cotton and legumes were unaffected by tillage regime. In addition, they found, for several crops, that negative yield effects tended to disappear after the first few years of abandoning conventional tillage, which emphasises the importance of long-term studies.

One important limitation of these meta-analyses is that the majority of studies available is focused on cash crops grown in no-till systems in North and South America (most importantly, maize, wheat and soy). There are much fewer data on root and tuber crops, such as potato, sugar beet, carrot and seed onion, which are profitable crops for European arable farmers (Eurostat, 2021). For example, in the meta-analyses of Pittelkow et al. (2015), root (including tuber) crops represented only 69 out of 6005 total observations (all climate zones) and only 6 out of 4842 observations in temperate climates. Based on these limited data, they found that root crop yields were strongly reduced in no-till systems (21.4%, all climate zones). Among the few studies investigating the effects of reduced tillage (rather than no-tillage) in temperate zones, Arvidsson et al. (2014) found that potato yield in Swedish crop rotations was not significantly different in shallow non-inversion tillage systems compared to conventional tillage systems.

Research questions:

1. What is the effect of reduced soil tillage on the marketable product of Dutch root and tuber cash crops like potato, sugar beet, carrot and seed onion on a Dutch sandy loam soil, in an organic and conventional system?
2. Is the effect of reduced soil tillage on the marketable product influenced by extreme climatic circumstances like drought or too much water and hot or cold weather?
3. Does the effect of reduced soil tillage on the marketable product become more pronounced over time, when the soil is undisturbed for multiple years?

1.2.2 Yield quality

Not only yield quantity but also yield quality was considered. For example, reduced soil tillage can increase topsoil compaction (Bijttebier et al., 2018), this might affect the percentage of carrots that is twisted or branched.

Research questions:

4. What is the effect of reduced soil tillage on the difference between the gross yield and marketable product?
5. What is the effect of reduced soil tillage on crop quality parameters like sugar content and thousand grain weight?

1.2.3 Physical soil aspects

The use of reduced soil tillage changes the soil structure compared to conventional ploughing. Pore systems and aggregate structures are disturbed less and soil structure can improve (Draghmeh et al., 2009). With non-inversion tillage crop residues remain in the top soil; together with the improved soil structure this can reduce the risk of erosion (Hoogmoed et al., 1999). The compaction in the topsoil can increase due to reduced soil tillage. High soil compaction makes it difficult for roots to penetrate the soil. However, a bit higher soil compaction can also increase the bearing capacity of the soil.

Research question:

6. What is the effect of reduced soil tillage on bulk density, soil moisture and penetration resistance?

1.2.4 Chemical soil aspects

Due to the implementation of reduced soil tillage, the soil is tilled in spring and cover crops can remain on the field during winter. Reduced soil tillage and the accompanying change in cover crop management can change soil chemical properties such as soil organic matter (SOM) and soil organic carbon (SOC) content and nutrient availability. When the soil is not inversed, the position of organic matter and nutrients in the soil profile can change as well.

Research questions:

7. What is the effect of reduced soil tillage on SOM and SOC and the position of these elements in the soil profile?
8. What is the effect of reduced soil tillage on pH, total nitrogen and the availability of other nutrients in the soil?
9. What is the effect of reduced soil tillage on nitrogen losses and nitrogen availability in spring?

1.2.5 Biological soil aspects

The effects of reduced tillage on biological soil aspects were not directly investigated within this project. However, other projects and researchers used the BASIS experiment to measure different aspects of soil biology. Their methodologies and results are not discussed in this report, but an overview of where to find these results is given here.

The presence and diversity of earthworms was measured from 2009 till 2013 by a PhD student (Crittenden et al., 2014) and in 2016 by Hoek et al. (2019). Hoek et al. (2019) also looked at fungal and bacterial biomass, hot water carbon and potentially mineralizable nitrogen, indicators of soil biological activity. Hoogmoed et al. (2021) also researched fungal and bacterial biomass. The resilience of the soil against pest and diseases was investigated in 2010, 2013, 2014, 2015 and 2019 by Postma et al., (2008), Postma et al., (2011) and Kurm et al., (2023).

1.2.6 Other research topics

1.2.6.1 Seedbed preparation for carrots

Reduced soil tillage can also have disadvantages, like difficulties with seedbed preparation, especially for small seeded crops. For the small seeded crop carrots, a separate experiment was done within the organic system with two machines for seedbed preparation: a standard rotary tiller and a Twinrotor rotary tiller, for preparing the carrot ridges.

Research question:

10. What is the effect of the use of the Twinrotor in the reduced tillage system and in the conventional tillage system on soil aggregate size and stability and emergence and yield of carrots?

1.2.6.2 Weed seedbank

Weeds compete with crops and could potentially cause yield losses up to 32% if not controlled (Oerke and Dehne, 2004). Therefore, farmers need to control weeds, preventing crop-weed competition and the reproduction of weeds. Increased weed pressure is often mentioned as a disadvantage of reduced tillage (Bijttebier et al., 2018). In conventional agriculture chemical weed suppression can offer a solution, but in organic production systems agronomical or mechanical solutions need to be found. Apart from direct control measures such as chemical and mechanical weeding, cultural control measures, are an important part of the toolbox for weed management. An integrated approach is needed for sustainable weed management. Riemens et al. (2022) proposed an integrated weed management (IWM) framework consisting of five pillars that contribute to weed management. Field and soil management is an important component of an IWM approach, of which primary soil tillage is one of the measures. The current research combines different tillage practices within both conventional and organic cropping systems. Tillage operations are an important factor that influence weed pressure. Hence, it is interesting to investigate whether these management strategies have led to differences in the weed community regarding weed density and species composition.

Research question:

11. What is the effect of reduced soil tillage on weed community, regarding weed density and species composition?

1.2.6.3 Nitrogen balance in Ndicea

Besides looking separately at the effect of reduced soil tillage on yields and on nitrogen in the soil, it is interesting to use all available data and investigate the whole nitrogen balance, to say something on nitrogen dynamics in the soil and nitrogen efficiency. A nitrogen balance was modelled in Ndicea by Geert Jan van der Burgt (Burgt Agrarische Diensten)(van der Burgt & Hanegraaf, 2021).

Research question:

12. What is the effect of the system of reduced soil tillage on the nitrogen balance in the soil?

1.3 Execution and financing

The project is being executed at the business unit Field Crops, part of Wageningen Research. The experiment is located at the test site Broekemahoeve in Lelystad. From the start of the project in 2009 till 2013, the main financier of the project was the Ministry of Economic Affairs. Co-financing came in those years from Stichting Proefbedrijven Flevoland for taking additional soil nitrogen measurements. In the same period, there was also a contribution to facilitate research on the influence of soil tillage and buffer strips on earthworm populations funded by the Ministry of Infrastructure and Environment.

From 2013 till 2017 BASIS came under the funding of the Public Private Partnership (PPP) Sustainable Soil, which was followed up from 2017 till 2021 by the PPP Better Soil Management. The latter project received a two-year extension in 2021. The main financer of these PPP’s was the Ministry of Agriculture, Nature and Food quality. Co-financing came amongst others from the BO-akkerbouw (arable farming trade organisation). The aim of these projects was to ensure short- and long-term production stability, reduce unwanted emissions and strengthen soil services such as biodiversity and water management. For this aim the BASIS experiment was used to gather data and gain practical knowledge.

2 Materials and Methods

Note: For the materials and methods of this report, some of the text and figures from Van Balen et al. (2023) is adapted.

2.1 Location and experimental design

The BASIS experiment was established in 2009 at the test site of Wageningen University and Research in Lelystad (52◦32’38.01”N, 5◦34’36.37”E). The field experiment is situated on land reclaimed from the sea in 1957, which can now be described as a Cambisol. It is a homogeneous sandy loam soil, composed of 61% sand, 22% silt and 17% clay, with a pH ranging from 7.2 to 7.4. The soil organic matter on the organic fields ranges from 3.4 to 3.8% and on the conventional fields from 3.2 to 3.5% in the upper soil layer (0-25 cm). The climate is a marine west coast climate (Cfb, Köppen climate classification). Since 1990, the average total annual precipitation is 789 mm and the mean annual temperature is 10.5 ºC (according to the KNMI weather station located +- 10 km of the experimental field in Lelystad).

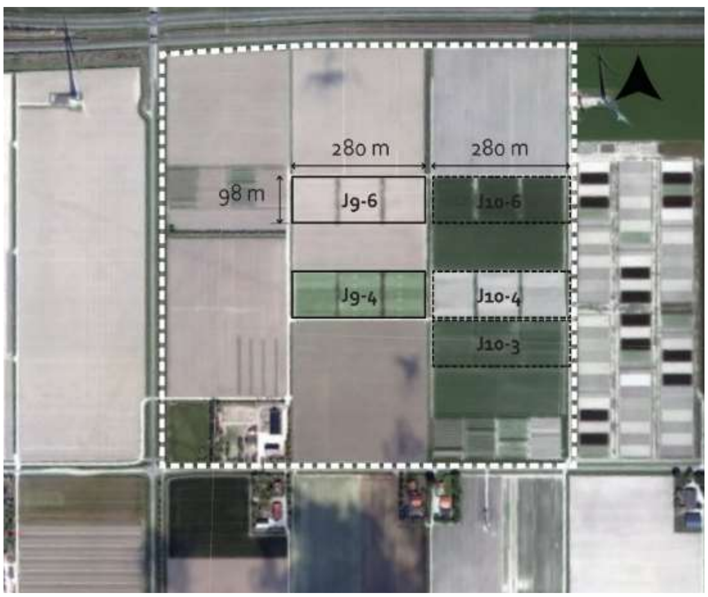


Figure 1. Aerial view of the Broekemahoeve (dashed white lines), showing the BASIS long-term experiment fields with two conventional fields (J9–4 and J9–6; solid black lines) and three organic fields (J10–3, J10–4 and J10–6; dashed black lines).
Photo: Satelietdataportaal.nl; accessed: May 2020

The BASIS experiment consists of three organic and two conventional fields (Figure 1). The organic fields were converted to organic agriculture in 2003. Each field was split into three sub-fields (Figure 2), of which two are used in the true experimental setup (withing experiment); the third field can be used for extra side experiments (outside experiment). The two fields within the experiment are divided in total in four blocks, that from the four replicates. Each block is divided in three plots, with the three tillage systems randomly assigned to each block. The three original tillage systems are conventional tillage with mouldboard plough (CT), reduced tillage with sub-soiling (RTS) and reduced tillage without sub-soiling (RT). An extra tillage system was introduced in 2018 (see details in Chapter 2.2.2). This setup results in a

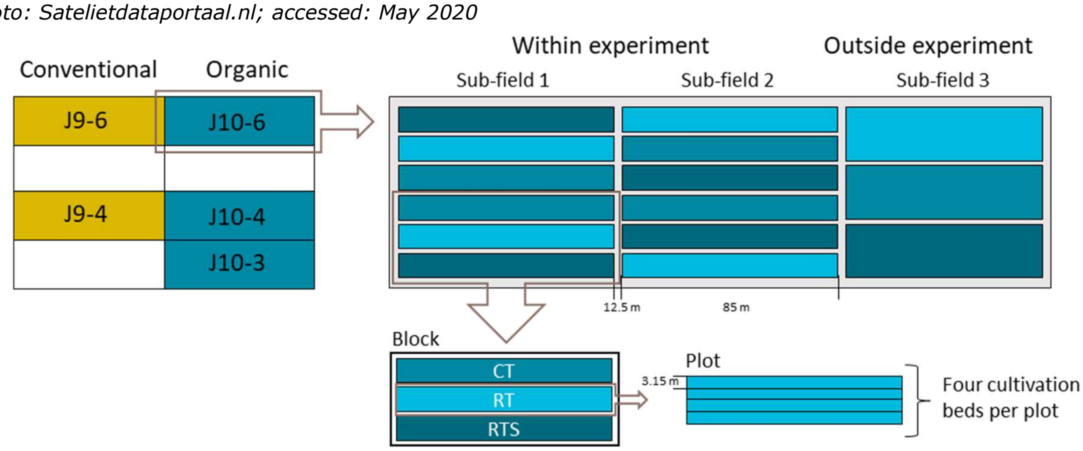


Figure 2. Schematic representation of the BASIS experimental design.

randomised complete block design with four replicates per tillage treatment per field.

To investigate the full potential of reduced tillage and to prevent soil compaction, all crops were managed using controlled traffic farming (CTF) at 3.15 meter, when the machinery was available. This allowed the use of conventional agricultural equipment. Before the start of the BASIS experiment in 2009, all fields were annually ploughed with a mouldboard plough.

The BASIS experiment was intentionally created as a farming systems experiment (Drinkwater, 2002), in which certain management practices are intrinsically linked to the compared tillage treatments. For example cover crop choice and management will differ in a ploughing system, compared to a reduced tillage system. Therefore, attributes other than the main factor of interest (tillage) have been adjusted in each treatment to fully optimize it. As a result, the three tillage treatments are continually evolving over the duration of the experiment. While tillage is the primary focus, it should be viewed in the context of the other attributes that have been modified around it.

2.2 Management practices

2.2.1 Crop rotation

For the conventional farming system a four year crop rotation was used with (1) seed potato (Solanum tuberosum), (2) sugar beet (Beta vulgaris), (3) spring barley (Hordeum vulgare) and (4) onion (Allium cepa). For the organic farming system a six year crop rotation was chosen with (1) ware potato (Solanum tuberosum), (2) grass clover (Trifolium-Lolium perenne), (3) white cabbage (Brassica oleracea) (4) spring wheat (Triticum aestivum), (5) carrot (Daucus carota subsp. Sativus), and (6) spring wheat – faba bean (Triticum aestivum – Vicia faba). In the organic system, potatoes were cultivated for human consumption. In the conventional system potatoes were produced for seed (tuber) production. Both potatoes and carrots are grown on ridges. The onions in the crop rotation were grown from seed. The organic crop rotation was derived from OBS Nagele (Burgt, 2001). An alternation was used of a more intensive root crops (potato, cabbage and carrot) and an extensive mowing crop (grass clover, spring wheat and spring wheat-faba bean). Due to nitrogen fixation from the atmosphere by the legumes in the rotation, nitrogen supply with animal manure could be reduced. In the conventional system a winter wheat or winter barley would be grown after sugar beet, to cover the soil in winter. However the soil conditions were often not good enough to sow a winter cereal crop; therefore spring barley is used.

These crop rotations were the template and are shown in Figure 3. Due to changes in the market and in soil and weather conditions, small changes were sometimes made in crop and cultivar choice. Table 1 gives an elaborate overview of the crop, cultivar and cover crop choices. In the organic system, cabbage was substituted with pumpkin (Curcurbita maxima) in 2017 and 2019; after 2017 the spring wheat was substituted with oats (Avena sativa); the spring wheat/faba bean mixture was in 2016 only spring wheat, and from then onwards it was substituted by green bean (Phaseolus vulgaris); and in 2021, instead of ware potato, spring wheat was grown. In the conventional system, instead of spring barley, winter wheat (Triticum aestivum) was grown in 2010.

Cover crops were sown after each harvest of the cash crop in all tillage systems, when time and weather conditions allowed. At the start of the experiment often monocultures of cover crops were grown, like yellow mustard, common vetch and white clover. From 2016 onwards, more often mixtures of cover crops were chosen. This shows the development of the use of cover crops in the Netherlands.

With two conventional fields and three organic fields, not every crop could be grown each year. This means the repetitions in the analysis has to be derived from the different years.

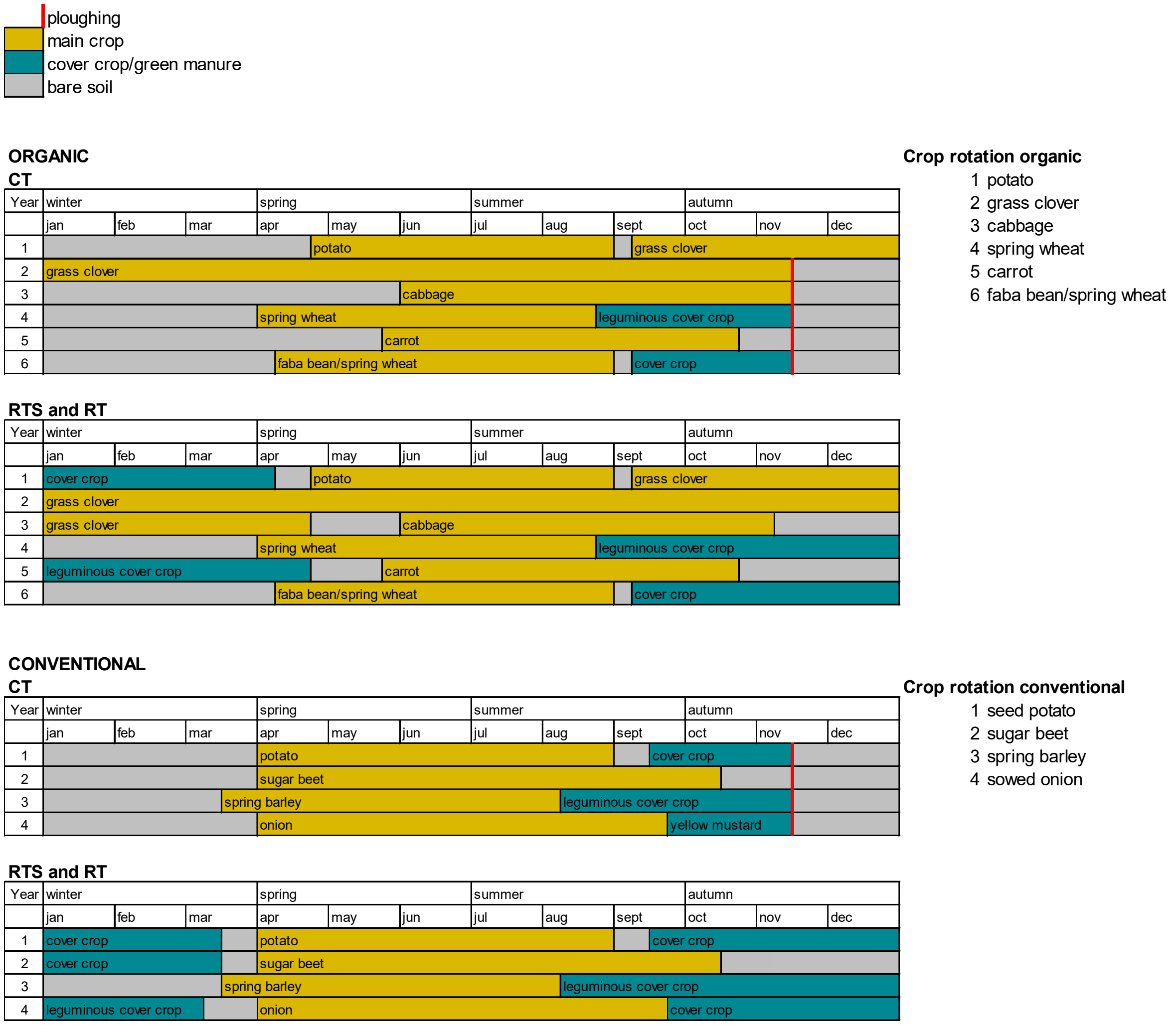


Figure 3. Crop rotation template for the organic and conventional fields. Due to the different tillage systems, the soil cover over the winter can differ.

Table 1. *Crops, cultivars (cursive) and cover crops (between brackets), per year and per field.*

	Organic farming system			**Conventional farming system**	
Year	**Field J10-3**	**Field J10-4**	**Field J10-6**	**Field J9-4**	**Field J9-6**
2009	Ware potato *Ditta* (grass clover)	Carrot *Nerac* (winter rye)	Spring wheat *Lavett* (white clover)	Spring barley *Tipple* (Italian rye grass)	Sugar beet *Emilia*
2010	Grass clover *	Faba bean - spring wheat *Imposa/Lavett*	Carrot *Nerac*	Seed onion *Summit*	Winter wheat *Tabasco*
2011	White cabbage *Hinova*	Ware potato *Ditta* (grass clover)	Faba bean - spring wheat *Imposa/Lavett* (yellow mustard)	Seed potato *Agria* (winter rye)	Seed onion *Summit* (yellow mustard)
2012	Spring wheat *Lavett* (common vetch)	Grass clover *	Ware potato *Ditta* (grass clover)	Sugar beet *Rhino*	Seed potato *Agria* (winter rye)
2013	Carrot *Nerac*	White cabbage *Attraction*	Grass clover *	Spring barley *Jennifer* *(mixture 1**)*	Sugar beet *Coyote*
2014	Faba bean - spring wheat *Imposa/Lavett* (yellow mustard)	Spring wheat *Lavett* (hairy fetch)	White cabbage *Reaction*	Seed onion *Dormo* (yellow mustard)	Spring barley *Tipple*
2015	Ware potato *Ditta* (grass clover)	Carrot *Norway*	Spring wheat *Lennox* (white clover)	Seed potato *Milva* (oats)	Seed onion Summit (yellow mustard)
2016	Grass clover *	Spring wheat Lennox (mixture 2**)	Carrot *Nerac* Oats	Sugar beet *Annelaura*	Seed potato Milva (mixture 3**)
2017	Pumpkin *Amoro* (yellow mustard)	Ware potato *Carolus* (grass clover)	Spring wheat *Lennox* (mixture 4**)	Spring barley *Irina* (mixture 5**)	Sugar beet *Florena*
2018	Oats *Dominik* (mixture 4**)	Grass clover *	Ware potato *Carolus* (grass clover)	Seed onion *Hybelle* (mixture 4**)	Spring Barley *Irina* (mixture 5**)
2019	Carrot *Nerac*	Pumpkin *Amoro* *(Mixture 6**)*	Grass clover *	Seed potato *Agria*	Pea *12180-1* *(mixture 7**)*
2020	Green bean *Compass* (mixture 8**)	Oats *Dominik* (mixture 4**)	White Cabbage *Storema*	Sugar beet *BTS 2345 N*	Seed potato *Agria*
2021	Spring wheat *Lennox* (grass clover)	Carrot *Nerac*	Oats *Symphony* *(clover)*	Winter barley *Kosmos* *(mixture 9**)*	Sugar beet *Caprianna KWS*
2022	Grass clover *	Green bean *Galanga* (mixture 10**)	Carrot *Nerac* *(winter rye)*	Pea *Zonda* *(mixture 10**)*	Spring barley *Irina* (mixture 5**)

* *Trivos, Astorga, Sultano, Lucrem, Klondik*

** *Mixture 1: Yellow mustard, common vetch, phacelia*

Mixture 2: White clover, red clover, Persian clover, English rye grass

Mixture 3: Oats, pea, common vetch, phacelia, Alexandrian clover, gingelli, flax, tillage radish, black oats

Mixture 4: Yellow mustard, common vetch, phacelia, Alexandrian clover, gingelli, flax, tillage radish

Mixture 5: Yellow mustard, common vetch, phacelia, Alexandrian clover, gingelli, flax

Mixture 6: Yellow mustard, common vetch, phacelia, Ethiopian mustard, niger, flax

Mixture 7: Yellow mustard, Ethiopian mustard, phacelia, camelina, buckwheat, flax, tillage radish, black oats

Mixture 8: Pea, vetch, serradella, Alexandrian clover, alsike clover, black oats, fodder radish, sunflower, flax, lupine

Mixture 9: Oats, barley, phacelia, camelina, gingelli, flax

Mixture 10: Yellow mustard, Phacelia, flax, black oats, gingelli, fodder radish, Ethiopian mustard, camelina, buckwheat, sunflower

(………) Crop sequence differs from template

2.2.2 Soil tillage systems

The focus of the BASIS experiment is the comparison of different soil tillage systems. The main difference between the soil tillage systems is the cultivation method used in autumn (often November), after the main crop of that year. The reference system is conventional tillage (CT): mouldboard ploughing down to 23-25 cm, an inversing soil tillage practice. This is compared to two systems with reduced, non-inversed, tillage. The first is reduced tillage with sub-soiling (RTS): chisel ploughing down to 18-20 cm. The second is reduced tillage without sub-soiling (RT): no autumn cultivation, except for chisel ploughing down to 18-20 cm after carrots (in the organic system), to reduce soil compaction for the next crop. The reduced tillage system is not a no-till systems, because seed or plant bed preparation is applied conventionally and it is similar in all systems within this experiment. See Appendix A for the details in the differences between the soil cultivations and on the tillage equipment that was used.

The production of fine seed crops like seed onion and carrot showed to be more difficult in the reduced tillage systems (see results and discussion for more details on this). Therefore, according to the system approach of this experiment, it was decided in 2018 to start with shallow ploughing in the system of reduced tillage without sub-soiling (RT), before growing these small seeded crops and to incorporate grass clover. This was done in two of the three organic fields and in one of the conventional fields. In the other fields the RT treatment remained the same, without any reversed soil tillage. Thus from 2018 onwards these fields have a new treatment called reduced tillage/shallow ploughing (RT/SPL). See Appendix A for details in which years shallow ploughing was used. This new treatment is not shown in Figure 3, however shallow ploughing is done in early spring at approximately the same moment as reduced tillage and thus has a comparable effect on soil cover in winter as reduced tillage (RT, RTS).

Before the start of the experiment in 2008, all fields were cultivated with chisel ploughing down to 30 cm, to remove a potential plough pan. Chisel ploughing was also used in the RT treatment in the first two years, because the soil was very compacted after harvest. However the depth of this cultivation was less than for the RTS treatment which was treated up to 18-20 cm depth.

2.2.3 Controlled traffic farming

In this experiment controlled traffic farming (CTF) was used as much as possible in all crops. Crops could be sown or planted and managed from the fixed lanes. Ploughing and harvesting of certain crops could not be done with CTF, but were carried out using conventional tractors and machinery with minimal soil impact by utilizing low-pressure tires, tracks and by not fully utilizing the storage capacity of the harvester or kipper. Over the years more crops could be harvested with CTF. In the experimental setup, buffer or service lanes were used, which could be fully traversed during crop harvest to relieve the cultivation beds used for observations. Table 2 provides an overview of which crops can or cannot be sown, maintained and harvested with CTF.

The cultivation beds are 3 meters wide, with a track width of tractors and machinery of 3.15 meters. This allows for the use of many standard machines with a 3-meter working width. Moreover, with this track width, it is possible to use public roads as the total width can remain within 3.50 meters. Adjustments have been made to machines and implements to deploy them in the CTF system. This mainly involved relocating guide wheels or increasing the working width to achieve a multiple of 3.15 meters.

Table 2. Use of controlled traffic farming (CTF) for the different crops. ORG: organic system, CON: conventional system. +: could be done completely with CTF, -: could not be done with CTF, +/-: could partly be realised with CTF.

Crop	Sowing or planting	Maintenance	Harvest	Explanation
Ware potato (ORG)	+	+	-	Harvest with low soil pressure
Grass clover (ORG)	+	+	+/-	Mowing with standard machinery, removal from service lanes
White cabbage (ORG)	+	+	+	First years harvest with standard machinery, later with CTF
Spring wheat (ORG)	+	+	+	First years harvest with standard machinery, later with CTF
Carrot (ORG)	+	+	-	
Faba bean/ spring wheat (ORG)	+	+	+	First years harvest with standard machinery, later with CTF
Seed potato (CON)	+	+	-	Harvest with low soil pressure
Sugar beet (CON)	+	+	-	Harvest with low soil pressure
Spring Barley (CON)	+	+	+	First years harvest with standard machinery, later with CTF
Seed onion (CON)	+	+	+/-	Harvesting with CTF, loading and transport with standard machinery

2.2.4 Crop protection

The use of crop protection against deceases, pests and weeds was done similarly for all soil tillage systems. Weed pressure showed often to be higher in the reduced tillage system. Approximately once every four or five years this made it necessary to carry out extra chemical weed control. The tillage treatments could not be sprayed separately, so when this was necessary all soil tillage systems were treated, even if it was not needed in the conventional tillage treatment. The only difference that was made between the tillage systems, was a false seedbed in the reduced tillage treatment. This was necessary every year in both the organic and conventional systems.

Crop protection did differ for the organic and conventional system. In the organic fields, crop protection was limited to incidental use of Bacillus thuringiensis in cabbage, to control diamondback moths (Plutella xylostella). This insecticide is allowed in organic systems according to Dutch and EU regulations. In the organic system weed control was done mechanically or by hand weeding. In the conventional system, crop protection and weed suppression were executed according to the local best agricultural practices. For weed control this meant a combination of chemical and mechanical solutions.

2.2.5 Fertilization

Fertilization schemes (type, rate and timing) did not differ between tillage systems. However fertilization did differ for the organic and conventional systems, because of different crop rotation and crop demands. In Appendix B the applied fertiliser types, average rates and the timing of application are shown in detail. Fertilization rates were based on crop demands, soil properties, legislation and good agricultural practises, like the leading fertilization recommendations for arable crops (Commissie Bemesting Akkerbouw en Vollegrondsgroenteteelt (CBAV)).

In the organic system, fields were fertilized with a combination of animal manure and other organic fertilizers types, following standard organic practices as prescribed by EU organic regulations. In the conventional fields only mineral fertilizers were used in the first years of the experiment. By only using mineral fertilizers, differences in soil organic matter and nitrogen requirements of crops between the different soil tillage systems could become more clear. Using only mineral fertilizers was common practice in conventional agriculture. However, this changed over the years and more organic fertilizers were used also. According to the systems approach of this experiment, the fertilization of the conventional fields was adapted to common practices and solid goat manure was used in 2021.

2.3 Data collection

2.3.1 Yield

To determine the effect of tillage system on crop yield, we took yield samples of the main crops each year (Appendix C), at harvest time. Yield sampling methods ranged from hand sampling in small plots to machine sampling in larger plots. Sampling methods and dimensions differed between crops and feasibility (Table D.1, Appendix D). For grass clover the different cuts are also analysed separately. When yield quantity is described in the results, marketable product is considered.

2.3.2 Yield quality

Yield was categorised into three classes: marketable product, net yield, and gross yield. Marketable product was defined as crop yield suitable for sale; net yield as marketable product plus the yield not meeting the size grading criteria; and gross yield as net yield plus rotten and deformed products (Table D.2, Appendix D). In the case of potato, carrots and seed onion, yield was also assessed in terms of size classes (Table D.3, Appendix D). For potatoes carrots and seed onions, yield quality is described as the difference between gross and marketable product. For the other crops, various crop characteristics are used to describe yield quality, such as sugar content for sugar beet and thousand grain weight for the cereal crops.

Yield quality was determined every year (Appendix C). Other yield characteristics such as crop density (Table D.4 in Appendix D), tillering number, crop height, dry biomass of the crop, mineral content of the crop and biomass of crop residue were determined in some of the years (Appendix C). Since this was not done consequently and little data is available, this is not further described or analysed. Only crop density of the fine seeded crops carrots and seed onions is taken into account.

2.3.3 Physical soil aspects

To determine the effect of soil tillage on soil compaction, the bulk density was measured. This was done with the volumetric cylinder method (ISO, 2017) at two depths: 2-7 cm and 14-19 cm. Depth was not always determined accurately, so we take these measurements as an indication of bulk density in the top layer (0-10 cm) and the deeper layer (10-20 cm) of the soil. With this measurement the moisture content of the soil was also determined. Besides this, possible soil compaction was investigated by measuring penetration resistance from 0 to 80 cm depth, with a 10 mm diameter 30º semi-angle penetrometer probe. Every centimetre a value for penetration resistance is given. Only the data of the top 60 centimetre of penetration resistance was analysed, since data from the lowest 20 centimetre is often not reliable. Changes in soil physical properties were not expected to occur with a few years, so these measurements were done every couple of years. However, the frequency over the years of these soil physical measurements was quite variable because of soil conditions or standing crop (Appendix C).

2.3.4 Chemical soil aspects

To investigate the effect of soil tillage and winter cover by cover crops on nutrient loss and recovery over the winter, the mineral nitrogen in the soil is measured. Soil samples are taken in November, after harvest, and in spring, in the layers 0-15, 15-30, 30-60 and 60-90 centimetres. Soil samples were send to Eurofins for analysis. This measurement was done yearly (Appendix C). Also a general soil analysis was done by sending soil samples to the soil chemistry laboratory of WUR (CBLB) in 2009 and 2011 and to Eurofins from 2013 onwards. The nutrient content and availability in the soil, the soil organic matter and the soil organic carbon were determined with the classical method (for organic matter with combustion). Changes in these soil characteristics were not expected within a few years, so measurements were done every couple of years (Appendix C).

2.3.5 Other research topics

2.3.5.1 Seedbed preparation for carrots

To investigate the effect of using a Twinrotor tiller (brand: Struik) for growing carrots in the organic system, an extra experiment was conducted in 2022 on the field J10-6 in the plots outside the experiment (Figure 2). In the conventional tillage (CT) and reduced tillage (RT) systems, the ridges for the carrots were made using either a standard rotary tiller of a Twinrotor tiller. The standard rotary tiller and the Twinrotor we alternately used on every bed of 3.15 m width.

To determine the effect of the different tillers, several factors were measured, including aggregate stability, aggregate size distribution, emergence rate, and yield. Aggregate stability was measured because it indicates the susceptibility of the soil to slacking. The smaller the soil aggregates are, the more unstable they are, leading to their rapid collapse and soil compaction during heavy rainfall. Aggregate size reflects the coarseness of the prepared soil, providing insights into its structure. Aggregate stability and size distribution were measure using the wet sieve apparatus from Eijkelkamp (Eijkelkamp, 2023). Emergence is influenced by the coarseness of the soil because carrots, being a small-seeded crop, require a loose and fine soil structure for proper germination and growth without branching or deformities. However, excessively fine and loose soil can increase the risk of seed washout and soil slacking during heavy rainfall. To show the effect of the different tillers on the crop development and final productivity, the emergence rate and yield were measured. All measurements in the additional carrot tillage experiment were done in two replications.

2.3.5.2 Weed seedbank

At the start of the 2022 season, the number of weeds in the soil seedbank and their species composition was estimated. The main objective was to determine the effect of soil tillage on the density and composition of the weed seedbank, comparing reduced tillage practices with conventional ploughing after a trial period of thirteen years.

To estimate the soil weed seedbank, soil samples were collected from three field with an organic management and two field with a conventional management. Samples were collected in the field from the 0-10 cm soil layer. In each field, 48 soil cores were collected following a fixed sampling scheme using a 40 mm width auger. For fields J9-6 and J10-3 only 36 soil cores were sampled. The cores were combined into one sample per field. This resulted in a total of 60 soil samples (3 tillage systems × 5 fields × 4 repetitions). Soil sampling was done on the 9th of March, shortly before the first tillage operations in 2022. For practical reasons, the soil samples were reduced to 10 kg of moist soil. To be able to compare densities between layer and treatments, the number of weeds were recalculated using the dry weight of each sample in the greenhouse and average soil bulk densities from earlier bulk density determinations.

The soil samples were taken to a greenhouse in Lelystad and assessed using the seedling emergence method. During the period between March and September, the weed seeds were germinated in the greenhouse and weed seedlings were determined on species level. After each germination flush, the soil was air dried, mixed again and rewatered to stimulate a new germination flux and let the remaining seeds germinate. In total, five cycles were completed by the end of the assessment.

2.3.5.3 Nitrogen balance in Ndicea

The nitrogen balance in Ndicea was build, based on yield data from the crops in this experiment and their nutrient content, the fertilization data, the sowing/planting and harvesting dates and on the general soil fertility and mineral nitrogen content of the soil. The PC version Ndicea 6 was used. Data from 2009 till 2022 from the conventional field J9-4 and the organic field J10-3 were used. A comparison was made between the conventional tillage treatment (CT), reduced tillage with sub-soiling (RTS) and without sub-soiling (RT). The modelled output was compared to the measurements done in the field. There was a good match with the measured mineral nitrogen. However, the match with total nitrogen in the soil and with soil organic matter was not good. Therefore the modelled balances cannot be used as reliable output and are not further documented in this report and research question 12 is not answered.

2.4 Statistical analysis

All statistical analysis was performed using R (v4.2.0).

2.4.1 Yield

First, the effect of tillage on yield was tested per crop and per year with an ANOVA test based on a randomized block design with four tillage treatments (CT, RT/SPL, RT, RTS) and four replicates. Normality and homogeneity were assumed and checked by QQ-plots and Levene's test. When a tillage effect within a crop and year combination was found, a post-hoc test (Tukey's test) was performed to see which tillage systems differed from each other. The results of these pairwise comparisons within years and crops can be found in chapter 3.1.2.

Secondly, tests were performed to see per crop for all years, what the general effect of tillage treatment on the yield was, by using an ANOVA-type III test. As crops were not grown every year in the crop rotations, a year effect could be present. Therefore, before heading to the ANOVA test, each crop was tested on interaction with year and tillage (only when crops were grown multiple years). Interaction was tested by using a linear mixed-effects model (package: lmerTest, using a linear mixed model fit by REML), with main effects (year + tillage) and the interaction effects (year*tillage). When interaction was present ($P < 0.05$), it was not possible to make direct comparisons between the treatments over years without combining a treatment with a year. So, pairwise comparisons were done only within a year (see previous paragraph). When interaction was not present ($P > 0.05$), it was possible to test whether tillage system affected the main effects (year and tillage), by running the linear mixed model only with the main effects. In this case, it was possible to make a conclusion whether tillage has a significant effect on yield, by checking the contrasts of tillage treatments over the years. The conclusions of these tests can be found in chapter 3.1.1.

2.4.2 Yield quality

The effect of tillage on yield quality was tested per year and crop with an ANOVA based on a randomized block design with four tillage treatments (CT, RT/SPL, RT, RTS) and four replicates. The dependent variables used in the analysis are described in chapter 2.3.2. Normality and homogeneity were assumed and checked by QQ-plots and Levene's test. When an effect of tillage on the yield quality was found, a pairwise comparison test (Tukey's test) was performed to investigate which tillage systems differed significantly from each other within a year and crop combination.

2.4.3 Physical soil aspects

To test whether tillage influences the physical soil aspects in a certain year, field and measuring depth, an ANOVA-test was performed on bulk density and moisture content. In case P-values were < 0.05, a pairwise comparison (Tukey's test) was used to see which tillage systems differed significantly from each other. The estimated means of the four replicates in a certain year, field, measuring depth and tillage system were calculated using the emmeans package in Rstudio.

2.4.4 Chemical soil aspects

To test whether tillage influences the chemical soil aspects in a certain year, field and measuring depth, an ANOVA-test was performed on bulk density, moisture, organic matter and nutrient content of the soil. In case P-values were < 0.05, a pairwise comparison (Tukey's test) was used to see which tillage systems differed significantly from each other. The estimated means of the four replicates in a certain year, field, measuring depth and tillage system were calculated using the emmeans package in Rstudio.

2.4.5 Other research topics

2.4.5.1 Seedbed preparation for carrots

Due to lack of replications over years and therefore reliable robust data, no statistical tests were performed on the data of the Twinrotor experiment.

2.4.5.2 Weed seedbank

The weed seedbank was only determined in 2022. Due to lack of a comparison with the original seedbank at the start of the experiment and due to a large variation in the data, no statistical tests were performed on the weed seedbank data.

3 Results

3.1 Yield

3.1.1 General effect of soil tillage system on yield

Figure 4 and 5 provides an overview of the yield per crop, respectively for the organic system and the conventional system. The yield in the systems reduced tillage with sub-soiling (RTS), reduced tillage without sub-soiling (RT) and reduced tillage with occasional shallow ploughing (RT/SPL) are shown relative to the reference system of conventional tillage (CT).

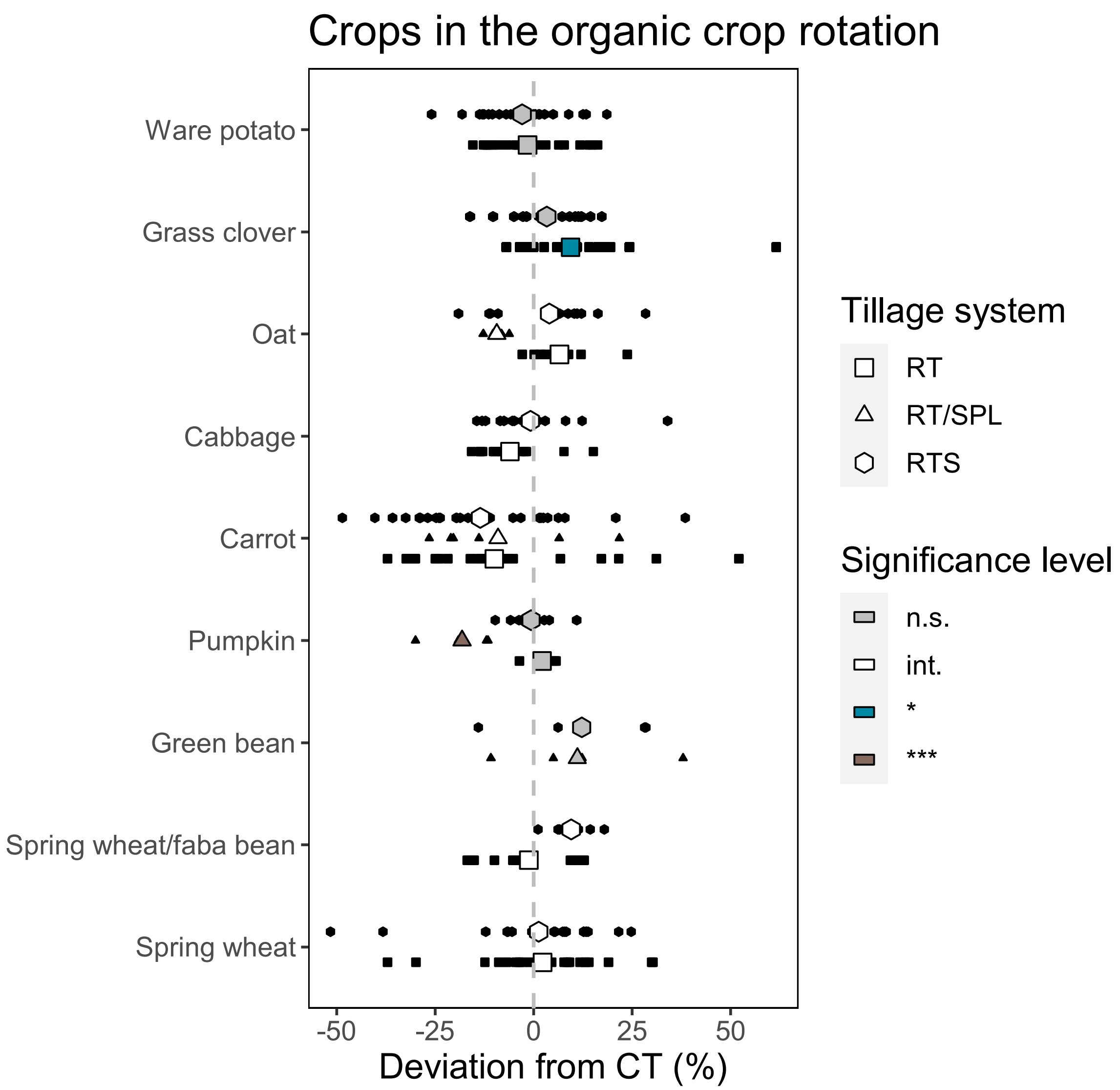


Figure 4. Yields per crop in the organic system. Reduced tillage with sub-soiling (RTS), reduced tillage without sub-soiling (RT) and reduced tillage/shallow ploughing (RT/SPL) are shown as a percentage (%) relative to conventional tillage (CT) on the x-axis. The small black markers represent observations per individual year and plot. The bigger markers show the average marketable yield over the years (2009-2022), the colour indicates significance within a crop: grey showing no significant differences between the tillage systems; white markers are the crops where interaction between year and tillage was found; blue means P < 0.05 and brown means P < 0.001.

The organic system contains nine crops in total. Oats, cabbage, carrot, spring wheat/faba bean and spring wheat were crops in which interaction was visible between the year and yield. So for example the oats crop yield in a certain tillage system strongly depended on the year in which the crop was grown. Therefore, significant differences can only be interpreted within a year. In ware potato, grass clover and pumpkin, no interaction effect was visible and therefore conclusions can be drawn on whether tillage system affected the crop yield over years. Green beans were only cultivated in one year so interaction was not possible. In ware potato and green bean, tillage type did not affect the marketable crop yield. In pumpkin and grass clover the tillage system did affect the marketable crop yield. The yield in the RT system was significantly higher (P = 0.021) than in the CT system in grass clover. The yield of marketable pumpkins was significantly lower (P < 0.001) in the RT/SPL system compared to the CT system.

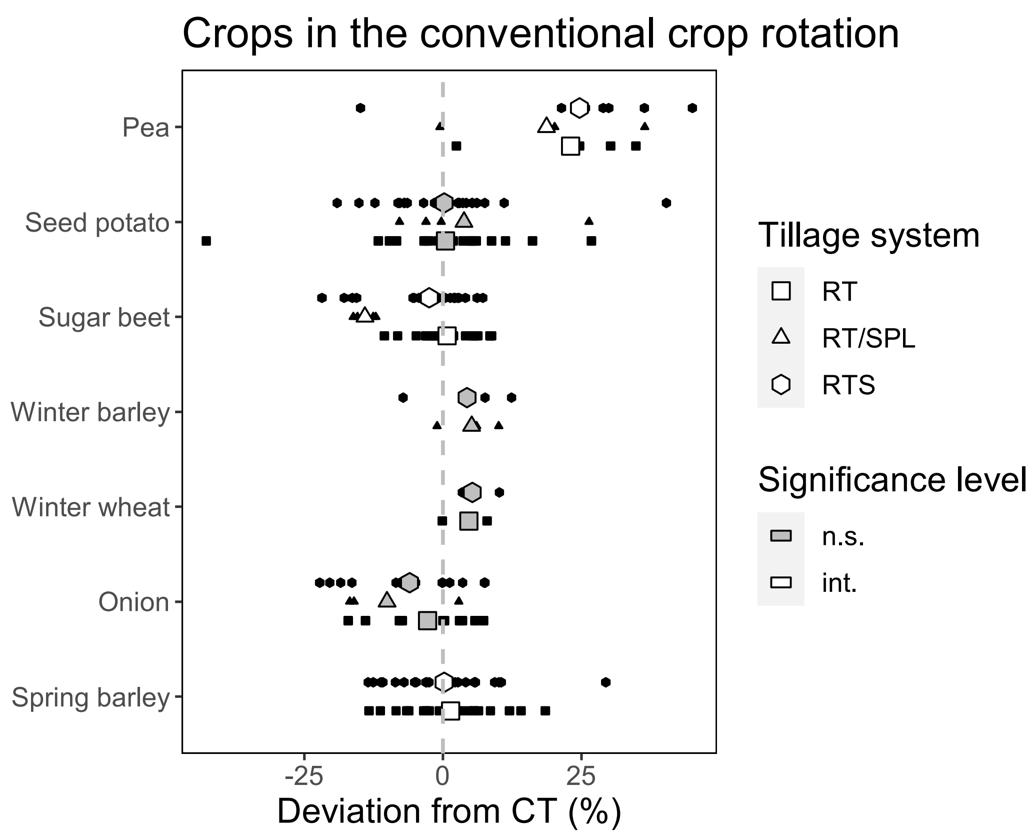


Figure 5. Yields per crop in the conventional system. Reduced tillage with sub-soiling (RTS), reduced tillage without sub-soiling (RT) and reduced tillage/shallow ploughing (RT/SPL) are shown as a percentage (%) relative to conventional tillage (CT) on the x-axis. The small black markers represent observations per individual year and plot. The bigger markers show the average marketable yield over the years (2009-2022), the colour indicates significance within a crop: grey showing no significant differences between the tillage systems; white markers are the crops where interaction between year and tillage was found; blue means P < 0.05 and brown means P < 0.001.

Seven different crops were grown in the conventional crop rotation since 2009. In pea, sugar beet and spring barley, a significant interaction was visible between the year and yield. Therefore, significant differences can only be interpreted within a year. Seed potato and seed onion did not show interaction between year and yield, but also did not show an significant effect of tillage system on yield. Winter barley and winter wheat were only grown once, therefore interaction was not possible. These crops also did not show significant yield effects between tillage systems.

3.1.2 Yearly effects of soil tillage system on yield

The effect of soil tillage system on the yield in each crop and year combination can be found in Appendix E. The crops x year combinations that show a significant P value, were tested in a Tukey's post-hoc test. The results are given per crop.

3.1.2.1 Ware potato in the organic crop rotation

The marketable product of ware potato in the organic crop rotation showed significant differences only in 2017, where the CT yielded higher than the RT (Figure 6). The other years did not show differences between the tillage system. Difference between the tillage systems do seem to be a bit larger in the last years (2017 and 2018), but not clearly in one direction.

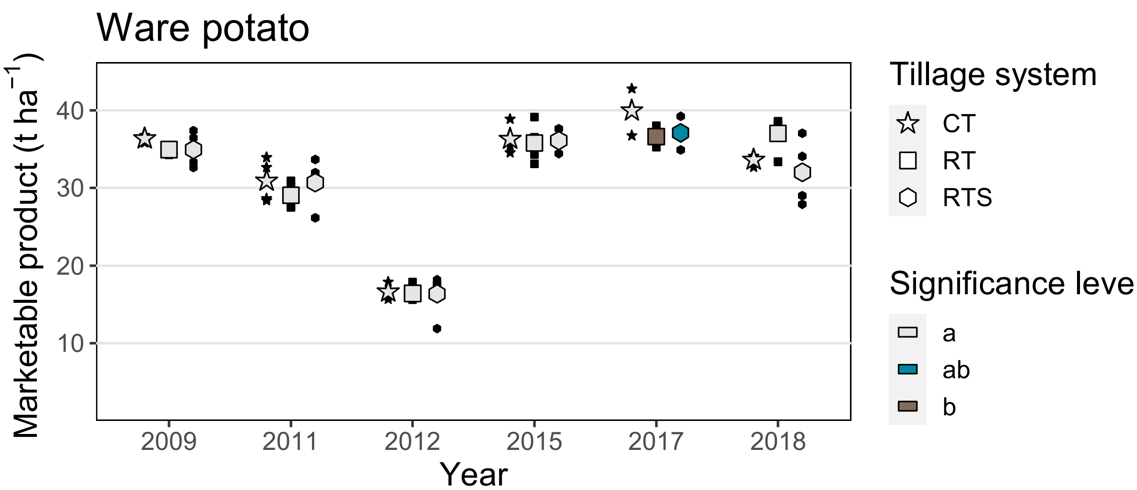


Figure 6. Yearly marketable product of ware potato in the organic crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.2 Grass clover in the organic crop rotation

The marketable product of grass clover was measured in terms of dry weight. In Figure 7a the different cuts are averaged over the year in one black marker. In 2012 a large rain event caused slacking in the CT system, probably caused by a lower mean weight diameter of the soil aggregates and aggregate stability of the topsoil in this system. Due to the bad soil conditions and loss of plants, this treatment was ploughed in October 2011 and resown in spring 2012.

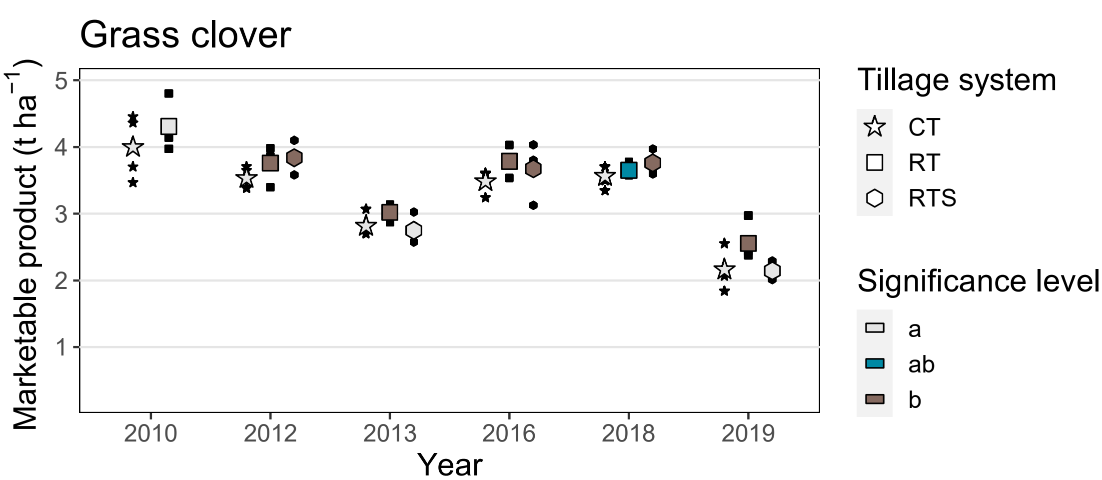


Figure 7a. Yearly marketable product of grass clover in the organic crop rotation. The small black markers show the separate yield measurements in each plot, averaged for the different grass clover cuts. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

Every year, RT showed higher yields, compared to CT. This difference was significant in four out of six years. RTS also often shows a higher yield compared to CT, however this is a bit more variable. The difference is significant in three years, but in 2013 and 2019 the yield is a bit lower compared to CT. Differences between the treatments do not increase over time.

In Figure 7b the different cuts of grass clover are shown. It appears that the largest difference between the tillage systems was made in the first cut. In 2010, 2013, 2016 and 2018, both RT and RTS treatments showed higher yields than CT in the first cut. In 2019 RT yielded higher than CT and RTS treatments. No large differences can be observed in the second cut. The yield in the CT system in the third cut was higher in 2013 and 2016, whereas in 2010 and 2012 it was lower than RT and RTS. Also no clear differences are visible in yield between the tillage systems in the fourth cut of grass clover.

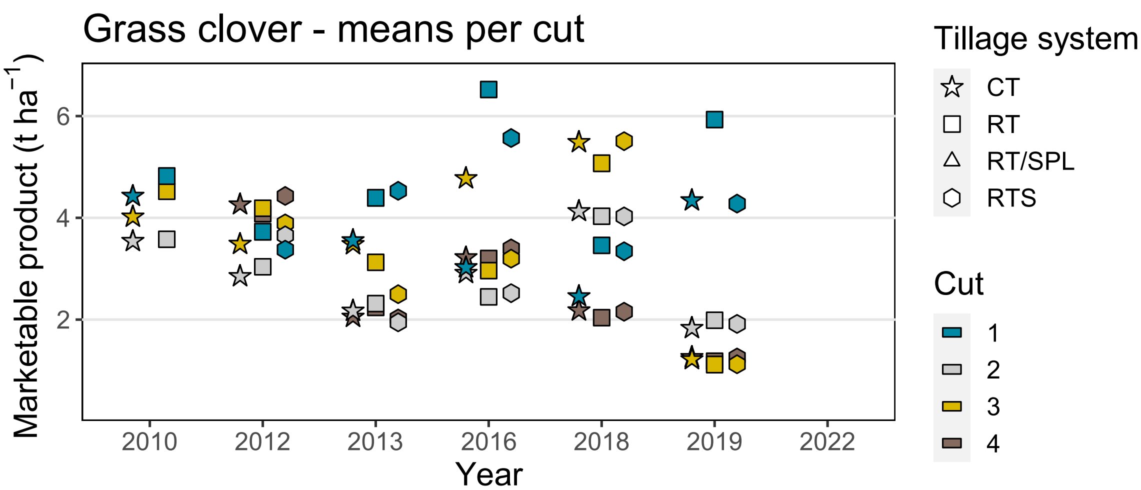


Figure 7b. Yearly marketable product of grass clover in the organic crop rotation, divided over the different grass cuts. In most years four cuts of grass clover were harvested, except in 2010, where only three cuts were harvested. Different colours indicate different cuts, no statistical tests were performed on these data.

3.1.2.3 Oats in the organic crop rotation

Oats were cultivated in the organic crop rotation from 2018 on, as a replacement of spring wheat (Figure 8). The yield of oats in the organic crop rotation showed some significant differences. In 2018 CT was significantly lower compared to RT and RTS, while in 2020 CT was significantly higher than the RT/SPL and RTS. In 2021 the yield of RTS was higher than the other tillage systems, however this difference was not significant.

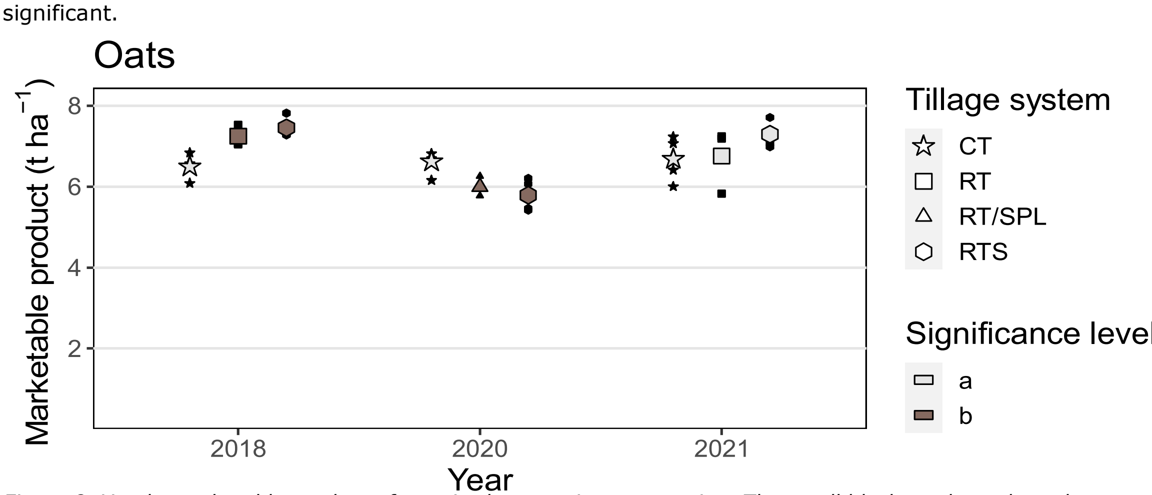


Figure 8. Yearly marketable product of oats in the organic crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.4 Cabbage in the organic crop rotation

The marketable product of cabbages in the organic crop rotation was significantly higher in the CT, compared to RT in all years, accept 2014 (Figure 9). RTS was also always higher compared to RT, however this difference was only significant in 2013. In 2020 the yield in CT was significantly higher compared to both RT and RTS.

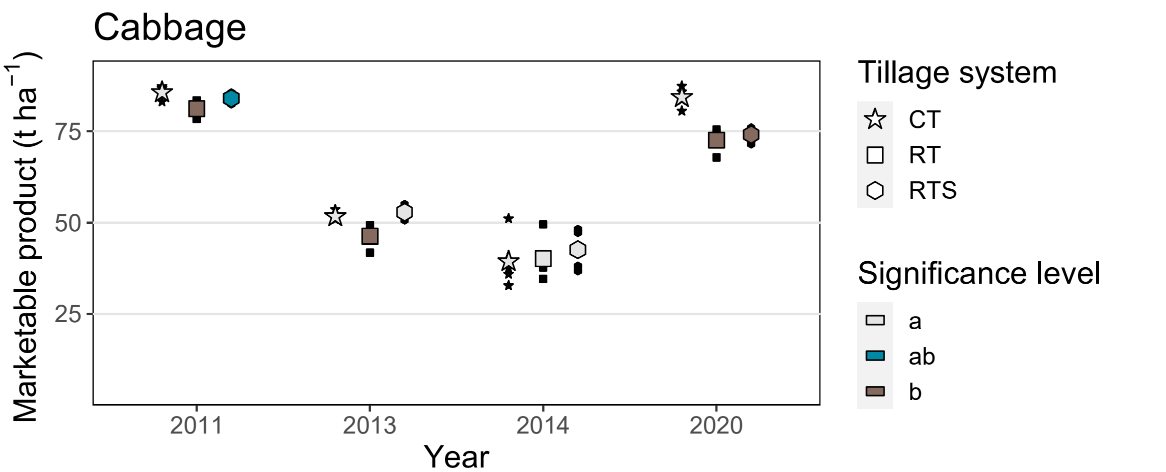


Figure 9. Yearly marketable product of cabbage in the organic crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.5 Carrot in the organic crop rotation

Figure 10a shows the marketable product of carrots over time. In all years, except 2015, the yield was higher for CT, compared to RT and RTS. This difference is bigger in the first years and only significant in 2009 and 2013. Over time the gap reduces and ceases to be significant. The difference between RT and RTS is small, only in 2009 RTS is significantly higher. When shallow ploughing is introduced in 2019 and 2021, the carrot yield in this tillage system (RT/SPL) was found to be between CT and RTS. In 2022 the difference between tillage systems is very small. In this year the Twinrotor was used for preparation and cultivating carrot ridges. See Chapter 3.5.1 for more details on this.

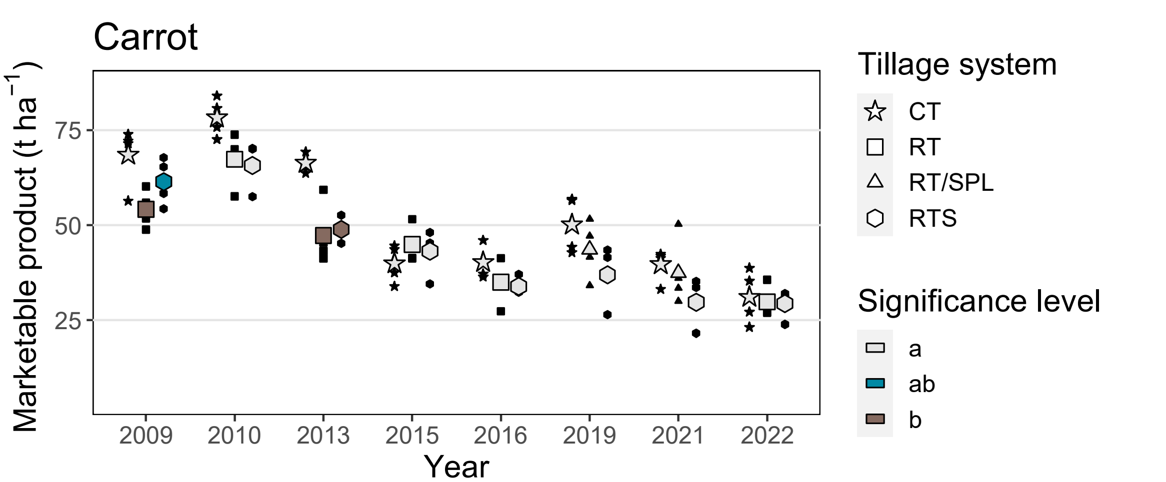


Figure 10a. Yearly marketable product of carrot in the organic crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

The crop emergence of carrots was measured in five years (Figure 10b). The plant density was divided by the amount of seeds sown to calculate the crop emergence per sown seed. 2013, 2021 and 2022 did not show differences in emergence between the tillage systems. 2009 did show a higher crop emergence for CT compared to RT and RTS, while in 2015 an exactly opposite result was found.

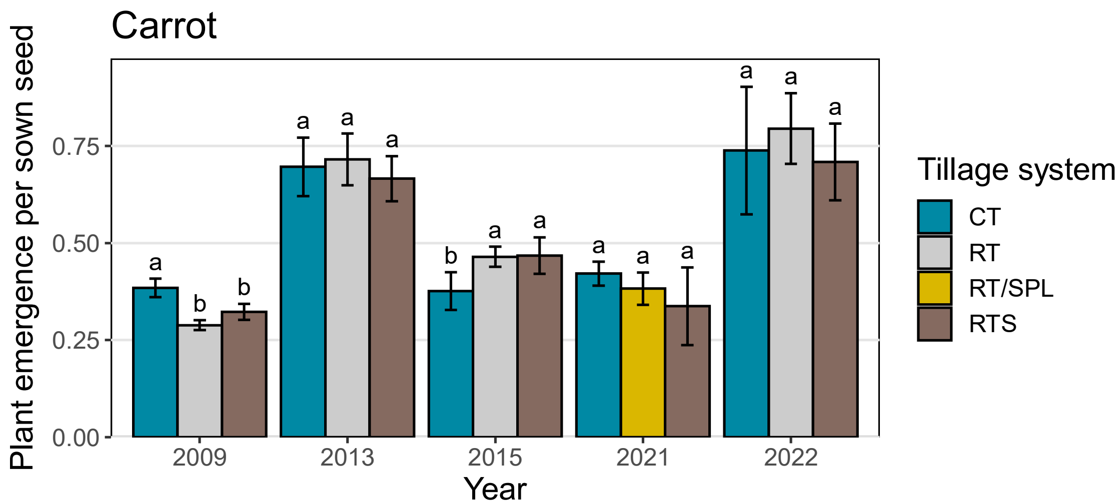


Figure 10b. Yearly average plant emergence of each tillage system in a specific year in carrots. Letters indicate levels of significance. Colours of bars indicate the tillage system.

3.1.2.6 Pumpkin in the organic crop rotation

Pumpkins were only grown in the organic crop rotation in 2017 and 2019 (Figure 11). The pumpkin yield in 2017 did not show any significant differences. In 2019 however, the yield for reduced tillage without subsoiling was significantly lower, compared to CT and RTS.

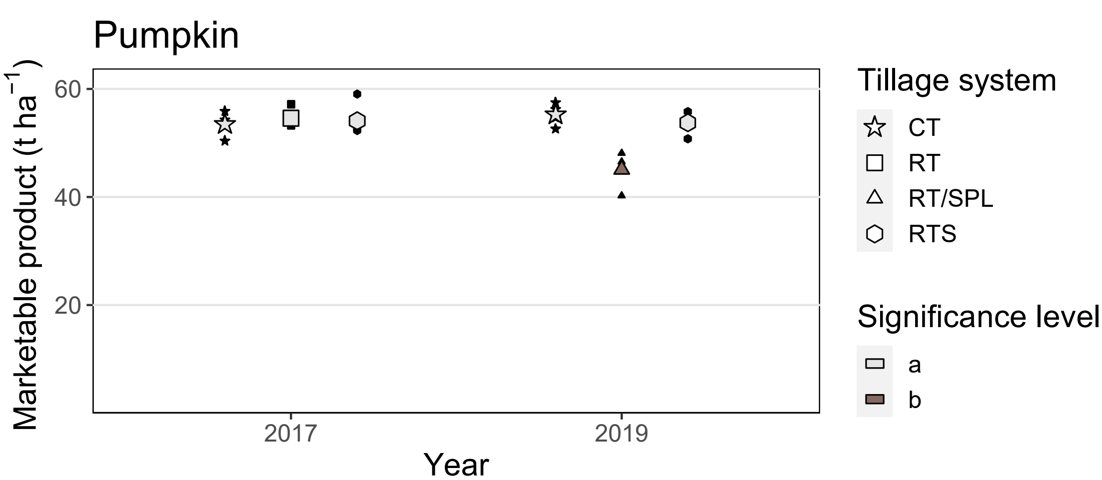


Figure 11. Yearly marketable product of pumpkin in the organic crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.7 Green bean in the organic crop rotation

Green beans were only harvested once after implementation in the organic cropping system in 2020. The field was drowned due to heavy rainfall, which destroyed the crop in 2020. The crop was not harvested that year. The marketable product of green beans in 2022 was a bit higher for RT and RTS, compared to CT; however, the differences between the tillage systems were not significant (Figure 12).

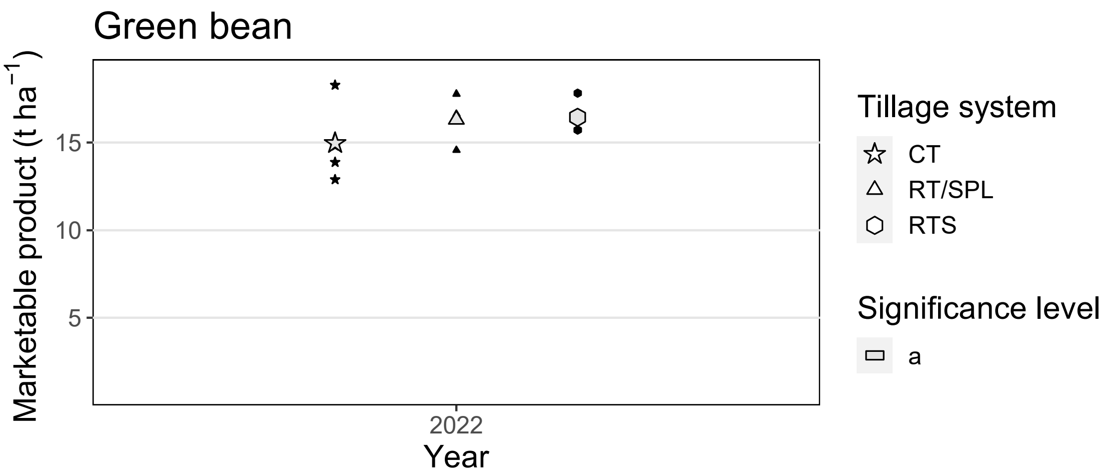


Figure 12. Yearly marketable product of green bean in the organic crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.8 Spring wheat/faba bean in the organic crop rotation

The spring wheat/faba bean intercrop was only grown in the first years of the organic crop rotation (Figure 13). Differences in yield between the tillage systems were quite variable over the years. In 2010 the yield was significantly higher for CT, compared to RT. However, in 2011 both RT and RTS were significantly higher compared to CT and in 2014 RTS was higher than both CT and RT.

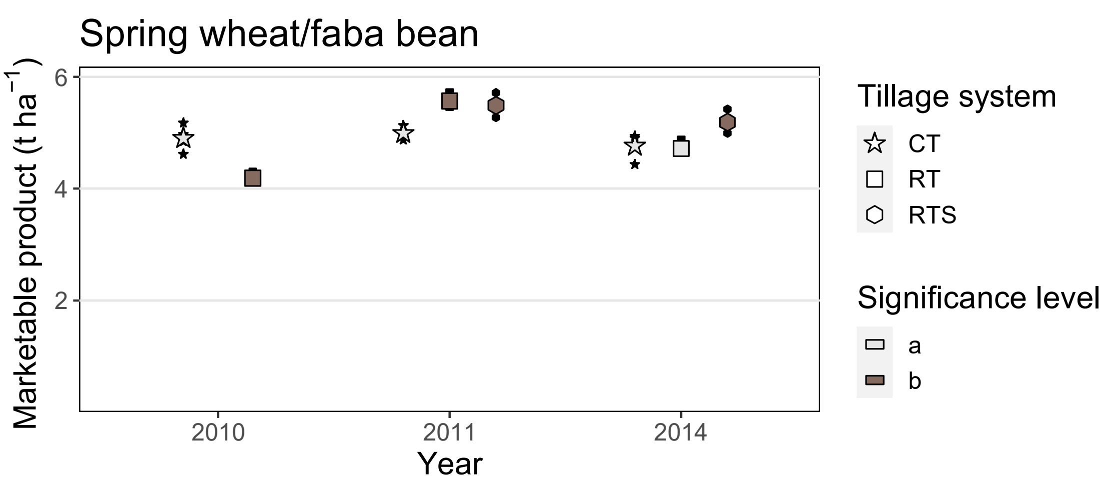


Figure 13. Yearly marketable product of spring wheat/faba bean in the organic crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.9 Spring wheat in the organic crop rotation

Spring wheat was cultivated in the organic crop rotation after cabbage until 2015, after which it was replaced by oats. However, in 2016 and 2017 it was cultivated after carrots as a replacement of the intercrop with spring wheat and faba bean. Since the pre-crops were different the result should be interpreted separately (Figure 14).

The yield of spring wheat, grown after cabbage, was always a bit higher for RT and RTS, compared to CT, except for 2015. However the differences were never significant. The yield of spring wheat, grown after carrot, did show significant differences. However the direction of the difference was opposite for the two years. In 2016 RT and RTS were significantly higher compared to CT and in 2017 CT was higher than RT and significantly higher than RTS.

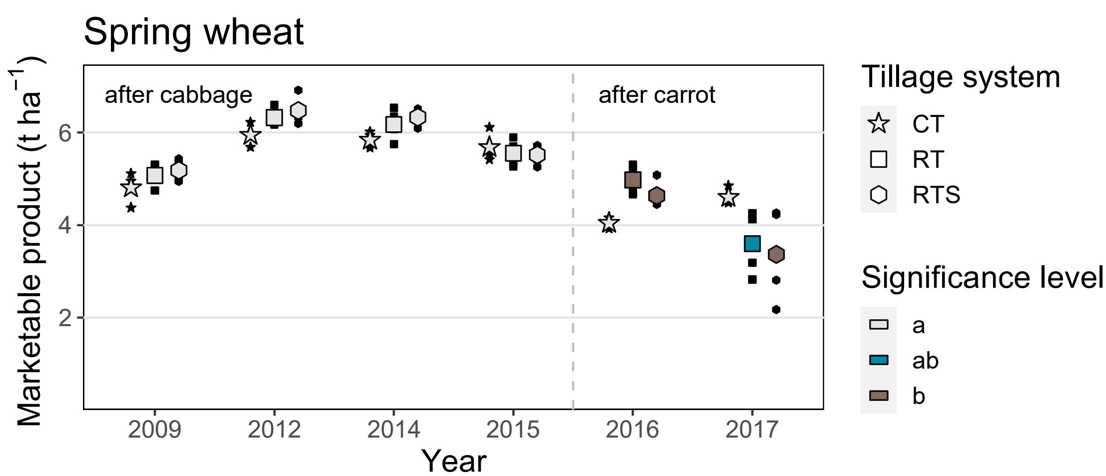


Figure 14. Yearly marketable product of spring wheat in the organic crop rotation. The pre crop was different between the first four and the last two years, this is written in the graph. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.10 Pea in the conventional crop rotation

Peas were grown in the conventional crop rotation from 2019 on, therefore only two years of crop yield are available (Figure 15). In both years the yield for CT was lower compared to the other treatments. In 2019 RT and in 2022 RTS were significantly higher.

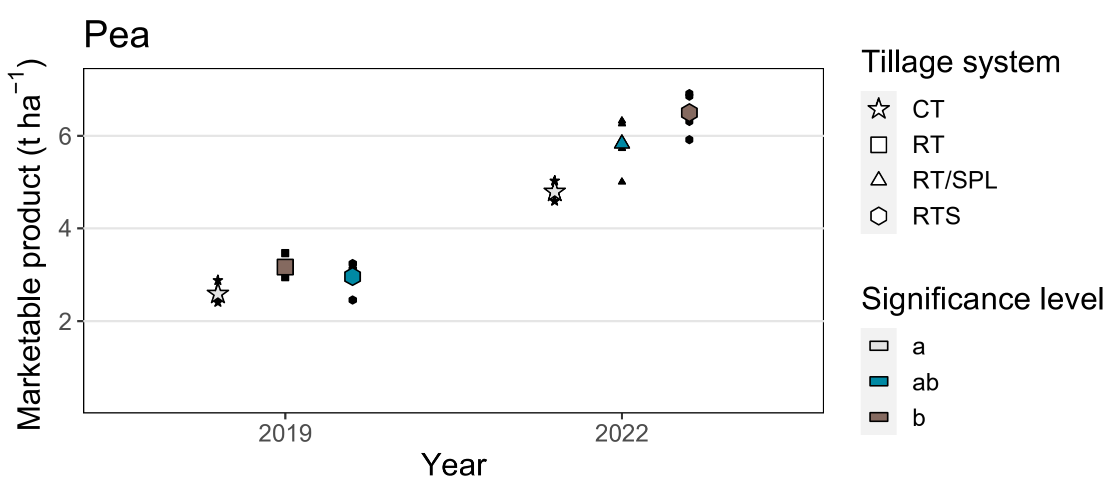


Figure 15. Yearly marketable product of pea in the conventional crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.11 Seed potato in the conventional crop rotation

The marketable product of seed potato per year can be found in Figure 16. Difference in average yield between tillage systems were very small and did not increase over the years. However, in the last two years, the variability in yield (black markers in the graph) increased. Only in 2016 the yield for RT and RTS was significantly higher compared to CT. Over the years different varieties were grown, this partly explains the substantial yield differences over the years ranging from 25 till 50 tons/hectare.

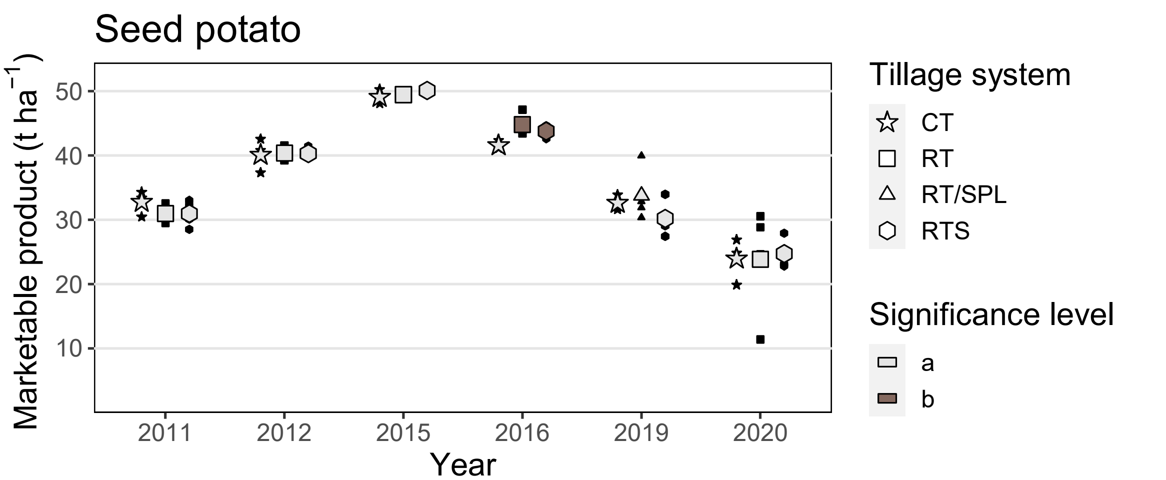


Figure 16. Yearly marketable product of seed potato in the conventional crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.12 Sugar beet in the conventional crop rotation

The marketable product of sugar beets did not show many difference between the tillage treatments and the difference did not increase over the years. However, in 2013 the yield for CT was significantly higher, compared to RT, and in 2020 CT was significantly higher compared to both RT/SPL and RTS.

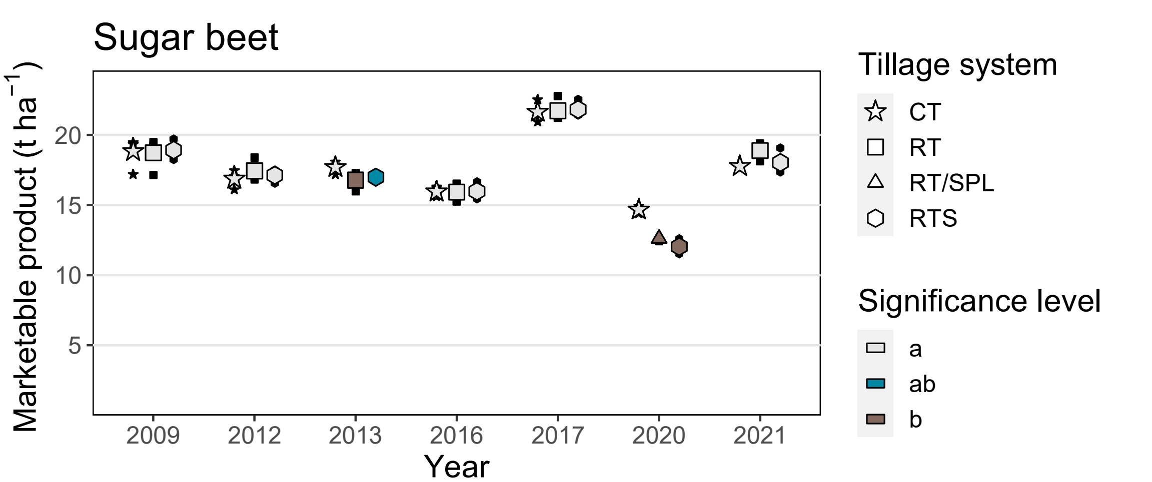
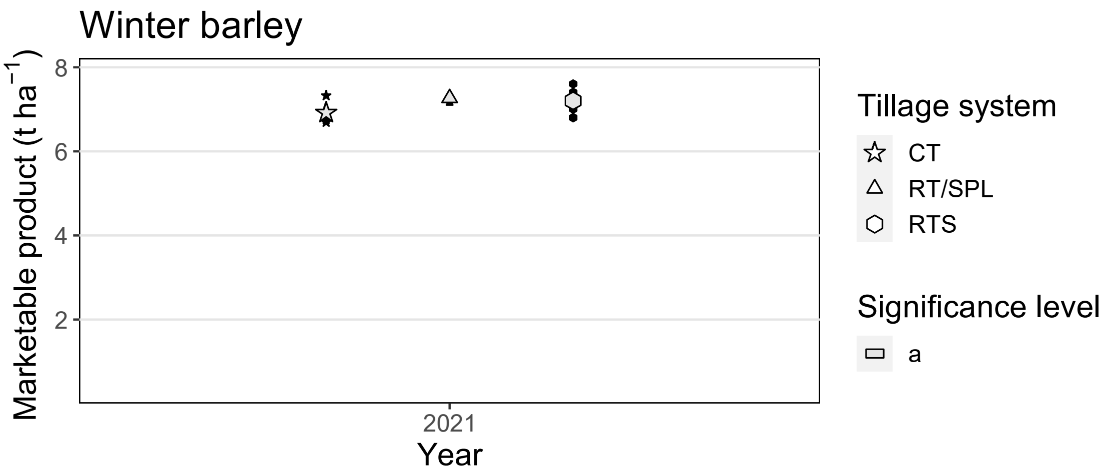


Figure 17. Yearly marketable product of sugar beet in the conventional crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.13 Winter barley and winter wheat in the conventional crop rotation

Winter barley (Figure 18) and winter wheat (Figure 19) were both cultivated once in the conventional crop rotation. For both crops the yield was a bit higher in the different forms of reduced tillage (RT, RTS and RT/SPL), compared to CT. However these differences were not significant.



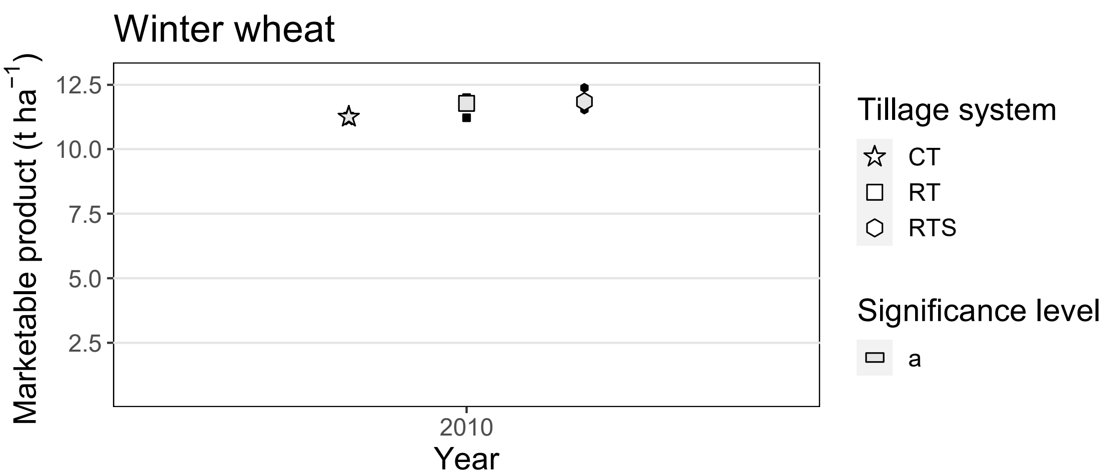


Figure 18 and 19. Yearly marketable product of winter barley and winter wheat in the conventional crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.1.2.14 Onion in the conventional crop rotation

The marketable product of onions in the conventional crop rotation showed substantial annual variations (Figure 20a). Differences between tillage systems are small. Only in 2018, when shallow ploughing was introduced, did the onion yield show a significant difference. However, the main difference was not in the RT/SPL object; but the yield in CT was significantly higher, compared to RTS.

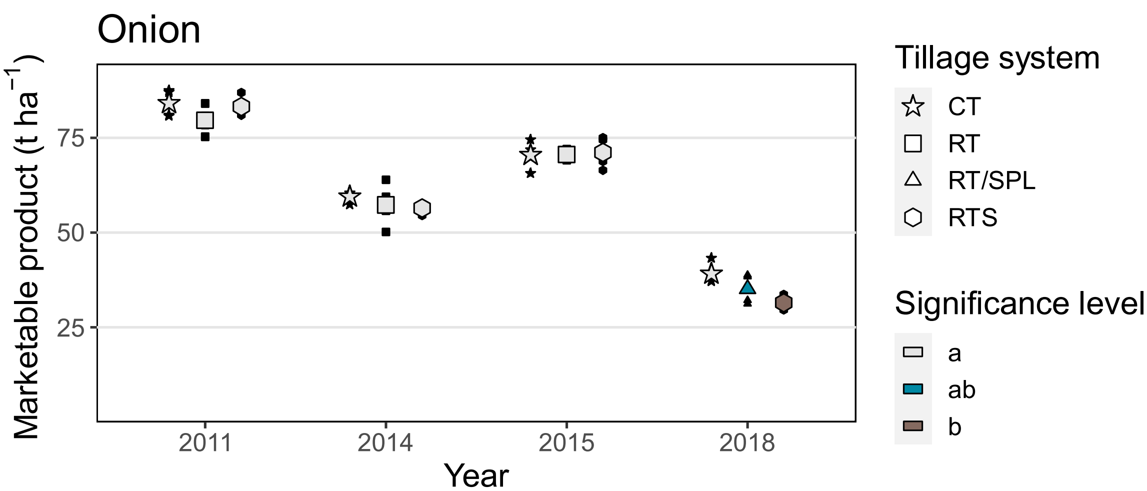


Figure 20a. Yearly marketable product of seed onion in the conventional crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

The plant density of onion was measured in three years (Figure 20b). Plant density was always higher in the CT, compared to the other tillage systems. In 2014 this effect was significant compared to RT and in 2018 compared to RT/SPL.

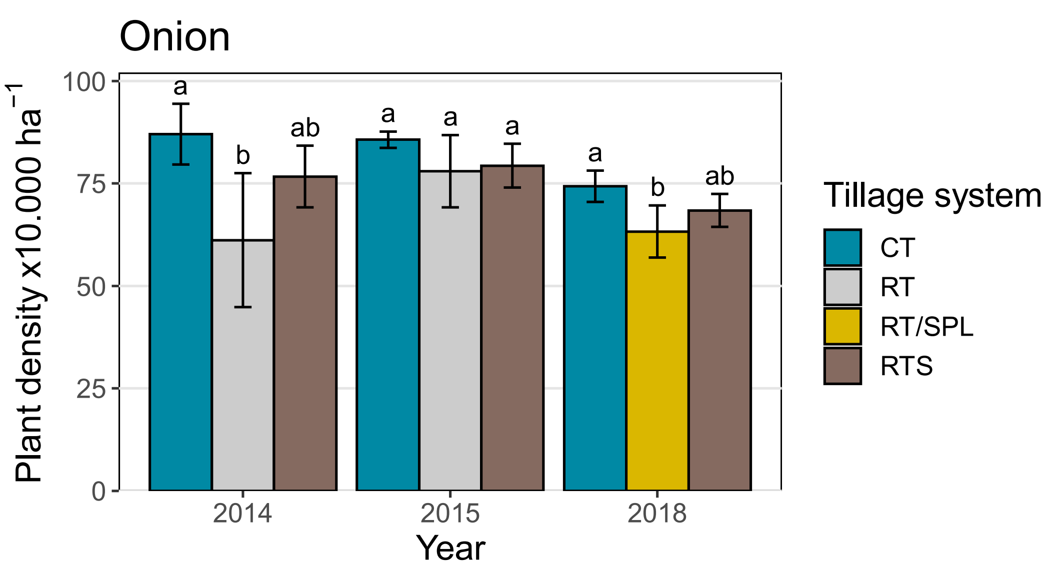


Figure 20b. Yearly average plant density of each tillage system in a specific year in carrots. Letters indicate levels of significance. Colours of bars indicate the tillage system.

3.1.2.16 Spring barley in the conventional crop rotation

Apart from a relatively high yield in 2009, the yields of spring barley were quite stable across the years (Figure 21). Differences between tillage systems were small. In 2013, 2017 and 2018 the yield was a bit higher in RT, compared to CT. However, these differences were never significant and in 2022 the opposite was true. The spring barley yield in RTS was always similar or a bit lower compared to CT. Only in 2017 it was suddenly significantly higher.

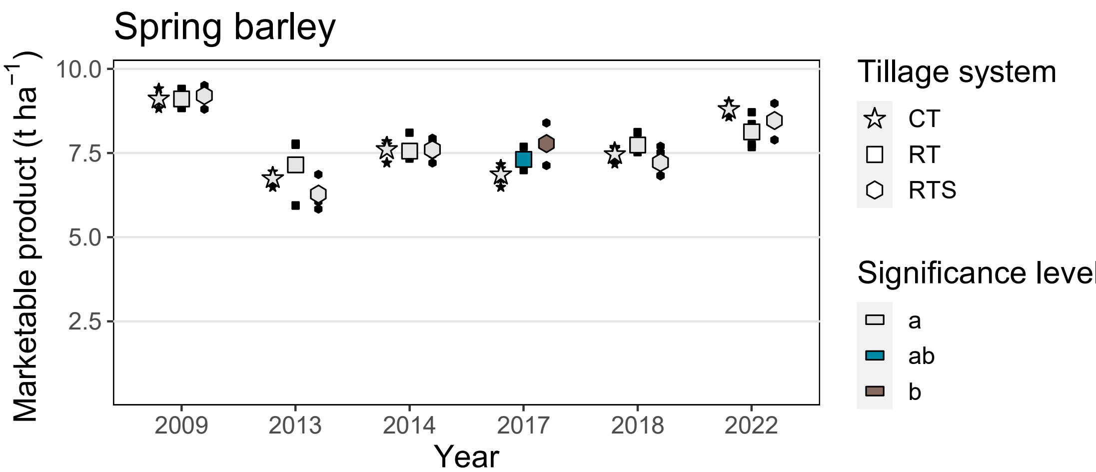


Figure 21. Yearly marketable product of spring barley in the conventional crop rotation. The small black markers show the separate yield measurements in each plot. The bigger marker shows the average yield over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.2 Yield quality

3.2.1 Yearly effects of soil tillage system on yield quality

The results of the ANOVA test for effects of tillage system on yield quality per year and crop, can be found in Appendix F. The significant crop x year combinations were tested with a Tukey's test, these results can be found in the graphs in the following subchapters. Grading in size or weight classes are not analysed; the data can be found in appendix F.

3.2.1.1 Ware potato in the organic crop rotation

The quality of ware potato was expressed in the ratio between marketable product and total gross yield, so the marketable share in the total yield (Figure 22). No significant differences or trends were found between tillage systems.

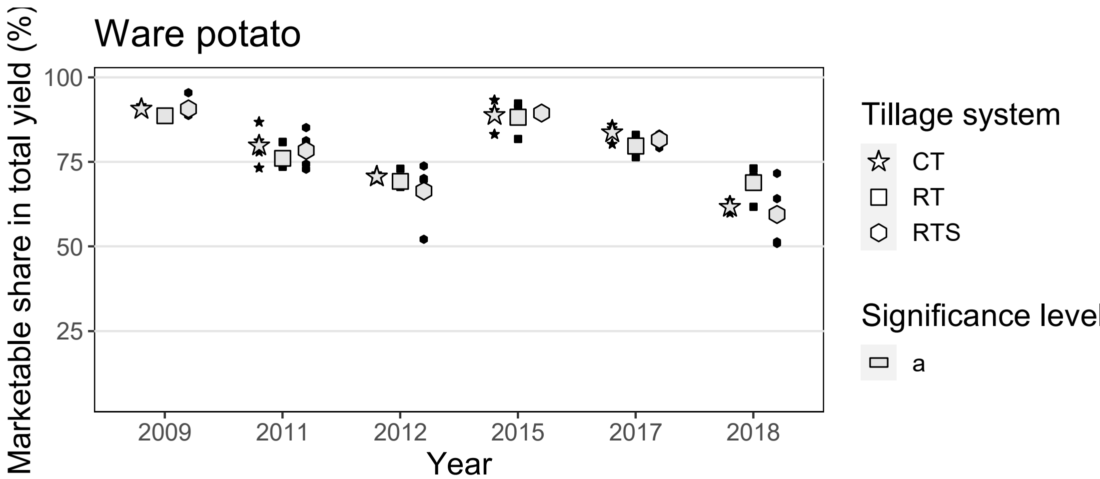


Figure 22. Percentage marketable product of the gross yield for ware potato in the organic crop rotation. The small black markers show the separate measurements. The bigger marker shows the average marketable share over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.2.1.2 Oats in the organic crop rotation

The quality of oats was expressed in the thousand grain weight (Figure 23). No significant differences or trends were found between the tillage systems.

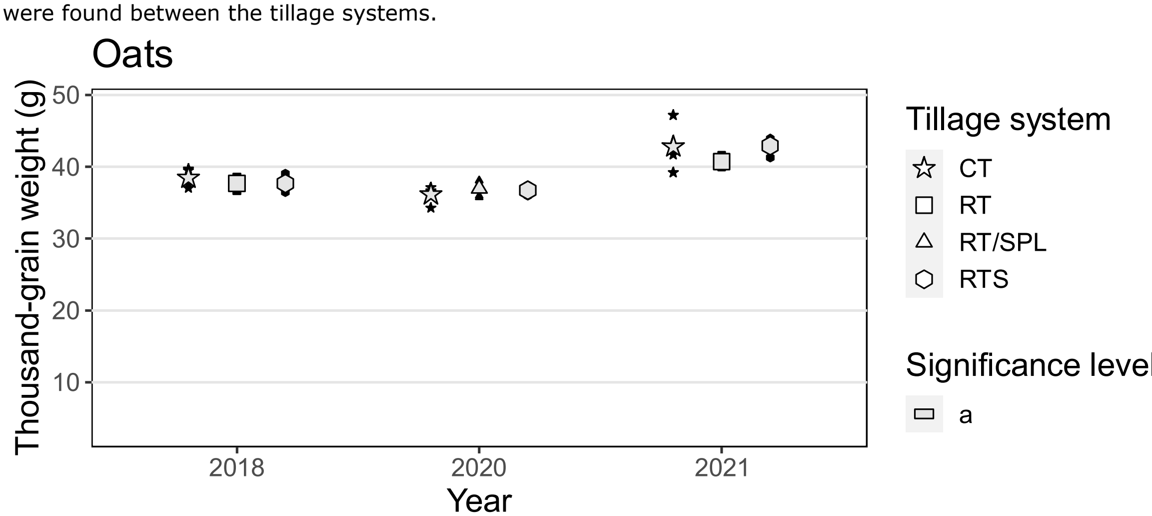


Figure 23. Thousand-grain weight of oats in the organic crop rotation. The small black markers show the separate measurements. The bigger marker shows the average thousand-grain weight over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.2.1.3 Carrot in the organic crop rotation

The quality of carrots was expressed in the ratio between marketable product and total gross yield, so the marketable share in the total yield (Figure 24). The marketable share is higher in conventional tillage (CT), compared to reduced tillage with (RTS) and without (RT) sub-soiling. This difference is only significant in 2009 and 2013. The marketable share for reduced tillage with shallow ploughing (RT/SPL) lies between CT and RT(S).

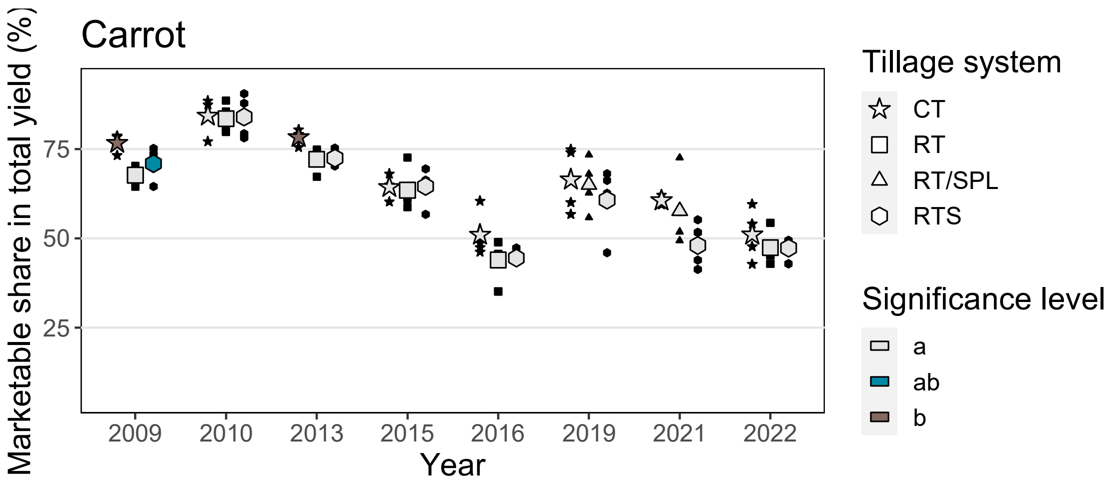


Figure 24. Percentage marketable product of the gross yield for carrot in the organic crop rotation. The small black markers show the separate measurements. The bigger marker shows the average marketable share over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.2.1.4 Spring wheat in the organic crop rotation

The quality of spring wheat was expressed in the thousand grain weight (Figure 25). In 2016 no significant differences were found between the tillage systems. However, in 2017 the thousand grain weight was significantly higher for CT, compared to RT and RTS.

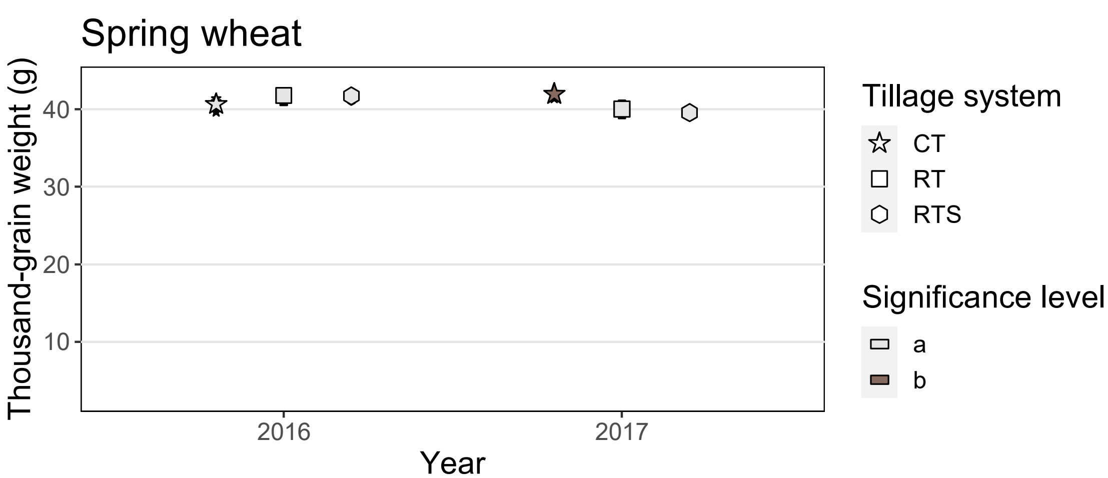


Figure 25. Thousand-grain weight of spring wheat in the organic crop rotation. The small black markers show the separate measurements. The bigger marker shows the average thousand-grain weight over that year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.2.1.5 Seed potato in the conventional crop rotation

The quality of seed potato was expressed in the ratio between marketable product and total gross yield, so the marketable share in the total yield (Figure 26). In most years no significant differences or trends between tillage systems were found. Only in 2015, the marketable share of seed potato was significantly higher for CT, compared to RT.

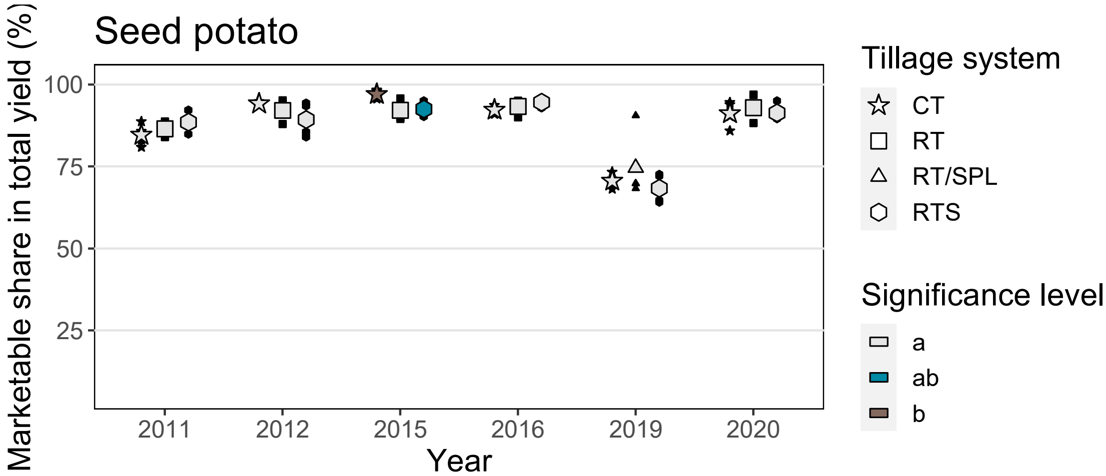


Figure 26. Percentage marketable product of the gross yield for seed potato in the conventional crop rotation. The small black markers show the separate measurements. The bigger marker shows the average marketable share over that year. Tillage systems are indicated with different shapes. Significance levels (p < 0.05) are indicated per year with different colours.

3.2.1.6 Sugar beet in the conventional crop rotation

The quality of sugar beet was expressed in the sugar content (Figure 27). No significant differences or trends were found between the different tillage systems.

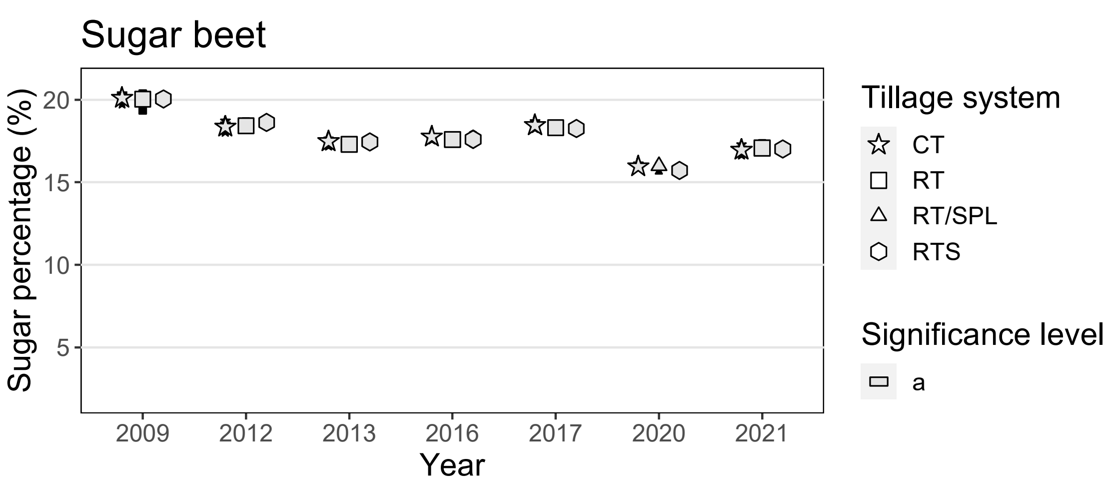


Figure 27. Sugar content of sugar beet in the conventional crop rotation. The small black markers show the separate measurements. The bigger marker shows the average marketable share over that year. Tillage systems are indicated with different shapes. Significance levels (p < 0.05) are indicated per year with different colours.

3.2.1.7 Onion in the conventional crop rotation

The quality of onions was expressed in the ratio between marketable product and total gross yield, so the marketable share in the total yield (Figure 28). No significant differences or trends were found between the different tillage systems.

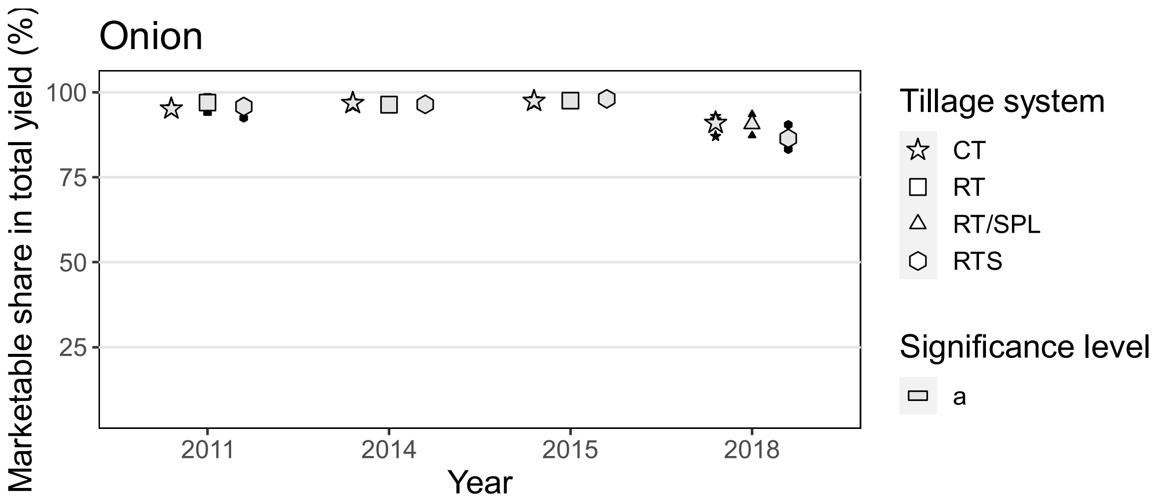


Figure 28. Percentage marketable product of the gross yield for onion in the conventional crop rotation. The small black markers show the separate measurements. The bigger marker shows the average marketable share over that year. Tillage systems are indicated with different shapes. Significance levels (p < 0.05) are indicated per year with different colours.

3.2.1.8 Spring barley in the conventional crop rotation

The quality of spring barley was expressed in the thousand grain weight (Figure 29). In most years the thousand-grain weight was a bit higher in the CT system. However, this was only significant in 2013, were the thousand grain weight of spring barley was significantly higher for CT, compared to RT.

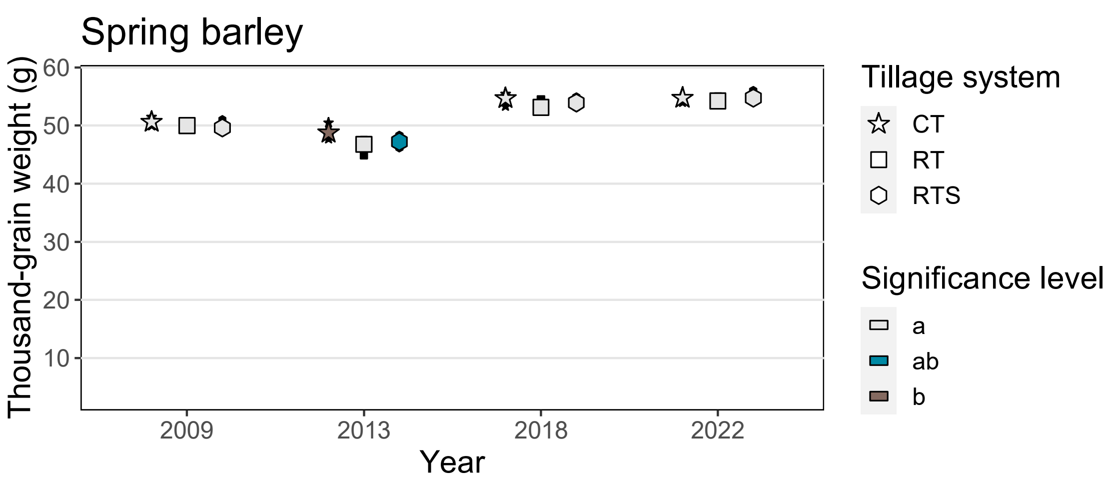


Figure 29. Thousand-grain weight of spring barley in the conventional crop rotation. The small black markers show the separate measurements. The bigger marker shows the average marketable share over that year. Tillage systems are indicated with different shapes. Significance levels (p < 0.05) are indicated per year with different colours.

3.3 Physical soil aspects

3.3.1 Bulk density and soil moisture

J9-4

In the field J9-4, with a conventional crop rotation, the bulk density and soil moisture were sampled in June 2010 in seed onion, shortly after the start of the experiment, and in May 2016 in sugar beet (Figure 30). Bulk density was measured in the 0-10 and 10-20 cm layer of the soil. In most fields it was only measured once or twice, so a change in soil bulk density over time cannot be determined. In the upper 0-10 cm layer over all fields, both organic and conventional, there were no differences in bulk density between the different tillage systems. There was some variation, once the bulk density was significantly higher in the reduced tillage (RT) system, compared to the conventional tillage (CT) system and once it was the other way around. But on average no differences were found. However, in the 10-20 cm layer the bulk density was in four out of the seven times it was measured, significantly higher in RT, compared to CT. Bulk density was not measured as often in the RTS. When it was measured in this system, the results were more comparable to CT then to RT.

In the upper 0-10 cm layer more soil moisture is found in the reduced tillage systems with (RTS) and without (RT) subsoiling, compared to CT. In the 10-20 cm layer more soil moisture is found in CT, compared to RT and RTS. In both layers these differences are often significant. However, the difference between reduced and conventional tillage is bigger in the 0-10 cm layer, compared to the 10-20 cm layer. In the total 0-20 cm layer, soil moisture seems higher for reduced tillage.

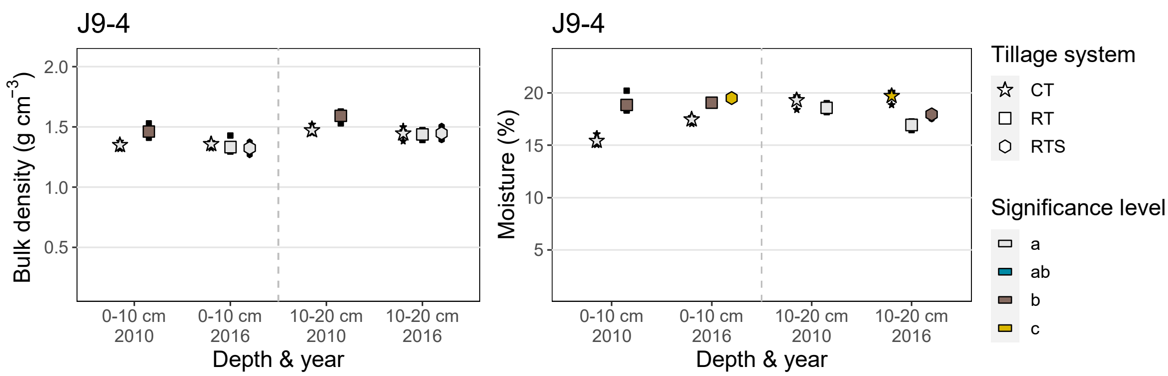


Figure 30. The results of the bulk density and soil moisture measurements in field J9-4. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

J9-6

In the field J9-6, with a conventional crop rotation, the bulk density and soil moisture content was measured once in August 2015 in onion (Figure 31). The 0-10 cm layer did not show significant differences in bulk density or soil moisture content. However, in the 10-20 cm layer, a higher bulk density was measured in RT, compared to CT and RTS. CT showed a higher soil moisture content compared to RT.

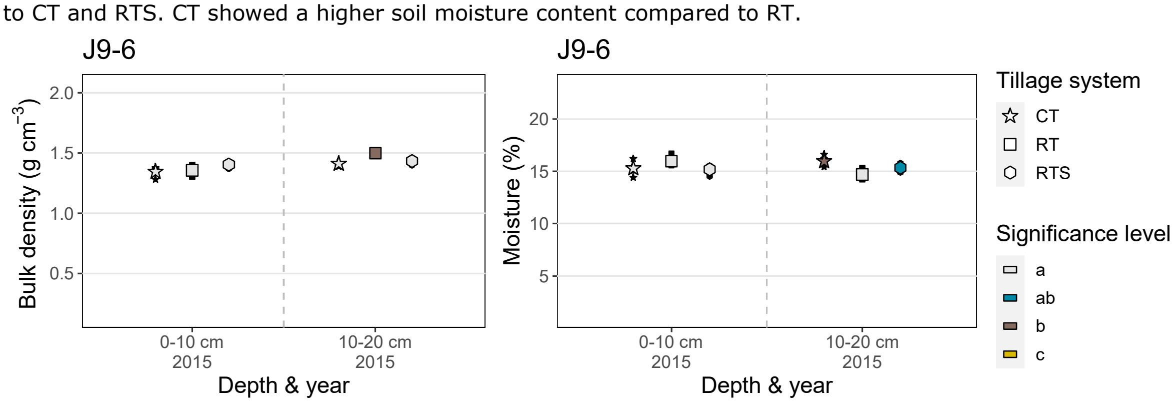


Figure 31. The results of the bulk density and soil moisture measurements in field J9-6. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

J10-3

In the organic field J10-3 RT and CT were sampled in May 2016, in grass clover (Figure 32). A small but significant difference in bulk density was found in the upper layer (0-10 cm), were CT led to a higher bulk density compared to RT. In the deeper layer, no differences between the tillage systems were measured. The soil moisture measurement shows a higher moisture content for RT in the upper soil layer (0-10 cm), compared to CT. However in the 10-20 cm layer this was inversed and the soil moisture content was higher for CT.

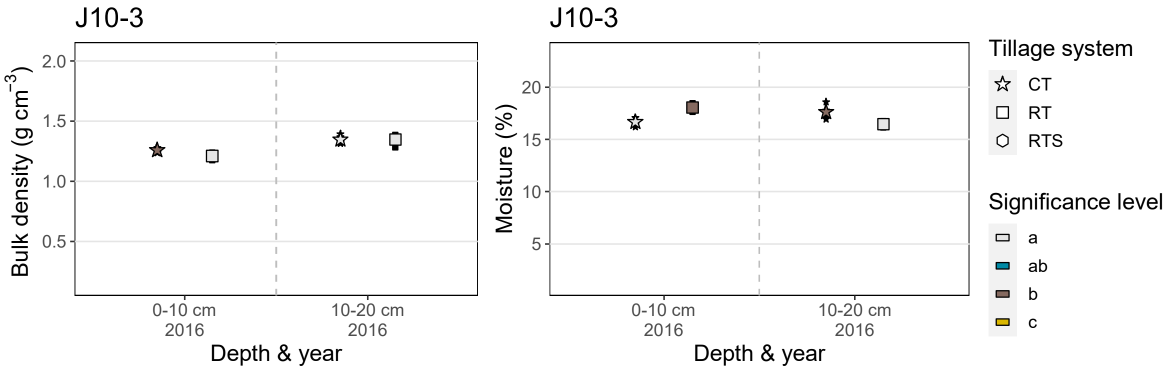


Figure 32. The results of the bulk density and soil moisture measurements in field J10-3. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

J10-4

The second organic field, J10-4, was sampled once in June 2013, in cabbage (Figure 33). The upper layer did not show differences in bulk density between the tillage systems, in the deeper layer a higher bulk density was found for RT compared to CT. Soil moisture content showed the same results as for field J10-3: higher soil moisture in the upper layer and lower soil moisture in the deeper layer for RT compared to CT.

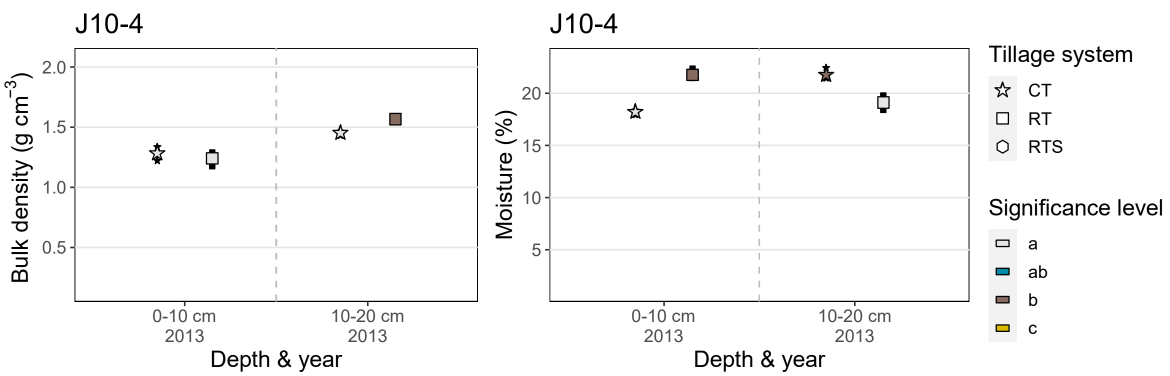


Figure 33. The results of the bulk density and soil moisture measurements in field J10-4. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

J10-6

The third organic field, J10-6, was sampled twice, once in 2013 in grass clover, and once in August 2015, in spring wheat (Figure 34). In bulk density no significant differences were visible, except in 2015 in the deeper layer (10-20 cm), where bulk density was significantly higher in RT compared to RTS, which was significantly higher than CT. Similar to bulk density, soil moisture content did only show significant differences in 2015 in the deeper layer, where soil moisture content in conventional tillage (CT) was higher compared to reduced tillage (RT).

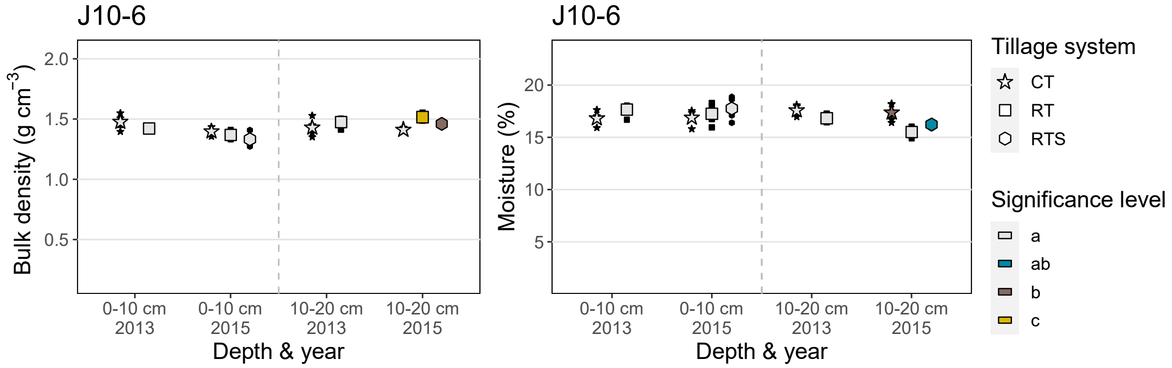


Figure 34. The results of the bulk density and soil moisture measurements in field J10-6. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

3.3.2 Penetration resistance

The penetration resistance was measured per cm in the soil. These data points were aggregated to soil layers of 10 cm, from 0-60 cm. The penetration resistance was measured in all fields in the period 2009-2016 almost each year. First the data was analyzed over the different years. Since no trend was found, it was decided to divide the datapoints in two time periods: 2009-2012 (Figure 35) and 2013-2016 (Figure 36), to see if a difference between the earlier and later years of the system showed a difference.

In 2009-2012 no large differences are visible between the tillage systems RT and CT in the organic field J10-3. In the next four years (2013-2016), in the same field, the differences between the soil tillage systems are still small. However, now there is a bit higher penetration resistance in the 10-30 cm layer in RT compared to CT.

In the organic field J10-4 the penetration resistance in both time periods was higher for reduced tillage (RT) in the layers up to 40 cm, compared to CT. In the two deepest layers no differences were found between the soil tillage systems.

In the first time period (2009-2012) no clear differences are visible between the tillage systems in the organic field J10-6, in 0-30 cm layer. In the deeper layers the RT system shows a lower penetration resistance than CT, while RTS shows a higher penetration resistance. In the later four years (2013-2016) the penetration resistance in RT increase in comparison to CT.

In the conventional field J9-4, both in the first and the later four years, the penetration resistance is higher for RT, compared to CT in all layers. This difference is largest in the 10-30 cm layer. Penetration resistance in RTS was often in-between RT and CT. The penetration resistance in the other conventional field J9-6 shows the same patters as in field J9-4. However, the differences are smaller.

Overall a clear trend could be seen for CT of a lower penetration resistance in the upper layer (0-30 cm) compared to the lower layer (30-60 cm). For RT this trend was less clear, since also in the lower layers the penetration resistance was higher. For all fields the difference in penetration resistance between RT and CT increased over time, with generally a higher penetration resistance for reduced tillage. Except for the field J9-4, the variation in measured penetration resistance was smaller in the later time period (2013-2016), compared to the first period (2009-2012).

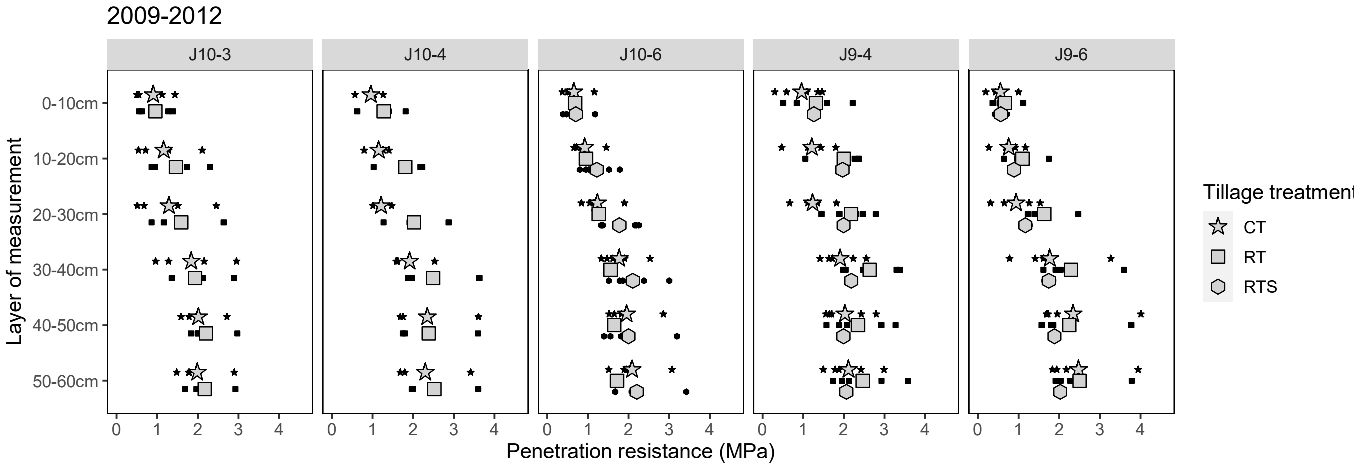


Figure 35. Results of penetration resistance measurements in 2009-2012 aggregated to layers of 10 cm. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means of the layer over the 4 years. Tillage systems are indicated with different shapes. No statistical analysis was performed on these data.

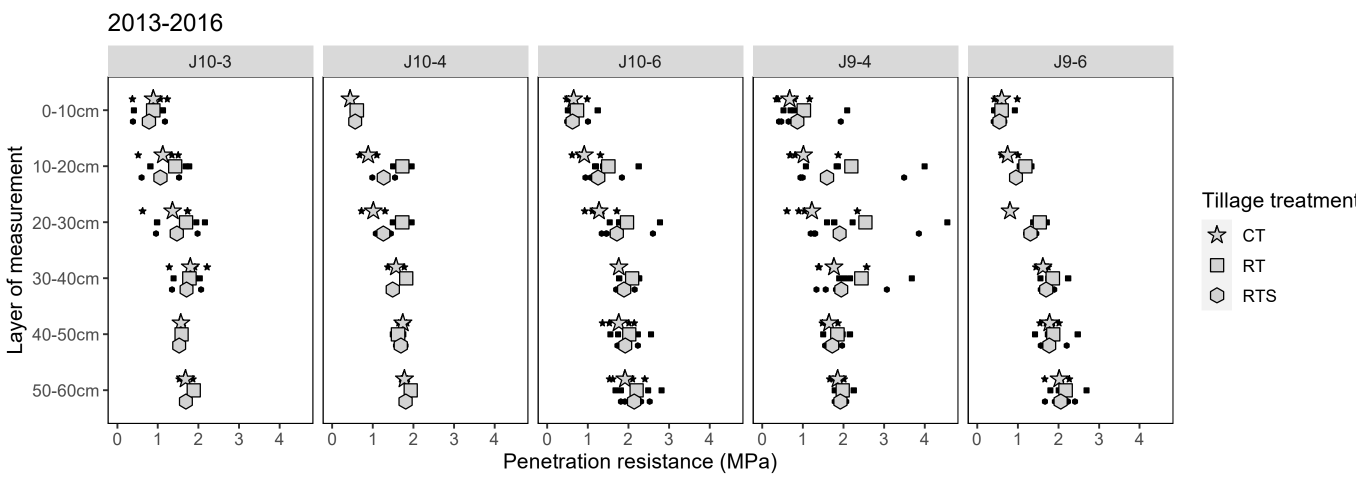


Figure 36. Results of penetration resistance measurements in 2009-2012 aggregated to layers of 10 cm. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means of the layer over the 4 years. Tillage systems are indicated with different shapes. No statistical analysis was performed on these data.

3.4 Chemical soil aspects

3.4.1 Organic matter content of the soil

The organic matter (OM) content in the soil was measured a few times in the experimental plots. The results of 2009, 2011, 2013, 2016 and 2018 are presented in Figure 37 (0-15 cm layer) and in Figure 38 (15-30 cm layer). At the start of the experiment, in 2009, a starting-measurement was done in the conventional and reduced tillage systems (CT, RT). These were mixed samples of all the plots of one treatment in one field in two layers. In the other years, organic matter was measured separately in each plot. The organic matter content at the start of the experiment in 2009 was very similar across the different tillage systems. The OM measurements in 2009 and 2011 were done by the soil chemistry laboratory of WUR (CBLB) and from 2013 onwards the OM was measured at the Eurofins lab. Therefore, direct comparisons between the results from the different labs should be interpreted with caution. Organic matter content was also measured in 2021, but due to the large and possibly unrealistic deviation from the other years, these data are not shown in the main results. The full results (including 2021) can be found in Appendix G.

The upper layer (0-15 cm) showed some interesting results. In both the conventional and the organic crop rotation the organic matter is in most years significantly higher in the reduced tillage systems with (RTS) and without (RT) subsoiling, compared to CT. This deviation is already visible in 2011, two years after the start of the experiment, and it seems to increase somewhat over the years. Only in the field J10-6 the same difference was visible, but never significant. In the deeper soil layer (15-30 cm) difference in organic matter between the different tillage systems were small and almost never significant, however a reversed trend from the upper layer was visible. Here the OM in the reduced tillage systems (RT & RTS) was often a bit lower, compared to CT.

In the reduced tillage systems, the organic matter is mainly situated in the upper layer. This makes it interesting to look at the OM in the total 0-30 cm layer. Table 3 shows an overview of this. In 2009, at the start of the experiment, the OM in all soil tillage systems is very similar. From then on the OM content is on average mostly higher in the reduced tillage systems (RT & RTS), compared to CT. This deviation slightly increases over time, but differences were almost never significant.

Table 3. Organic matter content (%) in 0-30 cm (aggregated from 0-15 and 15-30 cm layers) for the different years, different fields and different tillage systems. The measurements in 2009 were done by CBLB and from 2013 on by Eurofins. Different letters attached to the estimated means indicate significant differences between tillage systems in a year and field combination (P<0.05).

Field	**2009**			**2013**			**2016**			**2018**			
	CT	**RT**	**RTS**	**CT**	**RT**	**RTS**	**CT**	**RT**	**RTS**	**CT**	**RT**	**RT/SPL**	**RTS**
J10-3	3.74 [a]	3.75 [a]	-	3.24 [a]	3.28 [a]	3.34 [a]	3.48 [a]	3.85 [a]	3.79 [a]	3.41 [a]	3.60 [a]	-	3.48 [a]
J10-4	3.68 [a]	3.64 [a]	-	3.21 [a]	3.23 [a]	3.29 [a]	3.45 [a]	3.53 [a]	3.54 [a]	3.13 [a]	3.25 [a]	-	3.34 [a]
J10-6	3.41 [a]	-	3.50 [a]	2.99 [a]	2.93 [a]	3.01 [a]	3.19 [a]	3.21 [a]	3.16 [a]	3.04 [a]	3.13 [a]	-	3.13 [a]
J9-4	3.42 [a]	3.44 [a]	-	2.88 [a]	2.85 [a]	2.89 [a]	2.97 [a]	3.15 [b]	2.93 [a]	2.76 [a]	-	3.10 [a]	2.83 [a]
J9-6	3.35 [a]	3.29 [a]	-	2.86 [a]	3.00 [b]	2.85 [a]	2.94 [a]	3.04 [a]	2.99 [a]	2.79 [a]	2.89 [a]	-	2.94 [a]
Mean	3.52	3.53	3.50	3.04	3.06	3.08	3.20	3.35	3.28	3.03	3.22	3.10	3.14

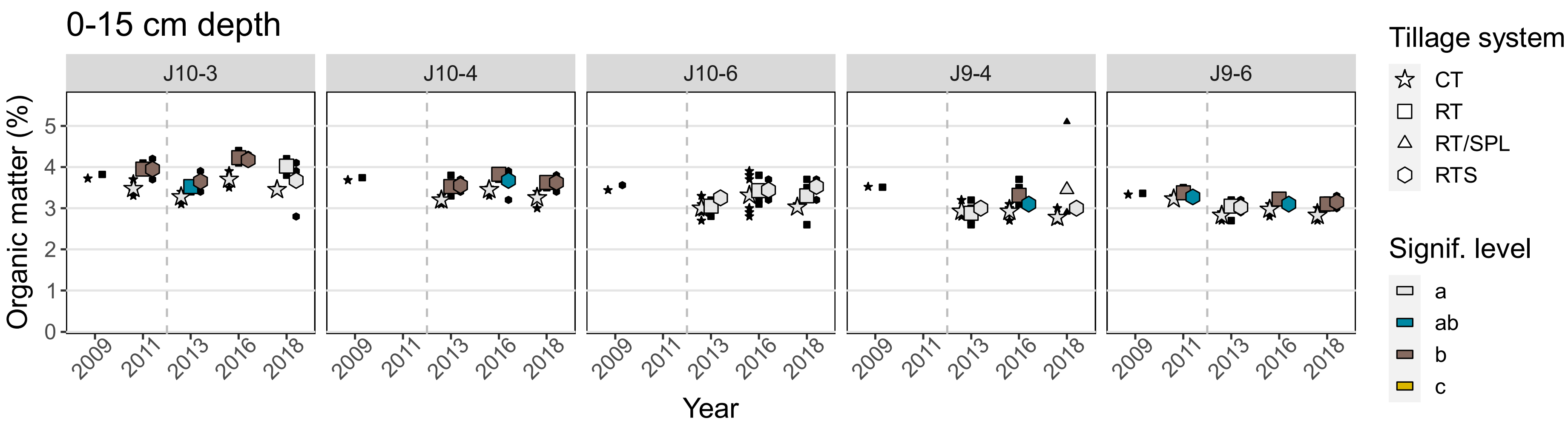


Figure 37. Organic matter content measured in soil samples from the different experimental fields in the layer 0-15 cm. The small black markers show the separate measurement of each plot, including a 0 measurement in 2009, which was a mixed soil sample from the different plots. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels (p < 0.05) are indicated per year with different colours. The measurements in 2009 and 2011 were done by CBLB and from 2013 on by Eurofins.

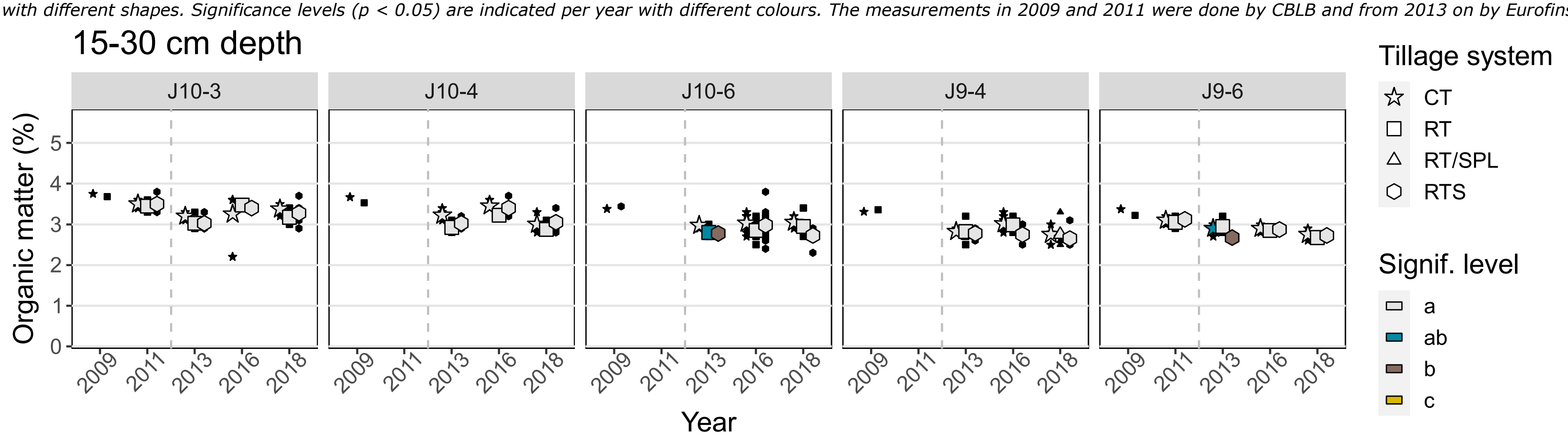


Figure 38. Organic matter content measured in soil samples from the different experimental fields in the layer 0-15 cm. The small black markers show the separate measurement of each plot, including a 0 measurement in 2009, which was a mixed soil sample from the different plots The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels (p < 0.05) are indicated per year with different colours. The measurements in 2009 and 2011 were done by CBLB and from 2013 on by Eurofins.

3.4.2 Total carbon content of the soil

Total carbon content of the soil, or C-total, was measured twice, in all fields in 2013 by Eurofins and in the field J10-6 and J9-4 in 2016 by CBLB (Figure 39 and 40). Carbon content of the soil is closely related to organic matter content. A similar pattern is visible, however, with only two years of carbon data, the comparison with OM is difficult. In the RT and RTS, the carbon content in the upper layer (0-15 cm) was often slightly higher than, or equal to the deeper layer (15-30 cm). While the carbon content in the CT in the upper layer was often slightly lower or equal to the deeper layer.

Looking at the total carbon content in both layers together (Table 4), the differences were very small and not significant. Averaged over the different fields, RTS had the highest C-total, followed by RT and then CT.

Table 4. Total carbon content of the soil (g C kg^{-1}), in the 0-30 cm soil layer (aggregated from 0-15 and 15-30 cm layers), per field and treatment in 2013 (measured by Eurofins) and in 2016 (measured by CBLB); together with the average C-total in all fields for a specific treatment. Different letters attached to the estimated means indicate significant differences between tillage systems in a year and field combination (P<0.05).

Field	2013 (Eurofins)			2016 (CBLB)		
	CT	RT	RTS	CT	RT	RTS
J10-3	20.7 [a]	20.4 [a]	20.6 [a]	-	-	-
J10-4	22.8 [a]	22.7 [a]	23.1 [a]	-	-	-
J10-6	19.2 [a]	19.3 [a]	20.2 [a]	17.1 [a]	18.9 [a]	18.4 [a]
J9-4	18.3 [a]	19.2 [a]	18.7 [a]	15.8 [a]	16.7 [a]	-
J9-6	18.6 [a]	18.9 [a]	18.6 [a]	-	-	-
Average	19.9	20.1	20.3	16.5	17.8	18.4

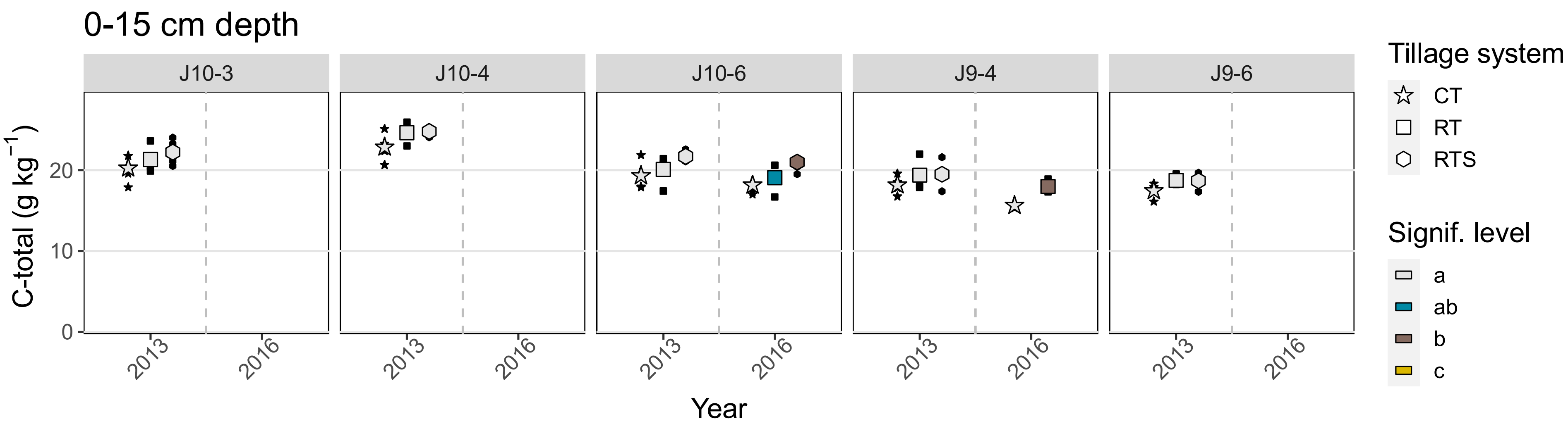


Figure 39. Total carbon in the soil, measured in soil samples from the different experimental fields in the layer 0-15 cm. The small black markers show the separate measurements of each plot. The bigger markers show the estimated means in a year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours. The measurements in 2013 were performed by Eurofins and in 2016 by CBLB.

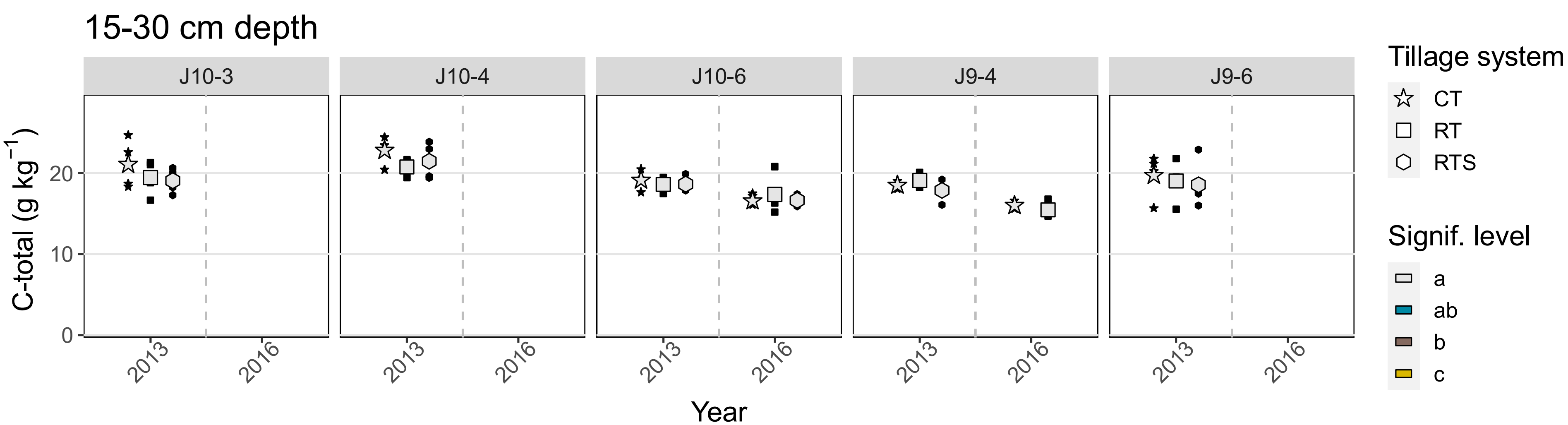


Figure 40. Total carbon in the soil, measured in soil samples from the different experimental fields in the layer 0-15 cm. The small black markers show the separate measurements of each plot. The bigger markers show the estimated means in a year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours. The measurements in 2013 were performed by Eurofins and in 2016 by CBLB.

3.4.3 Soil pH

The results of the soil pH measurements are shown in Figure 41. Measurements were done in 2013, 2016, 2018 and 2021. The samples taken in 2021 were the same samples as the organic matter samples, which showed a rather unrealistic drop in all values. A similar drop in soil pH is seen here and the results of 2021 should be interpreted with caution. Samples were taken in the 0-15 and 15-30 cm layers. The results of both layers are averaged in Figure 41, the full results can be found in Appendix H.

Especially in the organic fields, the soil pH seems a bit higher in the CT systems, compared to RT and RTS. This difference is only significant in 2018 in the field J10-3. Also, this difference seems to decrease over the years. In the conventional fields there are no differences or trends visible in the soil pH, when comparing tillage systems. In all fields and for all soil tillage systems an upward trend in soil pH is noticeable from 2013 to 2018, though the difference is only 0.1/0.2 pH point.

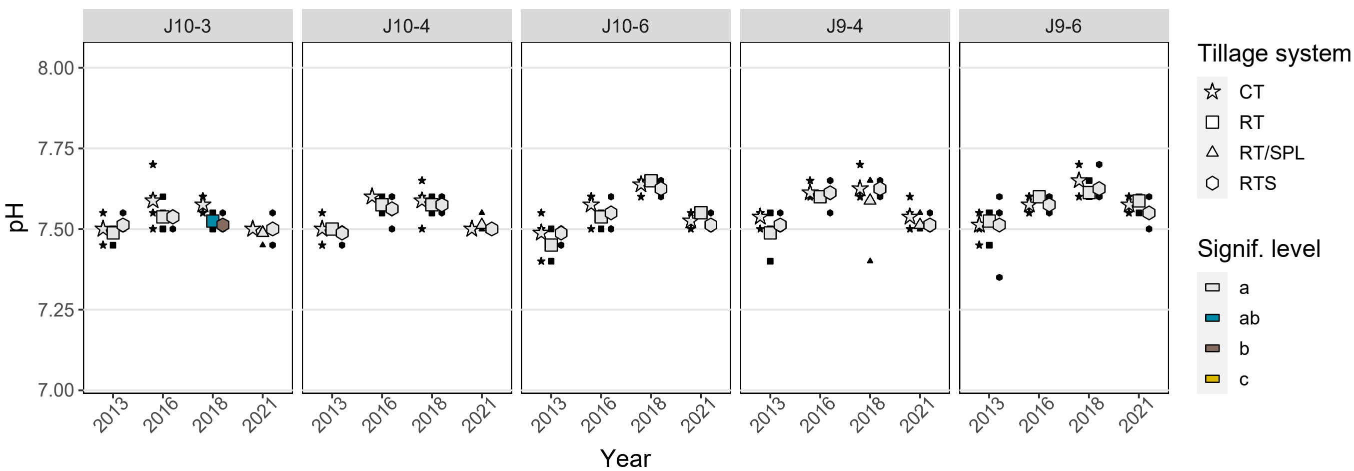


Figure 41. Results of the soil pH measurements. Measurements were done in two layers (0-15 cm and 15-30 cm) separately, which were averaged to create this figure. Each small black marker shows an average of the two layers in one plot within a field (4 plots per field) per year and tillage system. Large markers show the estimated means per year and tillage system. The colour of the large marker indicates significance.

3.4.4 Nutrient content of the soil

The total amount of nitrogen in the soil or N-total (g N kg^{-1}) was measured in all fields in multiple years. Samples were taken in the 0-15 and 15-30 cm layers. The results of both layers are averaged in Figure 42, the full results can be found in Appendix I. In 2013, four years after the start of the experiment, difference in total-N between the soil tillage systems was small. In the later years, over all fields, the trend is visible that the N-total was higher for reduced tillage (RT & RTS), compared to CT. For halve of the years this difference was significant. This difference mainly arises from a difference in the upper layer (0-15 cm), differences in the lower layer (15-30 cm) are smaller (Appendix I). Especially in the organic system the total-N was significantly higher in the reduced tillage systems in the upper layer, compared to conventional tillage.

Besides nitrogen content of the soil, the content of other nutrients in the soil was investigated. No interesting trends or significant differences were found considering tillage systems. Therefore the results are not shown here, but can be found in Appendix I table 2 to 8.

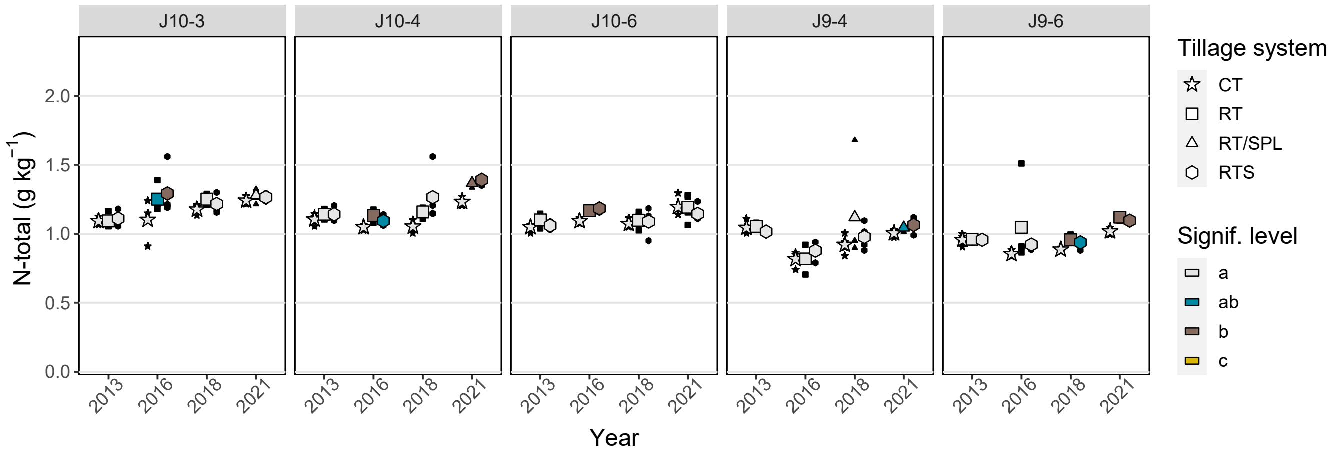


Figure 42. Results of the total soil nitrogen measurements. Measurements were done in two layers (0-15 cm and 15-30 cm) separately, which were averaged to create this figure. Each small black marker shows an average of the two layers in one plot within a field (4 plots per field) per year and tillage system. Large markers show the estimated means per year and tillage system. The colour of the large marker indicates significance (P < 0.05).

3.4.5 Mineral nitrogen in the soil (Nmin)

Mineral nitrogen in the soil (kg N ha^{-1}) was measured in most years, in autumn and in spring, in multiple soil layers (0-30 cm, 30-60 cm and 60-90 cm), to investigate the effects of tillage systems on N dynamics through seasons and soil layers. Table 5 shows the average Nmin overall years for the different soil layers and tillage systems per farming system (organic or conventional). Nmin values are in general very low. In autumn no significant differences or trends were found. In spring, in the organic fields, Nmin was significantly higher in the sub soil (30-90 cm) in the CT system, compared to reduced tillage (RT and RTS). In the conventional fields, this trend was not observed.

Table 5. Overview of average N_{min} results over all years, in three layers (0-30 cm, 30-60 cm and 60-90 cm), two sampling moments (spring and autumn), three tillage systems (CT, RT and RTS) and two framing systems (organic fields, including J10-3, J10-4 and J10-6 and conventional fields, including J9-4 and J9-6). Letters indicate level of significance with a layer, field and sampling moment combination (so only comparing the three tillage systems).

Fields	**Layer**	**Tillage**	**N_{min} autumn**	**N_{min} spring**
Organic	0-30 cm	CT	5.6 ^{a}	12.3 ^{a}
Organic	0-30 cm	RT	6.7 ^{a}	12.0 ^{a}
Organic	0-30 cm	RTS	6.4 ^{a}	10.3 ^{a}
Organic	30-60 cm	CT	11.7 ^{a}	20.9 ^{a}
Organic	30-60 cm	RT	11.3 ^{a}	15.5 ^{b}
Organic	30-60 cm	RTS	11.8 ^{a}	13.6 ^{b}
Organic	60-90 cm	CT	11.1 ^{a}	16.0 ^{a}
Organic	60-90 cm	RT	9.6 ^{a}	8.2 ^{b}
Organic	60-90 cm	RTS	11.6 ^{a}	10.3 ^{b}
Conventional	0-30 cm	CT	5.0 ^{a}	13.0 ^{a}
Conventional	0-30 cm	RT	5.6 ^{a}	15.8 ^{a}
Conventional	0-30 cm	RTS	5.7 ^{a}	7.0 ^{a}
Conventional	30-60 cm	CT	11.3 ^{a}	17.2 ^{a}
Conventional	30-60 cm	RT	8.9 ^{a}	15.4 ^{a}
Conventional	30-60 cm	RTS	14.6 ^{a}	18.9 ^{a}
Conventional	60-90 cm	CT	10.3 ^{a}	13.2 ^{a}
Conventional	60-90 cm	RT	9.8 ^{a}	9.5 ^{b}
Conventional	60-90 cm	RTS	9.5 ^{a}	12.8 ^{ab}

3.5 Other research topics

3.5.1 Seedbed preparation for carrots

The effect of the Twinrotor on the cultivation of carrots was measured in yield (marketable product) and in aggregate formation; both stability and size classes were investigated. No statistical analysis was performed due to lack of replicates in this experiment.

The marketable yield of carrots is shown in Figure 43 The marketable product of carrots was very similar in the conventional soil tillage system (CT), with the standard rotary tiller (STD) and with the Twinrotor tiller (TWIN). However, in the reduce tillage system (RT) there is a relevant difference. The yield for RT with the Twinrotor tiller was almost as high as yields in CT, though the yield in RT with the standard rotary tiller was more than 25% lower.

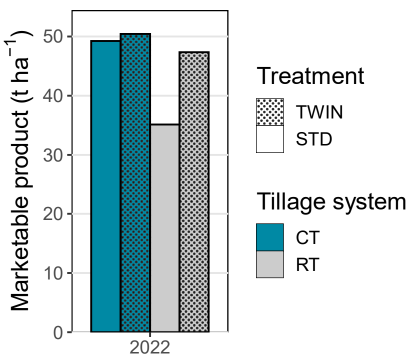


Figure 43. marketable product in carrots in the extra experiment where seedbed preparation was tested.

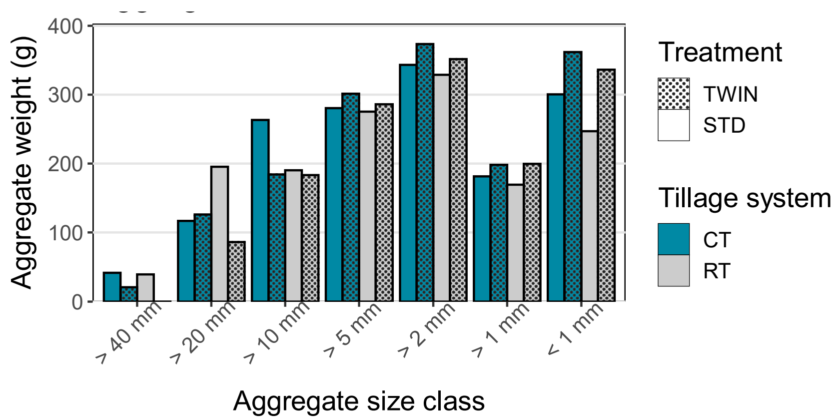


Figure 44. Weight of the aggregates in the different size classes. High weights in smaller size classes refer to a fine seedbed.

Looking at the size classes of the aggregates (Figure 44), the weight of the aggregates in class >5 mm and smaller was always higher with the Twinrotor tiller (CT+TWIN and RT+TWIN) compared to the corresponding soil tillage in with the standard rotary tiller (CT+STD and RT+STD). Thus, a finer seedbed could be created using the Twinrotor. The stability of the aggregates (Table 6) was higher for the RT system, compared to CT. Aggregate stability was also higher with the use of the standard rotary tiller, compared to the Twinrotor. Thus, the highest aggregate stability was found in the RT+STD treatment and the lowest in the CT+TWIN treatment.

Table 6. Percentage stable aggregates in the different treatments.

Treatment	**Stable aggregates (%)**
CT + TWIN	32%
RT + TWIN	52%
CT + STD	40%
RT + STD	58%

3.5.2 Weed seedbank

Figure 45 shows an overview of the weed seedbank density, averaged for both conventional fields (J9-4 and J9-6). See Appendix K for the results of the separate fields. In the field J9-4 reduced tillage/shallow ploughing (RT/SPL) was applied (the last year of shallow ploughing was 2018); in the field J9-6 only reduced tillage (RT) was applied. In this figure an average of both is shown and labelled RT/SLP. A trend towards lower weed seedbank densities in the soil tillage system RT/SPL was observed. But, due to high variation, the seedbank densities between the tillage practices were not found to be significantly different.

Figure 46 shows the same for the organic system, see Appendix K for the results of the separate fields. In the organic fields J10-3 and J10-4 reduced tillage /shallow ploughing (RT/SPL) was applied (the last year of shallow ploughing was 2019 for field J10-03 and 2021 for field J10-4), while in the field J10-6 only reduced tillage (RT) was applied. In Figure 46 an average of both is shown and labelled RT/SPL. In the organic system, weed seedbank densities did not differ as much between the three tillage system. For the reduced tillage with subsoiling (RTS), weed densities observed appeared to be higher. But the differences between tillage practices were not found to be statistically significant.

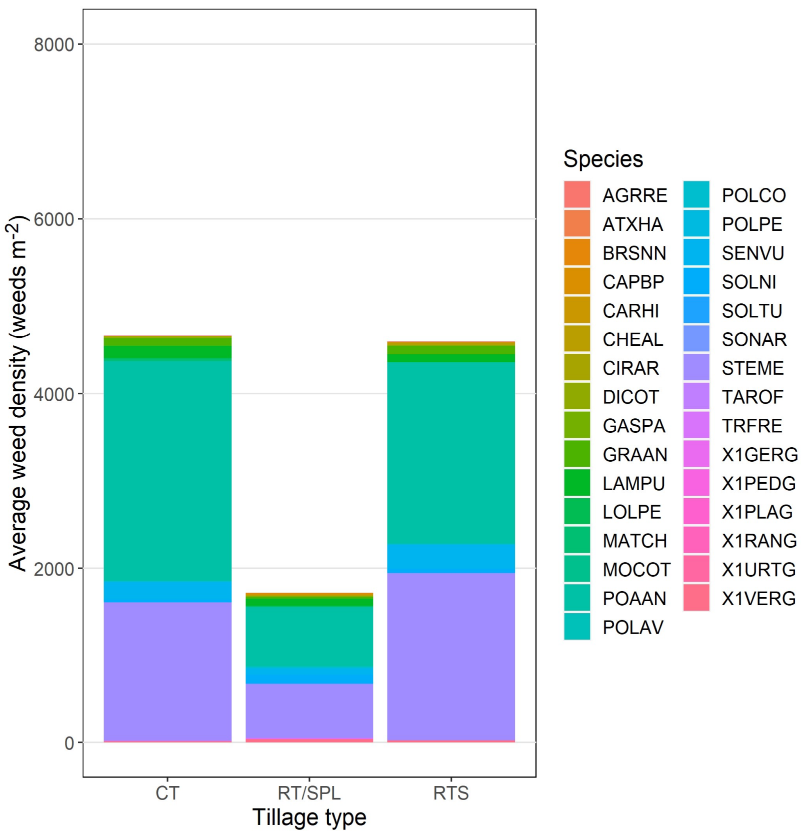


Figure 45. Weed density at 0-10 cm depth as affected by tillage system for the conventional system. Tillage types: CT = conventional tillage, ploughing; RT/SPL = reduced tillage/shallow ploughing; RTS = reduced tillage with subsoiling.

Regarding the species composition, no major differences were found between the tillage systems. In general, only a few species dominated the weed seedbank: annual meadow grass (*Poa annua* - POAAN), chickweed (*Stellaria media* – STEME), groundsel (*Senecio vulgaris* - SENVU) and red dead-nettle (*Lamium purpureum* - LAMPU), being 48, 38, 5 and 3% of the total seedling numbers found in the conventional system respectively. In addition, *Veronica* species (X1VERG) were more abundant in the organic system compared to the conventional farming system, accounting for 23% of the total seedlings observed in this system.

Chickweed accounted for approximately 40% of total weed numbers in both systems and was found in highest numbers for the RTS treatment. Furthermore, a number of perennial weed species were observed for the organic system These species occurred in only a few of the soil samples and no systematic differences were found between tillage systems. Thistles, both *Sonchus arvensis* (SONAR) and *Cirsium arvense* (CIRAR), were found and accounted for about 5% of the total weeds found in the organic system. In addition, species such as wild buckwheat *(Fallopia convolvulus),* hairy bittercress *(Cardamine hirsute)* and couch grass (*Elymus repens)* were observed in greater numbers in the organic system.

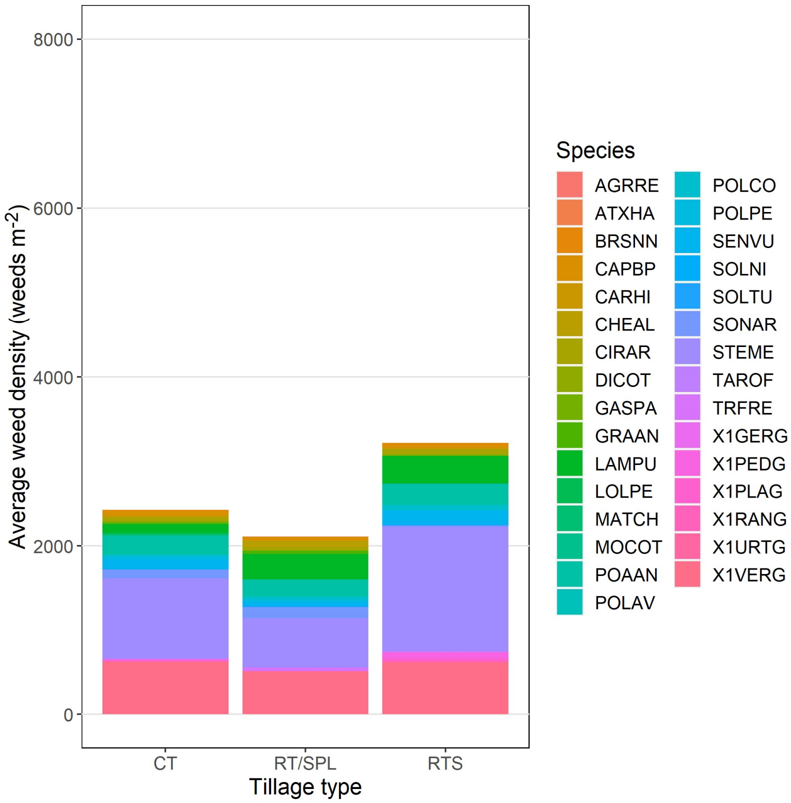


Figure 46. Weed density at 0-10 cm depth as affected by tillage system for the organic system. Tillage types: CT = conventional tillage; RT/SPL = reduced tillage/shallow ploughing; RTS = reduced tillage with subsoiling.

4 Discussion

4.1 Weather data

In the BASIS experiment not all crops are grown every year. Therefore, year effects, due to variations in the weather over the years, are important to take into consideration when discussing the results. The effects of soil tillage systems can be more pronounced during more extreme weather, like heavy rainfall or droughts. This makes it interesting to zoom in on the effects of soil tillage on yield and soil characteristic in years with extreme weather events. Figure 47 shows the minimum, maximum and average temperatures per month over the years, from 2009 until 2022. As a reference the average monthly temperatures over the last 30 years are shown. Figure 48 show the monthly precipitation from 2009 until 2022. As a reference the average monthly precipitation over the last 30 years is shown.

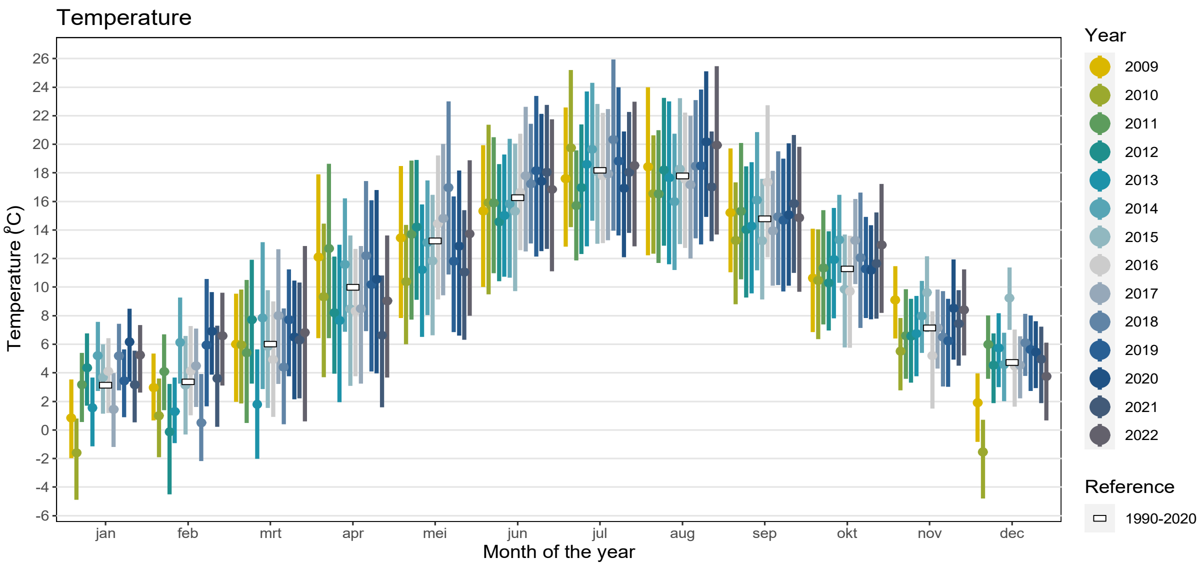


Figure 47. Minimum, maximum and average temperatures per months from 2009 till 2022. The white marker is the average monthly temperatures over the period of 1990-2020. Data retrieved from KNMI daily weather data at weather station Lelystad (269).

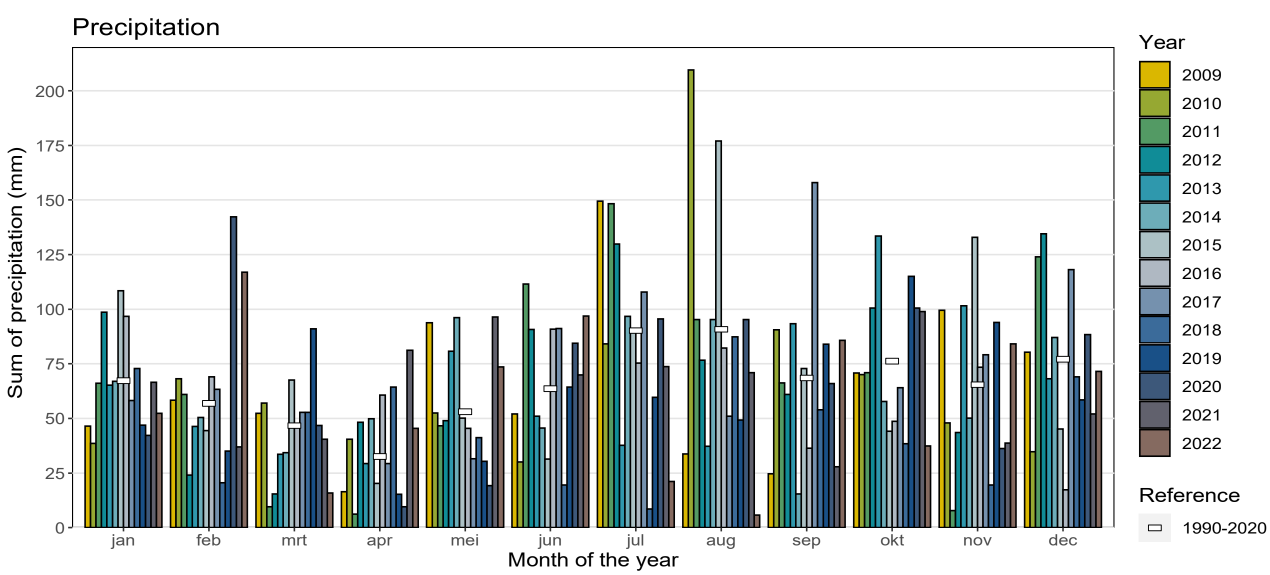


Figure 48. Monthly precipitation from 2009 till 2022. The white marker is the average monthly precipitation over the period of 1990-2020. Data retrieved from KNMI daily weather data at weather station Lelystad (269).

4.2 System research

Since the BASIS experiment uses a system approach, all the effects found are a result of the whole system. This means that not only the tillage influences the results, but also the longer growing period of cover crops for reduced tillage and sometimes differences in crop management between the tillage systems. Results should therefore be viewed in this context. Within a system approach it is possible to adapt the system with new found experience. Reduced tillage was a new tillage method for the farm mangers of this experiment. They learned over time and adapted the system accordingly. Therefore, we share some of the experience from Joost Rijk, the farm manager of this experiment from 2013 till 2022. The highlights he gives per crop in the conventional and organic crop rotation can be found in Appendix M.

Reduced tillage requires different machinery than a conventional ploughing system. So the equipment that was available at the beginning of the experiment, was not ideal. It was a learning process on what machinery we needed for reduced tillage on clay soils, with the crops in our systems. Therefore, especially in the beginning of the experiment, optimal results were probably not always achieved. The same holds for other decisions on crop management. Because the reduced tillage system was new to the experimental farm as well, judgement errors were sometimes made. Over the years we learned a lot, which influenced the resulting yields of the crops notably in the reduced tillage systems. We also learned that the conventional tillage system was disadvantaged a bit by the system of controlled traffic farming, because the compacted soil in the driving lanes was ploughed into the edges of the growing beds.

Some crops bring more challenges than other crops. The management and cultivation of grain crops, barley and wheat (both spring and winter), was generally going well in reduced tillage fields (RT and RTS) according to the farm manager. Suppression of weeds was one of the biggest challenges in the RT and RTS fields in multiple crops. The most noticed positive aspect in multiple crops was the improved bearing capacity of the soil and better drought resilience compared to the conventional tilled (CT) fields. These observations are not inherently ascribed to reduced tillage, but to the whole system including effect of the controlled traffic farming system and the longer growing period of cover crops in the reduced tillage systems compared to the conventional tillage system.

An important lesson from cultivation of different crops without ploughing was to make sure the seed- or planting bed was prepared well: RT and RTS topsoils have a tendency to be coarse due to cover crop residues. So, preparing a fine seed bed and cutting down cover crops or grass clover timely in RT and RTS fields was an important insight from Joost and his team. The Twinrotor for carrots is an example of an adaptation in machinery to a reduced tillage system.

Although the BASIS experiment is set up as a system research project, not all possibilities to change the system were used. The crop rotation in the organic system contains grass clover, which suits well in a conventional tillage system but not in a reduced tillage system, because of the tillage that is needed to incorporate crop residue. The potential of reduced tillage in a Dutch arable cropping system can be utilized better when the crop rotation is adapted to this tillage system.

4.3 Yield

Note: For the discussion of yield of this report, some of the text from Van Balen et al. (2023) is adapted.

To get an overview of the effect of soil tillage on the marketable product, the yield results were scored. Conventional tillage (CT), Reduced tillage with shallow ploughing (RT/SPL), Reduced tillage with sub-soiling (RTS) and reduced tillage without sub-soiling (RT) are compared and a score is given per crop and year. The scores are not interdependent over the years and crops. The tillage system with the highest marketable yield for every particular crop and year was always given score one, the highest possible score. When the production was lower for another tillage system, but this difference was not significant, the score was lowered by one point. When the difference was significant, the score was lowered by two points. In exceptional cases, when the difference was significant and very large, the score was lowered by three points. An overview of all scores for marketable product can be found in Appendix L in Table L.1 for crops in the organic crop rotation and in Table L.2 for crops in the conventional crop rotation. Table 7 shows a summary of these scores and gives only the averages over the years per crop and the weighted crop rotation average. Because there was little data available, reduced tillage with shallow ploughing (RT/SPL) and crops that are only grown one year are left out of this summary.

*Table 7. Score for marketable product averaged over the years of the different crops in the organic and conventional crop rotation, were tillage systems are compared. N indicates the number of years from which data on crop yield is available for a certain crop. * after RTS or RT indicates that the difference with CT is significant.*

Farming system	Crop	Tillage system			N
		CT	RTS	RT	
Organic	Ware potato	1.2	1.5	1.7	6
	Grass clover	2.8	2.0	1.2*	6
	Oats	2.0	1.7	1.5	3
	Cabbage	1.3	1.8	2.8*	4
	Carrot	1.1	2.1	2.2	8
	Pumpkin	1.0	1.0	1.0	2
	Spring wheat/ faba bean	2.3	1.0*	2.3	3
	Spring wheat	2.3	1.8	1.8	6
Weighted crop rotation average		1.8	1.7	1.9	
Conventional	Pea	3.5	1.5*	1.0*	2
	Seed potato	1.3	1.3	1.2	6
	Sugar beet	1.1	1.6	1.3	7
	Seed onion	1.0	1.8	1.7	4
	Spring barley	1.7	1.7	1.3	6
Weighted crop rotation average		1.5	1.5	1.3	

Table 7 shows that for most crops, reduced tillage is a viable alternative to conventional ploughing when considering marketable yield. Average marketable yield was similar or higher in the reduced tillage systems (both RTS and RT) for 10 out of the 13 crops grown, when compared to CT. When comparing RT with CT, marketable yield was significantly higher in RT for grass clover (organic) and pea (conventional). Marketable yield was significantly higher in RTS compared to CT for spring wheat/faba bean (organic) and pea (conventional). The marketable yield was significantly lower for RT compared to CT for cabbage (organic).

The marketable yield of ware potatoes in the organic crop rotation and seed potatoes in the conventional crop rotation was very similar across the different tillage systems. This differs from the findings in literature, were Cooper et al. (2016) found a 6% yield reduction in a meta-analysis of 11 studies on reduced tillage for root crops and Martínez et al. (2016) found a 15% average yield reduction for potato in a no-till system on a sandy loam soil. In the organic system the marketable yield of ware potatoes was significantly lower for RT and RTS compared to CT in 2017. However, in 2018 the marketable yield for RT was higher compared to CT. Climatically 2017 was a normal year with a wet September. 2018 Was a warm and dry year. Possibly reduced tillage retained more moisture in the soil. In the last years of the experiment the potato yield was more variable.

However, one year the marketable yield is lower for RT and one year it is higher; so no trend over the years is visible.

Grass clover yield in the organic system was significantly higher for RT and RTS, compared to CT. A difference occurred between conventional and reduced tillage due to slacking in CT after heavy rainfall in the autumn of 2012. RT and RTS did not have this problem, most likely because of the higher soil aggregate size and stability (Crittenden et al., 2015). In CT the grass clover had to be resown in the spring of 2013. This higher production of grass clover under reduced tillage is also described by Norén et al. (2021). The higher production of grass clover in reduced tillage is mainly due to higher production of the first cut. In the second to fourth cut the differences are smaller. The trend of higher production under reduced tillage was already visible in 2010, one year after establishment of the experiment, and it was significant from 2012 onwards. However the difference between RT and CT did not further increase over time. Since the production of grass clover was higher for RT in every year, it is not possible to discern any climatic effects.

For all the cereal crops grown in both the organic and the conventional crop rotation, averaged yields over the years were similar or higher for RT and RTS, compared to CT. Similar results were found by Arvidsson et al. (2014), Büchi et al. (2017) and Peigné et al. (2014). They all found comparable yields for reduced soil tillage compared to conventional soil tillage. Higher yields for the cereal crops might be due to a higher number of haulms per square meter. This was not measured often enough to draw conclusions, but it was observed in the fields. However, this would be opposed to what Arvidsson et al. (2014) found. They found lower plant establishment for shallow and no-till systems and thought this was due to larger soil aggregates and more plant residues in the field, compared to conventional tillage. In the BASIS experiment, lower haulm density for CT could be caused by a more loose topsoil, which might cause more plant loss during harrowing. For spring barley (conventional) a significant difference was only found in 2017. Climatically this was a normal year, so no conclusions concerning effects of weather on yield in reduced or conventional tillage can be drawn. Differences in yield between reduced and conventional tillage did not change or increase over time. However, spring wheat in the organic system did show more variation in yield in the last two years, when the pre crop was carrot instead of cabbage.

Our findings revealed that the average yield of a mixed crop of wheat and faba bean in the organic system was significantly higher in the RTS system, compared to CT. But the RT system exhibited a comparable yield, compared to the CT system.

The marketable product for cabbage was significantly lower for RT compared to CT. Cabbage was grown in the organic crop rotation after grass clover. Complete termination of the preceding grass-clover can be difficult, especially in reduce tillage systems. This might have cause the lower yield of cabbage in RT. Hefner et al. (2020) similarly found lower cabbage yields in cropping systems where the preceding cover crop was incompletely terminated or not fully incorporated into the soil. The cabbage is planted, for which loose soil is required. In the RTS system there was possibly more loose soil available compared to RT, which could account for the difference between these systems. It would be interesting to investigate the results for cabbage in a reduced tillage system, when they are grown in a different rotation, not following grass clover. The difference between reduced and conventional tillage seem to increase a bit over the years. In the last year (2020) RTS was also significantly lower compared to CT. 2020 was climatically a strange year, it had very dry and very wet months and the winter was quite warm.

The marketable yield of carrot, grown in the organic system, was lower for RT and RTS, compared to CT. However, over the years this difference was not significant. Literature reports similar (Willekens et al., 2014) or slightly reduced (Cooper et al., 2016) carrot yields for reduced soil tillage compared to conventional tillage. In reduced tillage systems, losses in crop yield are often associated with decreased seed germination and seedling emergence (Lamichhane et al., 2018). However, our experiment yielded different results, as we did not observe a significant difference in carrot crop emergence in most years. Instead, the lower marketable carrot yield in the RT and RTS can be partly attributed to a higher number of non-marketable, large-sized (250-400 gr) carrots and a significantly higher number of deformed and rotten carrots. Therefore the difference in marketable product between RT/RTS and CT is higher than the difference in gross yield.
There are two possible explanations for these findings. Firstly, the larger soil aggregate size observed in the RT and RTS plots, as reported by Crittenden et al. (2015), could have played a role. Similar results were found

by He et al. (2009), who discovered larger soil aggregates at depths up to 30 cm in a no-till system compared to a conventional tillage system. These larger soil aggregates might have influenced plant growth and affected the size of carrots produced in our experiment. Secondly, the different management practices between the conventional tillage and reduced tillage systems could have contributed to the observed differences. In the CT system, the soil was ploughed in autumn and left bare until carrot sowing the following spring. On the other hand, the RT and RTS systems had white clover or vetch as a preceding crop until 4 to 6 weeks before sowing carrots. Previous research by Bradow and Connick (1990) revealed that certain clover species such as Berseem clover (Trifolium alexandrinum), Crimson clover (Trifolium incarnatum), and Hairy vetch (Vicia villosa) can exhibit allelopathic effects on crops such as onions and carrots. In our experiment, this allelopathic effect, combined with the increased presence of plant residues in and on the ridges due to the previous cover crop, may have disturbed the growth of carrot plants and resulted in an increase in branched and unmarketable carrots.
Only in 2015 was the yield of carrots higher for reduced tillage, compared to conventional tillage, though not significantly. In this year a different cultivar, Norway instead of Nerac, was grown. It would be interesting to further investigate the production of this cultivar under reduced tillage.
In 2019 shallow ploughing was introduced prior to the cultivation of carrot, to create a more loose soil structure. The marketable yield of carrots in the RT/SPL system lies between the RT and the CT systems. Shallow ploughing seems to be a good way to reduce the yield gap between reduced and conventional tillage. Differences over time in marketable yield of carrots, between reduced tillage and conventional tillage, decreases. However, this is probably due to the introduction of shallow ploughing and the use of the twin rotor in 2022 (see chapter 4.7.2). Since the marketable product of carrots was always higher for CT, it is not possible to discern any climatic effects.
In general the carrot yield declined over the years for all tillage systems compared to the average carrot yield in the region. This could be caused by the limited irrigation that is applied. This is only done in dry conditions during germination in May or June. Even in the relatively dry months of July and August of last years (see 4.1), irrigation is not applied to clarify the differences in soil water retention. Another reason is the water quality of available irrigation water which reaches a value of EC 4 Ms which can cause leaf damage.

Pumpkin was only grown twice in the organic systems; therefore the results should be treated carefully. No significant difference between reduced tillage and CT were observed. However, in the last year the marketable yield was significantly lower in the RT/SPL system compared to CT. O'Rourke and Petersen (2016) conducted a study comparing the effects of reduced tillage methods, including no-till, strip-till, and conventional tillage systems, on pumpkin yields over two cropping seasons. They also did not observe any significant yield differences between the tillage systems when the average pumpkin yields were compared. However, upon analysing the data for each year separately, they did find some slight variations in yield between the tillage systems during one of the years. They attributed these marginal differences to weed management, as suggested by previous research by Walters et al. (2008) and their own study (O'Rourke and Petersen, 2016). In our own experiment, pumpkin cultivation only took place during the ninth cropping season in 2017. It can be assumed that by this time, weed management practices had been fully optimized, and the impact of weed competition on pumpkin yield was consequently minimized. With only two years of observations no conclusions can be draw concerning climatic effects or the increase of possible effects over time from reduced tillage on pumpkin production.

Peas were only grown twice in the conventional system. Due to this limited amount of data only limited conclusions can be drawn. The marketable yield of pea was significantly higher for reduced tillage (RT), compared to CT. Peas are the opposite of small-seeded crops like onions or carrots, the seeds are big and therefore most likely do have none or minimum hindrance of more cover crop residues in the seedbed with RT. A reason for the increased marketable yield of peas under RT could also be the symbioses of legumes with mycorrhizal fungi. Literature confirms that arbuscular mycorrhizal fungi (AMF) are often found to be more abundant under reduced or no tillage and the colonization of roots by AMF develops slower in tilled systems (McGonigle., 1999; Van Groenigen et al., 2010; Bowels et al., 2017). In the reduced tillage systems in this experiment, the cover crops were not incorporated into the soil before winter, but continued to stand in the fields till spring. The presence of cover crops can also increase the abundance of AMF and the colonization of the following cash crop (Bowels et al., 2017).

The marketable yield of sugar beet, grown in the conventional system, was not significantly affected by tillage system. Similar results are found in literature (Jabro et al., 2010; Van den Putte et al., 2010; Afshar et al., 2019). However, a lower sugar beet yield of 5.2% in reduced tillage systems has also been found by Arvidsson et al., (2014). Lower sugar beet yields in reduced tillage systems are often caused by a lower plant density, cause by bad emergence of the fine seeds due to higher crops residue presence. In this experiment crop emergence was not sufficiently measured to make any conclusions; however, a lower plant density was observed in the fields. A slightly lower plant density is compensated by sugar beets by producing bigger individual beets, thus not causing lower yield (Westerdijk et al., 1994).
Over time the yield difference of sugar beet between reduced and conventional tillage did not change. Only 2020 the marketable yield of sugar beet was lower for all tillage systems, because the harvest was early, so the plants had a shorter growing period. However in this year the marketable yield was also significantly lower for RTS and RT/SPL compared to CT. 2020 had a dry spring. In the reduced tillage plots the soil moisture was evenly distributed over the soil profile. In the conventional tillage plots there was a layer of moisture standing on the plough pan. This would normally not be very beneficial, however in this dry year the sugar beet in the convention tillage probably had more moisture available, after the top layer of the soil, in reduced tillage was already dried out, causing the difference in marketable yield.

The marketable product of onions in the conventional system was slightly lower, but not significantly different, in RT and RTS, when compared to the CT system. This finding stands in contrast to the results of Kesik and Marzena (2009), who observed significant marketable yield reductions of -30.7% in a conservation tillage system. However, our results align with findings from another study (Jardênia et al., 2020) that reported no significant impact of reduced tillage on marketable onion yield. It is essential to note that the diverse range of tillage systems tested in different studies calls for careful interpretation and caution when comparing findings. Potential causes of lower onion yields in reduced tillage systems, as noted by Kesik and Marzena (2009), include reduced seed germination. Physical seedbed factors like seedbed structure and seedbed water content likely play a significant role in this regard. In our field experiment, we observed that the average soil aggregate size was significantly larger in reduced tillage (Crittenden et al., 2015), which might have contributed to reduced seed germination. This is evident from the sometimes significantly lower plant densities in the RTS and RT systems compared to the CT system.
Despite the differences in bulb sizes and plant densities, reduced tillage in our experiment did not lead to significant changes in marketable, gross, or net onion yield. The reduced competition for resources in the RTS and RT systems, due to lower plant density, probably resulted in significantly larger average bulb sizes compared to CT. Moreover, yields of the larger bulb size classes (60–80 mm) and the non-marketable size class (>80 mm) were significantly higher in RTS and RT.
The yield was only significantly lower for reduced tillage in the last year (2018). Difference might have increased over time, however, 2018 was also a particularly warm and dry year. Whether the effects were due to more years of reduced tillage or due to climatic effects is hard to say.

4.4 Yield quality

To get an overview of the effect of soil tillage on the quality of the yield, the yield quality results were scored. Conventional tillage (CT), Reduced tillage with shallow ploughing (RT/SPL), Reduced tillage with sub-soiling (RTS) and reduced tillage without sub-soiling (RT) are compared and a score is given per crop and year. The scores are not interdependent over the years and crops. The tillage system with the highest quality for every particular crop and year was always given score one. When the quality was lower for another tillage system, but this difference was not significant, the score was lowered by one point. When the difference was significant, the score was lowered by two points. In exceptional cases, when the difference was significant and very large, the score was lowered by three points. An overview of all scores for yield quality can be found in Appendix L in Table L.3 for crops in the organic crop rotation and in Table L.4 for crops in the conventional crop rotation. Table 8 shows a summary of these scores and gives only the averages over the years per crop and the weighted crop rotation average. Because there was little data available, reduced tillage with shallow ploughing (RT/SPL) and crops that are only grown one year are left out of this summary.

Table 8 shows that for yield quality the differences between soil tillage systems are very small. The different aspects of yield quality seem slightly lower for reduced tillage, especially for the organic crops, however this difference is small and never significant. Also, in the statistical analysis interactions were often found between tillage system and year. This means there is an effect of tillage system on yield quality, but the direction of the effect changes over the years. This is most likely related to differences in weather conditions.

For ware potato in the organic system, no significant difference or trends were found in the marketable share of the total yield, between reduced and conventional tillage. Only in 2018 was the marketable share higher for RT compared to CT. The marketable yield for reduced tillage was also higher compared to conventional tillage, while the gross yield was similar. The difference in marketable yield was caused by a difference in yield quality. 2018 was a very dry and warm year. Possibly, more moisture was retained in the soil under reduced tillage.

Table 8. Score for yield quality averaged over the years of the different crops in the organic and conventional crop rotation, were tillage systems are compared. N indicates the number of years from which data on yield quality is available for a certain crop.

Farming System	Crop	Tillage system			N
		CT	RTS	RT	
Organic	Ware potato	**1.2**	**1.3**	**1.3**	6
	Oats	**1.0**	**1.5**	**1.0**	3
	Carrot	**1.0**	**2.0**	**2.0**	8
	Spring wheat	**1.0**	**1.5**	**1.5**	2
Weighted crop rotation average		**1.1**	**1.6**	**1.5**	
Conventional	Seed potato	**1.3**	**1.5**	**1.4**	6
	Sugar beet	**1.0**	**1.0**	**1.0**	7
	Onion	**1.0**	**1.3**	**1.0**	4
	Spring barley	**1.0**	**1.3**	**1.5**	4
Weighted crop rotation average		**1.1**	**1.2**	**1.2**	

For seed potato in the conventional system we also do not see significant differences or trends in the marketable share of the total yield. Only in 2015 the marketable share is significantly higher for CT, compared to RT. This difference does not translate to a higher marketable yield.

For all cereal crops in both the organic and the conventional crop rotation we do not find any significant difference or trends in thousand grain weight between the different tillage systems. However, for marketable yield we do see some difference, where reduced tillage is similar of higher in yield, compared to conventional tillage. In this experiment a higher number of haulms per square meter was observed, however, this was not measured often enough to draw conclusions. Opposingly, Arvidsson et al. (2014) found a lower plant establishment for shallow and no-till systems. The lack of difference in thousand grain weight between the tillage systems, supports the theory that differences in marketable yield in this experiment had to be caused by a higher number of hauls.

For carrots in the organic systems the difference between marketable product and gross yield was considered. The difference, found between the different soil tillage systems, followed the same trend as marketable yield. The yield quality was often higher for CT, compared to RT and RTS. Similarly as for marketable yield, this difference was only significant in 2009 and 2013. As mentioned in the discussion on yield, we did not observe significant differences in carrot crop emergence. The difference between marketable product and gross yields supports the theory that the difference in marketable yield is caused by a higher number of non-marketable deformed/rotten or large-sized (250-400 gr) carrots. See the discussion on yield for possible explanations.

For sugar beet in the conventional system the percentage of sugar was considered as yield quality aspect. There were no differences or trends between the different soil tillage systems. In marketable yield also no differences were found, except for the yield in 2020. However, also in that year the sugar content was similar for all tillage systems. Thus, differences in marketable yield were not connected to sugar content.

For onions in the conventional system the difference between marketable product and gross yield was considered. The marketable yield of onions seemed a bit lower for reduced tillage, especially in 2018. However, we did not find this difference between tillage systems for the yield quality. The difference in marketable product of onions is most likely cause by lower seed germination, see the discussion on yield for more details on this. Difference were not caused by difference between marketable and gross yield.

4.5 Physical soil aspects

4.5.1 Bulk density and soil moisture

Bulk density was only measured once or twice. In the upper 0-10 cm layer, no difference were found in bulk density between the different tillage systems. However, in the 10-20 cm layer, the bulk density was often significantly higher in the reduced tillage (RT), compared to conventional tillage (CT). For an overview of the results, scored comparing tillage systems, see Appendix L Table L.5 and L.6.

Even in the reduced tillage system, the upper 0-10 cm layer is still disturbed with other soil management, like harrowing and seedbed preparation, especially when building ridges for carrots and potatoes. This could explain why we did not find differences in bulk density in this upper layer between the tillage systems, but only in the deeper layer. This is in accordance with the findings of Bottinelli et al. (2013) after a 7 year experiment on a humic loamy soil in France. They found no difference in bulk density between shallow tillage and mouldboard ploughing in the 2-10 cm layer; but did find a significant difference in the 12-20 cm layer. Also their findings on zero tillage confirm this theory, since they did found a significantly higher bulk density in the 2-10 cm layer when comparing no tillage with mouldboard ploughing and shallow tillage. Bottinelli et al. (2023) attribute the higher bulk density in reduce tillage in the 12-20 cm layer to a vermicular microstructure (Verrecchia et al., 2021), created by earth worm activity. Higher earthworm abundance was found by Hoek et al. (2019) in reduced tillage systems. Also Rücknagel et al. (2017) found higher bulk density in the lower topsoil for conservation tillage, compared to conventional tillage, in seven medium- and long-term soil tillage experiments in Central Europe.

Soil moisture shows a similar pattern as bulk density, where a lower bulk density is correlated with higher soil moisture. This is related to the proportion of air, water and soil in the soil profile. When the bulk density is lower, there is more pore space available for water. Also the pore size influences the water holding capacity of the soil, with smaller micropores holding more water. See Appendix L Table L.7 and L.8 for an overview of the results for soil moisture, scored comparing tillage systems. Since soil moisture was measured as an extra while measuring bulk density, it was not measured at consistent time intervals or at particularly interesting moments considering very dry or wet periods. It is therefore difficult to draw strong conclusions based on this data.

4.5.2 Penetration resistance

The data on penetration resistance was divided into two time periods, 2009-2012 and 2013-2016, in order to see a possible change in penetration resistance, the longer the soil was not tilled. Penetration resistance is generally higher for RT, compared to CT. Reduced tillage with subsoiling (RTS) was often in-between RT and CT. The difference between the tillage systems is largest in the upper 10-30 cm of the soil. Over time the difference in penetration resistance between the different tillage systems increased indeed. In the later time period the variation among the measurements is smaller.

Other research suggests that higher penetration resistance in reduced tillage is caused by natural compaction, gradual consolidation of the soil matrix due to for example rainfall and the lack of loosening the soil with annual tillage (Schwen et al., 2011; Moret & Arrúe, 2007).

Higher bulk density and penetration resistance are often associated with compacted layers, were plant roots would have difficulty to grow. In the reduced tillage systems, bulk density appears to be a bit higher in the 10-20 cm layer and for penetration resistance we also see higher values in the 10-30 cm layer. The yield does not appear to be limited by the higher soil density in reduced tillage. Also, rooting of the topsoil is good due to a porous structure and abundant soil live. Therefore the higher bulk density and penetration resistance, seen in the reduced tillage system, is not necessarily disadvantageous compaction, but can also be seen as a positive higher bearing capacity; possibly enabling quicker and better accessibility to the land with heavy machinery.

4.6 Chemical soil aspects

4.6.1 Organic matter and total carbon content of the soil

In 2009 and 2011 the organic matter is a bit higher compared to the later years. This might be due to analysis by two different laboratories. In the upper 15 cm of the soil both the organic matter and the total carbon content are often higher in the reduced tillage (RT) system, compared to conventional tillage (CT). For organic matter this difference is often significant. This difference is for organic matter already visible two years after the start of the experiment, and seems to slightly increase further over the years. 14 Years might not long enough for soil organic matter or carbon to reach a new equilibrium; this can take more than 100 years, depending on management practice and soil type. (Smith et al., 1996). In the deeper soil layer (15-30 cm) the difference in organic matter and soil carbon content between the tillage systems was smaller and both organic matter and soil carbon content were often a bit lower in RT compared to CT. So, in the RT system the organic matter and carbon remains more in the upper soil layer. However, also for the whole soil layer of 0-30 cm the organic matter and soil carbon content is over all fields and years higher for RT, compared to CT. Though these differences are very small and not significant. See Appendix L Table L.9, L.10, L.11 and L.12 for an overview of the organic matter and soil carbon content results, scored comparing tillage systems.

Krauss et al., (2022) looked at carbon sequestration in nine organic field experiments where tillage systems were being compared, in France, Germany, Switzerland and including this BASIS experiment in the Netherlands. The experiments were between 8 and 21 years old. Samples up to 100 cm depth were taken to look at carbon sequestration. They found similar results, when comparing RT to CT: the soil organic carbon was higher in the upper 10/15 cm and a bit lower in the intermediate soil layers up to 50 cm depth. Reduced tillage had a little higher cumulative soil organic carbon stock over the entire soil depth of 1 meter. This stratification of organic matter over soil layers is also found by Luo et al. (2010) and Ogle et al., (2019). Stratification of soil organic matter and soil organic carbon under reduced tillage can be explained by a lack of mixing the soil with reduced tillage, compared to conventional tillage (Luo et al., 2010). In reduced tillage the deeper soil layer can also be more compacted, causing roots to grow more in the upper layer. We did not investigate root densities over different layers in our experiment, but this was confirmed by a global study of Mondal et al. (2019). This can also cause the higher organic matter in the upper layer of the topsoil (Krauss et al., 2022). An overall increase of organic matter or organic carbon in reduced tillage can be caused by a decrease in soil disturbance, decreasing soil organic carbon turnover, decreasing the exposure of soil organic matter to microbial consumption. Aggregate stability can be higher in reduced tillage (Loaiza Puerta et la., 2018). Also biomass input can affect the soil organic matter. Since differences in yield where small, the biomass input of crop residue most likely did not influence soil organic matter. However, in the RT systems, tillage was done in spring, as compared to ploughing in autumn. This meant the cover crop remained in the field for a longer period of time, giving it the change to produce a higher biomass, which is later incorporated into the soil.

The findings of this experiment, coupled with insights from existing literature (Haddaway et al., 2017; Krauss et al., 2022), indicate that RT holds greater promise for sequestering soil organic carbon in comparison to CT. Nonetheless, this heightened sequestration is constrained until a new equilibrium in soil organic carbon levels is attained. As a result, the practice of reduced tillage as a means of enhancing soil carbon sequestration should not be regarded as a comprehensive or singular remedy for addressing greenhouse gas emissions.

4.6.2 Soil pH

The differences in soil pH between tillage systems are small. In the organic fields the soil pH seems a bit higher in the CT system, compared to RT. In a long term experiment in Kansas a lower pH for no-till treatments compared to conventional tillage was also found. However, the difference between the tillage systems in our experiment in the organic fields decreases over the years. In the conventional fields no differences or trends are found between tillage systems when considering soil pH.

In all fields pH seems to increase a bit in the period 2013-2018 and decrease in 2021, though the differences are small. In 2021 the organic matter suddenly decreased substantially. pH was measured in the same soil samples as organic matter and this might be related. This fluctuation of pH over the years is not related to tillage system. It can also not be related to the crops grown in the different years, since the trend is visible in all fields, but different crops were grown in the different fields each year. It is most likely due to yearly climatic circumstances.

4.6.3 Nutrient content of the soil

To get an overview of the effect of soil tillage on total nitrogen content of the soil, the results were scored. Conventional tillage (CT), Reduced tillage with shallow ploughing (RT/SPL), Reduced tillage with sub-soiling (RTS) and reduced tillage without sub-soiling (RT) are compared and a score is given per field and year. The scores are not interdependent over the years and fields. The tillage system with the highest nitrogen content for every particular year and field was always given score one. When the nitrogen content was lower for another tillage system, but this difference was not significant, the score was lowered by one point. When the difference was significant, the score was lowered by two points. In exceptional cases, when the difference was significant and very large, the score was lowered by three points. An overview of all scores for total nitrogen content can be found in Appendix L in Table L13. Table 9 shows a summary of these scores and gives only the averages over the years per field and the weighted average over all fields. Because there was little data available, RT/SPL was left out of this summary.

Over all fields and years the trend was visible that the total nitrogen content of the soil was higher for reduced tillage, compared to conventional tillage. In half of the years, this difference was significant. This difference was also found by Martínez et al., 2016 in a long term tillage experiment in Switzerland. The difference in total nitrogen content between the tillage systems is more pronounced in the upper 0-15 cm layer. Studies from China, considering reduced or no tillage, confirm the stratification of nutrients in the soil, with more nitrogen in the upper layer (He et al., 2009, Dikgwatlhe et al., 2014, Xue et al., 2015). It was also found by D'Haene et al., 2008) in tillage experiments in Belgium. This stratification is similar to that of organic matter and carbon content of the soil and is related to more crop residue on the surface with reduced tillage, compared to conventional tillage. Differences between the tillage systems cannot be related to the crops grown in the different years, since different crops were grown in the different fields each year.

Table 9. Score for total nitrogen content of the soil averaged over the years of the different fields in the organic and conventional crop rotation, were tillage systems are compared. N indicates the number of years from which data on nitrogen content is available for a certain field.

Farming system	Field	Tillage system			N
		CT	RTS	RT	
Organic	J10-3	**1.8**	**1.5**	**1.0**	4
	J10-4	**2.8**	**1.5**	**1.5**	4
	J10-6	**1.8**	**1.5**	**1.3**	4
Conventional	J9-4	**2.0**	**1.3**	**1.5**	4
	J9-6	**2.5**	**1.5**	**1.0**	4
Weighted average		**2.2**	**1.5**	**1.2**	

4.6.4 Mineral nitrogen in the soil (Nmin)

All measured Nmin values in both autumn and spring are quite low. Therefore, any differences between tillage systems, even significant differences are not necessarily relevant differences. Mineral nitrogen found in the 60-90 cm soil layer in autumn is generally lost by leaching over the winter seasons. No differences in autumn Nmin in any of the layers was found. Since RT often has a cover crop over the winter, compared to bare soil for CT, it was expected that more nitrogen was retained in reduced tillage. In spring we find higher Nmin values in the sub soil (30-90 cm layer) for CT, compared to RT and RTS. This might confirm the downward movement of nitrogen through the soil profile in winter, when no cover crop is grown. It can also indicates the faster start of mineralisation in spring for conventional tillage.

4.7 Other research topics

4.7.1 Seedbed preparation for carrots

In a separate experiment to investigate the possibilities of increasing the carrot yield in reduced tillage, a Twinrotor rotary tiller was compared to a standard rotary tiller for building the carrot ridges. The use of the Twinrotor rotary tiller increased the amount of small sized soil aggregates, creating a finer seedbed. For reduced tillage this indeed increased the yield with more than 25% to approximately the same level as conventional tillage. For conventional tillage there was little difference in carrot yield between the Twinrotor and the standard rotary tiller. This separate experiment was only executed in 2022 on one of the organic fields (J10-6) and measurements were done in two repetitions. Therefore, the results should be interpreted cautiously. However, the Twinrotor tiller seems a good option for reducing the yield gap of carrots between reduced and conventional tillage. Further research would be needed to conclusively confirm this.

4.7.2 Weed seedbank

The weed seedbank analysis that is performed, should be regarded as a general survey that tries to investigate the overall changes in weed seedbank densities and composition after a trial period of 13 years. The results should be interpreted as such. Furthermore, the organic and conventional system were placed on different fields and not every crop was present in each year. Therefore, no direct comparisons between the organic and conventional systems can be made. In general, no explicit effects of the tillage systems were found on the size and composition of the weed seedbank in the top soil layer (0-10 cm). For the conventional system, a trend towards a lower weed density was observed for the reduced tillage system and occasional shallow ploughing (RT & RT/SPL). However, this is based on only two fields and mainly based on the observations from field J9-4 (RT/SPL). Unlike the presented results, non-inversion tillage systems are known to have higher weed seed numbers in the top layer compared to ploughing systems (Swanton et al. 2000; Yenish et al. 1992). No obvious explanation for the results found can be given. As no initial seedbank data are available, it is impossible to explore these effects in detail.

No major differences were found between the tillage systems in terms of species composition of the soil weed seedbank. But a higher abundance of chickweed in the reduced tillage with subsoiling (RTS) system was found for both systems. Chickweed seeds generally emerge from the top soil and have a limited longevity that could partially explain the higher abundance in this system. For annual grass however, which is favoured by similar conditions, this pattern was not found. In addition, the variability in occasional ploughing does not allow to fully untangle the tillage effects from the present data.

In the organic system, the seedbank composition observed is different from the conventional system. Especially in organic cropping systems, weed management has often been indicated as a major challenge for sustainable crop production (Liebman & Davis, 2009; Bàrberi, 2002; Bond & Grundy, 2002). The presence of thistles and other difficult to control weeds like wild buckwheat (*Fallopia convolvulus*) and couch grass (*Elymus repens*) is an important observation as weed control may become even more difficult with greater abundance of such species. From the trial, it is hard to identify the effects of tillage on the presence of perennial weed species. This would have required additional research as the methods used in this study are most suited for annual, seed propagated weeds.

5 Conclusion

5.1 Yield

Research questions from chapter 1.2

1. What is the effect of reduced soil tillage on the marketable product of Dutch root and tuber cash crops like potato, sugar beet, carrot and seed onion on a Dutch sandy loam soil, in an organic and conventional system? The effects on fine seeded crops, like seed onion and carrot was given extra attention.

   When considering marketable product, reduced tillage is a viable option on sandy loam soils in the Netherlands. Overall the marketable product is comparable or higher for the different crops in the reduced tillage systems, compared to conventional tillage. When looking at the weighted crop rotation average, the scores for marketable product are very similar. However, when looking at individual crops this mainly counts for potatoes, sugar beet, grain crops, bean crops, a mixture of grains and beans and for grass clover. Indeed the marketable product of fine seed crops like carrots and onions are lower under reduced tillage.

2. Is the effect of reduced soil tillage on the marketable product influenced by extreme climatic circumstances like drought or too much water and hot or cold weather?

   In years with more weather extremes, yields are sometimes higher and sometimes lower for reduced tillage, compared to conventional tillage. Thus, over all the crops we do not see a clear trend of higher or lower marketable product due to more extreme climatic circumstances.

3. Does the effect of reduced soil tillage on the marketable product become more pronounced over time, when the soil is undisturbed for multiple years?

   It cannot be concluded that observed yield gaps between reduced and conventional tillage became more pronounced over time, as for most crops we did not see a change over time. Sometimes the production was more variable in the last years. Cabbage (organic) and onion (conventional) were two of the three crops, for which the marketable product was lower for reduced tillage compared to conventional tillage. For both these crops the yield gap was larger in the last year. These were both climatically extremer years, but it could be, that for crops that do not fare well by reduced tillage, the negative effects of reduced tillage do become more pronounced over time. A longer time series of yield data and growing all crops every year in an experiment is needed to confirm this.

5.2 Yield quality

Research questions from chapter 1.2

4. What is the effect of reduced soil tillage on the difference between the gross yield and marketable product?

   Effect of tillage on differences between gross yield and marketable product were small and not significant. Only a negative effect of reduced tillage on the quality of carrots was found (see research question 10 for a possible solution).

5. What is the effect of reduced soil tillage on crop quality parameters like sugar content and thousand grain weight?

   No differences or trends were found in the thousand grain weight due to tillage system. Therefore yield quality of the grain crops was not the cause of possible differences in marketable product. Also, no differences were found in sugar content in the sugar beets between the different tillage systems.

5.3 Physical soil aspects

Research question from chapter 1.2

6. What is the effect of reduced soil tillage on bulk density, soil moisture and penetration resistance?

   In the upper 0-10 cm layer there are no differences in bulk density between the tillage systems. In the deeper 10-20 cm layer bulk density was significantly higher for reduced tillage, compared to conventional tillage and reduced tillage with subsoiling. Soil moisture is higher for reduced tillage in the upper 0-10 cm soil layer, compared to conventional tillage. In the lower 10-20 cm layer soil moisture is higher for conventional tillage. Penetration resistance is generally higher for reduced tillage, compared to conventional tillage, especially in the 10-30 cm layer. Over time the difference in penetration resistance between reduced and conventional tillage increased.
   In this experiment, higher bulk density and penetration resistance in the 10-30 cm did not cause lower yields, nor did it limit rooting in the topsoil. Higher compaction can possibly also be associated with higher bearing capacity of the soil.

5.4 Chemical soil aspects

Research questions from chapter 1.2

7. What is the effect of reduced soil tillage on SOM and SOC and the position of these elements in the soil profile?

   Soil organic matter and soil organic carbon are higher in the upper 0-15 cm of the soil under reduced tillage, compared to conventional tillage. In the deeper 15-30 cm layer the differences between tillage systems are smaller and both organic matter and soil carbon were slightly lower for reduced tillage, compared to conventional tillage. So with reduced tillage the organic matter is stratified to the upper layer.

8. What is the effect of reduced soil tillage on pH, total nitrogen and the availability of other nutrients in the soil?

   Differences in soil pH between the tillage systems are small and no clear trends or significant differences are found. Fluctuations in pH over the years is not related to tillage systems. Total nitrogen content of the soil was higher for reduced tillage, compared to conventional tillage. This difference was most pronounced in the upper 0-15 cm layer. Besides nitrogen, no differences or trends were found in the nutrient content of the soil.

   Overall reduced tillage increased the soil organic matter, total carbon content and total nitrogen content of the soil in the upper 0-15 cm layer. In the total 0-30 cm layer a trend towards higher values for these factors under reduced tillage was seen.

9. What is the effect of reduced soil tillage on nitrogen losses and nitrogen availability in spring?

Mineral nitrogen levels in the soil in both autumn and spring in all soil layers are low for all tillage systems, therefore difference are small and of little relevance. There is some indication for faster mineralization in spring for conventional tillage and for more downward movement through the soil of mineral nitrogen over the winter season, when no cover crop is grown.

5.5 Other research topics

5.5.1 Seedbed preparation for carrots

Research question from chapter 1.2

10. What is the effect of the use of the Twinrotor in the reduced tillage system and in the conventional tillage system on soil aggregate size and stability and emergence and yield of carrots?

    The Twinrotor seems a viable option in reduced tillage systems to create a finer seedbed and reduce the yield gap of carrots between reduced and conventional tillage.

5.5.2 Weed seedbank

Research question from chapter 1.2

11. What is the effect of reduce tillage on weed community, regarding weed density and species composition?
    In general, no explicit effects of the tillage systems were found on the size and composition of the weed seedbank in the top soil layer (0-10 cm).

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Appendix A – Soil tillage

Table A.1. Soil cultivation methods (best practice) in the organic (ORG) crop rotation, specified for tillage systems CT, RTS and RT. Crops listed in sequence of their place in the crop rotation. Crops presented are the most frequently grown crops. See Table A.3 for equipment details. (Van Balen et al., 2023)

Crop	Soil cultivation method	Equipment	Tillage system		
			CT	RTS	RT
Ware potato	Seedbed preparation main crop	Mouldboard plough	46*	-	-
		Cultivator with vibrating tines	-	15	15
		Rotary harrow	17	17	17
	Ridging	Rotary hiller	17	17	17
Grass clover	Seedbed preparation main crop	Chisel plough	35	35	-
		Cultivator with vibrating tines	35	35	35
		Rotary harrow	37	37	37
Cabbage	Seedbed preparation main crop	Disc harrow	45	-	-
		Mouldboard plough	46	-	-
		Cultivator with vibrating tines	-	16	16
		Cultivator with vibrating tines	-	18	18
		Rotary harrow	22	22	22
Spring wheat	Seedbed preparation main crop	Mouldboard plough	46	-	-
		Cultivator with vibrating tines	-	13	13
		Rotary harrow	14	14	14
Carrot	Seedbed preparation main crop	Mouldboard plough	46	-	-
		Cultivator with vibrating tines	-	16	16
		Cultivator with vibrating tines	-	17	17
		Rotary harrow	18	18	18
		Rotary hiller	18	18	18
Faba bean/ Spring wheat	Seedbed preparation main crop	Chisel plough	-	42	42
		Mouldboard plough	46	-	-
		Cultivator with vibrating tines	-	14	14
		Rotary harrow	15	15	15
	Seedbed preparation cover crop	Cultivator with vibrating tines	37	37	37
		Rotary harrow	37	37	37

* Week number, indicating the time of cultivation (average over 2009-2018). Note: weeks 42-47 refer to the autumn preceding the growing season of the crop in question.

Table A.2. Soil cultivation methods (best practice) in the conventional (CONV) crop rotation, for tillage systems CT, RTS and RT. Crops listed in sequence of their place in the crop rotation. Crops presented are the most frequently grown crops. See Table A.3 for equipment details. (Van Balen et al., 2023)

Crop	Soil cultivation method	Equipment	Tillage system		
			CT	RTS	RT
Seed potato	Seedbed preparation main crop	Mouldboard plough	44*	-	-
		Chisel plough	-	42	-
		Rotary harrow	15	15	15
	Ridging	Rotary hiller	20	20	20
	Seedbed preparation cover crop	Cultivator with vibrating tines	35	35	35
		Rotary harrow	37	37	37
Sugar beet	Seedbed preparation main crop	Mouldboard plough	46	-	-
		Chisel plough	-	44	-
		Cultivator with vibrating tines	-	13	13
		Rotary harrow	15	15	15
Spring barley	Seedbed preparation main crop	Chisel plough	-	44	-
		Mouldboard plough	47	-	-
		Cultivator with vibrating tines	-	12	12
		Rotary harrow	12	12	12
	Seedbed preparation cover crop	Cultivator with vibrating tines	33	33	33
		Rotary harrow	33	33	33
Seed onion	Seedbed preparation main crop	Mouldboard plough	46	-	-
		Cultivator with vibrating tines	-	12	12
		Rotary harrow	15	15	15
	Seedbed preparation cover crop	Cultivator with vibrating tines	39	39	39
		Rotary harrow	39	39	39

* Week number, indicating the time of cultivation (averaged over 2009-2018). Note: weeks 42-47 refer to the autumn preceding the growing season of the crop in question.

Table A.3. Soil cultivation equipment used in BASIS. (Van Balen et al. 2023)

Equipment	Description and remarks
Mouldboard plough	Rumptstad RPV 120-480 reversible plough with (2x) 4 mouldboards and a working width of 1.60 m (which allowed to plough the 3.15 m beds with one return pass). Ploughing depth 23-25 cm. During ploughing, the tractor (standard track width 1.50 m) drives with one wheel in the furrow; it is not possible to drive over the fixed traffic lanes. Construction year 2005. Weight 1430 kg.
Chisel plough	Kongskilde Paragruber ECO 3000 is a subsoiler, lifting and loosening the soil using 6 specially angled (slanted) tines. The mixing action of the Paragruber is limited so soil layers remain in place while being loosened. Distance between tines is 50 cm. Working width 3 m. Nr. of tines 6, Weight 780 kg.
Cultivator with vibrating tines	The Steketee C4000-4 cultivator with (heavy) vibrating tines is able to cut (belowground) the soil full-field. This implement is adapted to cover 3 m width by removing the folding elements and mounting the depth wheels 3.15 m apart. At the rear of the implement a roller can be mounted which crumbles the soil and assists in the depth control (see picture at the right). The Steketee has 13 tines 22.5 cm apart. The vibrating tines (spring steel) have goosefeet with a cutting width of 30 cm. Working width 3 meter, number of tines: 13. Year 1999. Weight 990 kg.
Rotary harrow	The Masschio HB 3000 power harrow is a standard version but modified for use in the front hitch system. To enable this, a special A-frame was mounted together with an extension of the PTO shaft. An additional roller was placed in front of the harrow. The harrow is more tightly attached to the tractor so lateral movement is minimized. Working width of the power harrow is 3 m. Number of rotors (each with two tines) is 14. Rotors overlap so soil over the full width of the machine is worked. Working width 3 m. Number of rotors 14. Number of tines 28. Construction year 1996. Weight 850 kg.
Rotary hiller	This Rumptstad RSF 2000 4x75 tined rotavator is used to produce ridges for potato and carrot. For building the ridges for carrots, the rotavator works over its full width, in the strips where the carrots will grow, extra-long tines are mounted for a deeper loosening of the soil. After planting potato the ridges will be re-built by the rotavator. In this situation the knives in the plant row are removed. The large parabolic disc visible on top of the machine in the centre-picture is mounted exactly in the centre of the rotavator in order to follow a narrow furrow (slot) created by the potato planter). The rotavator produces 4 ridges 75 cm apart. Working width 3 m / 4 ridges. Construction year 2000. Weight 1100 kg.
Disc harrow	The Evers V3000/51 R62 disc harrow is equipped with 2 gang3 of discs and a roller. Working width of the machine is 3,5 m. The angle of attack of the serrated discs can be adjusted according to the required soil penetrating effect. Total number of discs is 24. Working width 3,5 m. Nr. of discs 24. Weight 1148 kg. Construction year 1998.

Table A.4. Overview of when shallow ploughing (SPL) was used on the fields with reduced tillage (RT): executed soil tillage (EST); and how the system was called as a treatment from then on: treatment name (TN).

	Organic farming system						**Conventional farming system**			
	Field J10-3		**Field J10-4**		**Field J10-6**		**Field J9-4**		**Field J9-6**	
Year	**EST**	**TN**	**EST**	**TN**	**EST**	**TN**	**EST**	**TN**	**EST**	**TN**
2009	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2010	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2011	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2012	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2013	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2014	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2015	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2016	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2017	RT	RT	RT	RT	RT	RT	RT	RT	RT	RT
2018	RT	RT	RT	RT	RT	RT	SPL	RT/SPL	RT	RT
2019	SPL	RT/SPL	SPL	RT/SPL	RT	RT	RT	RT/SPL	RT	RT
2020	RT	RT/SPL	RT	RT/SPL	RT	RT	RT	RT/SPL	RT	RT
2021	RT	RT/SPL	SPL	RT/SPL	RT	RT	RT	RT/SPL	RT	RT
2022	RT	RT/SPL	RT	RT/SPL	RT	RT	RT	RT/SPL	RT	RT

Appendix B – Fertilization

Table B.1. Soil fertilization (N, P_2O_5, K_2O: best practice) for crops grown in the conventional farming system. Crops presented are the most frequently grown crops. (Van Balen et al., 2023)

Crop	Tillage system CT	RTS	RT	Fertilizer	Timing	N kg/ha	P_2O_5 kg/ha	K_2O kg/ha
Seed potato	X	X	X	Calcium ammonium nitrate	Spring	100	0	0
				Potassium chloride	Autumn	0	0	154
				Tripelsuperphosphate	Spring	0	79	0
Sugar beet	X	X	X	Calcium ammonium nitrate	Spring	128	0	0
				Potassium chloride	Autumn	0	0	119
				Tripelsuperphosphate	Spring	0	97	0
Spring Barley	X	X	X	Calcium ammonium nitrate	Spring	80	0	0
Seed onion	X	X	X	Calcium ammonium nitrate	Spring & Summer	123	0	0
				Potassium chloride	Autumn	0	0	285
				Tripelsuperphosphate	Spring	0	67	0

Table B.2. Soil fertilization (N, P2O5, K2O: best practice) for crops grown in the organic farming system. Crops presented are the most frequently grown crops. (Van Balen et al., 2023)

Crop	Tillage system CT	RTS	RT	Fertilizer	Timing	N kg/ha	P_2O_5 kg/ha	K_2O kg/ha
Ware potato	X	X	X	Solid cow manure	Autumn	170	97	217
				Cow slurry	Spring	101	42	146
Grass/clover	X	X	X	None		0	0	0
White cabbage	X	X	X	Solid cow manure	Autumn	165	81	219
				Cow slurry	Spring	163	80	225
Spring wheat	X	X	X	Dried chicken manure	Spring	69	43	57
Carrot	X	X	X	None		0	0	0
Spring Wheat/ Faba bean	X	X	X	None		0	0	0

Appendix C – Data collection

Table C.1. Overview of data collected (X) or not collected (-) for the different aspects (yield, yield quality, soil physical aspects and soil chemical aspects), per year and per crop for the two conventional fields.

			Yield	Yield characteristics							Soil physical			Soil chemical			
Field	Year	Crops	Yield	Yield quality	Crop density	Tillering number	Crop height	Dry biomass of crop	Mineral content of crop	Fresh biomass of crop residue	Penetration resistance	Soil moisture	Bulk density	Mineral Nitrogen	Total and available nutrients	Soil organic matter	Soil organic carbon
J9-4 (conventional)	2009	Spring barley	x	x	-	x	x	-	-	-	x	-	-	x	x	x	-
	2010	Seed onion	-	-	-	-	-	-	-	-	x	x	x	x	-	-	-
	2011	Seed potato	x	x	-	-	-	-	-	-	x	-	-	x	-	-	-
	2012	Sugar beet	x	x	-	-	-	x	x	-	x	-	-	x	x	x	-
	2013	Spring barley	x	x	x	x	x	-	-	x	x	-	-	x	x	x	x
	2014	Seed onion	x	x	x	-	-	-	-	-	x	-	-	x	-	-	-
	2015	Seed potato	x	x	-	-	-	-	-	-	x	-	-	x	-	-	-
	2016	Sugar beet	x	x	-	-	-	x	x	-	-	x	x	x	x	x	x
	2017	Spring barley	x	-	-	-	-	x	x	-	-	-	-	x	-	-	-
	2018	Seed onion	x	x	x	-	-	x	x	-	-	-	-	x	x	x	x
	2019	Seed potato	x	x	x	-	-	x	x	-	-	-	-	x	-	-	-
	2020	Sugar beet	x	x	-	-	-	-	x	-	-	-	-	x	-	-	-
	2021	Winter barley	x	x	x	-	-	x	-	-	-	-	-	x	x	x	-
	2022	Pea	x	x	-	-	-	-	-	-	-	-	-	x	-	-	-
J9-6 (conventional)	2009	Sugar beet	x	x	x	-	-	-	x	-	-	-	-	x	x	x	-
	2010	Winter wheat	x	-	-	x	x	-	-	-	x	-	-	x	-	-	-
	2011	Seed onion	x	x	-	-	-	-	-	-	x	-	-	x	x	x	-
	2012	Seed potato	x	x	-	-	-	x	x	-	x	-	-	x	x	x	-
	2013	Sugar beet	x	x	x	-	-	x	x	-	x	-	-	x	x	x	x
	2014	Spring barley	x	x	x	-	-	x	-	x	x	-	-	x	-	-	-
	2015	Seed onion	x	x	x	-	-	-	-	-	x	x	x	x	-	-	-
	2016	Seed potato	x	x	-	-	-	x	x	-	x	-	-	x	x	x	-
	2017	Sugar beet	x	x	-	-	-	-	x	-	-	-	-	x	-	-	-
	2018	Spring barley	x	x	-	-	-	x	x	x	-	-	-	x	x	x	-
	2019	Pea	x	x	-	-	-	x	x	-	-	-	-	x	-	-	-
	2020	Seed potato	x	x	-	-	-	-	-	-	-	-	-	x	-	-	-
	2021	Sugar beet	x	x	-	-	-	-	x	-	-	-	-	x	x	x	-
	2022	Spring barley	x	x	-	-	-	x	-	-	-	-	-	x	-	-	-

Table C.2. Overview of data collected (X) or not collected (-) for the different aspects (yield, yield quality, soil physical aspects and soil chemical aspects), per year and per crop for the three organic fields.

			Yield	Yield quality							Soil physical			Soil chemical			
Field	Year	Crops	Yield	Yield quality	Crop density	Tillering number	Crop height	Dry biomass of crop	Mineral content of crop	Fresh biomass of crop residue	Penetration resistance	Soil moisture	Bulk density	Mineral Nitrogen	Total and available nutrients	Soil organic matter	Soil organic carbon
J10-3 (organic)	2009	Ware potato	x	x	-	-	-	-	-	-	x	-	-	x	x	x	-
	2010	Grass clover	x	x	-	-	-	x	-	-	x	-	-	x	-	-	-
	2011	White cabbage	x	-	-	-	-	-	-	-	x	-	-	x	x	x	-
	2012	Spring barley	x	-	-	-	-	x	x	x	x	-	-	x	x	x	-
	2013	Carrot	x	x	x	-	-	x	x	x	-	-	-	x	x	x	x
	2014	Faba bean/spring wheat	x	x	-	-	-	-	-	-	x	-	-	x	-	-	-
	2015	Ware potato	x	x	-	-	-	x	x	-	-	-	-	x	-	-	-
	2016	Grass clover	x	-	-	-	-	x	-	-	x	x	x	x	x	x	-
	2017	Pumpkin	x	x	x	-	-	-	x	-	-	-	-	x	-	-	-
	2018	Oats	x	x	-	x	x	x	x	-	-	-	-	x	x	x	-
	2019	Carrot	x	x	-	-	-	x	x	-	-	-	-	x	-	-	-
	2020	Green bean	-	-	-	-	-	-	-	-	-	-	-	x	-	-	-
	2021	Spring wheat	-	-	-	-	-	-	-	-	-	-	-	x	x	x	-
	2022	Grass clover	-	-	-	-	-	-	-	-	-	-	-	x	-	-	-
J10-4 (organic)	2009	Carrot	x	x	x	-	-	-	-	-	x	-	-	x	x	x	-
	2010	Faba bean/spring wheat	x	x	-	-	-	-	-	-	x	-	-	x	-	-	-
	2011	Ware otato	x	x	-	-	-	-	-	-	-	-	-	x	-	-	-
	2012	Grass clover	x	-	-	-	-	x	x	-	x	-	-	x	x	x	-
	2013	White cabbage	x	-	-	-	-	x	x	-	x	x	x	x	x	x	x
	2014	Spring wheat	x	x	x	-	-	x	x	x	x	-	-	x	-	-	-
	2015	Carrot	x	x	x	-	-	x	x	-	-	-	-	x	-	-	-
	2016	Spring wheat	x	x	-	-	-	x	x	-	-	-	-	x	x	x	-
	2017	Ware potato	x	x	-	-	-	x	x	-	-	-	-	x	-	-	-
	2018	Grass clover	x	-	-	-	-	x	-	-	-	-	-	x	x	x	-
	2019	Pumpkin	x	x	x	-	-	-	x	-	-	-	-	x	-	-	-
	2020	Oats	x	x	-	-	-	-	-	-	-	-	-	x	-	-	-
	2021	Carrot	x	x	x	-	-	-	-	-	-	-	-	x	x	x	-
	2022	Green bean	x	x	-	-	-	-	-	-	-	-	-	x	-	-	-
J10-6 (organic)	2009	Spring wheat	x	x	-	x	x	x	-	-	x	-	-	x	x	x	-
	2010	Carrot	x	x	-	-	-	-	-	-	x	-	-	x	-	-	-
	2011	Faba bean/spring wheat	x	x	-	-	-	x	-	-	x	-	-	x	-	-	-
	2012	Ware potato	x	x	-	-	-	x	x	-	x	-	-	x	x	x	-
	2013	Grass clover	x	-	-	-	-	x	x	-	x	x	x	x	x	x	x
	2014	White cabbage	x	-	-	-	-	x	x	-	x	-	-	x	-	-	-
	2015	Spring wheat	x	x	x	-	-	x	x	x	x	x	x	x	-	-	-
	2016	Carrot	x	x	-	-	-	-	-	-	-	-	-	x	x	x	x
	2017	Spring wheat	x	x	-	-	-	x	x	-	-	-	-	x	-	-	-
	2018	Ware potato	x	x	x	-	-	x	x	-	-	-	-	x	x	x	-
	2019	Grass clover	x	-	-	-	-	x	-	-	-	-	-	x	-	-	-
	2020	White cabbage	x	-	-	-	-	x	x	-	-	-	-	x	-	-	-
	2021	Oats	x	x	-	-	-	x	-	-	-	-	-	x	x	x	-
	2022	Carrot	x	x	x	-	-	-	-	-	-	-	-	x	-	-	-

Appendix D – Yield and yield quality sampling method

Table D.1. Yield sampling methods per crop and farming system

Farming system	Crop	Harvest method	Harvested area	Remark
Organic	Grass clover	Trial field harvester (haldrup)	6 x 1.5 m	Middle of bed
	Cabbage	Hand	10 x 3 m	2010: 85 x 3 m
	Pumpkin	Hand	15 x 3 m	
	Spring wheat	Combine harvester	85 x 3 m	
	Oats	Combine harvester	85 x 3 m	
	Carrot	Hand	5 x 1.5 m	Middle rows of bed
	Wheat/faba bean	Combine harvester	85 x 3 m	
	Ware potato	Trial field harvester*	6-8 x 1.5 m	Middle rows of bed
Conventional	Sugar beet	Beet harvester	85 x 3 m	
	Seed potato	Trial field harvester*	6-8 x 1.5 m	Middle rows of bed
	Spring + winter barley	Combine harvester	85 x 3 m	
	Winter wheat	Combine harvester	80 x 3 m	
	Seed onion	Hand	6-8 x 1.5 m	Middle rows of bed

** By hand in 2009 and 2011*

Table D.2. Yield category inclusion criteria

Farming system	Crop	Yield quantity		Yield quality	
		Marketable product	Unit	Quality aspect	Unit
Organic	Ware potato	35-60 mm	kg ha^{-1}	Marketable product / total yield excl. soil tare * 100%	%
	Grass clover	total dry matter	kg ha^{-1}		
	Cabbage	marketable cabbages	kg ha^{-1}		
	Pumpkin	marketable pumpkins	kg ha^{-1}		
	Spring wheat	moisture content 15%	kg ha^{-1}	Thousand-grain weight	g
	Oats	moisture content 15%	kg ha^{-1}	Thousand-grain weight	g
	Carrot	50-250 gr	kg ha^{-1}	Marketable product / total yield excl. soil tare * 100%	%
	Wheat/faba bean	moisture content 15%	kg ha^{-1}		
	Green bean	marketable green beans	kg ha^{-1}		
Conventional	Seed potato	28-60 mm	kg ha^{-1}	Marketable product / total yield excl. soil tare * 100%	%
	Sugar beet	sugar yield	kg ha^{-1}	Sugar content	%
	Spring + winter barley	moisture content 15%	kg ha^{-1}	Thousand-grain weight	g
	Winter wheat	moisture content 15%	kg ha^{-1}		
	Seed onion	> 40 mm	kg ha^{-1}	Marketable product / total yield excl. soil tare * 100%	%
	Pea	yield at TM 120	kg ha^{-1}		

[1] *Product tare = weight of rotten and deformed produce*
[2] *Soil tare = weight of soil attached to the harvested produce*

Table D.3. Size classes per crop and farming system

Farming system	Crop	Size classes
Organic	Ware potato	0-28 mm, 28-35 mm, 35-45 mm, 45-50 mm, 50-60 mm, >60 mm
	Grass clover	-
	Cabbage	Dependent on yearly market standards
	Pumpkin	Dependent on yearly market standards
	Spring wheat	-
	Oats	-
	Carrot	0-50 gr, 50-250 gr, 250-400 gr, >400 gr
	Wheat/faba bean	-
	Green bean	-
Conventional	Sugar beet	-
	Seed potato	0-28 mm, 28-35 mm, 35-45 mm, 45-50 mm, 50-60 mm, >60 mm
	Spring + winter barley	-
	Winter wheat	-
	Seed onion	0-40 mm, 40-60 mm, 60-80 mm, >80 mm
	Pea	-

Table D.4. Crop density sampling methods per crop and farming system

Farming system	Crop	Method	Plot size	Remark
Organic	Cabbage *	Harvested heads	10 x 3 m	
	Pumpkin *	Harvested plants and pumpkins	15 x 3 m	
	Spring wheat	Number haulms at harvest time	4-6 m row	
	Oats	Number haulms in June	6 m row	
	Carrot	Number plants June-August	2-5 m ridge	2009, 2013
		Number plants harvested	10 m ridge	2016
	Wheat/faba bean	-		
	Ware potato	Harvested tubers	6-8 x 1.5 m	Middle rows of bed
Conventional	Sugar beet	Number plants in June	20-24 m row	
	Seed potato	Harvested tubers	6-8 x 1.5 m	Middle rows of bed
	Spring barley	Number haulms in June	6 m row	2009, 2018
		Number haulms at harvest	2 m row	2013, 2014
	Winter wheat	-		
	Seed onion	Number plants in June	5 m row	2014
		Number bulbs at harvest	32 m row	2015

** Only marketable crop counted*

Appendix E – Tillage effects on marketable product

*Table E.1. Results of the ANOVA test where significant differences in yield between the tillage systems are marked with stars. '***' means P <0.001, '**' means P < 0.01, '*' means P < 0.05 and '.' means P < 0.1*

Crop	Year	Sum of squares	Mean square	F value	P value	Stars
Ware potato	2009	5.297	2.649	1.3354	0.3159	
Ware potato	2011	8.184	4.092	0.5896	0.5769	
Ware potato	2012	0.153	0.077	0.0246	0.9758	
Ware potato	2015	0.562	0.281	0.0612	0.9411	
Ware potato	2017	25.967	12.983	4.8000	0.0427	*
Ware potato	2018	52.533	26.267	2.8812	0.1142	
Grass clover	2010	0.588	0.588	3.9302	0.0607	.
Grass clover	2012	0.672	0.336	8.7006	0.0007	***
Grass clover	2013	0.636	0.318	15.9142	0.0000	***
Grass clover	2016	0.744	0.372	8.1394	0.0010	**
Grass clover	2018	0.316	0.158	9.3164	0.0004	***
Grass clover	2019	1.733	0.867	18.1218	0.0000	***
Oats	2018	2.047	1.024	13.0907	0.0030	**
Oats	2020	1.503	0.751	20.6461	0.0007	***
Oats	2021	0.897	0.449	2.6334	0.1322	
Cabbage	2011	40.074	20.037	5.4571	0.0320	*
Cabbage	2013	95.360	47.680	9.6628	0.0097	**
Cabbage	2014	22.353	11.177	0.3890	0.6899	
Cabbage	2020	325.829	162.915	18.1002	0.0011	**
Carrot	2009	409.576	204.788	4.3473	0.0527	.
Carrot	2010	374.406	187.203	4.5797	0.0472	*
Carrot	2013	894.499	447.249	27.3508	0.0003	***
Carrot	2015	52.557	26.278	0.8321	0.4696	
Carrot	2016	76.495	38.248	1.9621	0.2210	
Carrot	2019	348.050	174.025	2.6875	0.1280	
Carrot	2021	217.363	108.681	2.7675	0.1220	
Carrot	2022	6.229	3.114	0.1109	0.8964	
Pumpkin	2017	2.486	1.243	0.2153	0.8108	
Pumpkin	2019	239.916	119.958	15.7409	0.0017	**
Green bean	2022	5.412	2.706	0.8947	0.4460	
Spring wheat/faba bean	2010	1.018	1.018	29.2977	0.0029	**
Spring wheat/faba bean	2011	0.782	0.391	23.6716	0.0004	***
Spring wheat/faba bean	2014	0.534	0.267	7.4810	0.0147	*
Spring wheat	2009	0.298	0.149	3.9209	0.0650	.
Spring wheat	2012	0.441	0.220	2.0091	0.2289	
Spring wheat	2014	0.508	0.254	3.8613	0.0670	.
Spring wheat	2015	0.059	0.030	1.0002	0.4095	
Spring wheat	2016	1.783	0.891	11.6679	0.0042	**
Spring wheat	2017	3.454	1.727	6.8726	0.0183	*
Pea	2019	0.685	0.343	4.4877	0.0493	*
Pea	2022	4.985	2.493	9.1961	0.0110	*
Seed potato	2011	8.403	4.202	1.3410	0.3146	
Seed potato	2012	0.185	0.092	0.0475	0.9539	
Seed potato	2015	2.238	1.119	2.6561	0.1304	
Seed potato	2016	22.484	11.242	13.2648	0.0029	**
Seed potato	2019	26.369	13.185	1.4813	0.2836	
Seed potato	2020	1.898	0.949	0.0330	0.9677	
Sugar beet	2009	0.074	0.037	0.1085	0.8985	
Sugar beet	2012	0.679	0.339	2.5059	0.1429	
Sugar beet	2013	1.822	0.911	4.7497	0.0437	*

Crop	Year	Sum of squares	Mean square	F value	P value	Stars
Sugar beet	2016	0.005	0.003	0.0104	0.9897	
Sugar beet	2017	0.064	0.032	0.0806	0.9233	
Sugar beet	2020	15.231	7.615	68.8220	0.0000	***
Sugar beet	2021	2.737	1.369	4.0667	0.0605	.
Winter barley	2021	0.278	0.139	1.6886	0.2445	
Winter wheat	2010	0.852	0.426	4.0214	0.0618	.
Onion	2011	45.078	22.539	1.8003	0.2262	
Onion	2014	19.115	9.557	0.6958	0.5265	

Crop	Year	Sum of squares	Mean square	F value	P value	Stars
Onion	2015	1.127	0.563	0.0440	0.9572	
Onion	2018	115.523	57.761	7.1874	0.0163	*
Spring barley	2009	0.026	0.013	0.1728	0.8444	
Spring barley	2013	1.525	0.763	2.3765	0.1549	
Spring barley	2014	0.006	0.003	0.0261	0.9743	
Spring barley	2017	1.726	0.863	5.3767	0.0331	*
Spring barley	2018	0.545	0.273	3.2360	0.0934	.
Spring barley	2022	0.902	0.451	2.5298	0.1408	

Appendix F – Tillage effects on yield quality

*Table F.1. Results of the ANOVA test where significant differences in yield quality between the tillage systems are marked with stars. '***' means P <0.001, '**' means P < 0.01, '*' means P < 0.05 and '.' means P < 0.1*

Crop	Year	Sum of squares	Mean square	F value	P value	Stars
Ware potato	2009	11.0028	5.5014	1.4167	0.2974	
Ware potato	2011	28.9349	14.4674	0.5082	0.6198	
Ware potato	2012	37.3413	18.6707	0.6395	0.5525	
Ware potato	2015	3.1346	1.5673	0.1304	0.8796	
Ware potato	2017	32.0289	16.0145	2.9303	0.111	
Ware potato	2018	193.024	96.512	2.0553	0.1904	
Oats	2018	1.5934	0.7967	0.6209	0.5615	
Oats	2020	1.4799	0.7399	0.7068	0.5216	
Oats	2021	12.375	6.1875	1.2906	0.3268	
Carrot	2009	166.1364	83.0682	6.6618	0.0198	*
Carrot	2010	1.2361	0.618	0.0202	0.98	
Carrot	2013	95.7349	47.8674	6.1348	0.0243	*
Carrot	2015	2.5268	1.2634	0.0432	0.958	
Carrot	2016	111.7805	55.8903	2.1107	0.2023	
Carrot	2019	69.8137	34.9069	0.3841	0.693	
Carrot	2021	345.6713	172.8357	4.1805	0.0572	.
Carrot	2022	35.8521	17.9261	0.5738	0.5849	
Spring wheat	2016	3.2673	1.6336	4.0663	0.0605	.
Spring wheat	2017	12.858	6.429	40.5636	0.0001	***
Seed potato	2011	30.6006	15.3003	2.1881	0.1746	

Crop	Year	Sum of squares	Mean square	F value	P value	Stars
Seed potato	2012	46.4769	23.2384	1.6368	0.2536	
Seed potato	2015	59.0201	29.5101	5.3601	0.0334	*
Seed potato	2016	11.0719	5.5359	1.734	0.2368	
Seed potato	2019	79.6026	39.8013	0.8314	0.4699	
Seed potato	2020	7.5976	3.7988	0.3072	0.7438	
Sugar beet	2009	0.0107	0.0054	0.1048	0.9018	
Sugar beet	2012	0.1473	0.0737	1.2528	0.3363	
Sugar beet	2013	0.0707	0.0354	1.3928	0.3027	
Sugar beet	2016	0.0724	0.0362	1.0066	0.4074	
Sugar beet	2017	0.079	0.0395	2.2675	0.1659	
Sugar beet	2020	0.1763	0.0882	1.8474	0.219	
Sugar beet	2021	0.0259	0.013	0.3052	0.7452	
Seed onion	2011	7.0153	3.5076	1.0316	0.3994	
Seed onion	2014	0.4689	0.2345	0.2399	0.7922	
Seed onion	2015	1.0618	0.5309	1.2796	0.3295	
Seed onion	2018	50.8272	25.4136	3.1146	0.0999	.
Spring barley	2009	2.0417	1.0208	1.563	0.2673	
Spring barley	2013	8.8067	4.4033	5.1695	0.0362	*
Spring barley	2018	4.7712	2.3856	2.4705	0.146	
Spring barley	2022	0.6667	0.3333	0.6957	0.5266	

Appendix G – Organic matter with 2021 measurements

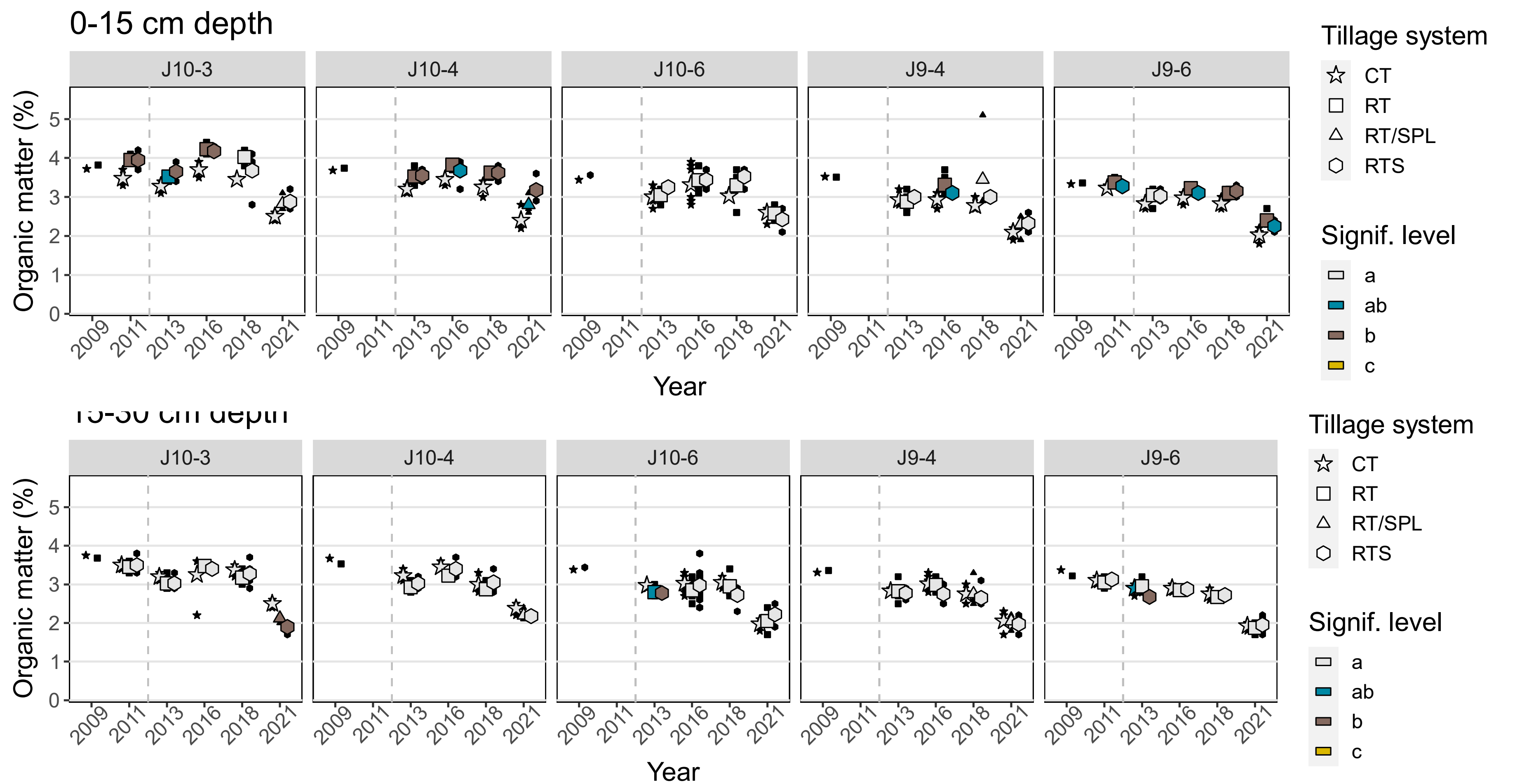

Figure G.1. Organic matter content measured in soil samples from the different experimental fields in the layers 0-15 cm and 15-30 cm. The small black markers show the separate measurement of each plot, including a 0 measurement in 2009, which was a soil sample mixed with soil from the different plots. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours. The measurements in 2009 and 2011 were done by CBLB and from 2013 on by Eurofins.

Appendix H – pH measurements

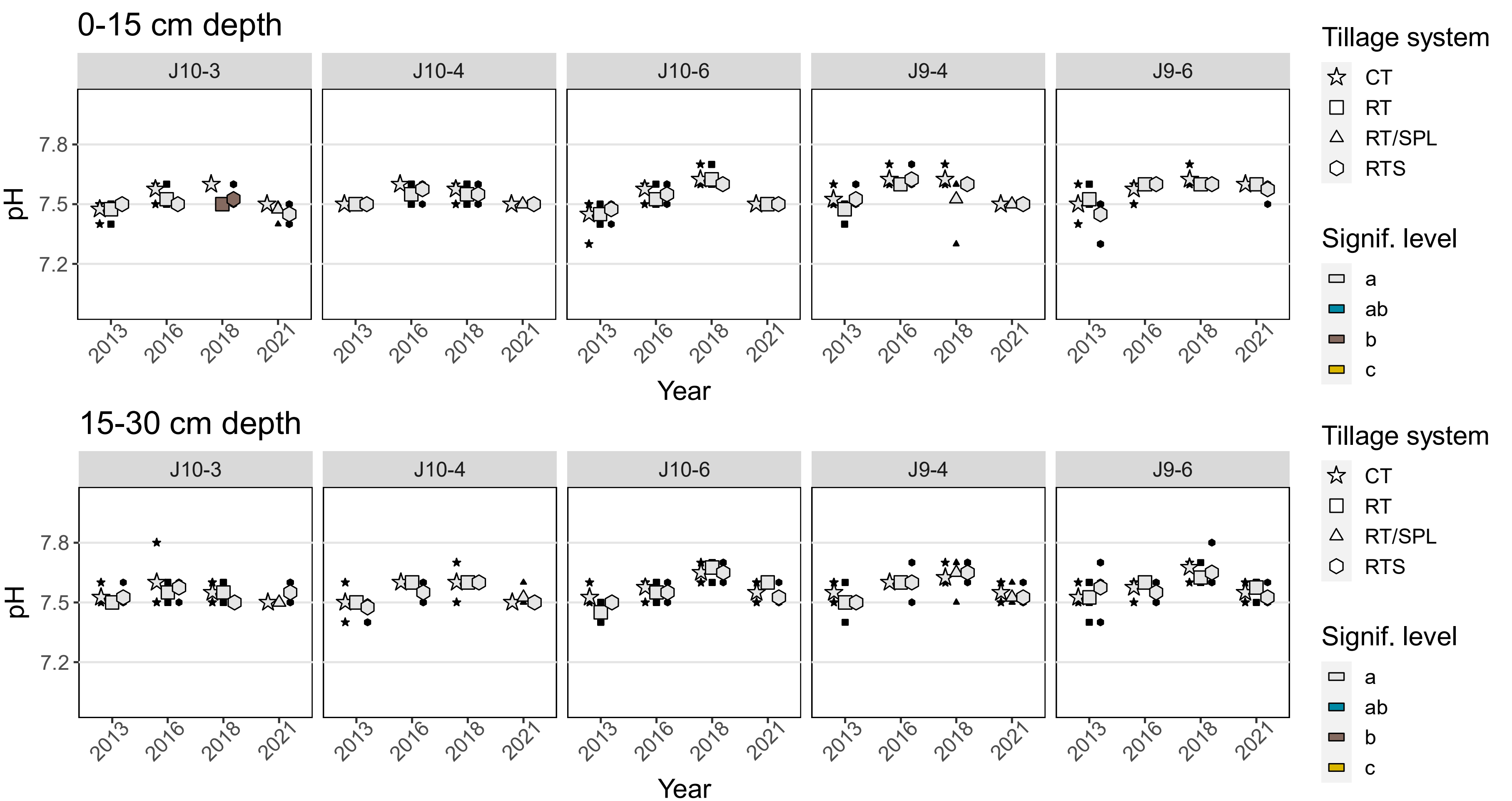

Figure H.1. Ph measured in soil samples from the different experimental fields in the layers 0-15 cm and 15-30 cm. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

Appendix I – Nutrient content of the soil

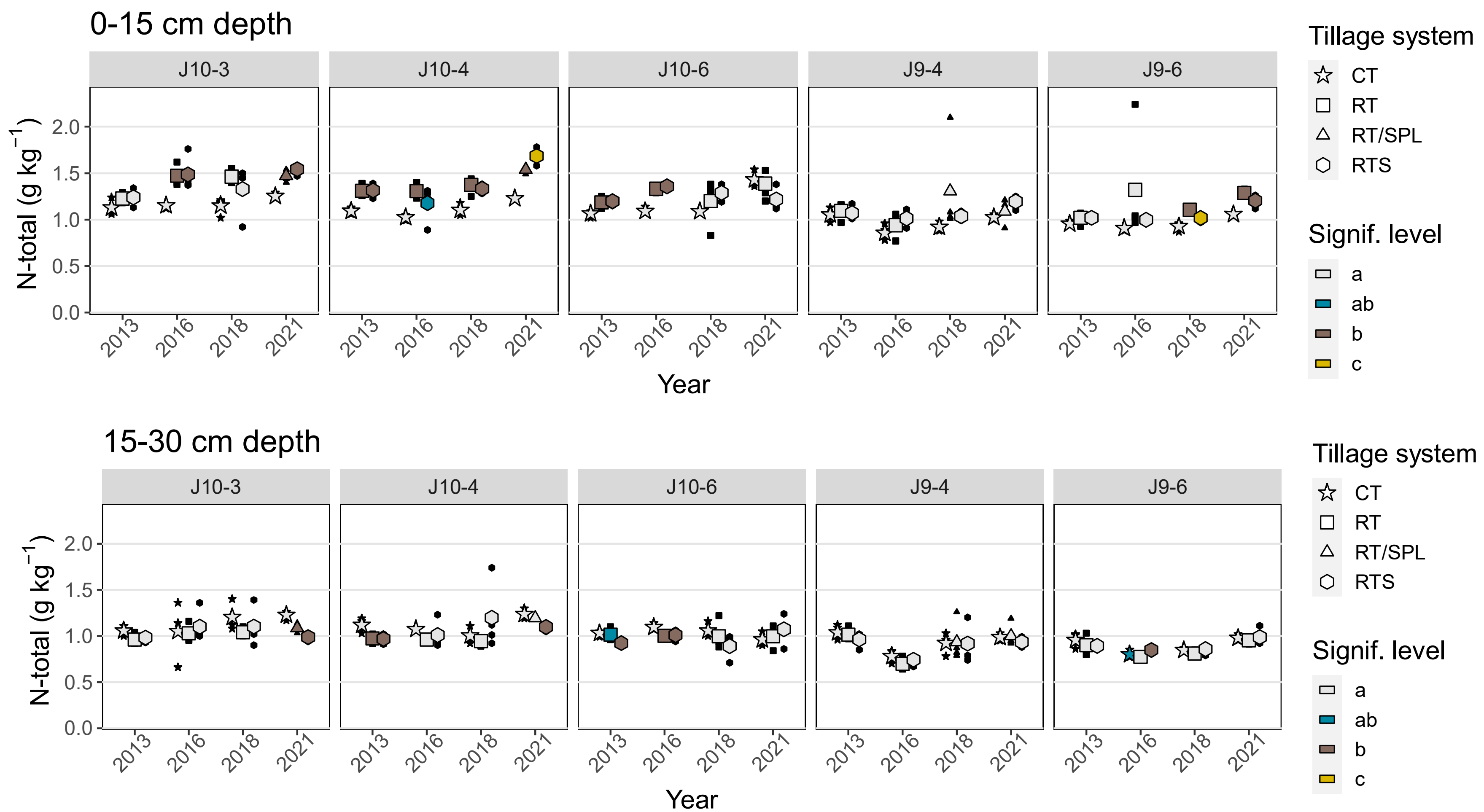

Figure I.1. N-total measured in soil samples from the different experimental fields in the layers 0-15 cm and 15-30 cm. The small black markers show the separate measurement of each plot. The bigger marker shows the estimated means over the year. Tillage systems are indicated with different shapes. Significance levels ($p < 0.05$) are indicated per year with different colours.

The following nutrient measurements in the soil did not show particular results and are therefore shown briefly below as average values over years and soil layers.

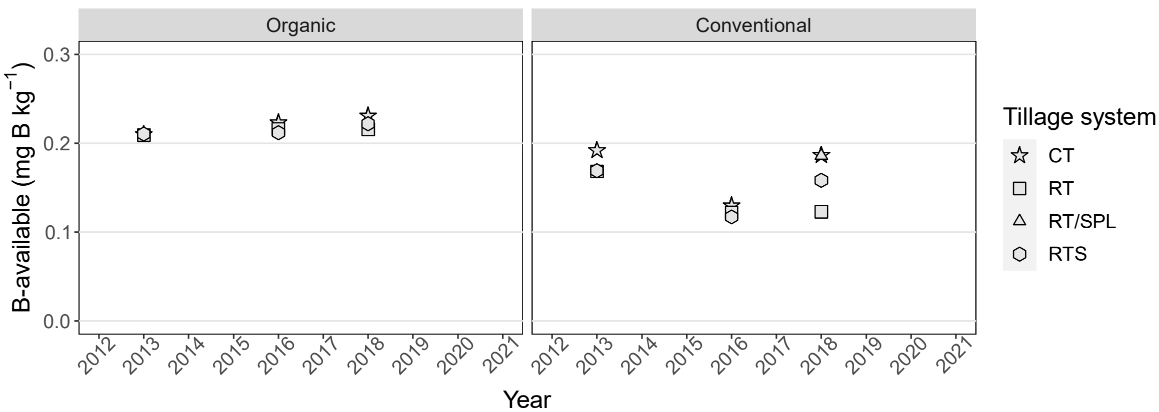

Figure I.2. Available boron measured in soil samples from the different organic (J10-3, J10-4 and J10-6) and conventional (J9-4 and J9-6) experimental fields in 0-30 cm. The marker shows the estimated means over the year. Tillage systems are indicated with different shapes.

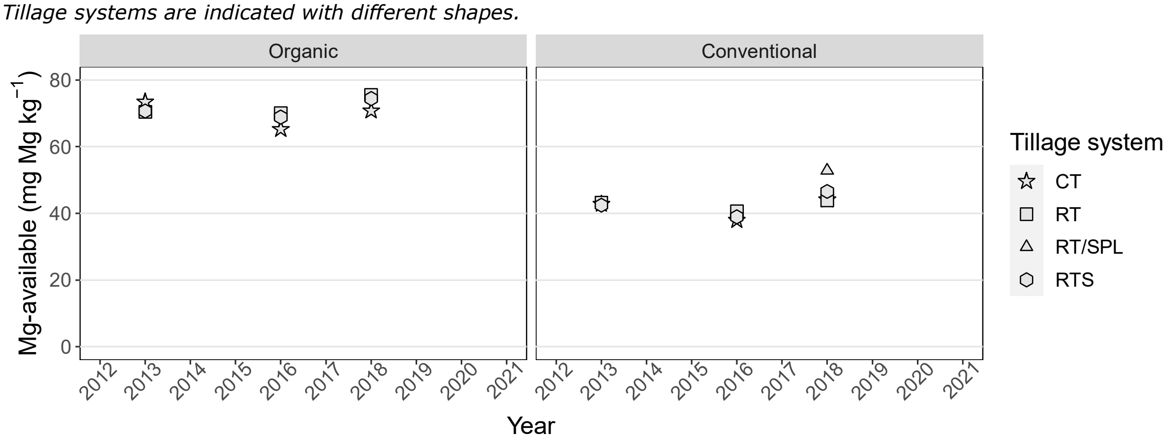

Figure I.3. Available magnesium measured in soil samples from the different organic (J10-3, J10-4 and J10-6) and conventional (J9-4 and J9-6) experimental fields in 0-30 cm. The marker shows the estimated means over the year. Tillage systems are indicated with different shapes.

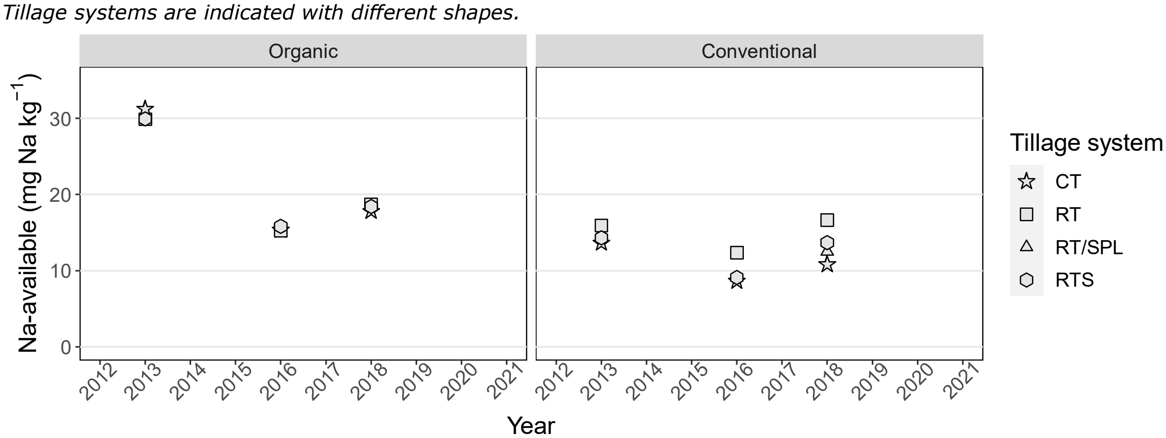

Figure I.4. Available natrium measured in soil samples from the different organic (J10-3, J10-4 and J10-6) and conventional (J9-4 and J9-6) experimental fields in 0-30 cm. The marker shows the estimated means over the year. Tillage systems are indicated with different shapes.

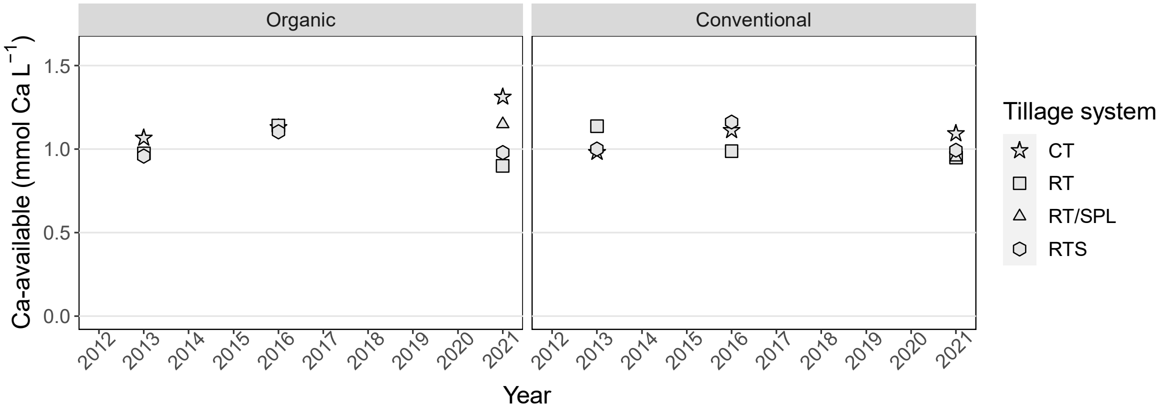

Figure I.5. Available calcium measured in soil samples from the different organic (J10-3, J10-4 and J10-6) and conventional (J9-4 and J9-6) experimental fields in 0-30 cm. The marker shows the estimated means over the year. Tillage systems are indicated with different shapes.

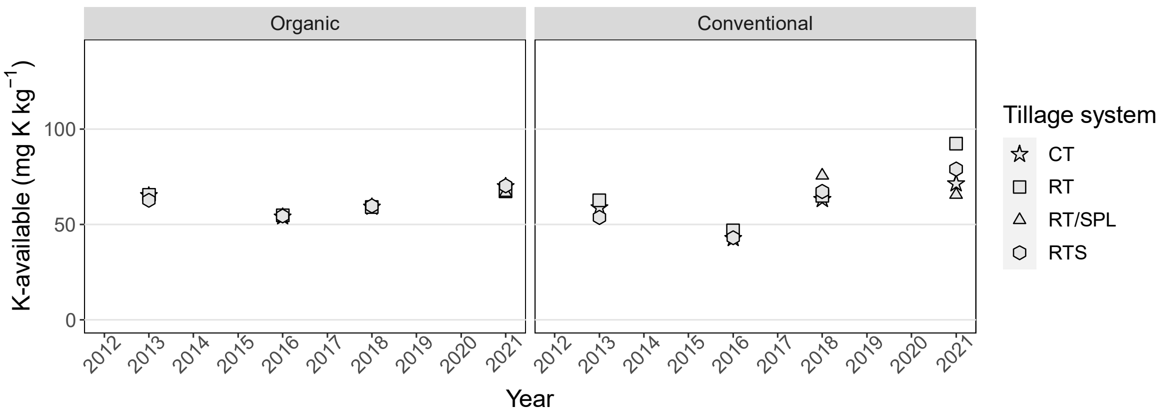

Figure I.6. Available potassium measured in soil samples from the different organic (J10-3, J10-4 and J10-6) and conventional (J9-4 and J9-6) experimental fields in 0-30 cm. The marker shows the estimated means over the year. Tillage systems are indicated with different shapes.

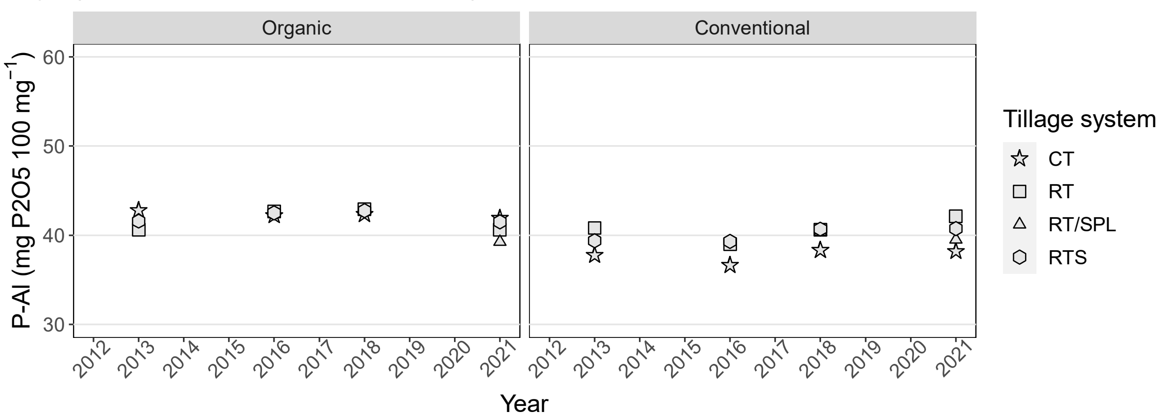

Figure I.7. P-Al values measured in soil samples from the different organic (J10-3, J10-4 and J10-6) and conventional (J9-4 and J9-6) experimental fields in 0-30 cm. The marker shows the estimated means over the year. Tillage systems are indicated with different shapes.

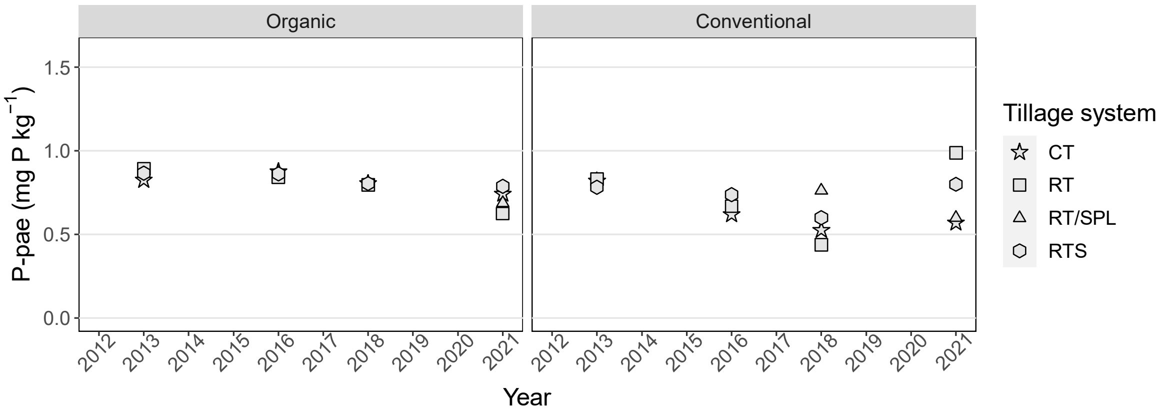

Figure I.8. P-pae values measured in soil samples from the different organic (J10-3, J10-4 and J10-6) and conventional (J9-4 and J9-6) experimental fields in 0-30 cm. The marker shows the estimated means over the year. Tillage systems are indicated with different shapes.

Appendix J – EPPO coding

Table J.1. EPPO coding and corresponding scientific and English naming of weed species observed during seedbank germination.

EPPO	SCIENTIFIC NAME	ENGLISH NAME
AGGRE	Elymus repens	Couchgrass
ATXHA	Atriplex prostrata	Halberd-leaf orache
BRSNN	Brassica napus	Coleseed
CAPBP	Capsella bursa-pastoris	Shepherd's purse
CARHI	Cardamine hirsuta	Cardamine hirsuta
CHEAL	Chenopodium album	Goosefoot
CIRAR	Cirsium arvense	Californian thistle
DICOT	Dicots	Dicots
GASPA	Galinsoga parviflora	Kew weed
LAMPU	Lamium purpureum	Purple archangel
LOLPE	Lolium perenne	English ryegrass
MATCH	Matricaria chamomilla	Wild chamomile
MOCOT	Monocots	Monocots
POAAN	Poa annua	Pathgrass
POLAV	Poa annua	Pathgrass
POLCO	Fallopia convolvulus	Bearbind
POLPE	Persicaria maculosa	Red-leg
SENVU	Senecio vulgaris	Birdseed
SOLNI	Solanum nigrum	Black nightshade
SOLTU	Solanum tuberosum	Potato
SONAR	Sonchus arvensis	Corn sowthistle
STEME	Stellaria media	Chickweed
TAROF	Taraxacum officinale	Blowball
TRFRE	Trifolium repens	White clover
X1GERG	Geranium	Geranium
X1PEDG	Petasites	Petasites
X1PLAG	Plantago	Plantago
X1RANG	Ranunculus	Ranunculus
X1UTRG	Urtica	Utica
X1VERG	Veronica	Veronica

Appendix K – Weed seedbank

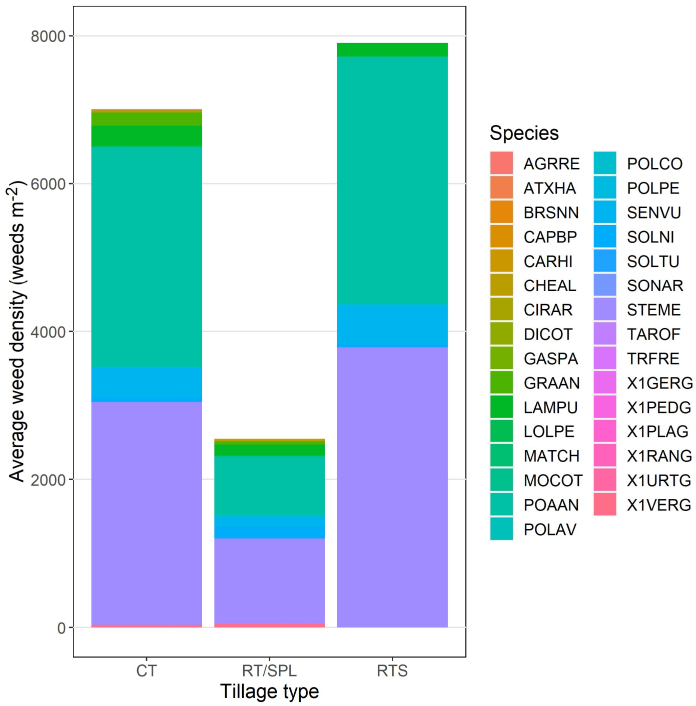

Figure K.1. Weed density at 0-10 cm depth as affected by tillage type for field J9-4 (conventional system). Tillage types: CT = conventional tillage; RT/SPL = reduced tillage/shallow ploughing; RTS = reduced tillage with subsoiling.

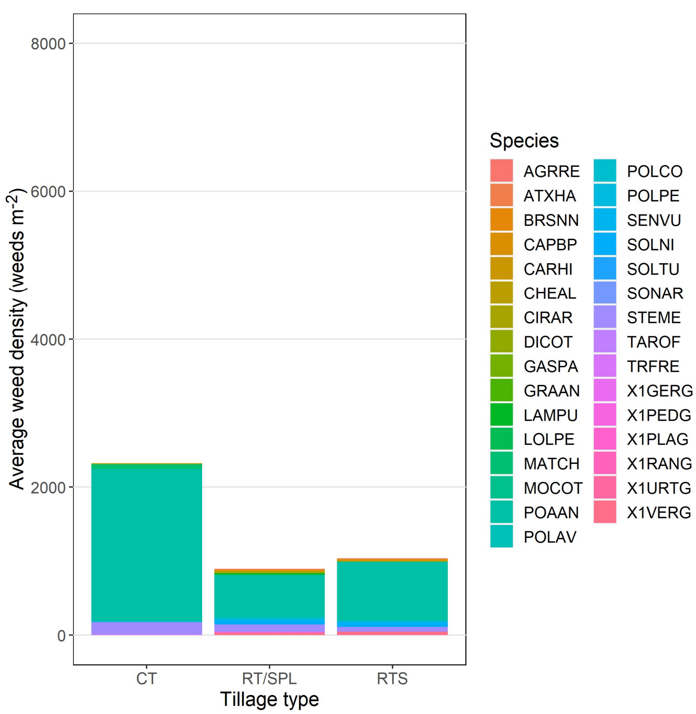

Figure K.2. Weed density at 0-10 cm depth as affected by tillage type for field J9-6 (conventional system). Tillage types: CT = conventional tillage; RT/SPL = reduced tillage; RTS = reduced tillage with subsoiling.

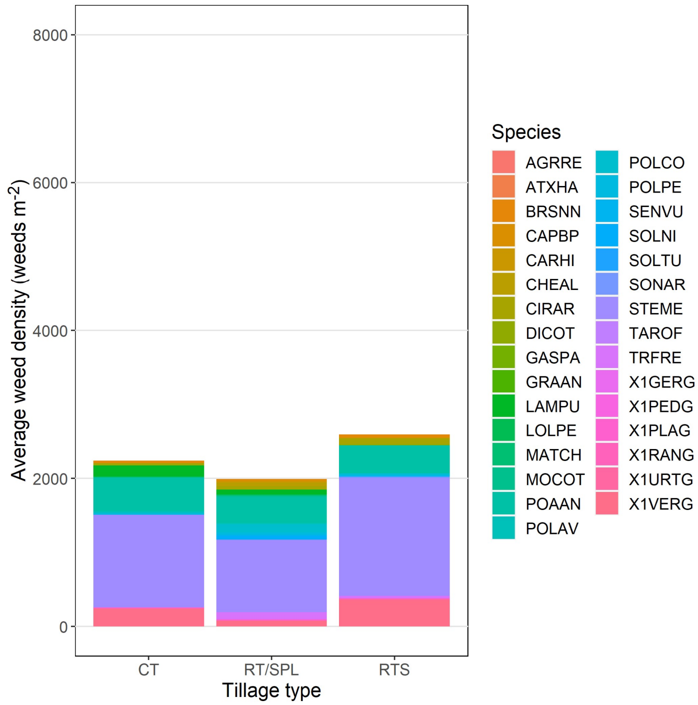

Figure K.3. Weed density at 0-10 cm depth as affected by tillage type for field J10-3 (organic system). Tillage types: CT = conventional tillage; RT/SPL = reduced tillage/shallow ploughing; RTS = reduced tillage with subsoiling.

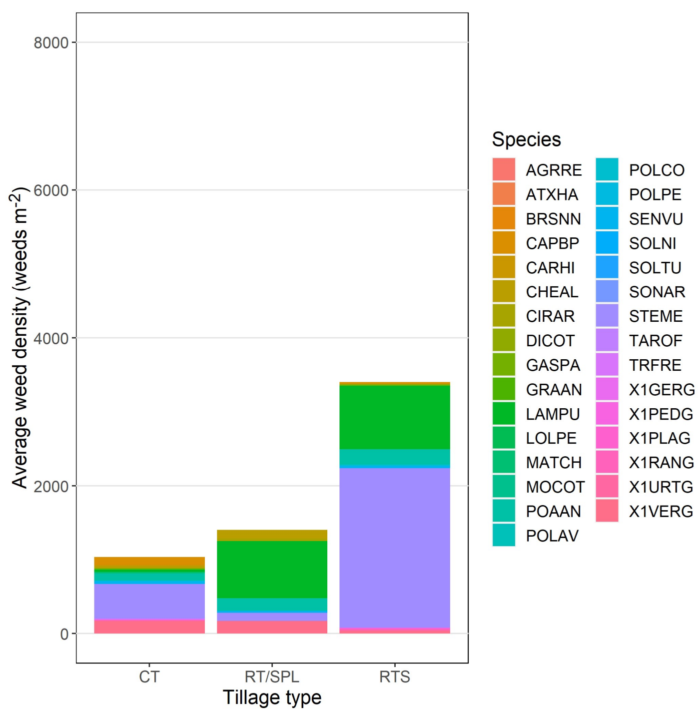

Figure K.4. Weed density at 0-10 cm depth as affected by tillage type for field J10-4 (organic system). Tillage types: CT = conventional tillage; RT/SPL = reduced tillage/shallow ploughing; RTS = reduced tillage with subsoiling.

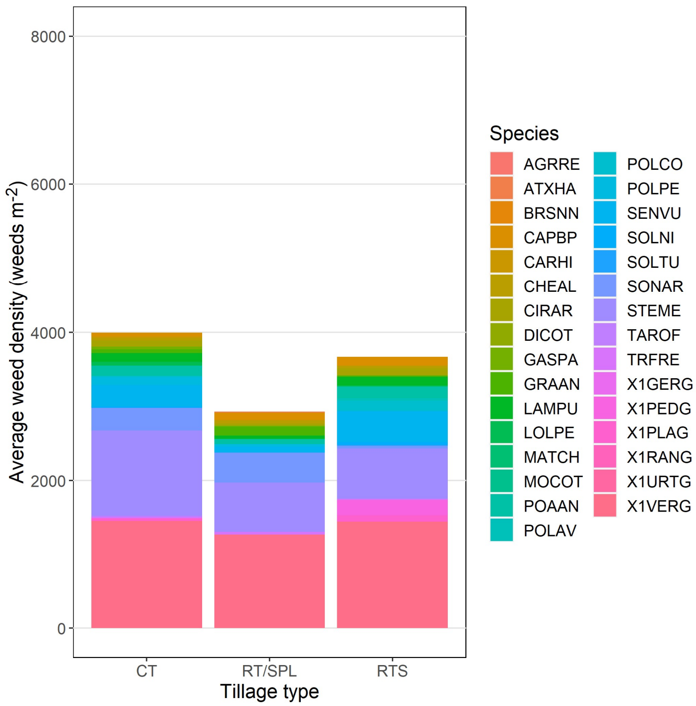

Figure K.5. Weed density at 0-10 cm depth as affected by tillage type for field J10-6 (organic system). Tillage types: CT = conventional tillage; RT/SPL = reduced tillage; RTS = reduced tillage with subsoiling.

Appendix L – Discussion

Table L.1. Score for marketable product per year of the different crops in the organic crop rotation, were tillage systems are compared. N indicates the number of years from which data on crop yield is available for a certain crop.

Crop	Year	Tillage system				N
		CT	**RT/SPL**	**RTS**	**RT**	
Ware potato	2009	1	*	2	2	
	2011	1	*	1	2	
	2012	1	*	1	1	
	2015	1	*	1	1	
	2017	1	*	2	3	
	2018	2	*	2	1	
	average	**1.2**	*****	**1.5**	**1.7**	6
Grass clover	2010	2	*	*	1	
	2012	3	*	1	1	
	2013	3	*	3	1	
	2016	3	*	2	1	
	2018	3	*	1	2	
	2019	3	*	3	1	
	average	**2.8**	*****	**2.0**	**1.2**	6
Oats	2018	3	*	1	1	
	2020	1	3	3	*	
	2021	2	*	1	2	
	average	**2.0**	**3.0**	**1.7**	**1.5**	3
Cabbage	2011	1	*	2	3	
	2013	1	*	1	3	
	2014	2	*	1	2	
	2020	1	*	3	3	
	average	**1.3**	*****	**1.8**	**2.8**	4
Carrot	2009	1	*	2	3	
	2010	1	*	2	2	
	2013	1	*	4	4	
	2015	2	*	1	1	
	2016	1	*	2	2	
	2019	1	2	3	*	
	2021	1	1	2	*	
	2022	1	*	1	1	
	average	**1.1**	**1.5**	**2.1**	**2.2**	8
Pumpkin	2017	1	*	1	1	
	2019	1	3	1	*	
	average	**1.0**	**3.0**	**1.0**	**1.0**	2
Green bean	2022	2	1	1	*	
	average	*****	*****	*****	*****	1
Spring wheat/ faba bean	2010	1	*	*	3	
	2011	3	*	1	1	
	2014	3	*	1	3	
	average	**2.3**	*****	**1.0**	**2.3**	3

Spring wheat	2009	2	*	1	1	after cabbage
	2012	3	*	1	2	
	2014	3	*	1	2	
	2015	1	*	2	2	
	2016	4	*	2	1	after carrot
	2017	1	*	4	3	
	average	**2.3**	*****	**1.8**	**1.8**	6
Weighted crop rotation average		**1.8**	**2.0**	**1.7**	**1.9**	39

Table L.2. Score for marketable product per year of the different crops in the conventional crop rotation, were tillage systems are compared. N indicates the number of years from which data on crop yield is available for a certain crop.

		Tillage system				
Crop	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Pea	2022	4	2	1	*	
	average	**3.5**	**2.0**	**1.5**	**1.0**	2
Seed potato	2011	1	*	2	2	
	2012	1	*	1	1	
	2015	1	*	1	1	
	2016	3	*	1	1	
	2019	1	1	2	*	
	2020	1	*	1	1	
	average	**1.3**	**1.0**	**1.3**	**1.2**	6
Sugar beet	2009	1	*	1	1	
	2012	1	*	1	1	
	2013	1	*	2	3	
	2016	1	*	1	1	
	2017	1	*	1	1	
	2020	1	3	3	*	
	2021	2	*	2	1	
	average	**1.1**	**3.0**	**1.6**	**1.3**	7
Winter barley	2021	2	1	1	*	
	average	*****	*****	*****	*****	
Winter wheat	2010	2	*	1	1	
	average	*****	*****	*****	*****	
Seed onion	2011	1	*	1	2	
	2014	1	*	2	2	
	2015	1	*	1	1	
	2018	1	2	3	*	
	average	**1.0**	**2.0**	**1.8**	**1.7**	4
Spring barley	2009	1	*	1	1	
	2013	2	*	3	1	
	2014	1	*	1	1	
	2017	3	*	1	2	
	2018	2	*	2	1	
	2022	1	*	2	2	
	average	**1.7**	*****	**1.7**	**1.3**	6
Weighted crop rotation average		**1.5**	**1.8**	**1.5**	**1.3**	

Table L.3. Score for yield quality per year of the different crops in the organic crop rotation, were tillage systems are compared. N indicates the number of years from which data on yield quality is available for a certain crop.

		Tillage system				
Crop	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Ware potato	2009	1	*	1	1	
	2011	1	*	1	2	
	2012	1	*	2	1	
	2015	1	*	1	1	
	2017	1	*	1	2	
	2018	2	*	2	1	
	average	**1.2**	*****	**1.3**	**1.3**	6
Oats	2018	1	*	1	1	
	2020	1	1	*	1	
	2021	1	*	2	1	
	average	**1.0**	**1.0**	**1.5**	**1.0**	3
Carrot	2009	1	*	2	3	
	2010	1	*	1	1	
	2013	1	*	3	3	
	2015	1	*	1	1	
	2016	1	*	2	2	
	2019	1	1	2	*	
	2021	1	2	3	*	
	2022	1	*	2	2	
	average	**1.0**	**1.5**	**2.0**	**2.0**	8
Spring wheat	2016	1	*	1	1	after carrot
	2017	1	*	2	2	
	average	**1.0**	*****	**1.5**	**1.5**	2
Weighted crop rotation average		**1.1**	**1.3**	**1.6**	**1.5**	

Table L.4. Score for yield quality per year of the different crops in the conventional crop rotation, were tillage systems are compared. N indicates the number of years from which data on yield quality is available for a certain crop.

		Tillage system				
Crop	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Seed potato	2011	2	*	1	1	
	2012	1	*	2	1	
	2015	1	*	2	3	
	2016	1	*	1	1	
	2019	2	1	2	*	
	2020	1	*	1	1	
	average	**1.3**	**1.0**	**1.5**	**1.4**	6
Sugar beet	2009	1	*	1	1	
	2012	1	*	1	1	
	2013	1	*	1	1	
	2016	1	*	1	1	
	2017	1	*	1	1	
	2020	1	1	1	*	
	2021	1	*	1	1	
	average	**1.0**	**1.0**	**1.0**	**1.0**	7
Onion	2011	1	*	1	1	
	2014	1	*	1	1	
	2015	1	*	1	1	
	2018	1	1	2	*	
	average	**1.0**	**1.0**	**1.3**	**1.0**	4
Spring barley	2009	1	*	1	1	
	2013	1	*	2	3	
	2018	1	*	1	1	
	2022	1	*	1	1	
	average	**1.0**	*****	**1.3**	**1.5**	4
Weighted crop rotation average		**1.1**	**1.0**	**1.2**	**1.2**	

Table L.5. Score for bulk density per year in the different fields of the organic and conventional crop rotation, in the upper 0-10 cm layer, were tillage systems are compared. N indicates the number of years from which data on bulk density is available for a certain field. Higher bulk density has a lower score.

		Tillage system				
Farming system	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
	2010	1	*	*	3	
	2016	1	*	1	1	
Conventional	**average**	**1.0**	*	**1.0**	**2.0**	2
	2015	1	*	2	1	
	average	*	*	*	*	
	2016	3	*	*	1	
	average	*	*	*	*	
	2013	1	*	*	1	
Organic	**average**	*	*	*	*	
	2013	2	*	*	1	
	2015	2	*	1	2	
	average	**2.0**	*	**1.0**	**1.5**	2
Weighted average		**1.6**	*	**1.3**	**1.4**	

Table L.6. Score for bulk density per year in the different fields of the organic and conventional crop rotation, in the lower 10-20 cm layer, were tillage systems are compared. N indicates the number of years from which data on bulk density is available for a certain field. Higher bulk density has a lower score.

		Tillage system				
Farming system	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
	2010	1	*	*	3	
	2016	1	*	1	1	
Conventional	**average**	**1.0**	*	**1.0**	**2.0**	2
	2015	1	*	1	3	
	average	*	*	*	*	
	2016	1	*	*	1	
	average	*	*	*	*	
	2013	1	*	*	3	
Organic	**average**	*	*	*	*	
	2013	1	*	*	2	
	2015	1	*	2	3	
	average	**1.0**	*	**2.0**	**2.5**	2
Weighted average		**1.0**	*	**1.3**	**2.3**	

Table L.7. Score for soil moisture per year in the different fields of the organic and conventional crop rotation, in the upper 0-10 cm layer, were tillage systems are compared. N indicates the number of years from which data on soil moisture is available for a certain field.

		Tillage system				
Farming system	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Conventional	2010	4	*	*	1	
	2016	3	*	1	2	
	average	**3.5**	*****	**1.0**	**1.5**	2
	2015	2	*	2	1	
	average	*****	*****	*****	*****	
Organic	2016	3	*	*	1	
	average	*****	*****	*****	*****	
	2013	4	*	*	1	
	average	*****	*****	*****	*****	
	2013	2	*	*	1	
	2015	2	*	1	2	
	average	**2.0**	*****	**1.0**	**1.5**	2
Weighted average		**2.9**	*****	**1.3**	**1.3**	

Table L.8. Score for soil moisture per year in the different fields of the organic and conventional crop rotation, in the lower 10-20 cm layer, were tillage systems are compared. N indicates the number of years from which data on soil moisture is available for a certain field.

		Tillage system				
Farming system	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Conventional	2010	1	*	*	1	
	2016	1	*	3	4	
	average	**1.0**	*****	**3.0**	**2.5**	2
	2015	1	*	2	3	
	average	*****	*****	*****	*****	
Organic	2016	1	*	*	3	
	average	*****	*****	*****	*****	
	2013	1	*	*	3	
	average	*****	*****	*****	*****	
	2013	1	*	*	2	
	2015	1	*	2	3	
	average	**1.0**	*****	**2.0**	**2.5**	2
Weighted average		**1.0**	*****	**2.3**	**2.7**	

Table L.9. Score for organic matter per year in the different fields of the organic and conventional crop rotation, in the upper 0-15 cm layer, were tillage systems are compared. N indicates the number of years from which data on organic matter is available for a certain field.

		Tillage system				
Farming system	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Organic	2009	1	*	*	1	
	2011	3	*	1	1	
	2013	3		1	2	
	2016	3	*	1	1	
	2018	2	*	2	1	
	average	**2.4**	*****	**1.3**	**1.2**	5
	2009	1	*	*	1	
	2013	3		1	1	
	2016	3		2	1	
	2018	3		1	1	
	average	**2.5**	*****	**1.3**	**1.0**	4
	2009	1	*	1	*	
	2013	2		1	2	
	2016	1		1	1	
	2018	3		1	2	
	average	**1.8**	*****	**1.0**	**1.7**	4
Conventional	2009	1	*	*	1	
	2013	1	*	1	1	
	2016	3	*	2	1	
	2018	2	1	2	*	
	average	**1.8**	*****	**1.7**	**1.0**	4
	2009	1	*	*	1	
	2011	3		2	1	
	2013	2		1	1	
	2016	3		2	1	
	2018	3	*	1	1	
	average	**2.4**	*****	**1.5**	**1.0**	5
Weighted average		**2.2**	*****	**1.3**	**1.2**	

Table L.10. Score for organic matter per year in the different fields of the organic and conventional crop rotation, in the lower 15-30 cm layer, were tillage systems are compared. N indicates the number of years from which data on organic matter is available for a certain field.

		Tillage system				
Farming system	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Organic	2009	1	*	*	1	
	2011	1	*	1	1	
	2013	1		2	2	
	2016	2	*	1	1	
	2018	1	*	1	2	
	average	**1.2**	*****	**1.3**	**1.4**	5
	2009	1	*	*	1	
	2013	1		2	2	
	2016	1		1	2	
	2018	1		1	1	
	average	**1.0**	*****	**1.3**	**1.5**	4
	2009	1	*	1	*	
	2013	1		2	3	
	2016	1		1	2	
	2018	1		2	1	
	average	**1.0**	*****	**1.5**	**2.0**	4
Conventional	2009	1	*	*	1	
	2013	1	*	1	1	
	2016	1	*	2	1	
	2018	1	1	1	*	
	average	**1.0**	*****	**1.3**	**1.0**	4
	2009	1	*	*	1	
	2011	1	*	1	1	
	2013	2		3	1	
	2016	1	*	1	1	
	2018	1	*	1	1	
	average	**1.2**	*****	**1.5**	**1.0**	5
Weighted average		**1.1**	*****	**1.4**	**1.4**	

Table L.11. Score for soil carbon content per year in the different fields of the organic and conventional crop rotation, in the upper 0-15 cm layer, were tillage systems are compared. N indicates the number of years from which data on carbon content of the soil is available for a certain field.

Farming system	Year	Tillage system: CT	RT/SPL	RTS	RT	N
Organic	2013	2	*	1	2	
	average	*	*	*	*	
	2013	2	*	1	1	
	average	*	*	*	*	
	2013	2		2	1	
	2016	1		2	2	
	average	**1.5**	*	**2.0**	**1.5**	2
Conventional	2013	2	*	1	1	
	2016	3	*	*	1	
	average	**2.5**	*	**1.0**	**1.0**	2
	2013	2		1	1	
	average	*	*	*	*	
Weighted average		**2.0**	*	**1.3**	**1.3**	

Table L.12. Score for soil carbon content per year in the different fields of the organic and conventional crop rotation, in the upper 15-30 cm layer, were tillage systems are compared. N indicates the number of years from which data on carbon content of the soil is available for a certain field.

Farming system	Year	Tillage system: CT	RT/SPL	RTS	RT	N
Organic	2013	1		2	2	
	average	*	*	*	*	
	2013	1		2	2	
	average	*	*	*	*	
	2013	1		1	1	
	2016	2		1	1	
	average	**1.5**	*	**1.0**	**1.0**	2
Conventional	2013	1	*	1	1	
	2016	1	*	*	1	
	average	**1.0**	*	**1.0**	**1.0**	2
	2013	1		1	1	
	average	*	*	*	*	
Weighted average		**1.1**	*	**1.3**	**1.3**	

Table L.13. Score for total nitrogen content of the soil per year in the different fields of the organic and conventional crop rotation, in the 0-30 cm layer, were tillage systems are compared. N indicates the number of years from which data on nitrogen content of the soil is available for a certain field.

		Tillage system				
Farming system	**Year**	**CT**	**RT/SPL**	**RTS**	**RT**	**N**
Organic	2013	1	*	1	1	
	2016	3	*	2	1	
	2018	2	*	2	1	
	2021	1	1	1	*	
	average	**1.8**	**1.0**	**1.5**	**1.0**	4
	2013	2	*	2	1	
	2016	3	*	2	2	
	2018	3	*	1	2	
	2021	3	*	1	1	
	average	**2.8**	*	**1.5**	**1.5**	4
	2013	2	*	2	1	
	2016	3	*	1	1	
	2018	1	*	1	2	
	2021	1	*	2	1	
	2017.0	**1.8**	*	**1.5**	**1.3**	4
Conventional	2013	1	*	1	1	
	2016	2	*	1	2	
	2018	2	1	2	*	
	2021	3	2	1	*	
	average	**2.0**	**1.5**	**1.3**	**1.5**	4
	2013	1	*	1	1	
	2016	3	*	2	1	
	2018	3	*	2	1	
	2021	3	*	1	1	
	average	**2.5**	*	**1.5**	**1.0**	4
Weighted average		**2.2**	**1.3**	**1.5**	**1.2**	

Appendix M – Management experiences

During the seasons, the research team was in close contact with the farm manager Joost Rijk. Although the research team was often found in the field, Joost was the daily manager of the crops. We asked him a few questions about what he learned on the job about reduced tillage in the different crops.

Joost has a farmers background, as he grew up on an organic farm and still works there. Immediately after his study Organic Agriculture in 2013, he started as farm manager of the organic part of the research farm in Lelystad. BASIS had been going for four years at that time. According to Joost, BASIS is an interesting large-scale designed research. Due to the large scale, it was possible to generate and analyze a lot of data. It also facilitated the two production systems within the research, a conventional part and an organic part. So, we could make conclusions on both systems. The downside of the scale is that flaws in the design could not easily be modified. Which is why we sometimes run into inconveniences on the fields.

The main challenges, positive aspects and important lessons in the cultivation of crops in a reduced tillage systems according to Joost, can be found in the tables below. Table M.1. shows the remarks concerning crops in the conventional crop rotation and Table M.2. crops in the organic crop rotation.

Table M.1. Main challenges, positive aspects and important lessons in management practices of reduced tillage fields with and without subsoiling (RT and RTS) in the conventional crop rotation as mentioned by BASIS farm manager Joost Rijk.

Crop	**Main challenges**	**Positive aspects**	**Important lessons**
Potato	Cutting down green manure without making the soil coarse (by large residue of green manure) where the potatoes will be planted, and avoiding formation of large clods.	Improved bearing capacity and water holding capacity of the field and better drought resilient.	The soils needs to be prepared relatively fine in spring, otherwise the planting bed is too coarse to plant potatoes in a dry spring.
Sugar beet	-	Improved bearing capacity and water holding capacity of the field and better drought resilient.	One of the crops that can be surprisingly easily cultivated in a reduced tillage system, especially in the conventional rotation.
Spring barley + winter barley + winter wheat	Suppression of weeds.	Better drought resilient.	Cultivation goes well.
Seed onion	Suppression of weeds, crop emergence and infestation.	Improved bearing capacity of the soil.	Fine seedbed preparation without coarse green manure residue is important for sowing of onions.
Pea	Suppression of weeds.	Improved bearing capacity of the soil.	-

Table M.2. Main challenges, positive aspects and important lessons in management practices of reduced tillage fields with and without subsoiling (RT and RTS) in the organic crop rotation as mentioned by BASIS farm manager Joost Rijk.

Crop	Main challenges	Positive aspects	Important lessons
Potato	Cutting down green manure without making the soil coarse (by large remains of green manure) where the potatoes will be planted, and avoiding formation of large clods.	Improved bearing capacity and water holding capacity of the field and better drought resilient.	The soils needs to be prepared relatively fine in spring, otherwise the planting bed is too coarse to plant potatoes in a dry spring.
Grass clover	-	Improved bearing capacity of the soil.	-
Cabbage	Suppression of weeds and removal of grass clover (pre-crop).	Improved bearing capacity of the soil and better drought resilient.	Grass clover stubble needs to be fully removed before planting cabbage.
Spring wheat + oats + spring wheat/faba bean	Suppression of weeds.	Better drought resilient.	Cultivation goes well.
Carrot	Suppression of weeds, crop emergence and amount of product tare.	Improved bearing capacity of the soil.	Fine seedbed preparation without coarse green manure remnants is important for sowing of carrots.
Pumpkin	-	Improved carrying capacity of the soil.	-
Green bean	-	-	-

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