A case study on the efficacy of regenerative agriculture

A comparative study in the Hoekse Waard, the Netherlands

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Dit rapport beschrijft de resultaten van een driejarige vergelijkende studie over regeneratieve landbouw en bevat een synthese met de uitkomsten van twee eerdere studies. Het doel van het project is het vergelijken van regeneratieve en conventionele landbouw in theorie en praktijk in een Nederlandse context. Dit rapport is het laatste in een serie van drie en beschrijft de uitgevoerde metingen, de interpretatie daarvan en de synthese van de resultaten van de drie rapporten. In het eerste rapport is onderzocht welke regeneratieve maatregelen worden toegepast en wat het potentiële en het daadwerkelijke voordeel van regeneratieve landbouw is voor het behoud en de opslag van koolstof in landbouwgronden in Nederland. In het tweede rapport zijn de effecten beschreven van verschillende regeneratieve maatregelen, die met behulp van simulaties met een bodem-watermodel zijn gekwantificeerd; de beschikbaarheid van water, afspoeling over het maaiveld en afwatering naar kanalen.

This report describes the results of the fieldwork and the interpretation for a 3-year project on regenerative agriculture. It also includes a paragraph with the synthesis of the first two reports. The goal of the project is to compare which regenerative and conventional agriculture in theory and practice in a Dutch context. This report is the latest in a series of three and describes the measurements carried out, their interpretation and the synthesis of the results of the three reports. The first report investigated which regenerative practices are applied and what the potential and actual benefit of regenerative agriculture is with regard to the preservation and storage of carbon in agricultural land in the Netherlands. The second report describes the effects of various regenerative measures, which have been quantified using simulations with a soil-water model. Described are the availability of water, surface runoff and drainage to canals.

Keywords: soil carbon, on-farm case study, regenerative agriculture, conventional agriculture, production.

The pdf file is free of charge and can be downloaded at https://doi.org/10.18174/641804 or via the website www.wur.nl/environmental-research (scroll down to Publications – Wageningen Environmental Research reports). Wageningen Environmental Research does not deliver printed versions of the Wageningen Environmental Research reports.

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Wageningen Environmental Research (WENR) values the quality of our end products greatly. A review of the reports on scientific quality by a reviewer is a standard part of our quality policy.

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name: Simone Verzandvoort

date: November 2023

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name: Mirjam Hack

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Preface

Soil carbon sequestration and regenerative agriculture have become household terms in discussions and research activities on soil, soil policy, agriculture and climate adaptation and mitigation in recent years, internationally and in the Netherlands. This has intensified in the context of the national debate in the Netherlands on adapting farming practices with the aims to improve soil health, reduce carbon emissions and increase sequestration, and to preserve and improve biodiversity.

In this context, the Soil Heroes Foundation was founded in 2017 from the firm belief that (re-)building soils through the practices of regenerative agriculture (regenerative agriculture) is a principal solution for the current degradation of agricultural soils all over the world and that the transition to regenerative (organic) farming practices will structurally sustain and improve the world’s capacity to provide healthy, nutritious and tasty food for a growing world population. Part of this belief is that regenerative farming also provides answers to climate change and to biodiversity and nature loss, resulting from an agricultural system that is broken.
Soil Heroes has been initiated by farmers, for farmers. The initiative is based on first-hand experiences with the transition to regenerative practices and the observation of the results (improved soil health and soil structure, increased organic matter content and soil biology, less artificial inputs and pesticides, higher resilience and mitigation against extreme weather conditions, higher (quality) yields) and driven by the need to create a large-scale change in the way the world is farming.
A detailed description of Soil Heroes’ interpretation of regenerative agriculture in the Netherlands is given in Soil Heroes, 2022.

Summary

Regenerative agriculture is a hot topic in the scientific world. The term regenerative agriculture is a generic term which is used differently depending on the country it is applied in and overlaps with various other terms such as organic agriculture, circular agriculture, permaculture.

This study is carried out at a farm in the Hoeksche Waard (The Netherlands). All fields are classified as being sandy clay soils and more than 75% of the crops in rotation are onion, potato, wheat and brown bean. Crop rotation is taking place at all fields. Wheat and potatoes are the most dominant crops. Besides wheat and potatoes, sugar beet, vegetable, onions, legume crops and grass seed are grown.
In the Hoeksche Waard, Netherlands, a farm has had several fields under long term regenerative management (since 2010), with some fields still in the process of being transformed (since 2015) and fields still under conventional agriculture.
At the plots with regenerative agriculture:
- Minimum tillage is applied.
- Crop residues are left and mulched into the soil;
- Cover crop is usually sown after wheat and legumes;
- Compost and solid cow manure are used as organic carbon input.

In the fields under conventional management:
- Ploughing is applied;
- Crop residues are left and mulched into the soil;
- Cover crops are sown but not after all crops;
- Slurry pig manure is used.

On the farm, management under regenerative and conventional agriculture is compared. Three different reports are written in this project:
- Carbon report (Heesmans et al, 2023)
  The focus of this report is on long term storage of organic carbon in the soil. It consists of a literature review on the effects of regenerative agriculture and a simulation on the effect of the three different management strategies on carbon sequestration.
- Report on simulation of crop growth and water holding capacity (Dik et al., 2022)
  This report describes the analysis of the water availability for crops and the change of runoff and drainage fluxes to canals. Fields of both regenerative and conventional agriculture are studied. The simulation model SWAP (Kroes et al., 2017) is used to analyze the soil water dynamics.
- This report with a focus on the measurements made and the effects of regenerative agriculture.

Carbon report (Heesmans et al, 2023)
The focus of this report is on long-term storage of organic carbon in the soil. The report consists of three parts.

Firstly, the effects of several management practices used in regenerative agriculture on organic carbon (OC) in Europe are described in the report according to literature. The selected management practices were expected to have an impact on soil organic carbon. The effects of the management practices on soil organic carbon are:
- minimum tillage increases the soil organic carbon content between 1 - 21% in the topsoil throughout Europe;
- organic fertilizer application had both positive and negative effects on soil organic carbon content when looking at indicators such as soil quality, climate change and productivity, but additions of farm yard manure amendments and cattle slurry significantly increased SOC by respectively 21% and 19%;
- crop management such as improved crop rotation and cover crops add far less carbon to the soil over 20 years (0.01-0.04% SOC);
- biodiverse grassland, which is grassland with herbs, accumulates carbon much faster than other types of permanent grassland.

Secondly, the report presents the results of field data on soil organic carbon, collected between 2019 and 2020.

Thirdly, the effect of the three different management strategies (CA, LT and ST) on carbon sequestration on the farm was analysed using modelling with the multi-pool deterministic C model RothC. The carbon balance was most positive on the fields that are under regenerative agriculture. These fields also received the highest amounts of C input. Regenerative agriculture brings more organic carbon to the soil compared to the conventional agricultural regime.

Report on simulation of crop growth and water holding capacity (Dik et al., 2022)
This report describes the water availability for crops and the change of runoff and drainage fluxes to canals. For the farmers water availability is of major importance to the development of the crop. The water board requires information on runoff and drainage fluxes to the canals for the water management in the area.

Fields with regenerative and conventional agriculture were studied. The simulation model SWAP (Kroes et al., 2017) was used to determine the effect of several practices in regenerative agriculture on the soil water dynamics. Collected data on soil properties and water contents were used to parameterize and calibrate the model. The practices and aspects of the soil water dynamics are shown in Table 1, together with the results of the scenario-analysis: in Table 2 the 5 point scale is presented.

Table 1 *Effects of measures on Transpiration and Runoff/Drainage (in reference to a situation without measure). Legend for effects in Table 2.*

Measure	Effect on Transpiration	Effect on Runoff	Effect on Drainage
Extra organic matter	+	+[1] ?	0/+[1] ?
Enlarged rooting depth by less soil compaction	++	0[2]	0/+[2]
Higher infiltration capacity	0	0/+[2]	0
Increased permeability (till 80 cm-ss)	0	0	0
Lower bulk density	-/+ ?	0 ?	0/+ ?

? uncertain: due to uncertainties in the method.
[1] not calculated.
[2] dependent on the soil.

Table 2 *Quantification to a 5 points scale of the effect on Transpiration and Runoff/Drainage.*

Classification	Effect on Transpiration (mm/y)	Effect on Runoff (mm/d)	Effect on Drainage (mm/d)
++	> 15	<-5	<-5
+	5 till 15	-5 till -2	-5 till -2
0	-5 till 5	-2 till 2	-2 till 2
-	-15 till -5	2 till 5	2 till 5
--	<-15	> 5	> 5

For transpiration (linked to the yield) the most sensitive parameter is the rooting depth. The rooting depth depends on soil compaction, the presence of macropores and the presence of fungi. Fungi can help crops to get more water: they increase the depth to which the roots can extract water. Regenerative agriculture influences all these dependencies in a positive way.

For runoff the most sensitive parameters are soil texture and structure, and as a result of that the infiltration capacity. The simulations show a low runoff in the reference situation. As a result, the decrease of runoff at higher infiltration capacities is also low. For drainage fluxes to the canals, the scenarios show a varied outcome. There can be a positive effect due to regenerative agriculture, but it depends on the circumstances (wet or dry soil).

Overall, according to the model study, extra organic matter, enlarged rooting depth, less soil compaction, higher infiltration capacity, and increased permeability will have a neutral or positive effect on transpiration, runoff and drainage. All the effects of regenerative agriculture are predicted to occur at the same time. So overall, it is expected that regenerative agriculture will have positive effects on 1) water availability for the crops and 2) reduction of runoff and drainage fluxes to the canals.

A case study on the efficacy of regenerative agricultura (This report)
An overview of the results on the determinations of soil properties in the farm is given in this chapter. The soil characteristics are valued on a five point scale. The interpretation of scores to effects of agricultural management is explained in Table 3. The scores are relative to the CA-management (and therefore this management is scored with solely the "="-indicator).

Table 3 *Legend for the assessment of soil characteristics (the symbol "?" means that a statistical test could not be performed or the results of the statistical test were ambiguous).*

Class	Effect of management relative to the reference management CA
	Positive
	Slightly positive
=	Inconclusive
	Slightly negative
	Negative
?	Unclear

In Table 4 the scores of the assessment of the soil characteristics are given.

Table 4 *Assessment of the soil characteristics.*

Characteristic	CA Reference	LT Long term	ST Short term
Lab measurements			
Bulk density	=	**?**	**?**
Water holding capacity	=	**?**	**?**
Soil organic matter (LOI)	=		=
Acidity	=	=	=
Nitrogen	=	=	=
Potassium	=		
Phosphate	=	=	
Carbon	=		=
Aggregate stability	=		=
Soil compaction	=	**?**	=
Qualitative observations			
Soil structure	=		**?**
Water holding capacity	=		**?**
Crop yield and quality	=		**?**
Workability	=		**?**
Soil life	=		**?**

For nitrogen there is an increase from 2019 to 2022 of 0.3 g/kg. But on the other hand, the Nmin concentration is significantly lower for the LT management than for the than the ST-management. Therefore, a score of indifferent "=" is chosen.

Overall the results of the field campaign shows that fields with long term regenerative agricultural management have a higher mean SOM content than fields with conventional management. For the long term regenerative management, soil organic matter content (LOI and organic carbon) and aggregate stability are higher in 2022 compared to 2019. For the short term regenerative management the effects are less pronounced. Probably it takes time for a field to pick the fruits of regenerative practices.

The measurements on soil compaction show that the soil compaction depth, where the mean penetration resistance surpasses 3 MPa, is largest for LT at around 50 cm, whereas it lies around 40 cm for both CA and ST. There is no trend over the years, so probably this is a result of other factors. Therefore we concluded that it is unclear what the effect of management is. It is known that soil compaction of deeper layers (>40 cm-sl) is very hard to recuperate (Brus and van den Akker, 2018).

Another positive effect is the high potassium concentration at the ST and LT field.

There are found no differences for the parameters acidity, nitrogen and soil compaction. For phosphate a slightly negative score was found for the short term regenerative management.

For the parameters bulk density and water holding capacity only one location per management type was selected. Therefore it is not possible to perform statistical significance tests on differences in mean WHC between CA, LT. Increasing the number of samples would probably help to determine the influence of these parameters. But these lab analysis are costly.

The qualitative field observations for the LT-field are scored as slightly positive, except for the workability. Chosen is for "slightly" because it concerns not a measurement but an experience of the farmer.
The qualitative observations of the farmer are a valuable source of information on what regenerative agriculture can do in practice. The farmer mentioned that the fields under regenerative agriculture had a better soil structure, a higher water holding capacity but a decreased workability. He also mentioned an improved soil life. Measurements on soil life were not taken, so these observations cannot be verified with measurements. The farmer also mentioned high(er) yields and crops of better quality. He also mentioned that for the long term regenerative fields the workability of the soil was less.

Synthesis: "A case study on the efficacy of regenerative agriculture" with the Carbon report and the WHC simulation report
Two research questions were formulated in this study, we will answer these questions in the synthesis of the project results as described in the three reports.

<u>Does regenerative agriculture change the soil and water properties?</u>
Overall, the results of the measurements presented in this report show that soil organic matter content (as determined by LOI, chapter 4, and Corg paragraph 6.3.5) is higher in the LT-field than in the other fields. This is in line with the Carbon report (Heesmans et al, 2023), where it is concluded that regenerative practices (minimal tillage, additions of farm yard manure and cattle slurry) work out positively on the carbon stock in the soil.

The qualitative observations of the farmer are a valuable source of what regenerative agriculture can do in practice. The farmer mentioned that he had a better soil structure, a higher water holding capacity but a decreased workability on the fields under regenerative agricultural management. He also mentioned an improved soil life. Measurements on soil life were not taken, so these observations cannot be verified with measurements. The farmer also mentioned high(er) yields and crops of better quality. He also mentioned that for the long term regenerative fields the workability of the soil was less.

The long term regenerative agriculture shows more aggregate stability in 2022 in comparison to 2019.

Differences could not be found between fields under conventional and regenerative agricultural management for soil compaction and the parameters acidity and nitrogen. It is known that recuperation of soil compaction of deeper layers is very difficult to realize. For phosphate a slightly negative score was found for the short term regenerative management. These aspects are not subject in the Carbon and WHC report, so these cannot be verified with these reports.

Does regenerative agriculture increase the water availability for crops in comparison to conventional agriculture?
The report on the simulation of crop growth states that the effective rooting depth depends on soil compaction, the presence of macropores and the presence of fungi. Fungi can help crops to get more water by increasing the depth to which the roots can extract water. This higher water availability is in line with this study where the qualitative field observations state that at the long term regenerative fields there is almost no irrigation required.

So overall the conclusions of the Carbon report (Heesmans et al, 2023), the Report on simulation of crop growth and water holding capacity (Dik et al., 2022) and this report are pointing in the same direction: the results show that the measures of regenerative agriculture can increase the soil organic matter content, can result in a better soil structure (more aggregate stability) resulting in as the farmer observes high(er) yields, crops of better quality and better water availability (less irrigation is required), but also a worse workability of the soil.

1 Introduction

1.1 A comparative study to demonstrate effects of regenerative agriculture

In order to substantiate the framework of thinking, processes and models behind regenerative agriculture, a monitoring program of soil quality parameters was designed and started on a farm in Zuid-Holland, The Netherlands. As of 2018 farm in the municipality of Hoeksche Waard has been set up as a farm to showcase regenerative farming (referred to as Regenerative agriculture from this point forward). On the farm, management under regenerative and conventional agriculture is compared.
Three different reports are written in this project:

- Carbon report (Heesmans et al, 2023)
  The focus of this report is on long term storage of organic carbon in the soil. It consists of a literature review on the effects of regenerative agriculture and a simulation on the effect of the three different management strategies on carbon sequestration.
- Report on simulation of crop growth and water holding capacity (Dik et al., 2022)
  This report describes the analysis of the water availability for crops and the change of runoff and drainage fluxes to canals. Fields of both regenerative and conventional agriculture are studied. The simulation model SWAP (Kroes et al., 2017) is used to analyze the soil water dynamics.
- This report.

In order to substantiate the effects of Regenerative agriculture, a monitoring program of soil quality parameters was designed.

The fields at the farm are in various stages of transition from conventional to regenerative farming, which allows a comparison between those approaches. Some fields have been under regenerative agriculture since 2010, while other fields were transformed to regenerative agriculture since 2015. Some fields are still under conventional practices. This variety of stages of transition allows an ideal set-up for a comparative study.

The comparative study has been set up by WENR to monitor and analyse data through indicators which relate to soil health. During three years after the start of the study in 2019, chemical and physical parameters were monitored on fields managed with either regenerative or conventional practices (carbon content, water content, soil structure, etc.). Also biodiversity was intended to be monitored, but project limitations restricted this.

1.2 Objective and research questions

The objective of the analysis of the results of the field campaign is to compare the effects of regenerative agriculture and conventional agriculture on soil physical and chemical properties.

The following questions were formulated to structure the research:

- Does regenerative agriculture change the soil and water properties?
- Does regenerative agriculture increase the water availability for crops in comparison to conventional agriculture?

1.3 The BLN indicator set is used as framework

The Soil Indicators for Agricultural Land in the Netherlands (BLN) is used as the framework for the field campaign in this study. The BLN is a scientifically-based indicator set for determining the quality of Dutch agricultural soils integrally (physically, chemically, biologically and visually) for the National Agricultural Soils Program.

The BLN, version 1.0, was delivered in 2019 by van den Elsen et al. (2019). A limited update has taken place in version 1.1 (de Haan et al., 2021). A larger update to arrive at a better founded assessment framework, version 2.0, is described in Ros et al. (2023). This new approach will be developed in more detail in the coming years.

At the start of the Soil Heroes project in 2019, the project set-up was based on BLN 1.0. The categories used in the BLN 1.0 system were also the base for the chapters in this report:

- Soil description (chapter 3);
- Soil organic matter (chapter 4);
- Soil physics (chapter 5);
- Soil chemistry (chapter 6);
- Qualitative field observations (chapter 7);
- A discussion on the results (chapter 8);
- Chapter 9 gives a summary of the results, conclusions and recommendations. It also gives a synthesis of the results of this report and the former two reports of this project: carbon report (Heesmans, 2023), report on the water holding capacity (Dik, 2022).

2 Field campaign

2.1 Study area

This study is carried out at an arable farm in the municipality of the Hoeksche Waard (The Netherlands), located in the southern part of the province of Zuid-Holland Figure 2-1). The agricultural fields in the area have an organic matter content that ranges between 1.6 and 1.9% and a clay percentage of about 21 to 25%. The pH of the soils is around 7.4. The lowest level of the groundwater table is between 1.5 and 1.8 m depth and the highest level is between 1.6 and 1.3 m depth in the area.

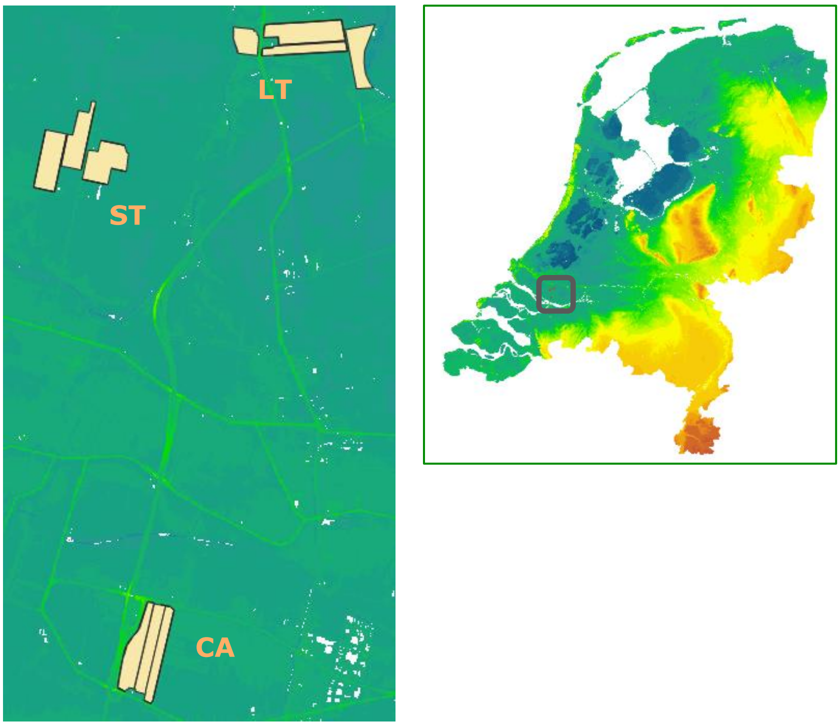

Figure 2-1 *Locations of the fields. CA: fields under conventional agricultural management, ST and LT: fields under resp. short-term and long-term regenerative agricultural management. Background: elevation model of the Netherlands. Source: www.ahn.nl.*

2.2 Management

Crop rotation is taking place with wheat and potatoes as the most dominant crops, besides sugar beet, vegetables, onions, legume crops and grass seed. Heesmans et al, 2023 (chapter 5) give an elaborative description on the fields characteristics and the crop rotation.

At the plots with regenerative agriculture (ST and LT):
- Minimum tillage is applied;
- Crop residues are left and mulched into the soil;
- Cover crop is usually sown after wheat and legumes;
- Compost and solid cow manure are used as organic carbon input.

In the fields under conventional management (CA):
- Ploughing is applied;
- Crop residues are left and mulched into the soil;
- Cover crops are sown but not after all crops;
- Slurry pig manure is used.

The long term plots receive the highest input of compost and solid manure and also have the highest input of carbon, see Figure 2-2.

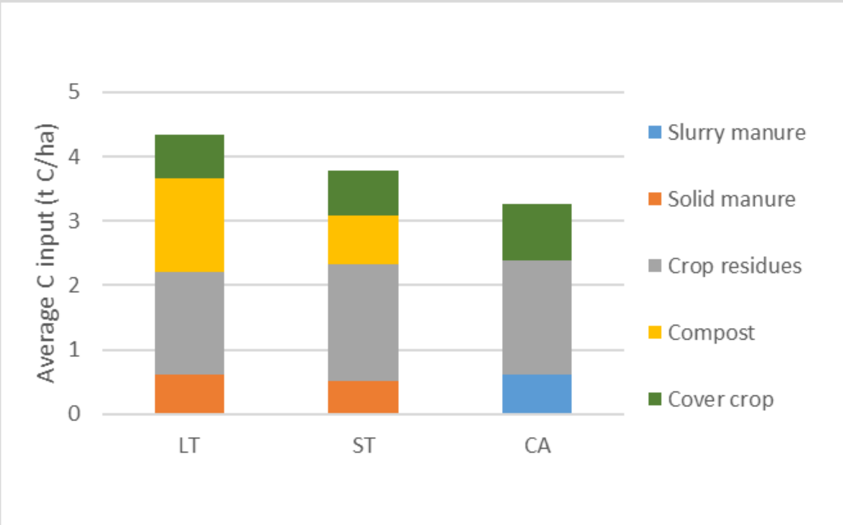

Figure 2-2 *The carbon input of the fields with the different management types (after Heesmans et al., 2023)[1].*

2.3 Measurements

Two samples were used:

1. A stratified simple random sample of 30 sites
   The stratified sampling has sought to achieve a wide spread in the property space, i.e. that different situations of soil conditions and both regular and regenerative agriculture are proportionally represented in the geographical space and that there is a good spatial distribution of the 30 sites.
   Sampling locations were chosen manually within the borders of generated homogeneous management zones. The management zones were calculated using the methodology described in chapter 5.2 in Kempenaar et al. (2019). As input to this zoning algorithm the 1:50.000 soil map of the Netherlands[2], the AHN3[3], available satellite imagery[4] and the field borders were used. The algorithm produces a specified number of spatially coherent and homogeneous zones per field.
   On these 30 points the following parameters are measured: soil profile description and penetration resistance.
   For 24 points out of these 30 points the following parameters are measured: soil profile description, penetration resistance, texture, aggregate stability, bulk density, organic matter content, water retention and permeability characteristics, nutrients and macro-chemical compounds. These 24 points are a subset of the stratified simple random sample of 30 sites (yellow and green points in the following). The subset was selected on base of an even distribution over the fields (2 or 3 points per field).

[1] Green manure in Heesmans et al., 2023 is a cover crop. From 2015 onwards no slurry was used at the ST management (replaced by solid manure).
[2] https://www.wur.nl/nl/show/Bodemkaart-1-50-000.htm
[3] https://www.ahn.nl/en
[4] Sentinel 2 image of 25 February 2018, TriSat image of 26 July 2018, TriSat image of 1 September 2018.

2. a cluster random sample of 40 sites
   The clusters are intended to gain insight into the soil organic matter (as defined by Loss of Ignation): the short-range variation, the change over time and the differences between the management types. 40 Sets of four topsoil samples in a line with one meter distance in between were taken and analysed. In chapter 4 this method is extensively described.

From 2019 till 2022 in the months October till November field descriptions, measurements and sampling of the soil were performed on the selected fields by trained WENR staff.

The sampling locations are depicted on Figure 2-3 till Figure 2-4. Penetrologger measurements and soil profile descriptions were made on all 30 points (green, yellow and red dots in the figures). On 24 locations, samples were taken for laboratory analysis of soil texture, plant nutrients, organic matter fractions and aggregate stability (green and yellow dots in the figures). On three locations, rings were taken for water holding capacity characterization (green dots in the figures).

The measurements are interpreted over time, but also the regenerative agriculture fields are compared to the conventional fields.

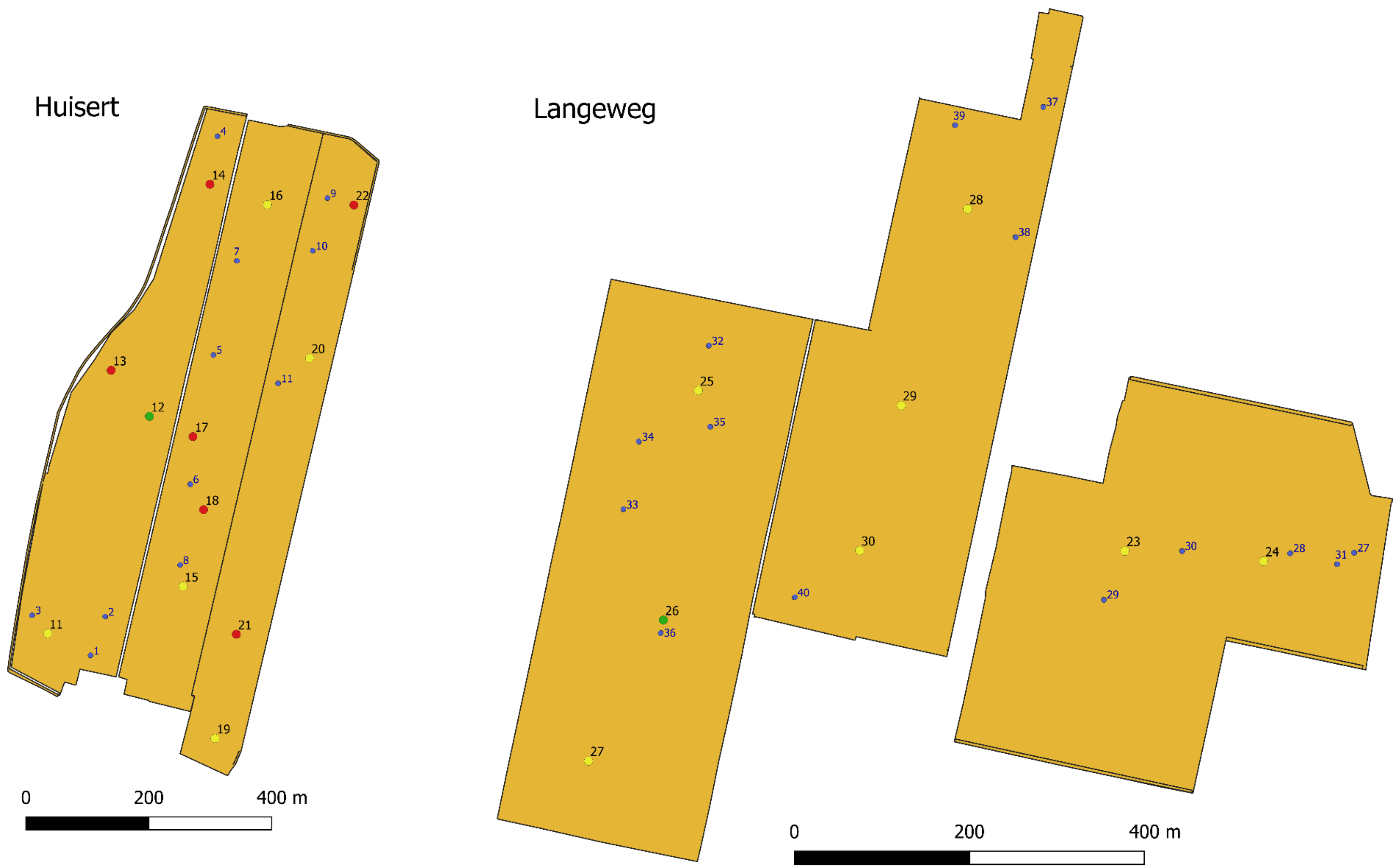

Figure 2-3 *Fieldwork points location Huisert (CA) and Langeweg (ST).*

Red points: *only soil profile description and penetrologger measurement (part of stratified simple random sample of 30 sites).*

Yellow: *soil profile description, penetrologger measurement, texture and chemical measurements (part of stratified simple random sample of 30 sites).*

Green: *same as Yellow plus soil physic measurements (part of stratified simple random sample of 30 sites).*

Smaller blue: *sample locations for soil organic matter analysis of topsoil (cluster random sample of 40 sites).*

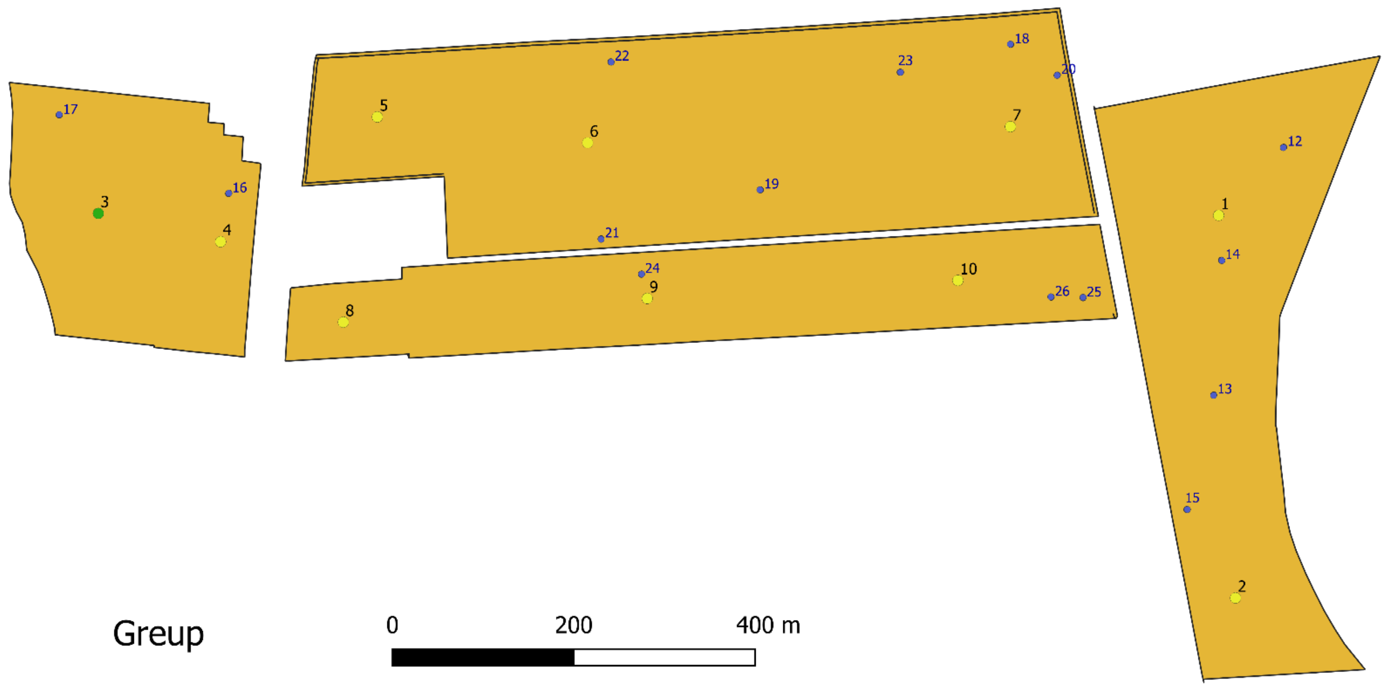

__Figure 2-4__ Fieldwork points location Greup (LT).
Yellow: soil profile description, penetrologger measurement, texture and chemical measurements (part of stratified simple random sample of 30 sites).
Green: same as Yellow plus soil physics measurements (part of stratified simple random sample of 30 sites).
Smaller blue: clusters for soil organic matter analysis of topsoil (cluster random sample of 40 sites).

Table 2-1 *Sample id, field names, sample category for soil description and sampling locations (green (cat 2), yellow (cat 1) and red dots (cat 0) in figures Figure 2-3 and Figure 2-4).*

Id	Fieldname	Sample category*
1	LT.4	1
2	LT.4	1
3	LT.1	2
4	LT.1	1
5	LT.2	1
6	LT.2	1
7	LT.2	1
8	LT.3	1
9	LT.3	1
10	LT.3	1
11	CA.1	1
12	CA.1	2
13	CA.1	0
14	CA.1	0
15	CA.2	1
16	CA.2	1
17	CA.2	0
18	CA.2	0
19	CA.3	1
20	CA.3	1
21	CA.3	0
22	CA.3	0
23	ST.3	1
24	ST.3	1
25	ST.1	1
26	ST.1	2
27	ST.1	1
28	ST.2	1
29	ST.2	1
30	ST.2	1

* categories see **Table 2-2**.

Table 2-2 *Soil analyses per sample category and per year (3: soil pit).*

Soil analysis	Cat. 0	Cat. 1	Cat. 2	2019	2020	2021	2022
Soil profile description	x	x	x	x			
Field estimates of soil texture and organic matter	x	x	x	x			
Texture (pipette <2, 2-16, 16-50, > 50 mu)		x	x	x			
Aggregate stability		x	x	x			x
Penetrologger measurement (5 fold)	x	x		x	x	x	x
Dry Bulk Density rho(d) (undisturbed) (T=105 dgr.C)			x	x			
Sandbox (h=0 until -100cm)			x	x			
Evaporation (Wind) (h=-50 until -700cm)			x	x			
Pressure Plate (h=-10^3 until -10^4cm)			x	x			
Saturated Hydraulic Conductivity Ksat (h=0)			x	x			
Loss on ignition (OS) (T=550 dgr.C)			x	x			x
pH		x	x	x			x
K (F-AES, K-Cl extraction)		x	x	x			x
C-POX (mg/kg)		x	x	x			x
DOC (mg/kg)		x					x
Pw (mg P2O5/l)		x					x
Pw (SFA-CaCl2) PO4		x	x	x			x
Ntot (H2SO4-Se destruction-Kjeldahl) (g/kg)		x	x	x			x
Ptot (H2SO4-Se destruction) (g/kg)		x	x	x			x
Ctot (LECO, Dumas) (g/kg)		x	x	x			x
Corg (LECO, Dumas) (g/kg)		x	x	x			x

In chapter 7 for the fields with long time regenerative agriculture (the LT-fields), some qualitative observations are described with reference to the fields under conventional agricultural management, that the farmer experienced in 2019/2020.

3 Soil description

3.1 Soil profile

3.1.1 Introduction

The soil profile description is the basis of the understanding the characteristics of the soil for the different soil functions.

3.1.2 Measurements

At 30 point locations a bore hole with an Edelman hand auger and a soil profile description was made until a depth of 150 cm -sl[5], including an estimate of the mean highest and mean lowest level of the groundwater table.

3.1.3 Results

For each of the different management types a point with a profile description is chosen which is presented in Figure 3-1 till Figure 3-3.

Depth	Profile 3	SOM [%]	Clay [%]
0	1Ap	4.0	24
25	1ACg	1.5	20
45	1Cg1	1.0	16
70	1Cg2	0.5	14
115	2Cw *Peaty layer*	25	14
150			

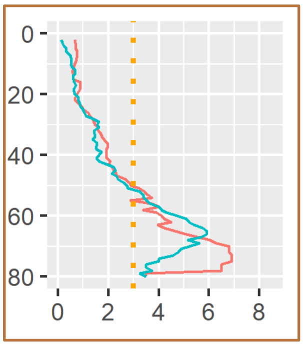

Figure 3-1 *Profile description, according to the Dutch Soil Classification system, for location 3 in the LT group of fields, with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y axis soil depth from soil surface is depicted. To the right the penetrologger measurements are depicted with penetration resistance in MPa on the x axis. Red is 2019, blue is 2020, the orange dotted line represents the 3 MPa border above which we expect difficulties for roots to penetrate this layer.*

[5] -sl: below the level of the soil surface

Depth	Profile 12	SOM [%]	Clay [%]
0–25	1Ap	4.0	19
25–40	1AC	3.0	16
40–90	1Cg1	1.0	12
90–130	1Cg2	0.5	14
130–150	1Cgr	0.2	16

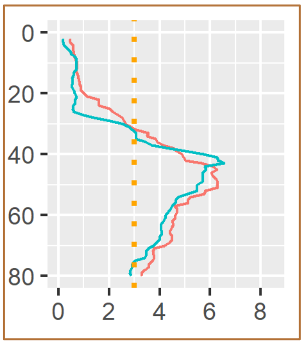

Figure 3-2 *Profile description, according to the Dutch Soil Classification system, for location 12 in the CA group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y axis soil depth from soil surface is depicted. To the right the penetrologger measurements are depicted with penetration resistance in MPa on the x axis. Red is 2019, blue is 2020, the orange dotted line represents the 3 MPa border above which we expect difficulties for roots to penetrate this layer.*

Depth	Profile 26	SOM [%]	Clay [%]
0–15	1Ap	4.0	24
15–30	1Ah	4.0	24
30–60	1Cg1	0.5	16
60–100	1Cg2	0.5	15
100–130	1Cg3	0.5	12
130–150	1Cgr	3.0	12

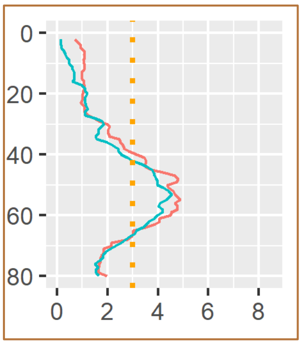

Figure 3-3 *Profile description, according to the Dutch Soil Classification system, for location 26 in the ST group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y-axis soil depth from soil surface is depicted. To the right penetrologger measurements are depicted with penetration resistance in MPa on the x axis. Red is 2019, blue is 2020, the orange dotted line represents the 3 MPa border above which we expect difficulties for roots to penetrate this layer.*

The mean highest and lowest level of the groundwater table were also estimated in the field when the boreholes were created. Figure 3-4 shows the fluctuation per management type. Because the soil description was made till 150 cm deep, deeper groundwater tables were not detected. In Figure 3-4, for presentation reasons the assumption was made that mean lowest groundwater levels “>150 cm-sl” are presented at a depth of 170 cm-sl. The figure shows that the highest summer groundwater levels are about the same per management type. The mean lowest groundwater level is highest at the fields with the LT-management, but there is a fluctuation between 110 till 150 cm-sl. For the fields with the ST-management the MLG is in all points deeper than 150 cm-sl.

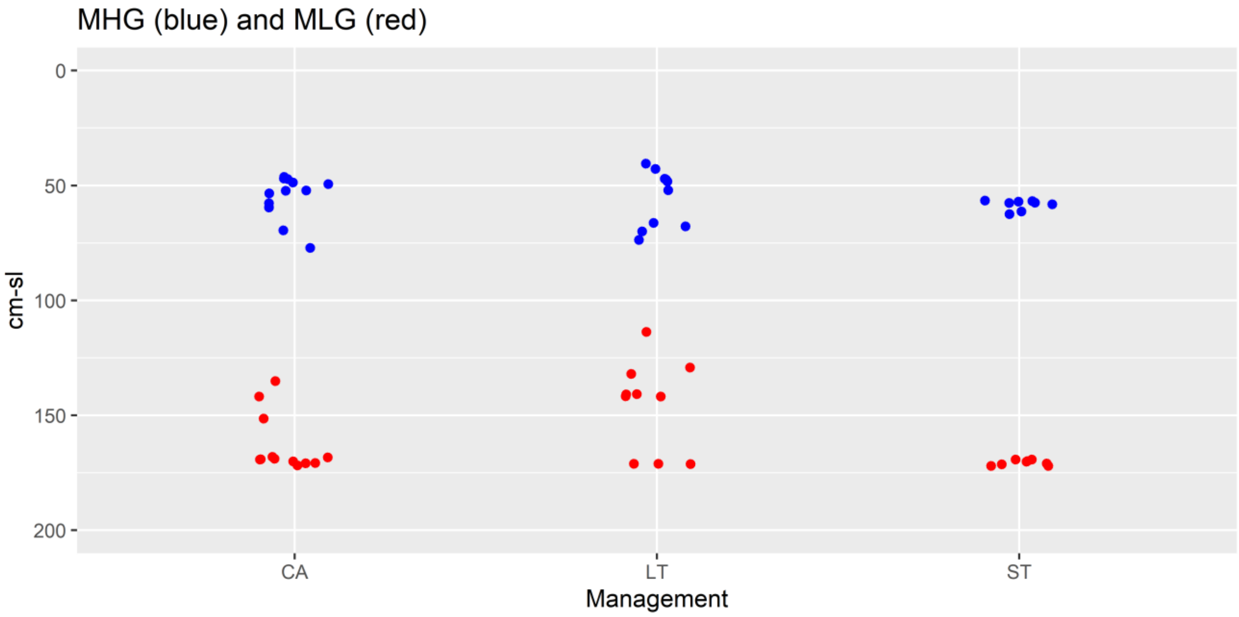

Figure 3-4 *Mean highest (blue) and mean lowest level (red) of the groundwater table (in cm minus soil level), based on visual inspection of the soil profile at 30 locations. Points at 170 cm-sl indicate MLG deeper than 150 cm-sl. Note that the dots are jittered in horizontal direction to avoid overplotting.*
CA: fields under conventional agricultural management, LT: fields under long term regenerative agriculture, ST: fields under short term regenerative agriculture.

3.2 Soil texture

3.2.1 Introduction

Soil texture represents the measured distribution of particle sizes, and the relative proportions of the various size ranges of particles in a given soil. The following grain size fractions are distinguished in this study: sand, silt and clay or lutum.

3.2.2 Measurements

On the 30 locations the soil samples were taken; the texture was analysed for two depths. The depth of the first layer approximately was from 0 till 25 cm-sl. The second layer has a depth of about 25 till 45 cm-sl.

3.2.3 Results

The soil texture observed in the fields is shown in Figure 3-5. The proportions of the various grain size fractions in the top layer (LG1, 0-25 cm) are quite similar between the fields for different management types. The fields with the CA-management seem to have a slightly lighter texture for the top layer in comparison with the LT- and ST-fields (lower percentage of soil parts < 2 µm and < 16 µm). The soil texture varies between fields within groups (CA, LT or ST), as can be seen from the variation in proportions of grain size fractions. Fields under conventional agricultural management (CA) show the largest variation in proportions. In fields under short term regenerative agriculture (ST), proportions of grain size fractions are most homogeneous between fields. It is expected that hydraulic properties of the soils in the fields will vary along with the soil texture.

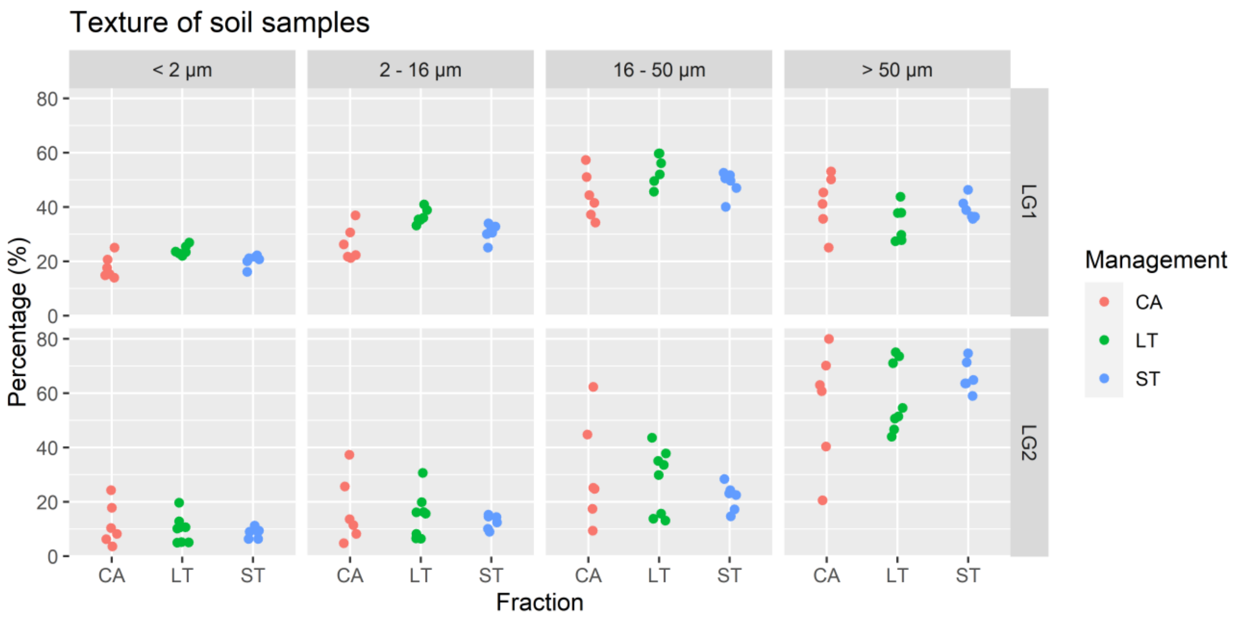

Figure 3-5 *Soil texture for layer LG1 (0 till 25 cm-sl) and LG2 (25 till 45 cm-sl). Note that the dots are jittered in horizontal direction to avoid overplotting.*

3.3 Conclusion

There are some differences in soil profile and texture between the distinguished fields, but in general, the fields are quite similar. Within the fields itself there is also variation. This can influence several soil properties, e.g. hydraulic conductivity and water retention.

4 Soil organic matter

4.1 Introduction

In this section, we will analyse differences in soil organic matter (SOM) content between the fields with conventional and regenerative management in the farm. We have two research questions:

1. are there differences in SOM content in the top soil (0-0.3 m below the soil surface) of fields with conventional (CA) and short/long-term regenerative management (ST, LT)? And is there a change in SOM content over the years?
2. are there differences in spatial microvariation of SOM content, i.e., variation at distances less than 0.6 m, between these management types?

4.2 Measurements

4.2.1 Fieldwork

Soil samples of the top soil (0-0.3 m below the soil surface) have been collected in the autumns of 2019 and 2022, at locations selected by means of cluster random sampling (de Gruijter et al., 2006; Brus, 2022).

We have chosen for cluster random sampling for two reasons:

1. it reduces travel time between locations in the field, and the regularity of locations within a cluster facilitates sampling. Although cluster sampling leads to lower precision, the larger sample size for the same budget may greatly compensate for that (de Gruijter et al., 2006);
2. to study spatial variation of SOM content at small distances (*i.e.*, distances less than 0.6 m).

Forty small clusters have been randomly selected proportionally to field size, i.e., larger fields get more clusters than smaller fields depending on its area. Each cluster consists of four sampling locations allocated along a 0.6 m long transect. An example of a transect is given in Figure 4-1. These four sampling locations coincide with the marks of an optimal and perfect Golomb ruler of order four. A Golomb ruler is a set of marks at integer positions along a ruler such that no two pairs of marks are the same distance apart. The number of marks is called the order. It is perfect because it is able to measure all distances up to its length of six, *i.e.* 1, 2, 3, 4, 5, and 6 units. It is optimal because no shorter Golomb ruler of order four exists. In our case, the smallest difference between two marks is set to 0.1 m. This means that with only four locations, all distances, i.e., 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 m, between two points along a transect are uniquely represented. This offers the opportunity to study the spatial variation of SOM content as function of distance. The orientation of the rulers are according to the eight main wind directions: N, NE, E, SE, S, SW, W, and NW. For more information on Golomb rulers see https://en.wikipedia.org/wiki/Golomb_ruler. The eight wind directions were assigned systematically to the 40 selected sites, resulting in five sites per wind direction.

The same cluster sampling design has been applied in 2019 and 2022. In both years, a total of 40 transects × 4 locations per transect = 160 samples of the top soil have been taken and analysed in the laboratory.

The clusters should give us an answer to the first research question, the samples along each transect to the second.

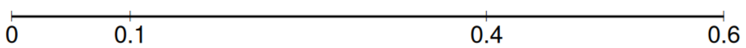

Figure 4-1 *Example of a transect based on an optimal and perfect Golomb ruler of order 4.*

4.2.2 Laboratory work

SOM content is determined by means of 'loss-on-ignition' (LOI, conform SWV E0100 WUR). In fine textured soils this method slightly overestimates SOM content, as not only organic matter, but also hygroscopic water will be lost by ignition.

4.3 Results

4.3.1 Descriptive analysis

Figure 4-2 gives a map of the studied fields showing the soil organic matter (SOM) content for each cluster of sample locations, observed in the years 2019 and 2022. We see higher SOM contents in the north of the area where regenerative management is applied, and lower contents in the south with conventional management.

Figure 4-2 *Soil organic matter (SOM, dag/kg or mass percentage) content in the topsoil (0-0.3 m) in the fields under study for 2019 and 2022. Each symbol represents four observations in a cluster.*

Cluster random sampling is a design-based method. No model assumptions are needed. We estimate the mean and standard error of the SOM content for each management type by the procedure described in de Gruijter et al. (2006) (p.299–103, Eqs 7.33 and 7.34). In Figure 4-3 the mean SOM content is given by the horizontal bars and the standard error by the horizontal error-bars for 2019 and 2022.

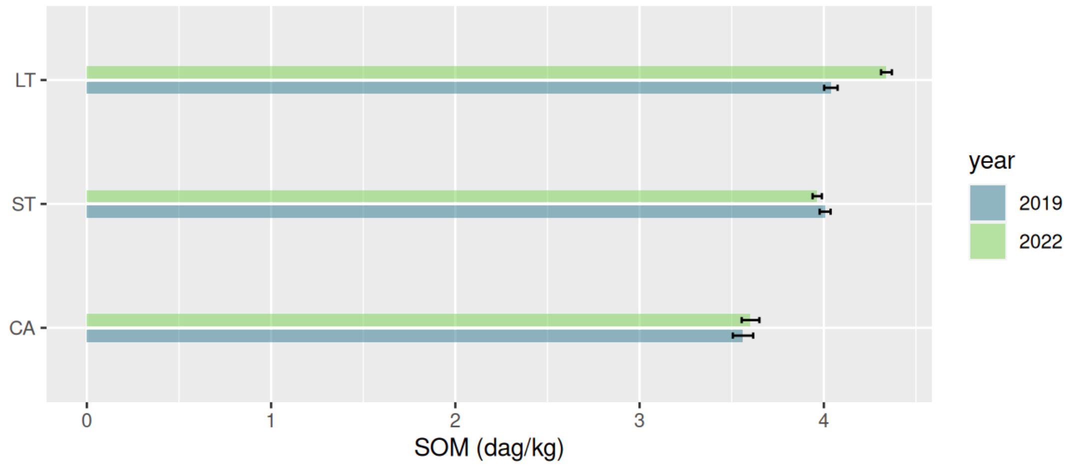

Figure 4-3 *Mean SOM (bars) and corresponding standard error of the mean (horizontal error bars, denoting one times the standard error) for conventional and regenerative management. The purpose of the error bars is to give an impression of the relative accuracies of the means, and should not be used for statistical testing by the eye.*

We see differences in SOM content between the fields under conventional and regenerative agriculture and between years. We will discuss the statistical significance of these differences below.

By applying indicator coding, we can estimate the spatial cumulative distribution functions (SCDF) for each management type and year (de Gruijter et al., 2006; p. 83). Figure 4-4 gives the results. We see somewhat higher SOM contents for regenerative agricultural management. For LT (long-term regenerative agriculture), we also see differences between the years: higher SOM contents were observed in 2022 than in 2019.

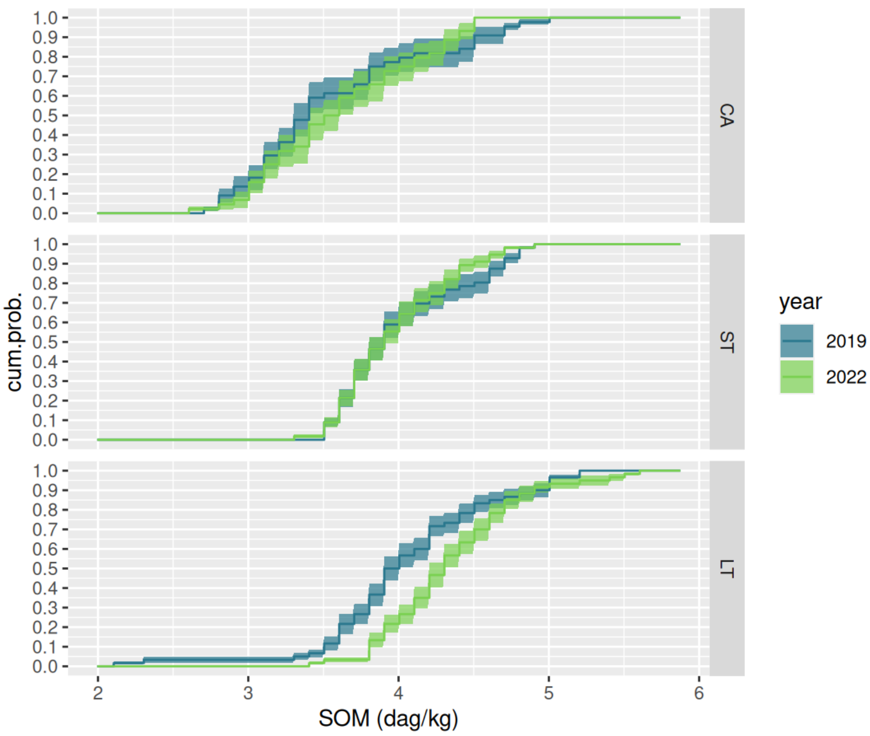

Figure 4-4 *Spatial cumulative distribution functions for SOM and corresponding standard error for conventional and regenerative management in 2019 and 2022.*

4.3.2 Statistical significance testing

We applied a Student two sample t-test to test for differences in SOM contents between management types, and we applied paired t-tests to test for differences between years. At a statistical significance level of 0.05 we conclude:

1. Fields with regenerative agricultural management have a higher mean SOM content in 2019 than fields with conventional management. The difference is 0.446 and 0.477 percent point for ST and LT respectively;
2. There is no evidence in the data that mean SOM contents have increased from 2019 to 2022 in fields under conventional management;
3. There is no evidence in the data that mean SOM contents have increased from 2019 to 2022 in fields under short term regenerative management;
4. Mean SOM contents have significantly increased from 2019 to 2022 in fields under long term regenerative agricultural management. The increase is about 0.302 percent point in three years.

4.3.3 Microvariation

Contrary to conventional agricultural practices, regenerative agriculture is a low or no-tillage based farming method. The fields under ST- and LT-management in this study are low tillage based (no ploughing). We may therefore expect differences in microvariation between conventional and regenerative agriculture. In conventional agriculture, ploughing will lead to a homogeneous topsoil, whereas low or no-tillage based management may lead to more spatial structure (more spatial continuity) at smaller distances (in this case, distances less than 0.6 m).

A tool to quantify spatial structure is the semivariogram. It gives the spatial variation (the semivariance, γ) of a variable (our case SOM content) as a function of the distance between (sample) locations. Since we used the marks of a Golomb ruler of order 4 (Figure 4-1) for sampling, we have six unique distances h: 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 m, each with an estimated semivariance γ.

A priori, we expect the following:

1. Due to ploughing, conventional management is expected to have less variation in soil organic matter content in the topsoil than regenerative management. The reason is that ploughing will homogenize the topsoil and reduce spatial variation. In more technical terms: the maximum value of the semivariogram (a.k.a. the sill variance) will be lower;
2. Due to ploughing, conventional management is expected to have a more constant level of spatial variation in soil organic matter content than regenerative management. In more technical terms: the semivariogram will be horizontal (a.k.a. a pure nugget model, Isaaks and Srivastava (1989));
3. Regenerative management is expected to result in more spatial variation and more spatial structure than conventional management. Semivariograms of SOM content for regenerative management are therefore expected to first increase with distance h and then asymptotically level out until a maximum semivariance has been reached (a.k.a. a transition model, Isaaks and Srivastava (1989)).

The semivariograms of the observations of SOM content are given in Figure 4-5. We do not see a low and constant variation γ for conventional management CA. We see the shape of a transition model for long term regenerative management LT, but only for 2019. As expected, the semivariance γ seems to be somewhat higher for regenerative management LT than for the two other management systems, but only in 2019.

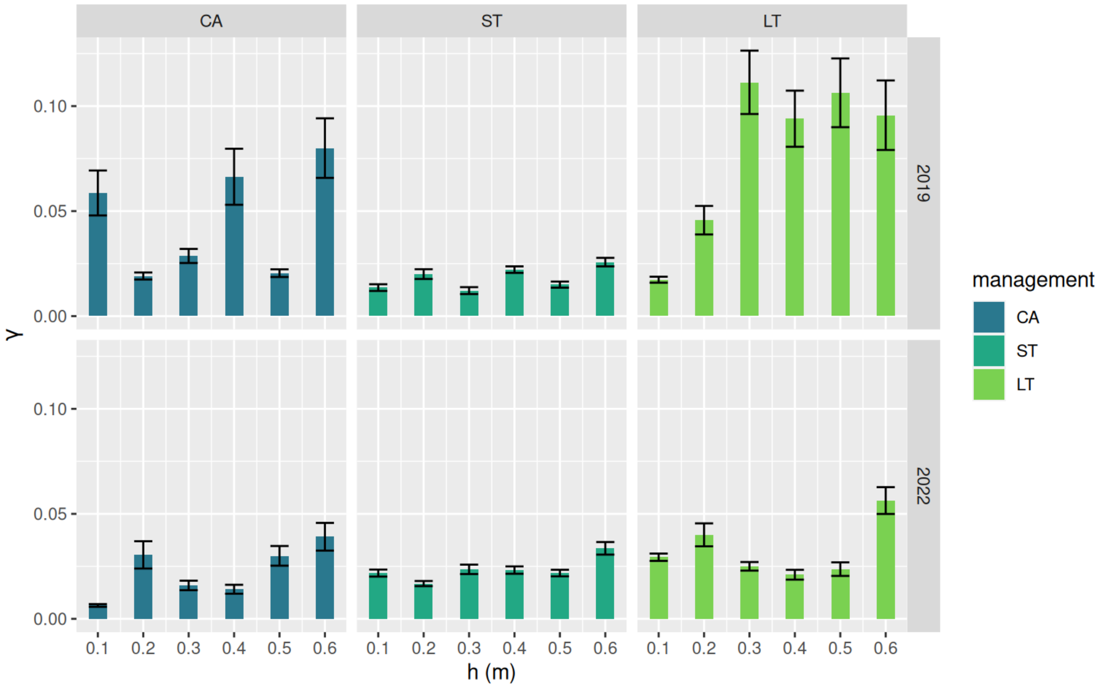

Figure 4-5 *Semivariograms for conventional and regenerative management for 2019 and 2022. The vertical axis gives the semivariance γ, the horizontal axis the distance h between soil sample locations (m) along a transect. Error bars denote one times the standard error of the semivariances and give information on the precision of the semivariances.*

4.4 Conclusion

Fields with regenerative agricultural management have a higher mean SOM content in the topsoil than fields with conventional management. For fields with long term regenerative agricultural management, it has been shown that the mean SOM content has significantly increased from 2019 to 2022 with 0.302 percent point.

Variations in SOM-content at small distances (< 0.6 m) between fields under conventional and regenerative agricultural management are less pronounced than expected.

5 Soil physics

5.1 Introduction

In this paragraph the measured physical properties of the soil are presented: water holding capacity, aggregate stability, soil compaction and bulk density.

5.2 Water holding capacity

5.2.1 Introduction

The water availability of a soil is determined by the soil hydraulic properties of the root zone and the soil below, from where capillary fluxes provide water to the root zone. In this paragraph the retention curve and the hydraulic conductivity are presented. The retention characteristic reflects the relationship between the pressure head and the water content. The hydraulic conductivity indicates the relationship between the pressure head and the permeability. Both are needed to determine the response of soil moisture to meteorological conditions.

5.2.2 Measurements

For the determination of the water retention and the permeability curves in the fields of the farm, undisturbed soil samples were taken and analysed in the Soil Physical Laboratory at Wageningen UR in 2019. Soil hydraulic parameters (SHP) are measured at one location for each management site (LT, ST, CA); one point of the stratified simple random sample of 30 sites was chosen (green points in figures paragraph 2.3). Samples were taken from two depth intervals (5-20 cm -sl and 35-55 cm -sl). These both determine the water availability in the field. The measurements were made using the methods of pressure plate extraction and also the evaporation method (NEN 5791: evaporation method Wind, 1991). These measurements are costly and therefore one measurement for two depths per management type has been done.

5.2.3 Results

In **Table 5-1** the measurements for the construction of the water retention curve are given.

Table 5-1 *Measured water content (theta) in the laboratory at varying hydraulic pressure head (2019).*

Management Soil profile	Layer	Starting depth (cm-sl)	End depth (cm-sl)	Theta (cc water per cc soil) Sand box -3	-10	-30	-70	-100	Pressure plate -3000	-14000	Air Dry -1000000
CA profile 12	1	5	15	0.427	0.419	0.376	0.337	0.318	0.146	0.127	0.041
CA profile 12	2	45	55	0.342	0.336	0.327	0.296	0.245	0.061	0.058	0.018
LT profile 3	1	10	20	0.414	0.404	0.392	0.373	0.363	0.282	0.245	0.072
LT profile 3	2	45	55	0.402	0.395	0.373	0.350	0.334	0.156	0.134	0.037
ST profile 26	1	5	15	0.361	0.348	0.345	0.345	0.344	0.265	0.235	0.072
ST profile 26	2	35	45	0.367	0.360	0.350	0.333	0.313	0.114	0.103	0.030

These measurements are used to construct the water retention curve (Table 5-2). The van Genuchten model was used for this purpose (van Genuchten, 1980). The van Genuchten parameters, derived from this model, can be used to calculate the water holding capacity.

Table 5-2 *Van Genuchten-parameters (WCr: residual water content, WCs: saturated water content, alpha, n and m: additional parameters, Ks: fitted Ksat-value for the MvG-equation, Ksatexm: in lab measured Ksat-value).*

Id	Location	Depth (cm-ss)	WCr (cm^3/cm^3)	WCs (cm^3/cm^3)	Alpha (1/cm)	N (-)	M (-)	Lambda (-)	Ks (cm/d)	Ksatexm (cm/d)
12LG1	CA	5-15	0.0000	0.4296	0.0228	1.1938	0.1623	1.6137	14.1949	16.3727
12LG2	CA	45-55	0.0325	0.3647	0.0096	2.8569	0.6500	1.8135	32.3202	42.5184
3LG1	LT	10-20	0.0000	0.4400	0.0123	1.1360	0.1197	-3.0794	3.0490	2685.8697
3LG2	LT	45-55	0.0000	0.4067	0.0099	1.2634	0.2085	5.0236	11.5745	14.9162
26LG1	ST	5-15	0.0000	0.3960	0.0405	1.1037	0.0939	6.0951	77.0470	192.1742
26LG2	ST	35-45	0.0344	0.3900	0.0103	1.5240	0.3438	4.1595	16.4862	21.2318

The water holding capacity (WHC) can be determined directly from the laboratory measurements or from the MvG-equation derived from the measurements (Table 5-3). As can be seen in the table, this results in different values for the water holding capacity. The main line is that for layer 1 the water holding capacity (difference in soil moisture content between pF 2 and 4.2) for the LT and ST location is considerably smaller than for the CA-field (see Table 5-3).
For layer 2 the differences are considerably smaller than for layer 1. This may be explained by the more uniform soil texture of this layer under the three management types (see chapter 3).

Table 5-3 *Water holding capacity of layer 1 (5-20 cm depth) and 2 (35-55 cm depth) (based on laboratory measurements and van Genuchten equation, Van Genuchten, 1980).*

Location	Water holding capacity (vol. %)			
	layer 1	layer 1	layer 2	layer 2
	pF2 – pF4.2	*pF2 – pF4.2*	*pF2 – pF4.2*	*pF2 – pF4.2*
	Lab measurement	*MvG-equation*	*Lab measurement*	*MvG-equation*
CA	19%	21%	19%	22%
LT	12%	18%	20%	25%
ST	11%	13%	21%	25%

5.2.4 Conclusion

For layer 1 the water holding capacity (difference in soil moisture content between pF 2 and 4.2) for the LT and ST location is smaller than for the CA-field (see Table 5-3).
For layer 2 the differences between the management types are considerably smaller than for layer 1. This may be explained by the more uniform soil texture of this layer under the three management types.

Due to the fact that one measurement per management type per depth has been made, it is not possible to perform a statistical significance tests on differences in mean WHC between CA, LT and ST. Therefore on base of the measurements, it cannot be concluded that there are significant differences in WHC.

5.3 Aggregate stability

5.3.1 Introduction

Soil aggregate stability is an important soil property for sustainable soil use and crop production. The stability of wet aggregates influences soil sealing and water infiltration capacity under rainfall. The analysis of aggregate stability may help to understand soil water behaviour including runoff, infiltration, redistribution, soil aeration and root growth. Aggregate stability expresses the degree of cohesion between soil particles. It depends on soil physical, chemical and biological influences (Part 4, chapter 2.6, Nimmo and Perkins, 2002).

The formation of soil aggregates influences soil organic matter. Micro-aggregates (<= 250 µm) protect SOM in the long term; macro-aggregates (> 250 µm) influence the stabilization of SOM.

The wet-aggregate stability relates to the force needed to break an aggregate apart.

There are different methods to measure the aggregate stability. In this project the wet sieving method is used (based on DIN 19683-16). The stability index for wet aggregates ranges from 0 (unstable) to 1 (stable).

5.3.2 Measurements and methods

On 24 (2019) and 23 (2022) locations undisturbed samples of 1 dm^3 were taken at a depth of 0 till 25 cm-sl. In Table 5-4 the number of samples per management type are given.

Table 5-4 *Number of soil samples per management type and per year.*

	CA	LT	ST
2019	6	10	8
2022	7	9	7

For the statistical analysis the non-parametric test of Wilcoxon has been used. When comparing management types a non-paired test has been used. When comparing years within a management type a paired test has been performed. We used a statistical significance level of 0.05. The null hypothesis is that the distributions of the management types do not differ.

5.3.3 Results

In Figure 5-1 the index of Water Stable Aggregates (WSA) is shown for the aggregate size classes of 1-2 mm and 2-4 mm. Most differences in WSA are not significant, neither between the years 2019 and 2022 nor the management types. An exception is found in the year 2022 that shows a statistically significant higher index of WSA in comparison with the year 2019 for the management type LT in the class of 1-2 mm; the increase equals 0.155 g/g.

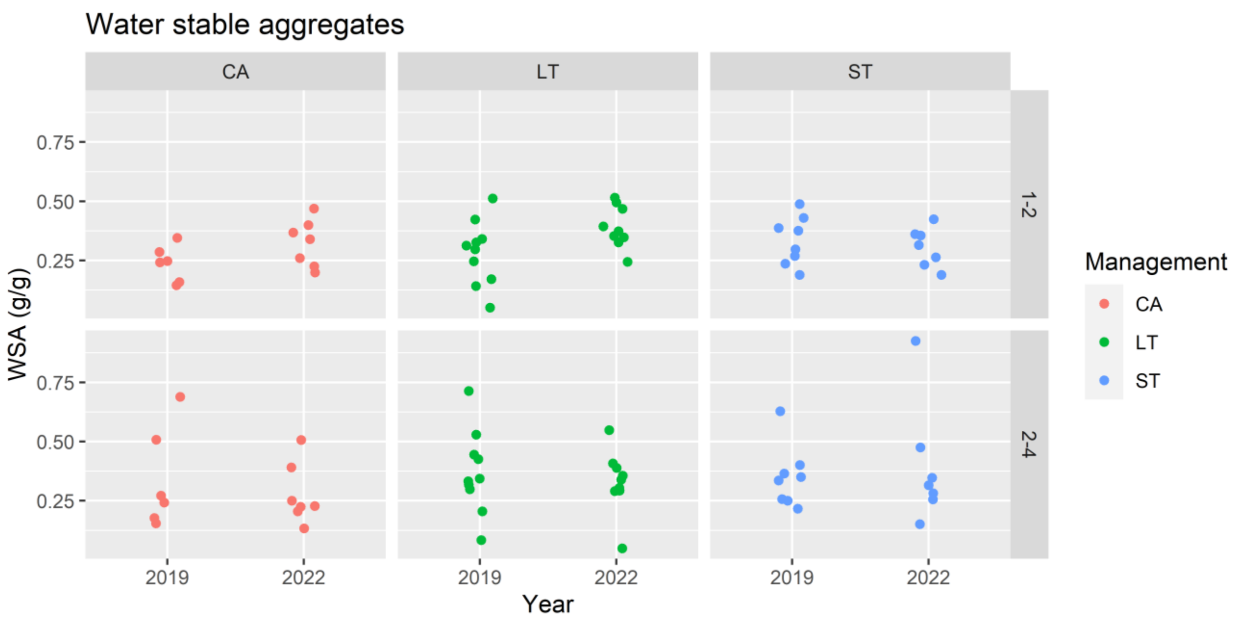

Figure 5-1 *Index of water stable aggregates for 2019 and 2022, grouped according to agricultural management type and aggregate fraction. Note that the dots are jittered in horizontal direction to avoid overplotting.*

The relative abundance of aggregates at the sizes of the sieve, after breaking the soil in individual aggregates in a prescribed way, may indicate stability, because an abundance of bigger aggregates indicates a higher stability. In Figure 5-2 the weight percentages per sieve size class are given for all the samples per management class (for the year 2019). On base of these observation there are some statistically significant differences: for the class < 0.5 μm the percentage for the ST-management is 5.4 and 3.6 percent point lower than for resp. the CA- and LT-management and for the class 1-2 μm the percentage for the ST-management is 1,0 percent point higher than for the CA-management.

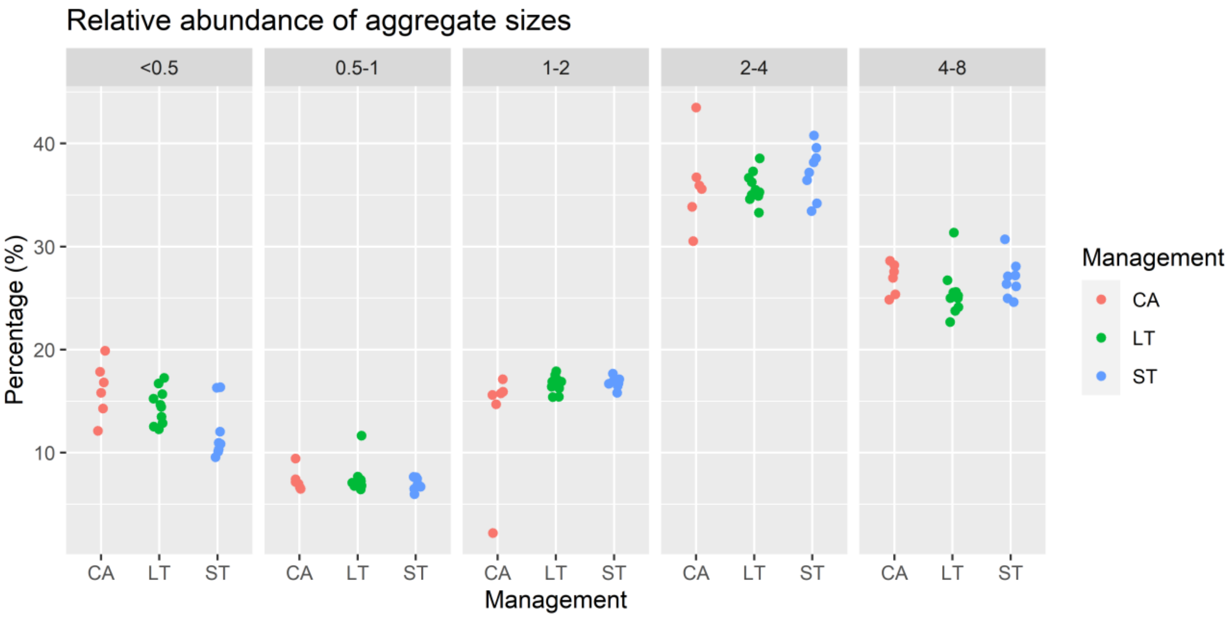

Figure 5-2 *Relative abundance for the aggregate sizes per sample (per management type). Note that the dots are jittered in horizontal direction to avoid overplotting.*

A Mean Weighted Diameter[6] per aggregate can be calculated; results are shown in Figure 5-6. A high mean diameter of the aggregates indicates more aggregation. A non-paired Wilcoxon test doesn't show a statistically significant difference between the management types.

[6] Weighted: relative abundance per class, diameter: mean class diameter, for 1-2 mm it is 1.5 mm.

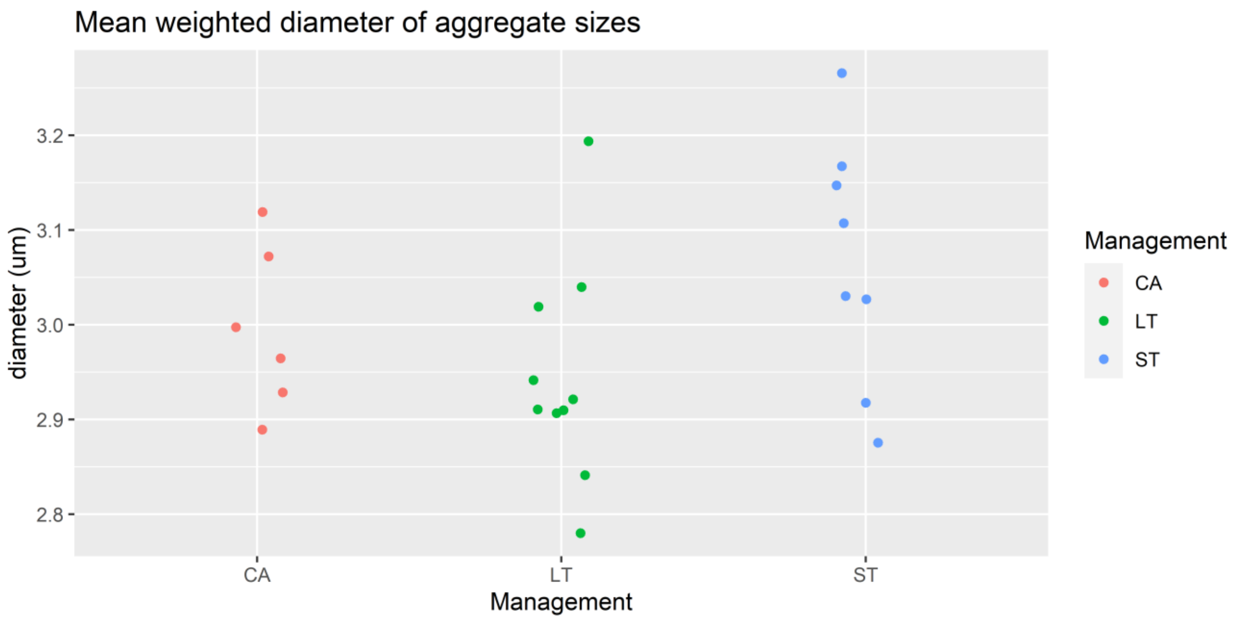

Figure 5-3 *Mean weighted diameter of aggregates per sample (2019). Note that the dots are jittered in horizontal direction to avoid overplotting.*

5.3.4 Conclusion

For wet aggregate stability and the mean weighted diameter no differences could be shown between agricultural management types. For the development in time for the management type LT in the class of 1-2 mm the year 2022 shows a statistically significant higher index of WSA in comparison with the year 2019, the increase equals 0.155 g/g.

5.4 Soil compaction

5.4.1 Introduction

Soil compaction influences several soil hydraulic properties which are important for crop growth, for example water infiltration capacity and rootability of the soil. An indication of the degree of compaction in a soil can be obtained by measuring the penetration resistance. The variation of the penetration resistance with depth in the soil profile can give an indication if and where compacted layers occur in the soil.

The critical limit for rootability [7] by crops is at a penetration resistance of 2.5 to 3.0 MPa (ten Cate et al., 1995). If a system of sufficiently large pores is present, the critical limit shifts to 3 – 5 MPa for sandy soils (ten Cate et al., 1995). As a kind of average, this report takes for rooting a threshold value for the penetration resistance equal to: Iw = 3 MPa. In this report the depth at which the penetration resistance surpasses this threshold value is called the critical depth.

5.4.2 Measurements and methods

The penetration resistance (Iw) was measured in the fields with a penetrometer, using a cone with a base surface of 1 cm^2 and a top angle of 60°. Values of the penetration resistance, expressed in MPa, are obtained by dividing the force with which the cone is pushed into the ground by the surface of the base of the cone. Because the penetration resistance is highly dependent on the moisture state of the soil, penetration resistance must be measured when the soil is moist, for example when the soil is more or less at field capacity. Penetration resistance measurements were carried out in 2019, 2020, 2021 and 2022 on the

[7] Rooting of plants (crops) in soil is not only limited by excessive penetration resistances, but also by aeration possibilities. So not only a high penetration resistance inhibits the root growth, but also the soil density, or rather the air content.

30 sampling locations (see Figure 2-3 and Figure 2-4). On every sampling location, 5 stitches in a radius of 1 to 2 meters were made, following the protocol described in van Tol-Leenders et al. (2019). This means that 150 penetration resistance measurements were taken in total in every year. In 2021 however, due to the presence of crops on the field, 4 sample locations were not visited. A single measurement contains a penetration resistance value (in MPa) for every centimetre in depth until a depth of 80 cm.

Measurements of the penetration resistance depend on soil type and soil moisture content. This must be taken into account in extracting information on the degree of soil compaction from these measurements. At a single sample location, already a lot of variation can be found between the five measurements (Figure 5-4). Also between years the penetration resistances on a single location, and connected to the resistances the critical depth, can vary strongly (Figure 5-5). More examples can be seen in Annex 1.

To compare the measurements of the penetration resistance between sampling locations within a single field or between different management types the measurements of the penetration resistance at each sampling location are summarized by the following metrics:

- **DPgem3**, the depth where the mean penetration resistance of the 5 stitches surpasses the 3 MPa threshold;
- **DPmed3**, the depth where the median penetration resistance of the 5 stitches surpasses the 3 MPa threshold.

For example, the depth profile in Figure 5-4 would be summarized in the metrics as;

- DPgem3 = 55 cm
- DPmed3 = 49 cm

As mentioned before, the 3 MPa threshold is considered as the value of the penetration resistance above which plant roots cannot penetrate the soil. The depth where this threshold is reached can be considered to be the point where the soil is compacted. The larger this depth in the soil, the more space is available for roots. It is important to mention that usually soils at some depth reach the 3 MPa threshold due to natural compaction. However, due to management and soil type, soil compaction can occur at a more shallow depth. The goal of this analysis is to see if long-term (LT) or short-term regenerative agriculture (ST) result in a lower degree of soil compaction or compaction deeper in the soil profile, than in conventional agriculture. And to see whether there is a trend through time.

The differences in soil texture between the fields with different management complicate direct comparison (see paragraph 3.2). Comparison however is possible using the aforementioned metrics. The metrics were calculated for every sampling location and compared between management types and years.

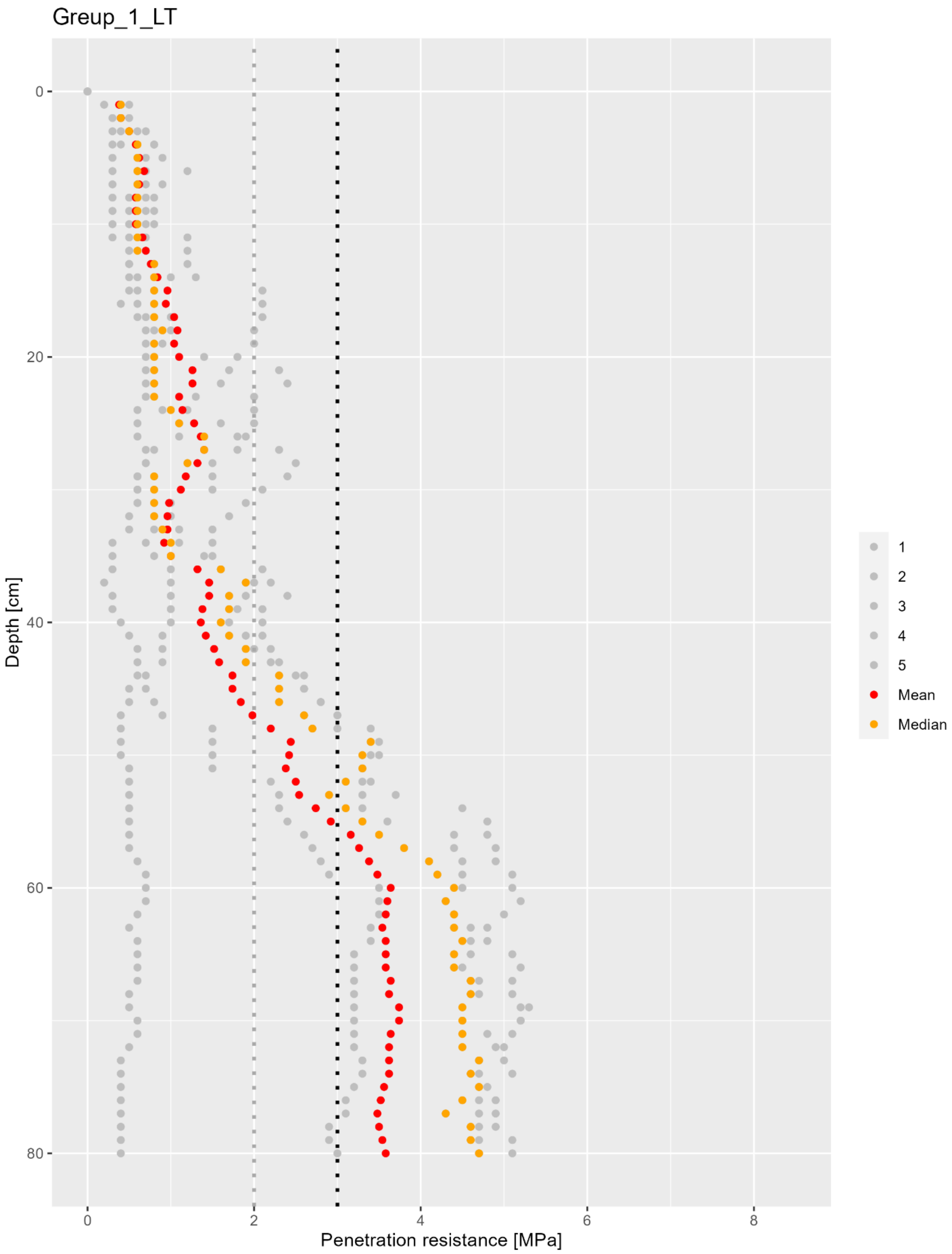

Figure 5-4 *Depth profile of 5 different penetration resistance measurements (grey) at a single sampling location (Greup_1_LT, 2019), with the mean in red and median in orange. The black dotted vertical line marks the 3 MPa threshold.*

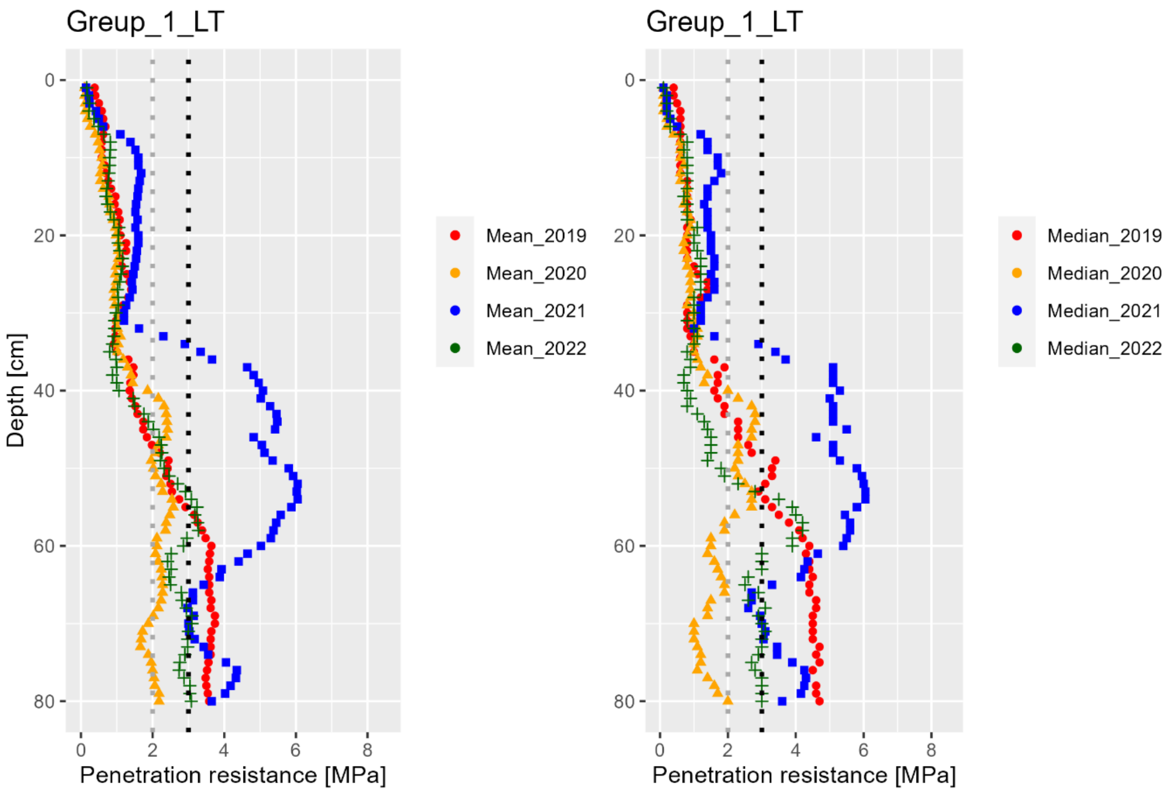

Figure 5-5 *Depth profiles of the mean (left) and median(right) penetration resistance between years.*

5.4.3 Results

5.4.3.1 Mean depth of threshold for soil compaction

The DPgem3, or the depth where the mean penetration resistance at a location surpasses 3 MPa, can be seen in Figure 5-6. The average DPgem3 is largest for LT at around 48 cm, whereas it lies around 42 cm for both CA and ST. It seems that in four years, no real trend can be recognized in DPgem3.
It should be noted that less data is available from 2021, because during the field visit the carrots grown on ridges made it impossible to make a measurement comparable to former years.

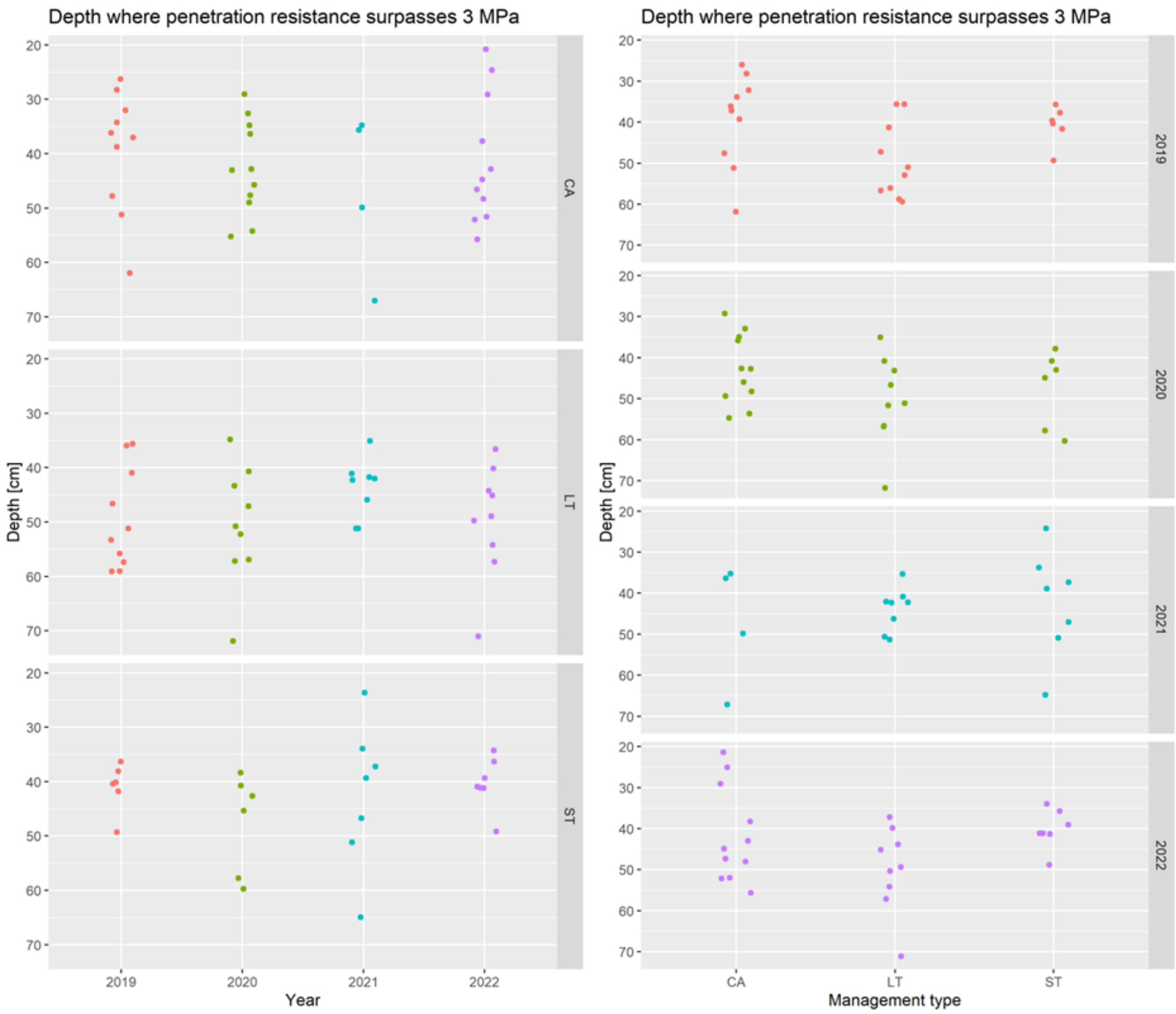

Figure 5-6 *Depth where the penetration resistance surpasses 3MPa (averaged values per location), over time (left) and over management type (right). Note that the dots are jittered in horizontal direction to avoid overplotting.*

5.4.3.2 Median depth of threshold for soil compaction

The median is less sensitive to possible extreme measurements and might show a more realistic metric of the depth profile. In Figure 5-7, the median depth where the penetration resistance exceeds 3 MPa can be seen. Choosing the median, doesn't change the figure very much. The same conclusions drawn on the basis of DPgem3 can be drawn based on DPmed3.

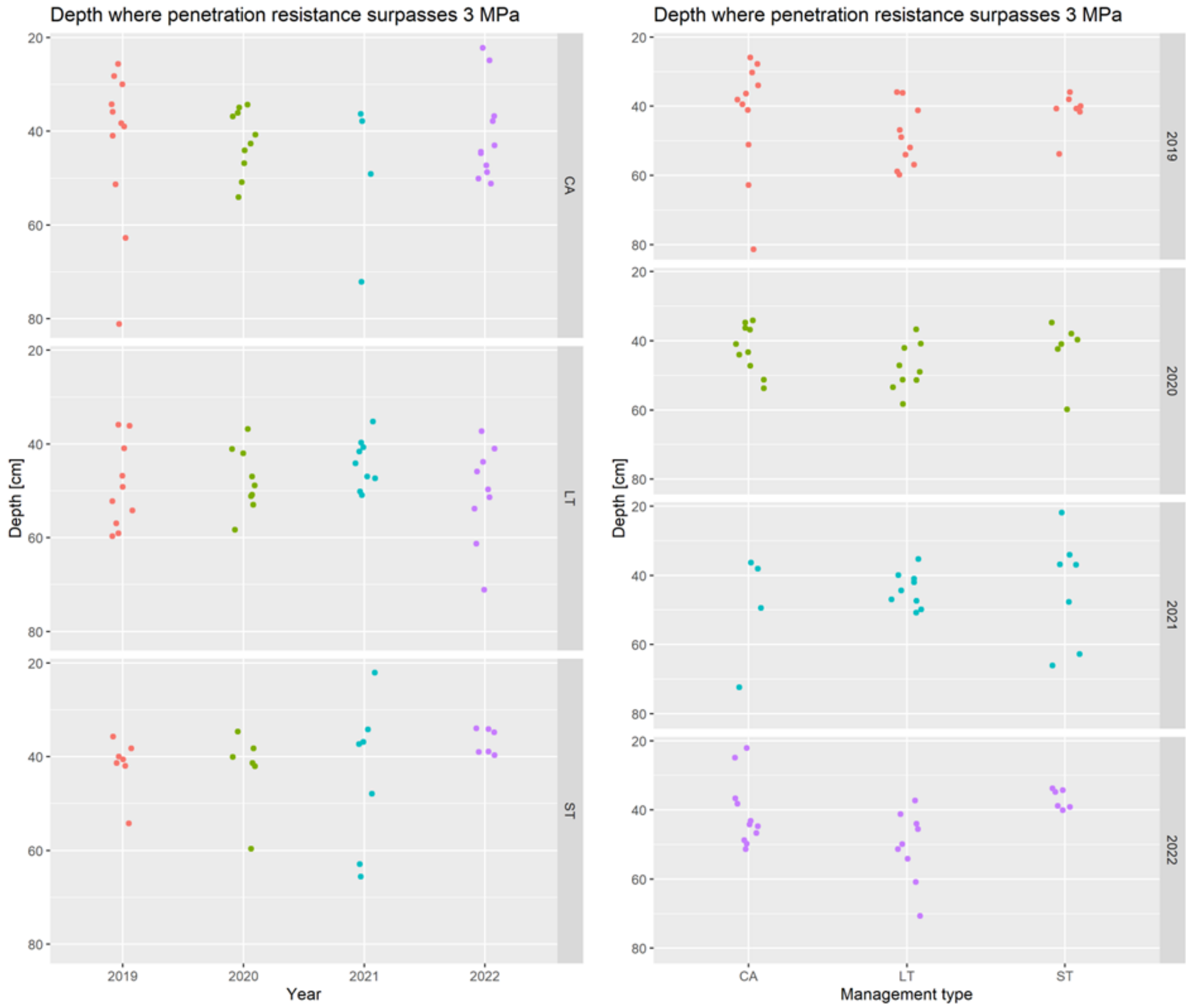

Figure 5-7 *Depth where the penetration resistance surpasses 3 MPa (median values per location), over time (left) and over management type (right). Note that the dots are jittered in horizontal direction to avoid overplotting.*

5.4.4 Conclusion

It seems that in four years, no trend can be recognized in the soil compaction depth.
The average or median depth, where the mean penetration resistance surpasses 3 MPa, is largest for LT at around 50 cm, whereas it lies around 40 cm for both CA and ST. Can we attribute the larger compaction depth for the LT-fields to the management? There is no trend over the years, so probably it is a result of other factors. Therefore we conclude that it is unclear what the effect of management on the LT-fields on soil compaction depth is. For the CA- and ST-fields no changes or effects in time are determined.

5.5 Bulk density

5.5.1 Introduction

The dry bulk density represents the dry mass of the solid fraction (soil particles + organic matter (OM)) per volume of soil in an undisturbed state. The dry bulk density is subject to changes due to natural (e.g. swelling and shrinkage) and human causes (e.g. tillage and riding). The dry bulk density, just like the penetration resistance, gives an indication of the degree of soil compaction and therefore also insight into the permeability of the soil for roots, air and water.

Thresholds are used as an indication for soil compaction. The threshold depends on soil type and soil composition.

For sandy soils with a low organic matter content (as is generally the case with a sandy subsoil), the threshold value for the volumetric weight Db (de Haan et al., 2021) indicating a non-compacted soil:

$$Db < 1.6 \ g.cm^{-3}$$

For heavy sablon and clay soils (>17.5% lutum), the threshold for the pore volume depends on the clay or lutum content:

$$Db < 1.75 - 0.009C \ g.cm^{-3}$$

Where C = mass percentage lutum (clay) (-)

For the fields in this study the percentage lutum in the top layer (till 25 cm -sl) equals about 20% and therefore the threshold for the bulk density Db is at 1.57 $g.cm^{-3}$. In this study for the deeper layer (25 till 45 cm-sl) the mean lutum percentage equals about 10%; in that case the threshold for the bulk density Db equals 1.6 $g.cm^{-3}$.

5.5.2 Measurements

For the measurement of the dry bulk density, in total 12 ring samples were taken at two depths: 5 till 20 cm-sl and 35 till 55 cm-sl. The protocol for inserting rings is described in NEN-EN-ISO 11272:2017. Six samples with a volume of 100 cc for the evaporation method and six samples with a volume of 651 cc for the pressure plate were taken for the measurement of the water retention curve and the water conductivity (see paragraph 5.2). For these samples also the dry bulk density was measured.

5.5.3 Results

In Figure 5-8 the measurements of the dry bulk density for the two layers are shown. For layer 1 the figure shows a low bulk density for the CA-field in comparison to the LT- and ST-management. This can be a result of ploughing: the density can be low in the just ploughed topsoil, and during the growing season it can develop a higher density. In comparison with the threshold for the bulk density with 20% lutum the measured values for layer 1 are only for the ST-management higher. For layer 2 the measured bulk densities are for most of the samples about equal to the threshold. Layer 1 shows that the 100 cc samples have sometimes a lower and sometimes a higher density than the bigger samples. Layer 2 has for all the fields a very constant density. Only on the LT-field the smaller sample does have a lower density (1.5 g/cc).

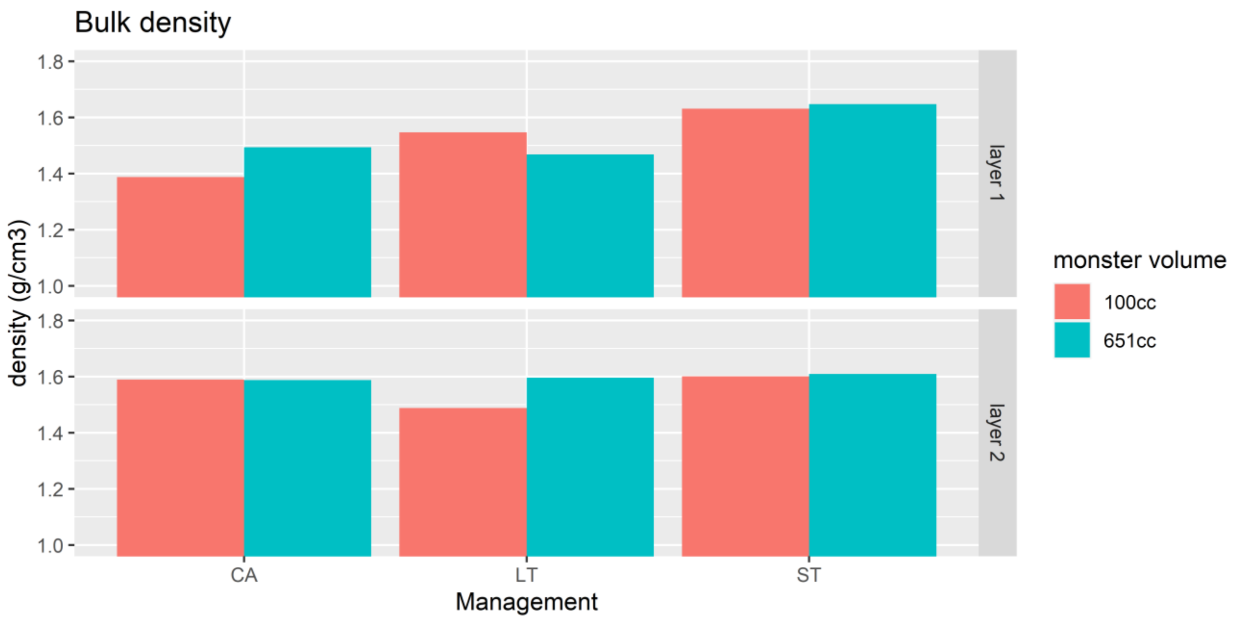

Figure 5-8 *Dry bulk density for layer LG1 (5 till 20 cm-sl) and LG2 (35 till 55 cm-sl, based on 12 observations).*

5.5.4 Conclusion

Most of the samples have a dry bulk density lower or equal to the threshold for non compacted soils. Only the samples of layer 1 with the LT-management seem to have a bit to high bulk density. Because of the low number of samples taken, there is no or at least not sufficient information available on the variation in the field. Besides that, the bulk density can be variable during the year. For instance just after ploughing, the density (CA) can be low in the ploughed topsoil, and during the growing season it can develop a higher density. Therefore no conclusions are made about the influence of management on bulk density.

6 Soil chemistry

6.1 Introduction

Soil chemistry is of importance for several reasons: as nutrients for crops, for soil structure. In van den Elsen et al. (2019) based on the extensively measured dataset (CC-NL) the state of Dutch agricultural soils is shown in the Netherlands, a so-called baseline measurement soil quality. It thus reflects the state of the Dutch agricultural soils in 2018 again without a quality assessment. That is also what we do in this chapter, we present the results without a quality assessment.

6.2 Measurements and methods

Measurements of the soil chemical parameters pH, POXC, Ntot, Ptot, Ctot, Corg, DOC and Pw were carried out in 2019 and 2022. Nmin and DOC were only measured in 2022 and K only in 2019. The mixed samples were taken in the top layer of the soil (depth 0 till 20-30 cm-sl) in the month October. In 2019 24 samples were taken and in 2022 23 samples. The location of the sampling points are given in chapter 2. The analysis methods are given in Table 6-1.

Table 6-1 *Parameters and analysis method.*

Parameter	Description	Device	Method	Reference
pH	Acidity soil	pH-meter	pH-H2O	ISE989 ISO 10523
K	Kali status	ICP-OES	Extraction K-HCl	ISE989 Houba et al, 1988
C org	Total organic carbon	LECO	HCl fumigation	ISE 854 Walthert et al, 2010
C tot	Total carbon	LECO-CHN	-	ISE989 Bisutti et al, 2004
DOC	Hot water carbon	SFA-TOC	Water extraction 80C	ISE 854 Ghani et al, 2003
N min	Potentially mineralizable nitrogen	SFA-KCl	7 days incubation 40C	ISE 854 Robertson et al, 1999
N tot	Kjeldahl total nitrogen	SFA-0.8M H2SO4	destruction H2SO4-H2O2-Se	Novozamsky, 1983
POX-C	Stable fraction organic material	spectrofotometer	KMNO4 Permanganate Oxidizable Carbon	ISE 854 Culman et al, 2012
P tot	Kjeldahl total Phosphorus	SFA-0.8M H2SO4	destruction H2SO4-H2O2-Se	ISE989 Novozamsky et al, 1983
P	Phosphate status	SFA-H2O/CaCl2	Pw SFA-CaCl2	ISE989 Murphy and Riley, 1962

In the following paragraphs the analysis of chemical compounds is presented. In figures the sample concentrations are given. Also an statistical analysis has been performed. The non-parametric test of Wilcoxon has been used. When comparing management types a non-paired test has been used. When comparing years within a management type a paired test has been performed. We used a statistical significance level of 0.05. The null hypothesis is that the distributions of x and y do not differ.

6.3 Results

6.3.1 Acidity

The acidity (pH) of the soil influences the availability of nutrients in the soil for absorption by a crop (de Haan et al, 2021). In addition, the acidity also influences soil life (including activity), decomposition of organic matter and the structure of the soil. Target and/or reference values of soil acidity depend on soil type, organic matter percentage and crop rotation. Target values for pH determined in a CaCl2 solution can be found in the "Handboek bodem en bemesting" (CBAV, n.d.). The optimal range for pH-CaCl2 values usually lies between 6.4 and 7.6 (arable land on clay). The method used in this study (pH-water) usually results in 0.5 till 1.0 point higher than pH-CaCl2 values.
Figure 6-1 shows measurements for acidity. The measured pH-water values are in the range 8.1 till 8.5, which equals pH-CaCl2 values of 7.3 till 7.7. That is in the optimal range for arable land on clay.

There are no significant changes between the management types (per year) and between the years (per management type).

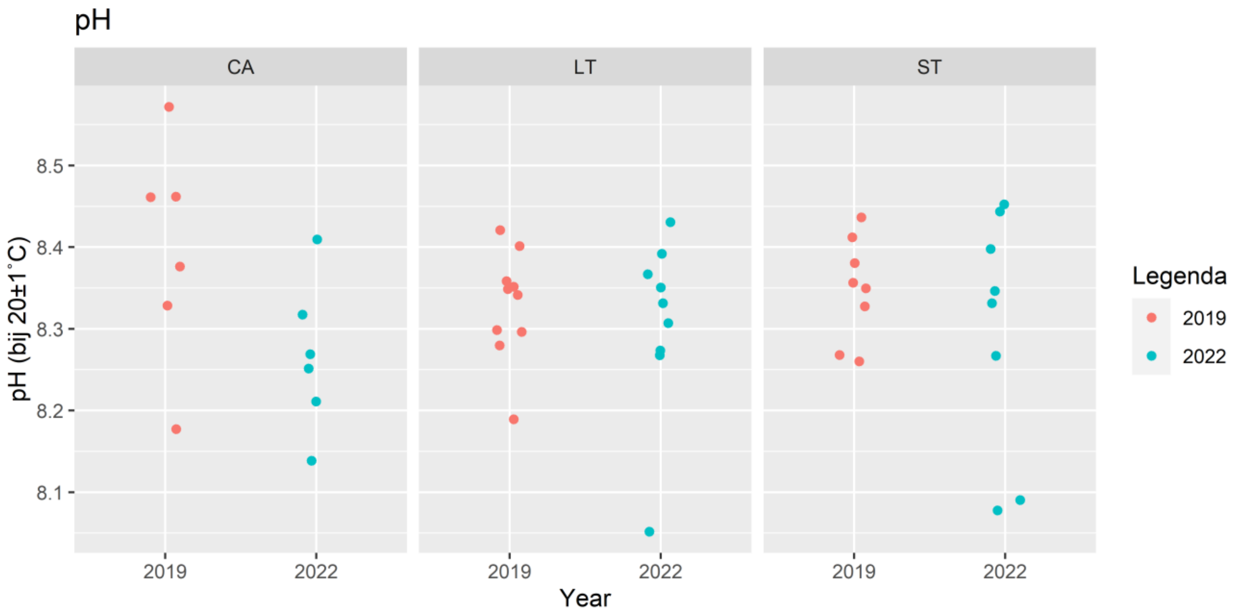

Figure 6-1 *Soil Acidity (pH) in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

6.3.2 Nitrogen

Nitrogen (N) is one of the essential nutrients for plant growth and development.

N-total consists of nitrogen which for the most part (approx. 99%) is present in organic material and is therefore not immediately available for uptake by a crop. As shown in Figure 6-2, the total nitrogen concentrations show quite a big variation and the ranges overlap. Statistically only for the LT-management there is a significant increase 0,3 g/kg from 2019 till 2022. Significant changes between the management types (per year) could not be shown.

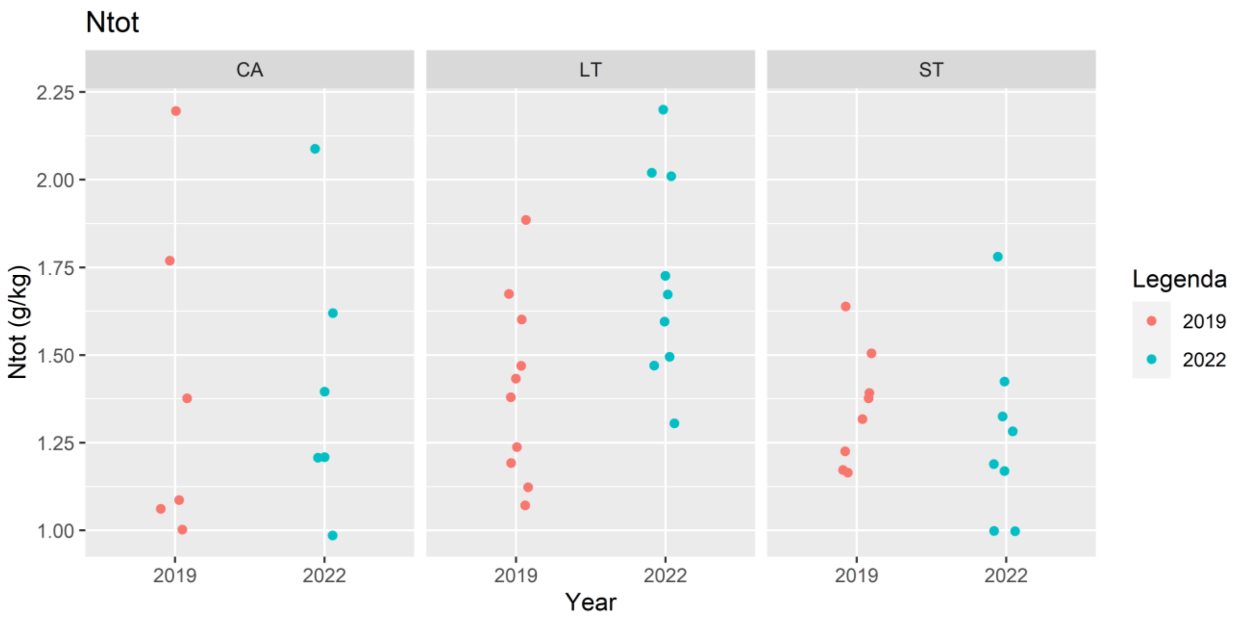

Figure 6-2 *Total Nitrogen in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

The potentially mineralizable nitrogen (Nmin) is the amount of soluble mineral nitrogen (NO_3 and NH_4) in the sampled layer of the profile. Nmin was only analysed for the year 2022 and therefore gives an insight in the differences between the management of the fields in this year. In the fields with regenerative agriculture, the variation in Nmin is larger in comparison to the CA-fields (Figure 6-3). There is a statistically significant lower Nmin concentration for the LT-management in comparison to the CA-management; this difference equals 6.3 mg/kg. As can be seen in the figure, most of the points for the LT-management are in the part with the lower concentrations, which explains the detected significant difference.

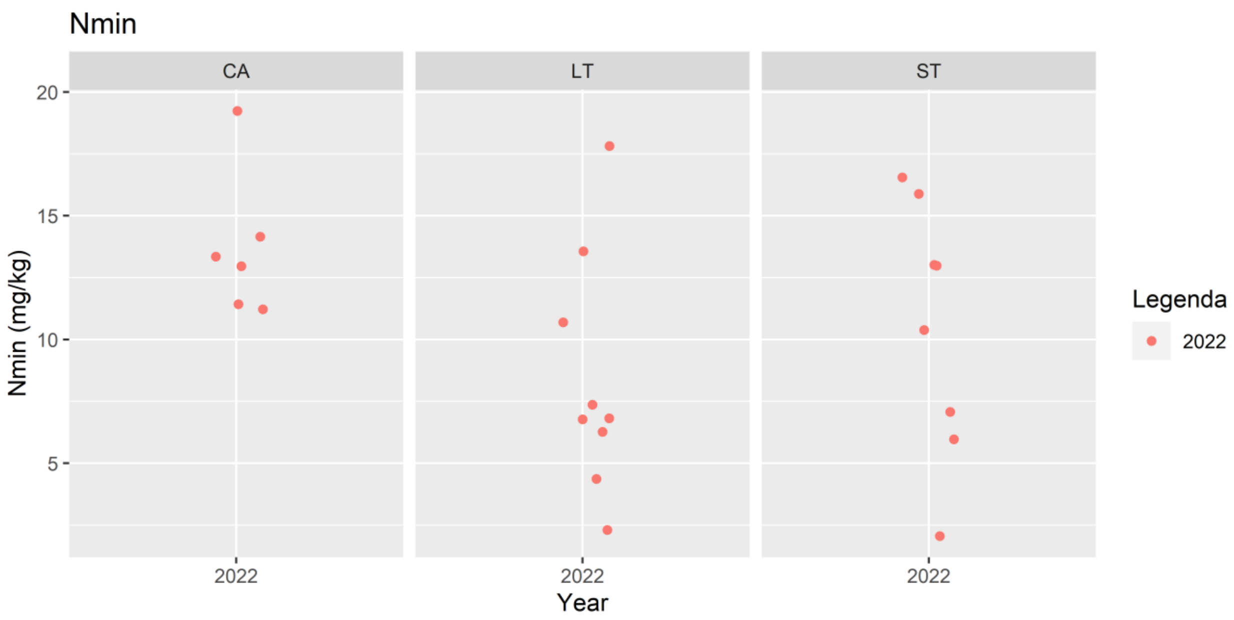

Figure 6-3 *Mineralizable soil nitrogen in the topsoil (0-30 cm) in 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

6.3.3 Phosphate

Phosphorus is one of the essential nutrients for plant growth and development, in the form of phosphate. Fertilization recommendations take into account the phosphate status.

The measurements of available phosphate (P-CaCl2) per management type are displayed in Figure 6-4. The ranges in concentrations do not show significant differences for the management types and there is also no difference between 2019 and 2022 for the CA- and LT-management. An exception is the lower median P-CaCl2-concentration in 2022 for the ST-management compared to 2019 (there is a significant decrease of 6 mg/l).

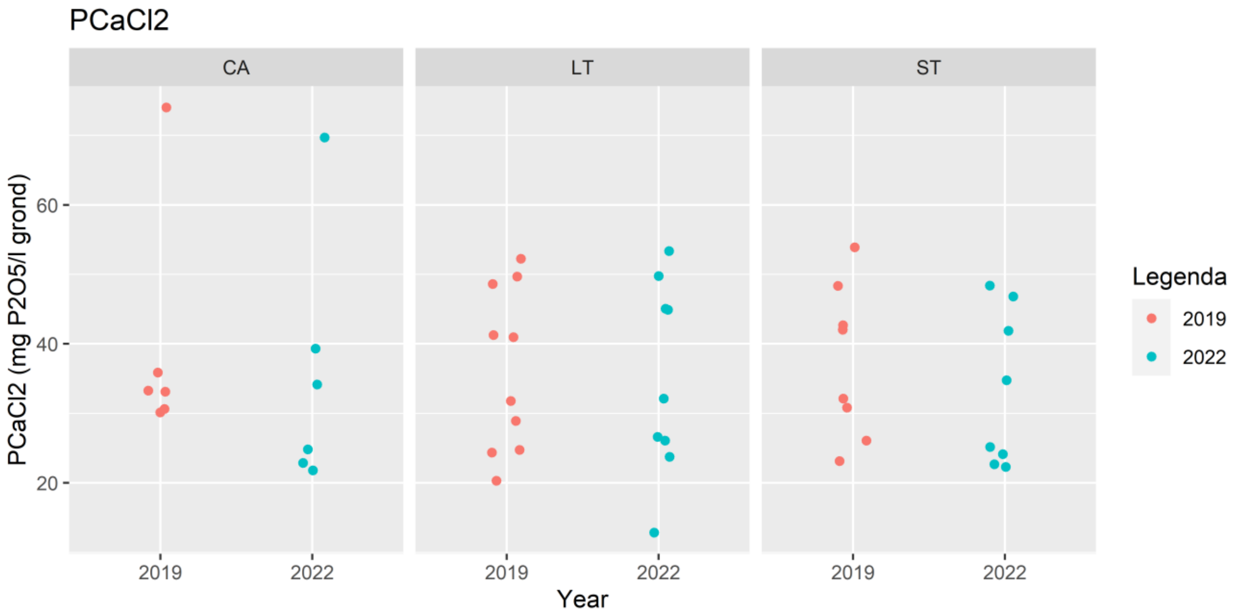

Figure 6-4 *Available phosphate (P-CaCl2) in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

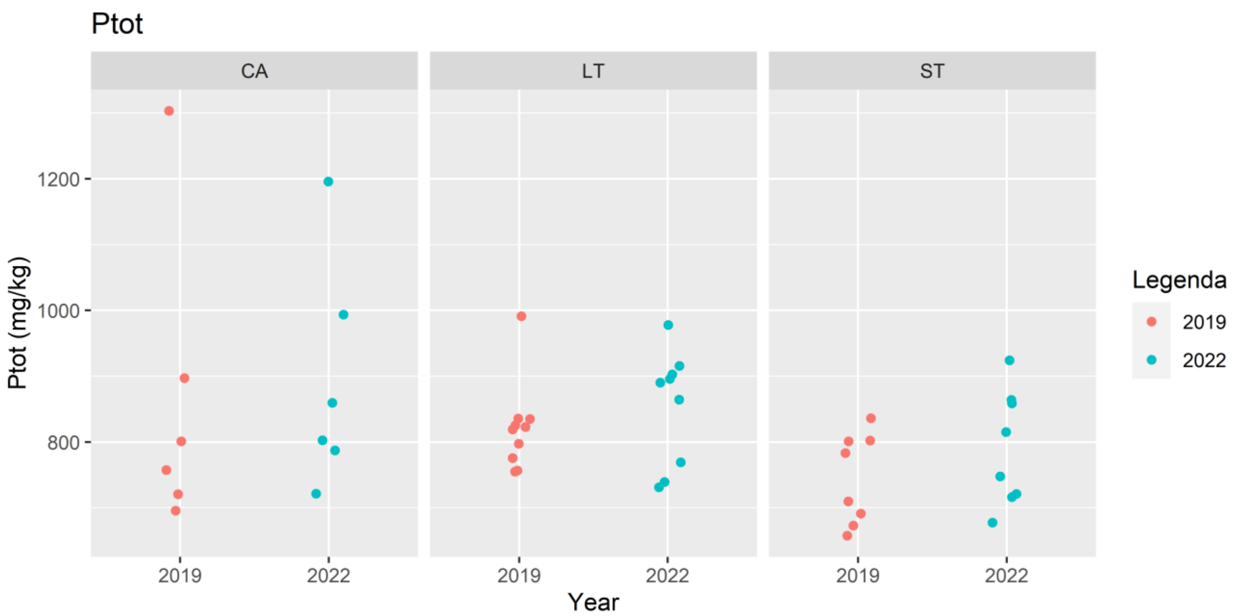

Figure 6-5 *Total P in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

Figure 6-5 shows a big variation in concentrations of total phosphate for all management types. The ranges for the management types do overlap, therefore on base of these data there is no significant difference per management type. A significant change in concentration between 2019 and 2022 is only present for management type ST; this equals a rise in concentration of 56 mg/kg.

6.3.4 Potassium

Potassium, like phosphorus and nitrogen, is one of the essential nutrients for plant growth and development. Potassium is relatively mobile in soil and sensible to leaching during rainfall.

Figure 6-6 shows the results of the measurements on potassium in the topsoil of the study fields in 2019 and 2022. In both years, potassium was found in higher concentrations in the fields with regenerative agricultural management than in the fields under conventional agricultural management. The fields with the regenerative management have an 80 till 110 mg/kg higher potassium concentration. Probably this is a result of the use of compost and solid cow manure for the regenerative management, which slowly releases potassium and therefore builds up a bigger stock in the soil.

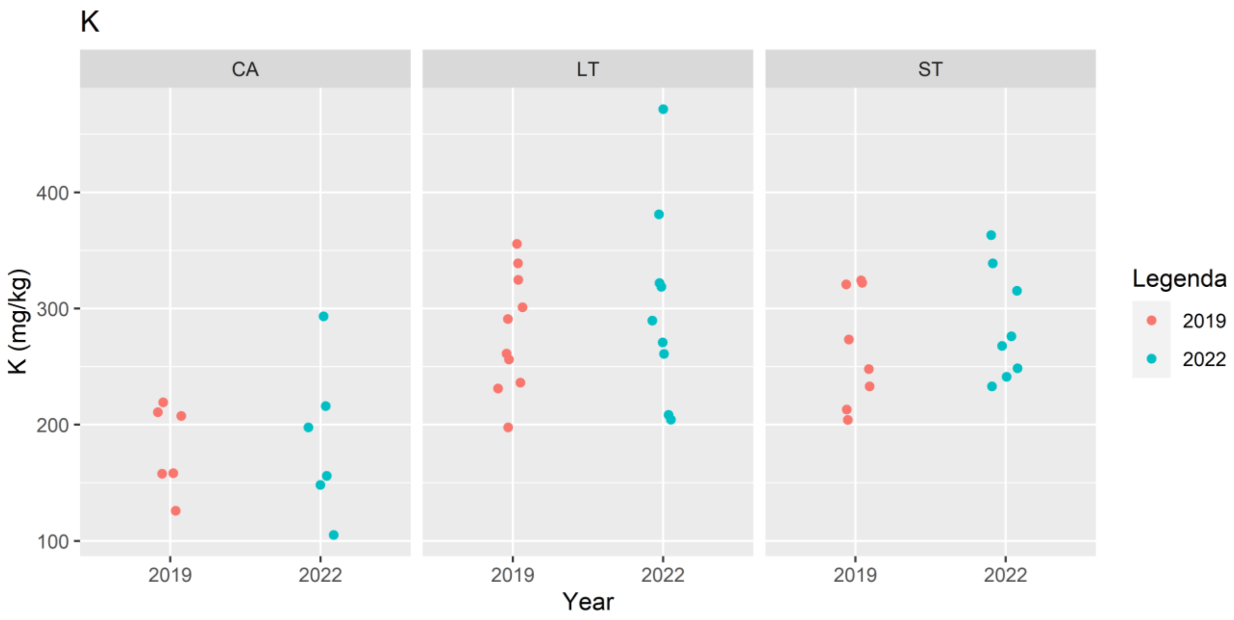

Figure 6-6 *Potassium (K) in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

6.3.5 Soil carbon

Different types of soil carbon are discriminated. In Table 6-2 three types are mentioned that are analyzed in this paragraph. In chapter 4 an extensive analysis of soil organic carbon is given. The results in this paragraph are complementary to those in chapter 4.

Table 6-2 *Overview of measurements on soil carbon.*

Parameter (method)	2019	2021	Description	Range	Unit
C (POXC)	V	V	labile organic matter	ca 400-600	mg/kg
Corg	V	V	total organic carbon	ca 15-24	g/kg
Ctot	V	V	total carbon	ca 23-24	g/kg

Labile soil carbon (indicated by C in this report) is an important component of soil organic matter because it embodies the mineralizable material that is associated with short-term fertility. The labile fraction of the soil carbon pool is sensitive to soil management.

Figure 6-7 shows the measured POXC-concentrations per management type. At the short-term (ST) regenerative fields there is a significant increase of 50 mg/kg in three years. There are no significant changes between the management types (per year).

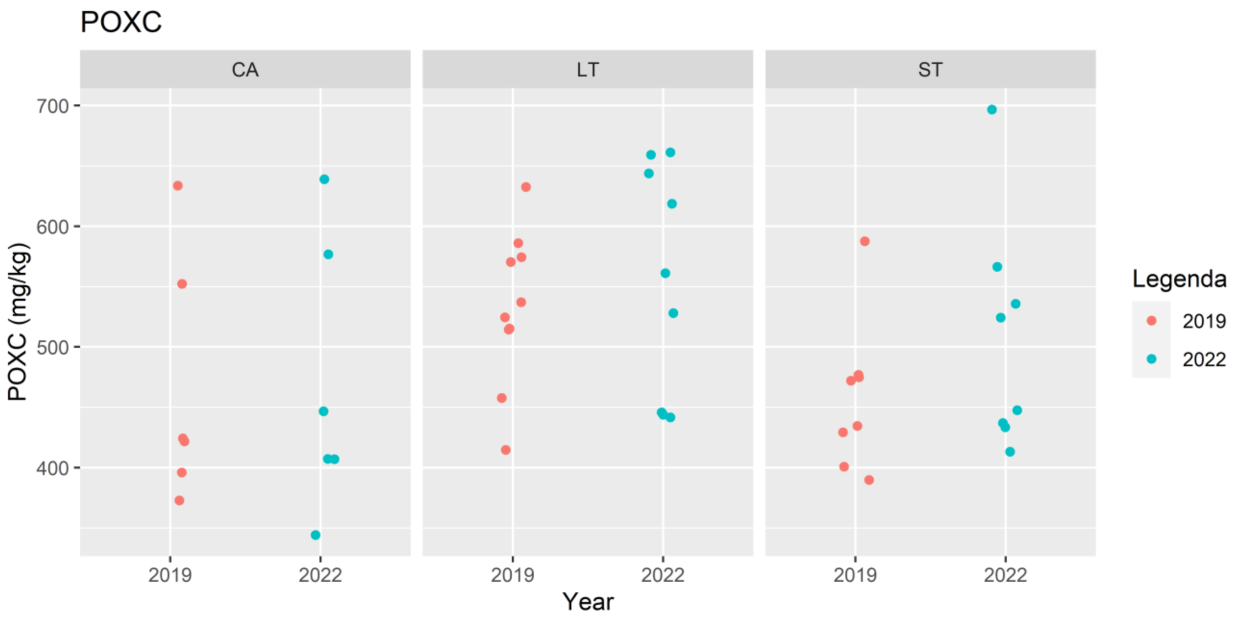

Figure 6-7 *Labile soil carbon content (POXC) in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

Total carbon (Ctot) consists of all forms of carbon in the soil (organic and inorganic); the soil organic carbon (Corg) content includes only the organic form. The observations on total organic carbon are presented in Figure 6-8. The total carbon content (Ctot) has decreased a little over the years. This is statistically significant for the LT and ST management; the decrease in concentration equals resp. 1.1 and 0.9 g C/kg. It is not clear what the causes of this decline are; probably differences in weather or in the type of manure applied.
Statistically no significant difference could be shown in concentration between the management types, although the range in concentrations is higher at the CA-management in comparison to the regenerative fields.

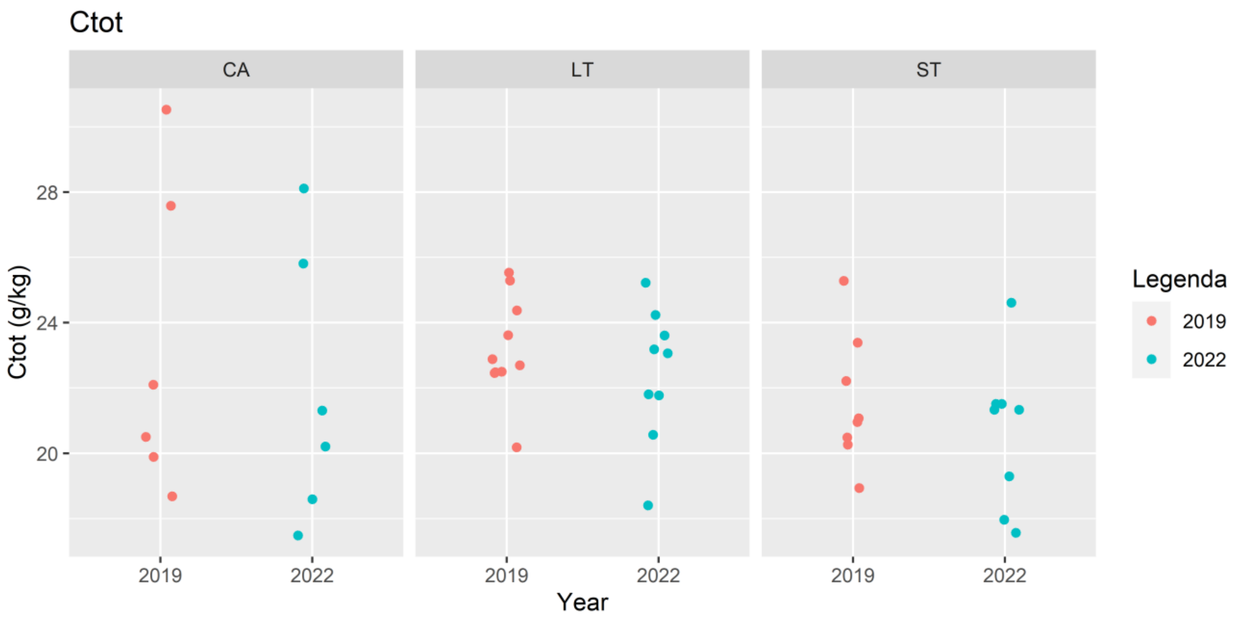

Figure 6-8 *Ctot: Total carbon in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overplotting.*

The observations on soil organic carbon are presented in Figure 6-9. Statistically there can no significant differences be shown in concentrations between the management types. Only for the LT-management there is a significant increase in concentration from 2019 till 2022, equaling 1.3 g C/kg. To convert g C/kg to g SOM/kg a multiplication factor of about 2.0 (Pribyl, 2003) should be used; so 1.3 g C/kg equals an increase of 2.6 g SOM/kg, which equals an increase of 0.83 g SOM/kg.year, that's about 0.083 percent point/year. This increase is close to the increase found in chapter 4, which equals 0.101 percent point per year.

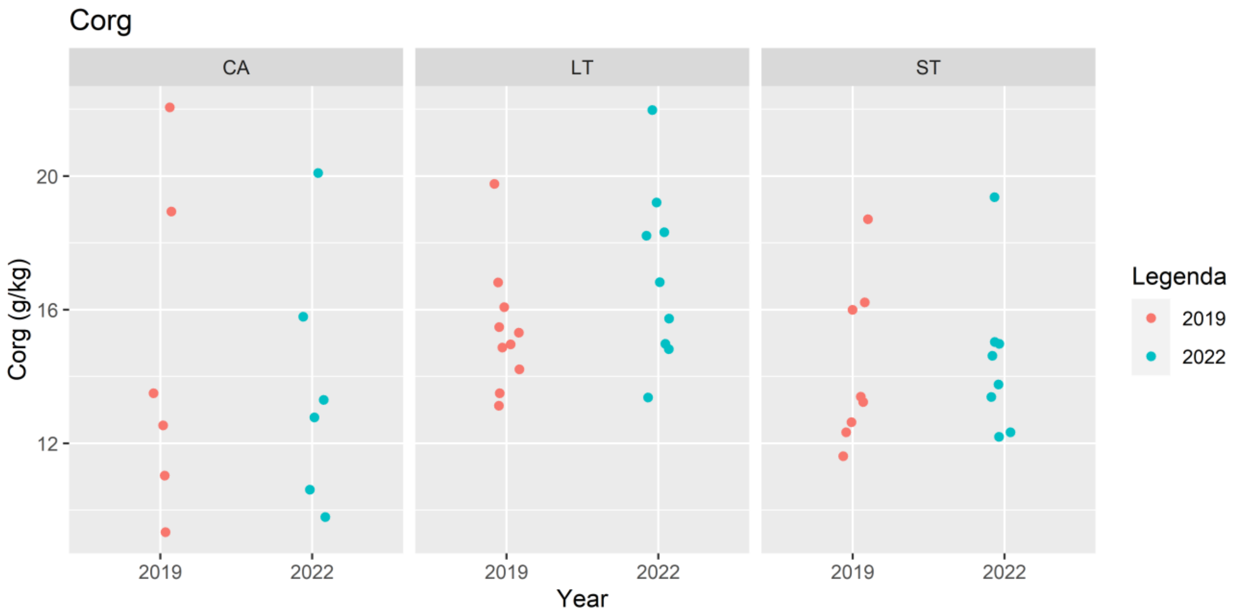

Figure 6-9 *Corg: Labile soil carbon in the topsoil (0-30 cm) in 2019 and 2022 per management type. Note that the dots are jittered in horizontal direction to avoid overfitting.*

6.4 Conclusion

An overview of the analysis results is given in Table 6-3, presenting the changes in time (2019 and 2022) per management type, and Table 6-4, which gives the differences between the management types.

Table 6-3 *Time dependent differences in concentration per management type (n.s.: not significant, for PCaCL2 and ST management -6.0 means the concentration in 2022 was 6 mg/l lower in 2022 than in 2019).*

	Difference between 2019 and 2022		
Parameter	**CA**	**LT**	**ST**
pH (-)	n.s.	n.s.	n.s.
Ntot (g/kg)	n.s.	0.3	n.s.
PCaCl2 (mg/l)	n.s.	n.s.	-6.0
Ptot (mg/kg)	n.s.	n.s.	55.5
K (mg/kg)	n.s.	n.s.	n.s.
POXC (mg/kg)	n.s.	n.s.	49.7
Corg (g/kg)	n.s.	1.3	n.s.
Ctot (g/kg)	n.s.	-1.1	-0.9

Table 6-4 *Differences in concentration depending on management type (n.s.: not significant, -6.3 means the concentration in 2022 at the LT management was 6 mg/l lower at the CA management).*

	Difference between management			
	2019	**2022**	**2019**	**2022**
	CA en LT	**CA en LT**	**CA en ST**	**CA en ST**
pH	n.s.	n.s.	n.s.	n.s.
Ntot	n.s.	n.s.	n.s.	n.s.
Nmin	-	-6.3	-	n.s.
PCaCl2	n.s.	n.s.	n.s.	n.s.
Ptot	n.s.	n.s.	n.s.	n.s.
K	93.0	113.0	77.5	95.0
POXC	n.s.	n.s.	n.s.	n.s.
Corg	n.s.	n.s.	n.s.	n.s.
Ctot	n.s.	n.s.	n.s.	n.s.
DOC	-	n.s.	-	n.s.

A change in the acidity between 2019 and 2022 could not be shown. Differences in acidity between management types could also not be shown. The measured pH-water values are in the range 8.1 till 8.5, which equals pH-CaCl2 values of 7.3 till 7.7. That is in the optimal range for arable land on clay.

The total nitrogen concentrations in the fields of the farm show quite a big variation and the ranges overlap. Statistically only for the LT-management an increase 0,3 g/kg from 2019 till 2022 could be shown. Significant changes between the management types (per year) could not be shown.

For the year 2022, there is a statistically significant lower Nmin concentration for the LT-management in comparison to the CA-management; this difference equals 6.3 mg/kg. No significant difference was found between the ST and CA-management.

The measurements of available phosphate (P-CaCl2) per management type do not show significant differences for the management types and there is also no difference between 2019 and 2022 for the CA- and LT-management. Only for the ST-management the P-CaCl2-concentration has a statistically significant a decrease of 6 mg/l in 2022 compared to 2019.
For Ptot there is no significant difference per management type. A significant change in concentration between 2019 and 2022 is only present for management type ST; this equals a rise in concentration of 56 mg/kg.

Potassium in the topsoil in 2019 and 2022 was found in higher concentrations in the fields with regenerative agricultural management than in the fields under conventional agricultural management. The fields with the regenerative management have an 80 till 110 mg/kg higher potassium concentration.

For both POX-C and Corg there are no significant differences in concentrations between the management types. Only for the LT-management there is a significant increase in concentration from 2019 till 2022, equaling 1.3 g C/kg. To convert g C/kg to g SOM/kg a multiplication factor of about 2.0 (Pribyl, 2003) should be used; so 1.3 g C/kg equals an increase of 2.6 g SOM/kg, which equals an increase of 0.83 g SOM/kg.year, that’s about 0.083 mass%/year. This increase is close to the increase found in chapter 4, which equals 0.101 percent point per year.

7 Qualitative field observations

Farmers have a close relation with the soil they are living on and with. They work the soil, feel with their hands how consistent it is and watch the crops grow. This is not quantitative information, but it is the information on the basis of which in earlier times the farmer made decisions. For example, to plough the soil or to postpone it, to apply irrigation or to wait for a possible shower, to harvest the crops or to continue growing. This, too, is valuable information, although perhaps less reliable than measurements. On the other hand, a measurement in the field usually concerns a point location, whereas the experience of a farmer concerns the whole field.

For the fields in longer transition to regenerative agriculture (the LT-fields), some qualitative observations were obtained in 2019 and 2020, with reference to the fields under conventional agricultural management:

- **Improved soil structure:** airy, less compacted soils were observed, with better water infiltration.
- **Improved water holding capacity:** despite dry summer(s), no or almost no irrigation was required.
- **Higher crop yields and improved quality:** high(er) crop yields and crops of better quality were obtained.
- **Decreased workability of the fields:** the workability of the soil was less easy.
- **Improved soil life:** high counts of worms and the presence of fungi structures throughout the soils demonstrated an improved status of soil life.

8 Discussion

In the analysis of the SOM and SOC content it turned out that both results are very close to each other. For SOC an increase in SOM at the long term regenerative management of 0.083 percent point/year was derived. This increase is close to the increase in SOM (based on Loss of Ignition as described in chapter 4), which equals 0.101 percent point per year. This strengthens the conclusion on the positive effect of regenerative agriculture om the soil organic matter content.

This soil organic matter is decomposed by soil life, it is the fuel for soil life. In this study no measurements on soil life were not taken, so these observations cannot be verified with measurements. Probably in future it will be easier and cheaper to do so.

Aggregate stability is also related to soil life (Nimmo and Perkins, 2002). As worms can aggregate soil particles and also fungi do (by producing glomalin, a kind of soil glue). Also for the LT-management a significant increase in WSA (Water Stable Aggregates) was found.

It is striking that for the short term regenerative management the same positive effects as for the long term regenerative management were not found. Probably it takes time for regenerative practices to manifest effects or probably the lower manure inputs at this site were the cause.

For soil compaction no differences in time were found at the fields with regenerative management, but it is known that recuperation of soil compaction of deeper layers is very difficult to realize ().

In van den Elsen et al. (2019) based on the extensively measured dataset (CC-NL) of more than a thousand locations across the country in 2018, the state of Dutch agricultural soils is shown in the Netherlands, a so-called baseline measurement soil quality. For the determination of the quality of agricultural soils in the Netherlands, the list 'Soil Indicators for Agricultural Soils in the Netherlands (BLN 1.0) was leading. It thus reflects the state of the Dutch agricultural soils in 2018 again without a quality assessment. The data in this study are used as reference values for the clay soil type with arable crops. These values are not indicators values for soil quality. They only reflect the common state of soils in the Netherlands.

Table 8-1 *Reference values Dutch agricultural soils and project measurements.*

Parameter	Unit	Reference value	This project
SOM (LOI)	%	3.25 (2.79 -3.70)	3 – 5
Intrusion resistance	MPa	1.09 (0.61 – 1.56)	Variable with depth!
Bulk density	kg/dm3	1.29 (1.15 – 1.43)	1.4 – 1.6
pH	-	7.23 (6.46 – 8.00)	7.3 – 7.7
Ntot	mg/kg	1700 (1458 - 1941)	1000 - 2200
PMN	mg/kg	50.3 (43.0 – 57.6)	2.5 – 19
P-CaCl2	mg/100g	2.29 (1.44- 3.15)	1.3 – 4.6
Ptot	mg/100g	55.4 (37.8 – 72.9)	65 – 120

9 Summary of results, conclusions and project synthesis

9.1 Overview results measurements and conclusions

An overview of the results on the determinations of soil properties in the farm is given in this chapter. The soil characteristics are valued on a five point scale. The interpretation of scores to effects of agricultural management is explained in Table 9-1. The scores are relative to the CA-management (and therefore this management is scored with solely the "="-indicator).

Table 9-1 *Legend for the assessment of soil characteristics (the symbol "?" means that a statistical test could not be performed or the results of the statistical test were ambiguous).*

Class	Effect of management relative to the reference management CA
	Positive
	Slightly positive
=	Inconclusive
	Slightly negative
	Negative
?	Unclear

In Table 9-2 the scores of the assessment of the soil characteristics are given.

Table 9-2 *Assessment of the soil characteristics.*

Characteristic	CA Reference	LT Long term	ST Short term
Lab measurements			
Bulk density	=	?	?
Water holding capacity	=	?	?
Soil organic matter (LOI)	=		=
Acidity	=	=	=
Nitrogen	=	=	=
Potassium	=		
Phosphate	=	=	
Carbon	=		=
Aggregate stability	=		=
Soil compaction	=	?	=
Qualitative observations			
Soil structure	=		?
Water holding capacity	=		?
Crop yield and quality	=		?
Workability	=		?
Soil life	=		?

For nitrogen there is an increase from 2019 to 2022 of 0.3 g/kg. But on the other hand, the Nmin concentration is significantly lower for the LT management than for the than the ST-management. Therefore, a score of indifferent "=" is chosen.

Overall the results of the field campaign shows that fields with long term regenerative agricultural management have a higher mean SOM content than fields with conventional management. For the long term regenerative management, soil organic matter content (LOI and organic carbon) and aggregate stability are higher in 2022 compared to 2019. For the short term regenerative management the effects are less pronounced. Probably it takes time for a field to pick the fruits of regenerative practices.

The measurements on soil compaction show that the soil compaction depth, where the mean penetration resistance surpasses 3 MPa, is largest for LT at around 50 cm, whereas it lies around 40 cm for both CA and ST. There is no trend over the years, so probably this is a result of other factors. Therefore we concluded that it is unclear what the effect of management is. It is known that soil compaction of deeper layers (>40 cm-sl) is very hard to recuperate (Brus and van den Akker, 2018).

Another positive effect is the high potassium concentration at the ST and LT field.

There are found no differences for the parameters acidity, nitrogen and soil compaction. For phosphate a slightly negative score was found for the short term regenerative management.

For the parameters bulk density and water holding capacity only one location per management type was selected. Therefore it is not possible to perform statistical significance tests on differences in mean WHC between CA, LT. Increasing the number of samples would probably help to determine the influence of these parameters. But these lab analysis are costly.

The qualitative field observations for the LT-field are scored as slightly positive, except for the workability. Chosen is for "slightly" because it concerns not a measurement but an experience of the farmer.
The qualitative observations of the farmer are a valuable source of information on what regenerative agriculture can do in practice. The farmer mentioned that the fields under regenerative agriculture had a better soil structure, a higher water holding capacity but a decreased workability. He also mentioned an improved soil life. Measurements on soil life were not taken, so these observations cannot be verified with measurements.

9.2 Synthesis of the three reports

To come to an overview of the results of the three reports, we first summarise the results of the two previous reports and then synthesize these with the results of this report.

Regenerative agriculture at the studied farm
The term regenerative agriculture is used differently depending on the country it is applied in and overlaps with various other terms such as organic agriculture, circular agriculture, permaculture, etc.

Regenerative agriculture is investigated on the farm de Klompe in de Hoeksche Waard. The farm has ten fields with three different management strategies: 1) fields that are under regenerative agriculture since 2010 (LT), 2) fields that are in transition towards regenerative agriculture (ST), and 3) fields still under conventional agriculture (CA). All fields have sandy clay soils. More than 75% of the crops in the rotation applied are onion, potato, wheat and brown bean. The most present crop in the rotation is wheat (32%).

From 2019 till 2022, fields have been sampled on different locations of the farm to compare effects of regenerative and conventional agriculture on soil quality and crop yield and quality. For this comparison several physical and chemical soil properties were measured.

Carbon report (Heesmans et al, 2023)
The focus of this report is on long-term storage of organic carbon in the soil. The report consists of three parts.

Firstly, the effects of several management practices used in regenerative agriculture on organic carbon (OC) in Europe are described in the report according to literature. The selected management practices were expected to have an impact on soil organic carbon. The effects of the management practices on soil organic carbon are:

- minimum tillage increases the soil organic carbon content between 1 - 21% in the topsoil throughout Europe;
- organic fertilizer application had both positive and negative effects on soil organic carbon content when looking at indicators such as soil quality, climate change and productivity, but additions of farm yard manure amendments and cattle slurry significantly increased SOC by respectively 21% and 19%;
- crop management such as improved crop rotation and cover crops add far less carbon to the soil over 20 years (0.01-0.04% SOC);
- biodiverse grassland, which is grassland with herbs, accumulates carbon much faster than other types of permanent grassland.

Secondly, the report presents the results of field data on soil organic carbon, collected between 2019 and 2020.

Thirdly, the effect of the three different management strategies (CA, LT and ST) on carbon sequestration on the farm was analysed using modelling with the multi-pool deterministic C model RothC. The carbon balance was most positive on the fields that are under regenerative agriculture. These fields also received the highest amounts of C input. Regenerative agriculture brings more organic carbon to the soil compared to the conventional agricultural regime.

Report on simulation of crop growth and water holding capacity (Dik et al., 2022)
This report describes the water availability for crops and the change of runoff and drainage fluxes to canals. For the farmers water availability is of major importance to the development of the crop. The water board requires information on runoff and drainage fluxes to the canals for the water management in the area.

Fields with regenerative and conventional agriculture were studied. The simulation model SWAP (Kroes et al., 2017) was used to determine the effect of several practices in regenerative agriculture on the soil water dynamics. Collected data on soil properties and water contents were used to parameterize and calibrate the model. The practices and aspects of the soil water dynamics are shown in Table 9-3, together with the results of the scenario-analysis: in Table 9-4 the 5 point scale is presented.

Table 9-3 *Effects of measures on Transpiration and Runoff/Drainage (in reference to a situation without measure). Legend for effects in Table 9-4.*

Measure	Effect on Transpiration	Effect on Runoff	Effect on Drainage
Extra organic matter	+	+[1] ?	0/+[1] ?
Enlarged rooting depth by less soil compaction	++	0[2]	0/+[2]
Higher infiltration capacity	0	0/+[2]	0
Increased permeability (till 80 cm-ss)	0	0	0
Lower bulk density	-/+ ?	0 ?	0/+ ?

? uncertain: due to uncertainties in the method.
[1] not calculated.
[2] dependent on the soil.

Table 9-4 *Quantification to a 5 points scale of the effect on Transpiration and Runoff/Drainage.*

Classification	Effect on Transpiration (mm/y)	Effect on Runoff (mm/d)	Effect on Drainage (mm/d)
++	> 15	<-5	<-5
+	5 till 15	-5 till -2	-5 till -2
0	-5 till 5	-2 till 2	-2 till 2
-	-15 till -5	2 till 5	2 till 5
--	<-15	> 5	> 5

For transpiration (linked to the yield) the most sensitive parameter is the rooting depth. The rooting depth depends on soil compaction, the presence of macropores and the presence of fungi. Fungi can help crops to get more water: they increase the depth to which the roots can extract water. Regenerative agriculture influences all these dependencies in a positive way.

For runoff the most sensitive parameters are soil texture and structure, and as a result of that the infiltration capacity. The simulations show a low runoff in the reference situation. As a result, the decrease of runoff at higher infiltration capacities is also low. For drainage fluxes to the canals, the scenarios show a varied outcome. There can be a positive effect due to regenerative agriculture, but it depends on the circumstances (wet or dry soil).

Overall, according to the model study, extra organic matter, enlarged rooting depth, less soil compaction, higher infiltration capacity, and increased permeability will have a neutral or positive effect on transpiration, runoff and drainage. All the effects of regenerative agriculture are predicted to occur at the same time. So overall, it is expected that regenerative agriculture will have positive effects on 1) water availability for the crops and 2) reduction of runoff and drainage fluxes to the canals.

Synthesis: "A case study on the efficacy of regenerative agriculture" with the Carbon report and the WHC simulation report
Two research questions were formulated in paragraph 1.2, we will answer these questions in the synthesis of the project results as described in the three reports.

<u>Does regenerative agriculture change the soil and water properties?</u>
Overall, the results of the measurements presented in this report show that soil organic matter content (as determined by LOI, chapter 4, and Corg paragraph 6.3.5) is higher in the LT-field than in the other fields. This is in line with the Carbon report (Heesmans et al, 2023), where it is concluded that regenerative practices (minimal tillage, additions of farm yard manure and cattle slurry) work out positively on the carbon stock in the soil.

The qualitative observations of the farmer are a valuable source of what regenerative agriculture can do in practice. The farmer mentioned that he had a better soil structure, a higher water holding capacity but a decreased workability on the fields under regenerative agricultural management. He also mentioned an improved soil life. Measurements on soil life were not taken, so these observations cannot be verified with measurements. The farmer also mentioned high(er) yields and crops of better quality. He also mentioned that for the long term regenerative fields the workability of the soil was less.

The long term regenerative agriculture shows more aggregate stability in 2022 in comparison to 2019.

Differences could not be found between fields under conventional and regenerative agricultural management for soil compaction and the parameters acidity and nitrogen. It is known that recuperation of soil compaction of deeper layers is very difficult to realize. For phosphate a slightly negative score was found for the short term regenerative management. These aspects are not subject in the Carbon and WHC report, so these cannot be verified with these reports.

<u>Does regenerative agriculture increase the water availability for crops in comparison to conventional agriculture?</u>
The report on the simulation of crop growth states that the effective rooting depth depends on soil compaction, the presence of macropores and the presence of fungi. Fungi can help crops to get more water by increasing the depth to which the roots can extract water. This higher water availability is in line with this study where the qualitative field observations state that at the long term regenerative fields there is almost no irrigation required.

So overall the conclusions of the Carbon report (Heesmans et al, 2023), the Report on simulation of crop growth and water holding capacity (Dik et al., 2022) and this report are pointing in the same direction: the results show that the measures of regenerative agriculture can increase the soil organic matter content, can result in a better soil structure (more aggregate stability) resulting in as the farmer observes high(er) yields, crops of better quality and better water availability (less irrigation is required), but also a worse workability of the soil.

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Annex 1 Penetration resistance plots

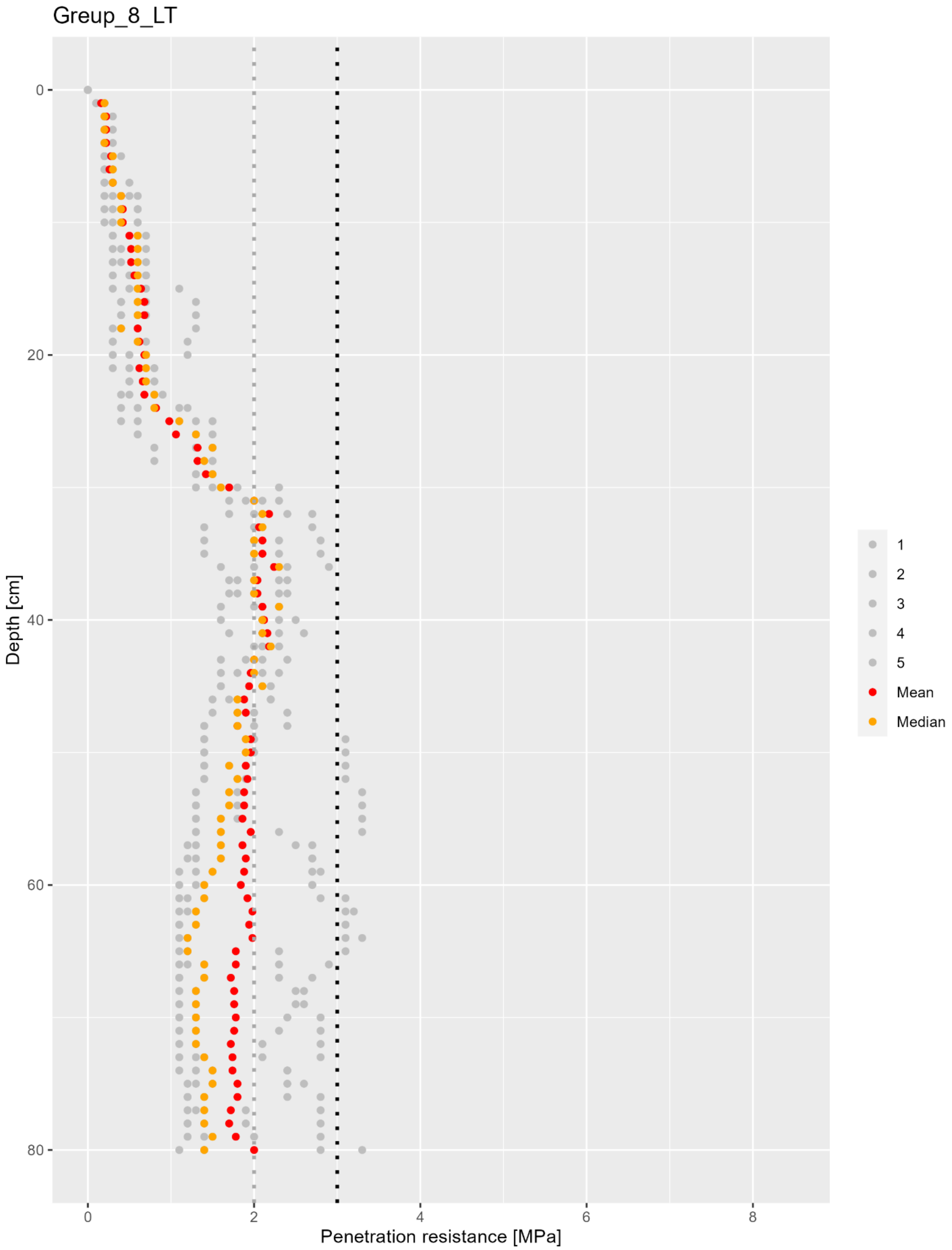

Figure A1.1 *Example of penetration resistance depth profile that does not surpass the 3 MPa threshold.*

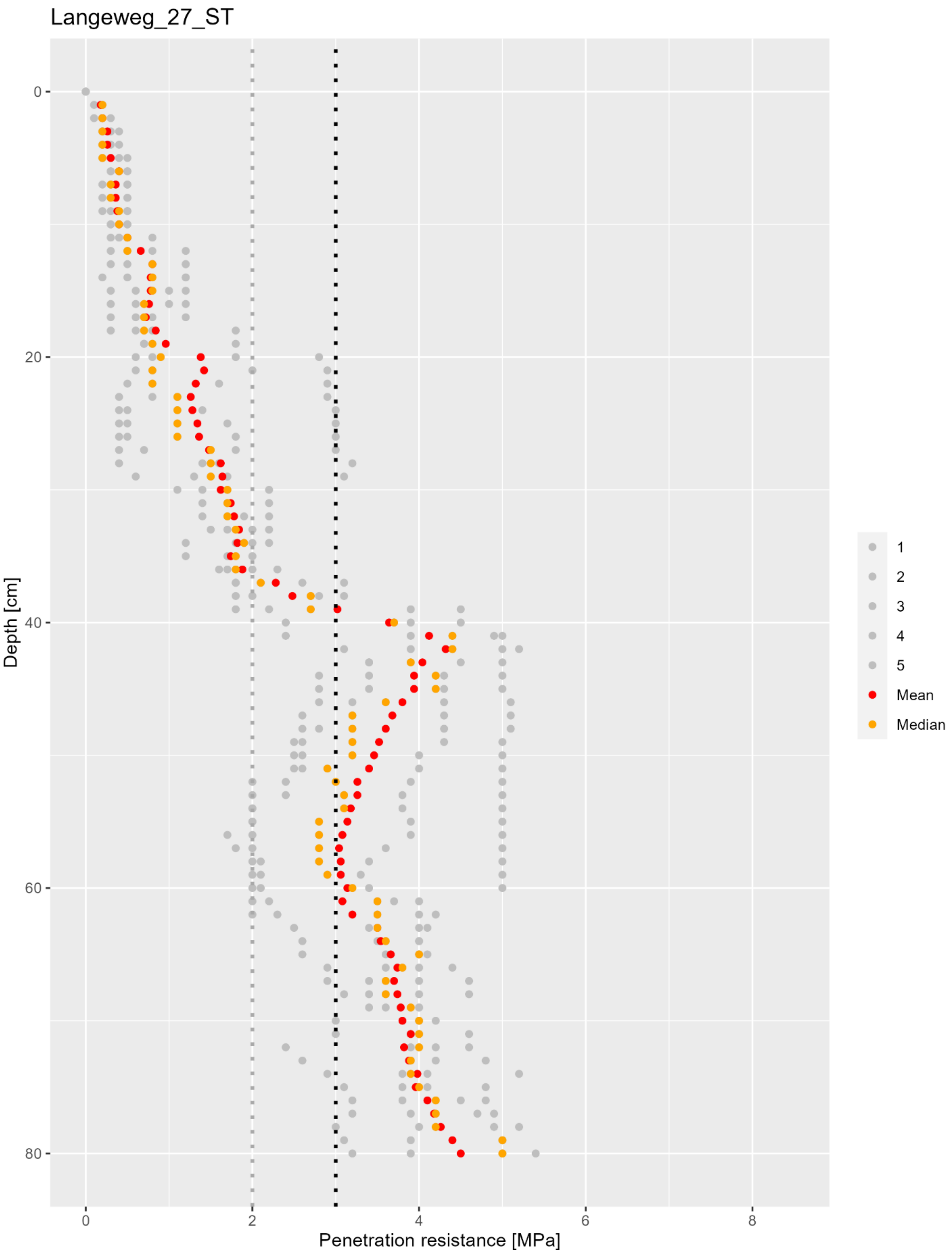

Figure A1.2 *Example of penetration resistance depth profile with a clear disturbing layer on the 40 cm depth, surpassing the 3 MPa threshold.*

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