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This research was commissioned by Stichting Soil Heroes Foundation.

Wageningen Environmental Research
Wageningen, April 2023

Reviewed by:
Jan Peter Lesschen (Wageningen Environmental Research)

Approved for publication:
Mirjam Hack-ten Broeke, teamleader of Soil, Water, Landuse

Report 3251
ISSN 1566-7197

WAGENINGEN
UNIVERSITY & RESEARCH

Heesmans, H.I.M., C.M.J. Hendriks, L. Barbieri, F.M. van Egmond, J. van der Veer, K. Teuling, 2023. *Regenerative Agriculture – a case study; Application and analyses of regenerative versus conventional agriculture in a case study in De Hoeksche Waard, the Netherlands.* Wageningen, Wageningen Environmental Research, Report 3251. 58 pp.; 22 fig.; 8 tab.; 69 ref.

Het rapport beschrijft wat regeneratieve en conventionele landbouw kan betekenen in de Nederlandse context. Daarnaast laat het rapport de feitelijke en potentiele voordelen van regeneratieve akkerbouw ten opzichte van conventionele akkerbouw zien met betrekking tot bodemkoolstofvastlegging voor een praktische case study op een Nederlandse boerderij op zeeklei.

The report describes what regenerative and conventional agriculture can mean in a Dutch context and shows the actual and potential benefit of regenerative agriculture compared to conventional agriculture with respect to soil carbon sequestration for a practical case study of a Dutch farm on marine clay soils in the Netherlands.

Keywords: soil carbon, soil carbon modelling, regenerative agriculture, on farm case study, Dutch regenerative agriculture, conventional agriculture

The pdf file is free of charge and can be downloaded at https://doi.org/10.18174/590704 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.

Wageningen Environmental Research Report 3251 | ISSN 1566-7197

Photo cover: PPO-agv, onions experiment Rusthoeve

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Verification

Report: 3251
Project number: 5200045476

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.

Approved reviewer who stated the appraisal,

position: researcher

name: Jan Peter Lesschen

date: 01-05-2021

Approved team leader responsible for the contents,

name: Mirjam Hack-ten Broeke

date: 07-04-2023

Preface

Soil carbon sequestration and regenerative agriculture have become household terms in soil, soil policy, agriculture and climate adaptation and mitigation discussions, research and activities in recent years internationally and in the Netherlands. This has intensified in the context of the national debate on adapting farming practices to improve soil health, reduce carbon emissions and increase sequestration, preserve and improve biodiversity. In this report we examine what regenerative agriculture means in a Dutch context in practice and what the potential and actual benefit of regenerative agriculture can be with regard to the maintenance and storage of carbon in agricultural soils in the Netherlands. Although this is exemplified by one practical case study on the Klompe farm of Soil Heroes in the Hoeksche Waard (South-West area in the Netherlands) the research methods and proposed soil management methods can be applied in other areas under similar conditions.

The report was written in 2021 and is published in 2023.

Summary

Regenerative agriculture is a hot topic in the scientific world, but applied examples in the field are scarce or not well monitored at the time of writing (2021). In the Hoeksche Waard, Netherlands, a farm has had several fields under long term regenerative management (8 years), with some fields still in the process of being transformed. During this period, field experiments are taking place on different locations on the farm to determine not only qualitative differences between regenerative and conventional agriculture, but also a more qualitative comparison. For this comparison several biophysical parameters (such as soil moisture, carbon content, pH) were measured.

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, etc. The focus of this report is on long term storage of organic carbon in the soil and the results of field data collected between 2019 and 2021.

Several management practices used in regenerative agriculture (chapter 2) are described as far as they are expected to have an impact on organic carbon content (OC) in the soil according to (Dutch) literature. Literature show that the circumstances under which experiments are executed are diverse. Minimum tillage showed soil carbon increases between 1 - 21% in the topsoil throughout Europe. A review on literature on organic fertilizer application found both, positive and negative effects 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). For biodiverse grassland, grass with herbs, carbon accumulated much faster than on other permanent grassland.

The differences between the measured impact of these practices and their relationship with soil organic matter show that it is important to look at all aspects of the farming systems, as organic carbon can be influenced by different elements.

The farm in de Hoeksche Waard 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 are classified as being sandy clay soils and more than 75% of the crops in rotation are onion, potato, wheat and brown bean. The most present crop in the rotation is wheat (32%). The effect of the three different management strategies on carbon sequestration was analysed using multi-pool deterministic C model RothC. All fields showed a positive carbon balance. The carbon balance was most positive on the fields that are under regenerative agriculture since 2010. These fields also received the highest amounts of C input.

Additionally, two scenarios were modelled to analyse the effect on soil organic carbon content where all fields would have made the transition towards regenerative agriculture in 2010 (scenario 1), and where all fields would have stayed under conventional agriculture in 2010 (scenario 2).

The effect of scenario 1 on the carbon balance was largest at the conventional fields. Especially the field with lowest initial C content has potential for increased carbon storage under regenerative agriculture. On average, an increase of 0.34 t C/ha in the C-balance and 1.25 t CO_2/ha/year was predicted. Under the second scenario, the C-content declined in most of the fields that are under regenerative agriculture since 2010. Removing all crop residues, not sowing any cover crop after harvest and only applying slurry manure has a large effect on the C-content. Regenerative agriculture brings more organic carbon to the soil compared to the conventional agriculture regime. However, the effect of this additional amount of carbon only pays off after a longer time period. It also seems that a positive effect of regenerative agriculture can be reached faster in soils with a low initial carbon content, because the potential carbon sequestration is higher. It is recommended to continue collecting data on the C inputs (crop residues, green manure, organic

manure, compost) and soil parameters, to minimize the assumptions that need to be made for the modelling. Besides, it is recommended to run multiple models to be able to provide a range of values for C balance and the CO_2 sequestration, instead of a single value.

1 Introduction

Soil Heroes was started in 2017 from the firm belief that (re-)building soils through the practices of regenerative agriculture (Regen Ag) 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.

In 2019 Soil Heroes initiated development of their digital platform (the Soil Heroes Fairchain platform) connecting farmers and businesses around regenerative agriculture and supporting farmers to quantify the impact from regenerative farming practices and to offer them new business models, generating additional income flows for the farms.

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.

Soil Heroes wants to approach farming in a holistic way in balance with nature, contributing to:
- **Improved soil health** by restoring natural processes, based on a balanced cycle with as essential elements: 1) organic matter, improving soil structures and providing suitable conditions for the roots, 2) improved mineral content, as essential inputs for the plants and natural processes and as a key element for healthy and tasty produce and food (from farm to fork) and 3) soil biology, supporting essential natural processes. Improved organic matter content and related to that, carbon sequestration plays an important role in that process.
- **Improved position of farmers** through supporting them in the transition to regenerative farming and to offer them additional business models and income flows via the Soil Heroes Fairchain platform.
- **Improved perspective** for next generation farmers by making farmers part of the solution rather than the problem and to turn around the downwards spiral farmers are locked in today (majority of the risks reside with the farmers, whereas profits are being made further up in the value chain) and making a shift from low margins and high volumes to high value and quality produce.
- **Improved health and taste** by building soils and restoring natural processes; essential elements and building blocks will become available in the soil again and improved biology will make these available for plant life; leading to produce and end products with higher nutrient density and as a result, more healthy and tasty food.

In order to substantiate the framework of thinking, processes and models behind the platform, a monitoring program of soil quality parameters was designed and started on a reference farm in the province of Zuid-Holland, the Netherlands. As of 2018 this farm in Hoeksche Waard has been set up as an experience farm to showcase regenerative farming and to compare farm management on fields which have been managed for years under either regenerative, or conventional management. The fields of the experience farm are in various stages of the transition from conventional to regenerative farming, which allows a good analysis between those practices. A set of farm fields has been under regenerative agriculture since 2010, some fields were shifted to regenerative agriculture at the start of the experiment, and some fields are still under conventional practices. This variety across stages of transition creates an good set-up for field experiments. The experimental design has been set up by Wageningen University and Research to monitor and analyse data through indicators which relate to soil health.

The experiment monitored biophysical parameters (carbon content, water content, soil structure, etc.) as well as more qualitative parameters such as biodiversity, of fields under either regenerative or conventional practices. The data were collected through lab measurements. These data, together with farm management, weather data and data on the carbon inputs (crop residues, organic manure, compost, cover crops) were used as input for the modelling study. Because different management strategies were used at the fields (i.e., different stages of regenerative agriculture), the effect of regenerative agriculture on the soil organic carbon content could be modelled. Besides, two scenarios were modelled to analyse the effect on soil organic carbon content when all fields made the transition towards regenerative agriculture in 2010 (scenario 1) and when all fields stayed under conventional agriculture (scenario 2). Also the CO_2 sequestration of the fields under the current situation and for the two scenarios was assessed.

The first part of this report conveys what is already published in literature related to regenerative agriculture. Where possible other types of agriculture are included, especially field experiments play an important part in comparing the different types of agriculture. The second part focusses on a case study in the Hoeksche Waard, where fields at different stages of regenerative agriculture are being compared using field measurements and carbon modelling.

As not all ‘good agricultural practices’ are clearly defined as regenerative agriculture, but the description of regenerative agriculture does specify certain management as regenerative (Rodale white paper, 2014), these practices were also considered. Where possible literature from the Netherlands was used first, with additions of other (European) review articles.

When the Soil Heroes Fairchain platform system is successfully operated in the Netherlands and (soil and climate wise) related regions, expanding this system to other areas becomes interesting to gain knowledge and increase impact. As farm practices may differ because of agro-ecological differences, this would be a next step in validating the fair chain system for those regions. The focus of this report is a short review and definition of regenerative agriculture, on field description and SOC modelling.

2 Background

The term regenerative agriculture (Regen Ag) is used to describe a holistic approach in farm management.

The term regenerative agriculture was first introduced in the 1980s in the USA (Rodale, 1983) after which it became absent from literature for some years. Other authors have since described similar agricultural approaches and defined Regen Ag under other names such as organic or restoration agriculture.

In Rodale Institute white paper (2014) Regen Ag is described as a holistic approach where yield increases over time and topsoil deepens. It does not only focus on sustainability, as it uses the "*regenerative tendency an ecosystem shows when being disturbed*". The main topics described to summarize Regen Ag in the paper were:

- **Strengthening farm soil through topsoil regeneration**; through minimal soil disturbance (conservation tillage) and use of composting (in general closed nutrient loops, but also retention of crop residue) with cover crops.
- **Carbon stabilization**. Especially carbon sequestration is increased by adding clay to manure. Also Mycorrhizal fungi are applied to increase carbon in the soil.
- **Increase biodiversity;** fewer annuals and more perennials, increased nutrient uptake by plants.
- **Enhance crop rotation** by not using a bare soil period, but instead use rotational crops such as legume, grass and sunflower, in a continuous system.
- **Improvement water cycle** with an increase of yield in dry years of 28-34% higher than conventional.
- **Enhance ecosystem services**.
- **Increase resilience climate change**; through on-farm soil carbon sequestration; potentially sequester all of the current annual global greenhouse gas emissions of roughly 52 giga tons of carbon dioxide equivalent, (~52 $GtCO_2e$). Decrease greenhouse gas emissions.
- **Improve farm profitability** through a steady increase or maintenance in yield.

The term Regen Ag was further strengthened by Harwood (1983) mentioning it is less important to focus on a small or specific aspect of farm management at farm level, when other processes are not monitored as well (including the farmer and family). Regen Ag should include all biological relationships in an (eco)system.

The term Regen Ag has gained new energy in recent years. Especially picked up by NGOs and major food companies, it shows there is an increasing international debate regarding the "global food system", and its environmental consequences of agricultural incentivisation, such as pollution and biodiversity loss.

(Schreefel et al., 2020) mentioned that the term regenerative agriculture is loosely used, and usually describes similar objectives in agriculture such as reach global food security, reduce use of external inputs and reduce environmental damage.

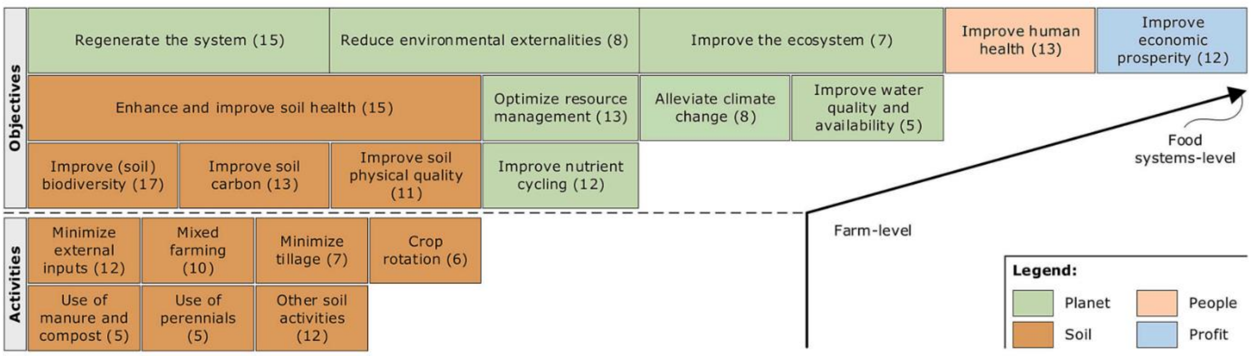


Figure 1 *The core themes of regenerative agriculture, in which the number between brackets represents the number of search records (Schreefel et al., 2020).*

The difference between regenerative agriculture and other terms using similar objectives are that regulation is in place for the other examples (such as organic agriculture and climate-smart agriculture). Regen Ag does not have a clearly defined scientific description yet.

279 Articles mentioning regenerative agriculture were analysed and Schreefel (2020) found that the following overlapping terms were used to describe Regen Ag: enhance and improve soil health, optimize resource management, alleviate climate change, improve nutrient cycling and water quality and availability (Figure 5). The environmental aspect and sustainability focus are very clear, yet the socio-economic dimension not so much.

Giller et al (2021) states that from an agronomic point of view, Regen Ag links two challenges: 1) restoration of soil health, and 2) the reversal of biodiversity loss. Related to the first challenge, sequestration of carbon in the soil is also mentioned as a way to mitigate climate change.

Both Schreefel (2020) and Giller (2021) mention that more defined benchmarks should be made while describing regenerative agriculture.

2.1 Regen Ag and organic agriculture

FAO[1] describes organic agriculture as a process claim, not a product claim. One product can be identically produced under default organic agricultural practices as well as organic practices, but the latter is produced with specific management regimes. Some of the main techniques used are intercropping, crop rotation, double-digging, mulching, integration of crops and livestock. Furthermore, few synthetic inputs are allowed. Natural resources such as manure, crop residue, compost and animal-based fertilizers are allowed, and this elimination of chemical substances also apply for pesticide use. Regenerative agriculture has a large overlap with organic agriculture especially in the holistic approach of farming, but though organic farming has regenerative principles in its core, regenerative farming does not rely only on organic principles. Regen Ag is mentioned to be more holistic, inclusive and expansive than organic, especially in the social justice and cultural equity realms Quora (2019), Terra Genesis International[2].

2.2 Farming systems trial with regenerative agriculture

In 1981 Rodale Institute started an experiment comparing the differences between conventional and regenerative agriculture. Some of the results have been published on the website of Rodale; the increase in farm carbon sequestration is based on data from sites in Iran and Egypt (respectively peanuts and corn) which describes an increase from 4.1 Mg C ha/y to 21 Gt CO_2/all global cropland/y.

Mostly grain cropping systems are compared, looking at conventional and organic farming. The crops used in rotation include corn, soy, oats, and wheat (Rodale website, 2020).

According to the Rodale website, their 30+ years farming experiment has yielded some results. Peer reviewed articles which sustain these results are lacking. On the website the results are claimed are:
1) yields are able to compete with yields in conventional agriculture, 2) Less use of chemical fertilizers than organic farming.

Though other examples of Regen Ag can be found on the internet, such as Regeneration International (2021), few trials or experiments are scientifically researched or the topic is published under other terms such as agroforestry, sustainable agriculture, sustainable food system practices, or organic agriculture.

[1] https://www.fao.org/organicag/oa-faq/oa-faq1/en/
[2] https://terra-genesis.com

3 Literature review of management practices related to Regen Ag in Europe

The research on regenerative agriculture as a practice has started years ago in the USA, yet similar management is practiced for many years all over the world. It may not be defined as regenerative agriculture, yet the methods used overlap. In this chapter an overview is given on literature related to practices identified as regenerative agriculture. The focus is on the Netherlands first, but expands to other European countries when more literature is found. A list of management practices that are linked to regenerative agriculture is compiled and based on this list. The effect of a management practice on soil chemical, physical and biological properties is extracted, together with effects on carbon sequestration and soil water holding capacity.

3.1 Minimum tillage

The practices which are related to regenerative agriculture work with terms such as no-till farming, direct drilling, zero farming, reduced tillage, shallow tillage, all of which are practices to minimize soil disturbance in the farm field.

Zero tillage is a practice described as soil disturbance being reduced to sowing operations and limited traffic only and chemical means to deal with weed control. Specific conditions under which these practices can be applied are mentioned (maize production on sloping unstable soil, pasture renovation). Some of the positive effects mentioned are a higher water content in the top soil layer, reduced soil aeration, stronger mechanical resistance to root penetration, smaller soil temperature amplitudes, and a change in pattern of nutrient distribution in the soil profile (Beaumer and Bakermand, 1974). Though already used for thousands of years, modern no-till practices are described by Faulkner (1940). Depending on crop rotation and climate some cultivation is possible, which is considered a low-till method.

A review by Carr et al (2013) mention that an increase in carbon through the use of non-tillage range between 0.2 g C/kg soil in France (Vian et al, 2009) to 4.5 g C/kg soil in Switzerland (Gadermaier et al, 2011). These values equal an increase of respectively 1 and 21% of carbon in the top soils. The depths range from 0-10 till 0-20 cm (Table 1).

Table 1 *Carr et al (2013) review on non-tillage practices in different countries and monitored differences in soil organic carbon.*

Reference	**Country**	**Time Year**	**Depth cm**	**Difference g C/kg soil**
Lewis et al 2011	USA, Rock Springs	3	0-15	Δ2 (+15%)
Lehocká et al 2009	Slovakia, Borovce	2	2-20	Δ1.2 (+9%)
Weber et al 2005	Germany, Mainz	3	0-15	Δ1.5 (+9%)
Berner et al 2008	Switzerland, Frick	3	0-10	Δ2.3 (+11%)
Gadermaier et al 2011	Switzerland, Frick	6	0-10	Δ4.5 (+21%)
Vian et al 2009	France, Lyon	1	0-15	Δ0.2 (+1%)

McConkey et al (2003) looked at different soil types in a similar environment in Canada (Table 2).

Table 2 *Carbon increase in different soil types in prairie grassland Canada.*

Soil type in Canadian prairie soils	Increase in carbon in continuous cropping (tn C/ha.y)	Difference in carbon from minimum tillage to no tillage (tn C/ha.y)
Hatton fine sandy loam (15.3% clay, semiarid)	110	1.4
Swinton silt loam (27.6% clay, semiarid)	217	1.8
Sceptre silt loam (42.7% clay, semiarid)	27	4.1
Elstow loam (31% clay, subhumid)	430	7.9
Indian Head clay (63.1% clay, subhumid)	363	9.5
Melfort silty clay loam (44% clay, subhumid)	n.s.	n.s.

n.s.= not significant.

A study of 67 long-term agricultural experiments resulted in an average carbon sequestration of 57± 14 g C/m^2/yr when management changed from conventional tillage to no-till practices (West and Post, 2002). As far as depths in which the changes were monitored are concerned, Kern and Johnson (1993) found that changing from conventional tillage to no-till has especially effect on the first 8 cm of soil, and less in the 8-15 cm soil. The assumption was that C-sequestration took place between 10 and 20 years.

Sandén et al (2018) showed in 251 long term experiments all over Europe that no tillage increased soil penetration resistance with 22%, earth worm presence with 84% and earthworm biomass with 370% and microbial carbon with 23%. N_2O emissions increased with 68%, while yields did not change significantly.

In 2017 however, Haddaway et al (2017) showed from 351 studies, that the top 30 cm showed increased SOC stocks when comparing no tillage to minimum or high tillage practices, while at lower depths these increments were not seen.

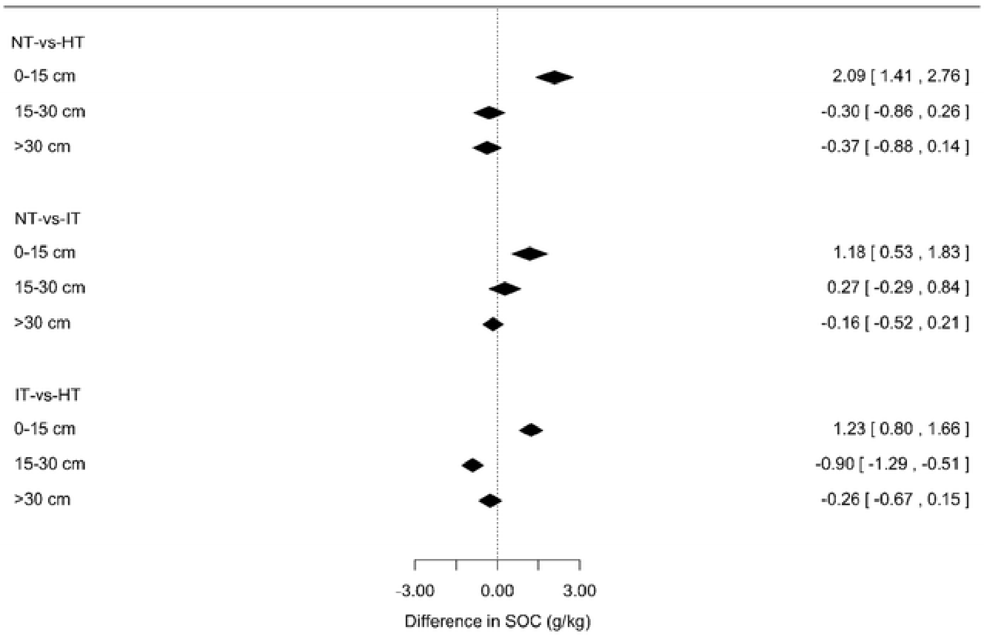


Figure 2 *Summary effect estimates (difference in SOC, g/kg) for concentration data meta-analyses in Haddaway et. al (2017). Three tillage comparisons are shown: NT no tillage, IT intermediate intensity tillage, HT high intensity tillage. Diamonds are centred on the summary effect estimate for each meta-analyses, with the points of the diamonds representing the 95% confidence intervals. Numbers in the right hand column are summary effect estimates [lower 95% CI, upper 95% CI].*

The differences between intermediate tillage (IT), and high tillage (HT) are described as IT not inverting the soil, while HT does invert the soil, as well as ploughing as deep as 40 cm or deeper.

3.2 Organic fertilizer application

Developing crops take up nutrients from the soil to grow. Each crop will take up nutrients in specific ratios which are different compared to other crops and as an agricultural field is managed to have a maximum yield, this difference in uptake of nutrients can be substantial. When intensive monoculture is applied biodiversity loss, loss of non-crop species, replacement of wildlife with common species, soil erosion, loss of organic matter, contamination with pesticides, water contamination, air pollution, reduced capacity of carbon sequestration (Stoate et al. 2001) can be found. In order to stop the natural soil mining of nutrients, fertilizers are applied. In a balanced field, uptake of nutrients by the crop is equal to what is applied as a fertilizer, with the remark that in order to ensure biological soil health and ensure carbon sequestration in the soil, more carbon needs to be applied than what is decomposed in one year. The type of fertilizer applied depends very much on the combination of soil characteristics and crop. Clay soils have a higher natural soil fertility than sandy soils and between crops there is also variation in nutrient uptake. Vegetables are known for demanding a lot of nutrients for good crop yields.

The application and uptake of fertilizers is soil and crop specific. Chemical fertilizers (fertilizers generated in factories or mined and extracted) mostly contain Nitrogen (N), Phosphorus (P) and Potassium (K) and to a lesser content Sulphur (S), Magnesium (Mg), and Calcium (Ca) which will be available for plant uptake within the growing season of application. These types of fertilizers do not contain any form of organic matter and will therefore not benefit soil fertility and soil health. The preferred fertilizers applied are organic fertilizers such as manure, green compost, compost tea, and biofertilizer as they not only supply nutrients, but also increase soil organic matter and as such stimulate soil fertility and soil health. Table 3 shows the most widely used types of organic applications for Dutch agriculture.

Table 3 *Median nutrient content of major used Dutch manure and residual flows (kg/ton).*

Organic application	DM	OM	HC	EOS	P2O5	N-total	Nm	Norg	Nm%
Cattle slurry	92	71	0.7	50	1.5	4	1.9	2.1	48
pig slurry	107	79	0.33	26	3.9	7	3.7	3.3	53
Sows slurry	67	25	0.34	9	3.5	5	3.3	1.7	66
cattle manure (with straw)	267	155	0.7	109	4.3	7.7	1.1	6.6	14
pig manure (with straw)	260	153	0.33	50	7.9	7.9	2.6	5.3	33
Solid goat manure	291	174	0.7	122	5.3	9.9	2.4	7.5	24
Dry chicken manure	616	393	0.33	130	25.6	32.7	3.8	28.9	12
Compost (organic waste from households)	696	242	0.9	218	4.4	8.9	0.8	8.1	9
Compost (Green)	599	179	0.9	161	2.2	5	0.5	4.5	10
Wheat straw	850	765	0.3	230	1.6	5.8	0	5.8	0

DM=dry matter, OM=organic matter, HC=humification coefficient, EOS=effective organic matter, P_2O_5=phosphate, N= nitrogen, Nm= mineral nitrogen, Norg=organic nitrogen

Source: www.handboekbodemenbemesting.nl Data from Eurofins Agro, vereniging afvalbedrijven, and branche vereniging Organische reststoffen

In the table the yellow bars show to what extend a specific kind of organic fertilizer has the highest values of the described parameter. As far as OM, wheat straw adds the most organic matter per ton applied to the soil. Due to a lower conversion (0.3) during the year, the amount of straw which is left behind in the field (and which is considered soil organic matter after one year) is decreased to 230 kg/ton applied. For compost the conversion is much higher and this shows a much more efficient transition from applied compost to soil organic matter.

The basic rule is that with an organic fertilizer with a C:N ratio closest to the natural soil ratio of C:N[3] (±14), less effort is needed for that fertilizer to decompose and become soil organic matter after one year.

Sandén et al (2018) showed from 251 long term European field experiments (of which two in the Netherlands) that both positive and negative effects were found when evaluating management practices on

[3] A C:N ratio of 14 means that for every 1 C particle, 14 N particles can be found. Manure usually has a lower C:N, less C than N can be found in the manure.

different indicators dealing with soil quality, climate change and productivity (maintain high yield, reduce greenhouse emissions, improve chemical, physical and biological soil quality) and none of the practices could describe positive results for all indicators. For farm yard manure (FYM) amendments and cattle slurry application SOC contents increased significantly by respectively 21% and 19%. For compost amendments SOC contents were significantly enhanced with 30%.

3.3 Cropping

3.3.1 Optimized Crop rotation

Crop-fallow systems can be replaced by crop rotation systems. Crop rotation indicates the cultivation of two or more crops rotated over time on the same field. Which and how many different crops to grow to sustain soil carbon levels depends on several factors. In the Netherlands often a 1:3 crop rotation scheme is practiced including potatoes, grains, and sugar beets. Changing this scheme to a 1:4 or a 1:6 rotation scheme in potatoes can increase the yield of all crops (Van Dijk et al., 2012). The organic matter content can increase when wheat is more frequently included in the rotation scheme, because large parts of the wheat crop are mulched after harvest and after harvest there is the potential for sowing a cover crop (Van Dijk et al., 2012). Including crops that stimulate the restorative ability of the soil (for example, grasses, wheat and cover crops) is substantially efficient in sandy areas in the Netherlands (Van Dijk et al., 2012). The rotation frequency and the order of the crops in the rotation scheme are especially important for soil pathogen prevention.

The rotation of crops per season can enhance the chemical, physical and biological resilience of the soil and soil organic carbon sequestration. An analysis on 67 long-term experiments on rotation optimization resulted in an average carbon sequestration of 20±12 g $C/m^2/y$ (West and Post, 2002). Lesschen et al. (2019) estimated a potential maximum of carbon sequestration caused by optimized crop rotation of 1205 kg CO_2/ha/yr for Dutch soils. Van Dijk et al. (2012) concluded that an increase in soil organic matter content between 0.01 and 0.04% is possible after 20 years of improved crop rotation. Compared to the increase in soil organic carbon content that can be gained by changing from pig slurry to cattle slurry (0.25% in 20 years), changing the crop rotation scheme only contributes limited to carbon sequestration.

3.3.2 Cover crops

Cover crops are not sown for the purpose of being harvested, but for the purpose of increasing the soil organic matter content, and thus improves soil characteristics like the water holding capacity and the soil structure. Cover crops also reduce erosion because it covers the soil surface in the period that the land was normally fallow. Legumes have the ability to fix nitrogen, which makes legumes an extra interesting cover crop.

An advantage of cover crops compared to other measures that aim to improve the soil organic carbon content, is that cover crops increase the soil organic carbon content without declining yields or losing carbon in other systems (Poeplau and Don, 2015). The meta-analysis of Poeplau and Don (2015) concluded that the SOC stock changed about 0.32±0.08 Mg/ha/yr over an average soil depth of 22 cm and a time period of 54 years. On a global scale this results in a carbon sequestration of 30±8 Tg CO_2/yr, approximately 8% of the total greenhouse gas emissions caused by agriculture. Lesschen et al. (2019) assumed a carbon sequestration of maximum 398 kg CO_2/ha/yr as a result of cover crops.

3.3.3 Agroforestry

Agroforestry or alley cropping is an agricultural system whereby woody crops or trees are combined with other agricultural crops. This system makes (horizontally and vertically) efficient use of the land. Besides, it aims for a positive interaction between tree and crop by increasing the nitrogen availability, stimulating the nutrient cycle, accumulation of extra organic matter, creating shadow, and suppress plant or soil diseases. Agroforestry has high potential in terms of carbon sequestration. Technically, a total CO_2-equivalent of 1566 million ton/yr can gained in the EU-27 when agroforestry systems are introduced (Aertsens et al., 2013). Practical issues often hamper the introduction of agroforestry. The use of machinery for land management will become more difficult in agroforestry systems. Cardinael et al. (2017) introduced agroforestry on six intensive agricultural systems and measured an average carbon sequestration of 880 kg CO_2/ha/yr in the upper 30 cm. Van Vooren et al. (2016) concluded that greening on arable land by planting trees is economically competitive to conventional cropping systems and therefore requires financial support.

3.3.4 Perennial agriculture

Perennial agriculture is the cultivation of crops that live longer than two years. The cultivation of these crops requires less tilling, and in some cases less labour and fewer pesticides, compared to annual cropping systems. The effect of perennial agriculture on carbon sequestration can therefore be compared to no-till or reduced tillage.

3.3.5 Intercropping

Intercropping, or companion cropping or multi-cropping, means that at the same time, multiple crops are cultivated in proximity. This can reduce pest control, enhance pollination, provide habitat for beneficial insects, and stimulate the nitrogen availability (in case a legume crop is used). Intercropping can enhance the soil organic carbon content when a low intensity crop (e.g., wheat, grass) is used as intercrop (Liu et al., 2020). In an arid area in China, wheat-maize strip intercropping in combination with conservation tillage and crop residues mulching resulted in an increase in water use efficiency, net primary and ecosystem production, and it decreased the carbon emissions (Hu et al., 2016). Tree-based intercropping resulted in a gain in C sequestration, but a (smaller) loss in C due to lower crop yields (Grant et al., 2017). Contour cropping is a technique whereby strips of two or more crops are cultivated across the contour lines instead of perpendicular to the contour lines. Intercropping with a cover crop reduces slope length, and therefore it reduces erosion caused by (sub)surface runoff. Contour cropping is most efficient in areas with slopes between 2 and 10 percent.

3.4 Grassland management

3.4.1 Holistically managed grazing

This grazing system builds upon ecosystem processes including the water, nutrient and carbon cycle, energy flows and community dynamics. It aims for grazing at the right place and time, and for the right reason by holding a high density of livestock fenced for a short time. The system is also known as intensive, rotational time-controlled grazing, or short duration-, cell-, multi-paddock- and mob-grazing. The positive effects of holistically managed grazing are under debate for a long time. This grazing system has clearly no consensus among scientists, conservationists and land-users (Hawkins et al., 2017). The systems increase primary and secondary production, soil characteristics change due to animal impact and the herd effect. The complex interaction between climate, lithology, animal type and numbers, human intervention and politics makes the effect of holistically managed grazing site and livestock system specific (Hawkins et al., 2017). Savory and Butterfield (2016) claim that the grazing system increased productivity, reversed climate change while doubling the stocking rate, and established plant and litter that protects the soil.

3.4.2 Pasture cropping or silvopasture

This grazing system combines livestock grazing with crop or tree cultivation. In the Netherlands, the most common silvopasture is a combination of sheep grazing and fruit trees. In the southern part of the Netherlands a silvopasture with grazing cows and fruit trees is located (Franke, 2017). Biomass significantly increases in silvopastures compared to other pasture systems (Chauhan et al., 2010). The negative effect of tree density on grass yield was not significant, whereas tree age and height (Guevara-Escobar et al., 2007; Hawke 1991; Sharrow et al., 1996; Yunusa et al., 1995).

3.4.3 Species rich grassland

Pastures that harbour a large variety in grass and herb species are a habitat for invertebrates, birds and small mammals. It also stimulates soil life and builds resilience of the land to pests and diseases. Most studies on species rich grassland are studies on former grasslands that are now designed as nature area.

De Deyn et al. (2011) did not find a significant relation between species richness and C accumulation rate. However, the change from conventional grassland management to species rich grassland often includes sowing of extra grass species, reduced or no ploughing, and reduced or no application of NPK fertilizer. These practices can cause an increase in the soil organic carbon content (De Deyn et al., 2011). Cong et al. (2014) found an increase in C and N stocks in eight-species mixtures compared to the average of monocultures of the same species. This study concludes that enhanced plant productivity caused the increase in C and N stock. A study on rainfed permanent grassland showed that a mixture of twenty different species, rich in legumes, are more productive compared to other permanent grassland (Teixeira et al., 2008). The species rich grassland also accumulated more rapidly organic carbon in the soil compared to other permanent grassland (Teixeira et al., 2008).

3.4.4 Non-inversion tillage of grassland

Ploughing aerates the soil, which causes a rapid decomposition of organic carbon. CO_2 and N_2O emissions reduce when grasslands are ploughed in spring instead of autumn (Kasper et al., 2002) and therefore only a few months a year, Dutch farmers are allowed to plough grasslands. Immediately after ploughing grasslands, the agricultural land needs to be sown with a crop that requires high amounts of nitrogen (RVO, 2020). Reduced ploughing or turning of temporary grassland will minimize soil disturbance. This will lead to soil organic carbon accumulation in the topsoil. Studies are consistent about the positive effect of carbon sequestration caused by not ploughing grassland (De Wit et al., 2018; Fornarare et al., 2016), although effects are often only visible after a few decades. Van Eekeren et al. (2007) referred to a study in Belgium where a field with continuous grassland and continuous maize cultivation had a difference in organic matter content of 4% after 36 years. A rotational scheme of three years maize and three years grassland resulted in an organic matter content of 3.4%.

4 Regenerative practices applied in The Netherlands

4.1 Characteristics Regen Ag and Dutch regulation

For Dutch conditions the difference between regenerative agriculture and conventional agriculture are similar a to the original white paper described by Rodale Institute, yet some adaptations are needed to convert these practices to Dutch conditions:

- In the Netherlands there is some distinct crop rotation in certain areas. The area where Soil Heroes is focused on is in "*Hoeksche Waard*"; an area dominated by a crop rotation of sugar beets, potatoes, wheat and onions.
- Conventional systems in The Netherlands till the soil once or twice a year.

Crop rotation in de Hoeksche Waard consists of a minimum of 4-year rotation with potato-grain-sugar beets before 2017/beans after 2017-onion. In this scheme, potato, sugar beet and onion are intensive root crops that, in general, need more soil cultivation than other crops such as cereals, and remain high nutrient concentrations in the soil after harvest which can leach to ground- and surface waters.

Fertilizer recommendations for different crops can be found in Table 1 (Handboek Bodem en Bemesting Website, 2020). Table 4 shows some of these recommendations. However, these recommendations vary much between different types of crops, in amount applied, time of application and environmental circumstances.

Table 4 *N-fertilizer limitations depending on crop/soil combinations in The Netherlands. Adjusted from Handboek Bodem en Bemesting website (2021).*

Crops	First gift	Second gift	Third gift	Specified for
	Kg N/ha			
Wheat	100	90	40	Winter wheat 140-N_{min}
Potato	285 – 1.1*N_{min}			Consumption potatoes Clay, 0-60 cm
Sugarbeet	30			$100<N_{min}<140$
Beans	165-N_{min} (0-60)			Brown beans
Onion	175			Sowing onion

In some places, farmers have experienced a positive response (e.g., improved crop development) after no tillage/shallow tillage. This did not always translate into a higher crop production, but it was noted that crops faced less water stress compared to fields where intensive tillage was applied. Especially in dry years (2017-2018 and early spring 2019) a difference in water holding capacity was observed.

5 Case study on implementation of Regen Ag in Hoeksche Waard

Case study in De Hoeksche Waard with the outcome to compare results CA with Regen Ag with data from 2 years.

5.1 Study area

5.1.1 General description

The area is located in the Southern part of South Holland. The agricultural fields in the area have an organic matter content that ranges between 1.6 and 1.9% and a clay percentage of 21 to 22%. The pH of all soils is around 7.4. The lowest groundwater table is between 1.5 and 1.8m depth and the highest groundwater table is between 1.6 and 1.3 m depth in the area.

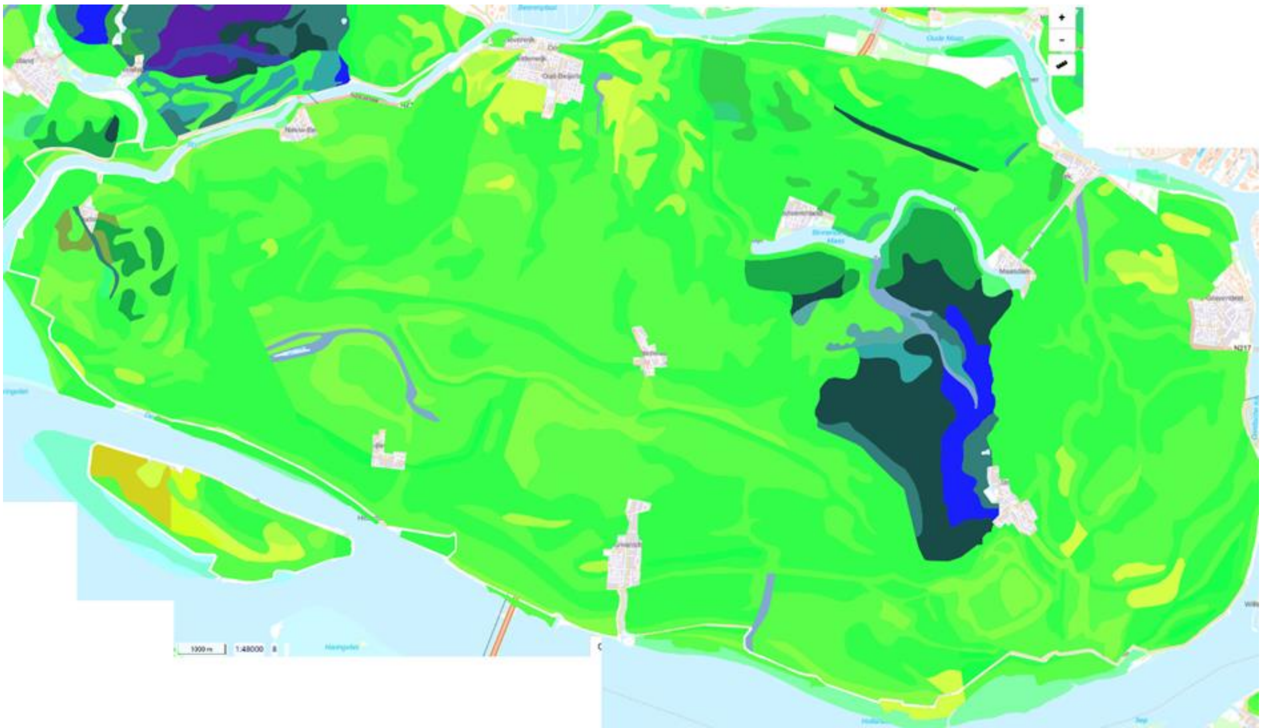


Figure 3 *Soil map of de Hoeksche Waard (bodemdata.nl 2021). Dark green and purple colours are clay on top of peat, lighter green colours are clay and sandy clay soils, yellow colours are clay on top of sandy soils or sandy soils.*

This study is carried out at a farm in the Hoeksche Waard (The Netherlands) (Figure 6). This area is dominated by crop rotations involving sugar beets, potatoes, wheat and onions. 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. At the plots with regenerative agriculture, crop residues are left and mulched into the soil. Cover crop is usually sown after wheat and legumes. Plots with regenerative agriculture receive compost and solid cow manure as organic carbon input, whereas the conventional fields only receive slurry pig manure. Minimum tillage takes place at the plots with regenerative agriculture, while at the conventional plots ploughing still takes place.

5.1.2 Farm characteristics

The farm counts ten plots. The fields LT.1 (6 ha), LT.2 (17.6 ha), LT.3 (9.13 ha) and LT.4 (11.7 ha) have been under regenerative agriculture since 2010 (i.e., Long term-RA). The organic matter content in these soils range between 2.2 and 2.5%, the clay content between 21 and 25%. The fields ST.1 (14.5 ha), ST.2 (11.25 ha) and ST.3 (14 ha) have been under regenerative agriculture since 2015 (i.e., short term-RA). The plots have an organic matter content that ranges between 1.8 and 2.2% and a clay content of 21 to 22%. The fields CA.1 (13.5 ha), CA.2 (11 ha) and CA.3 (10 ha) are still under conventional agriculture (CA). These plots have an organic matter content that ranges between 1.6 and 2.1% and a clay content of 21 to 22%.

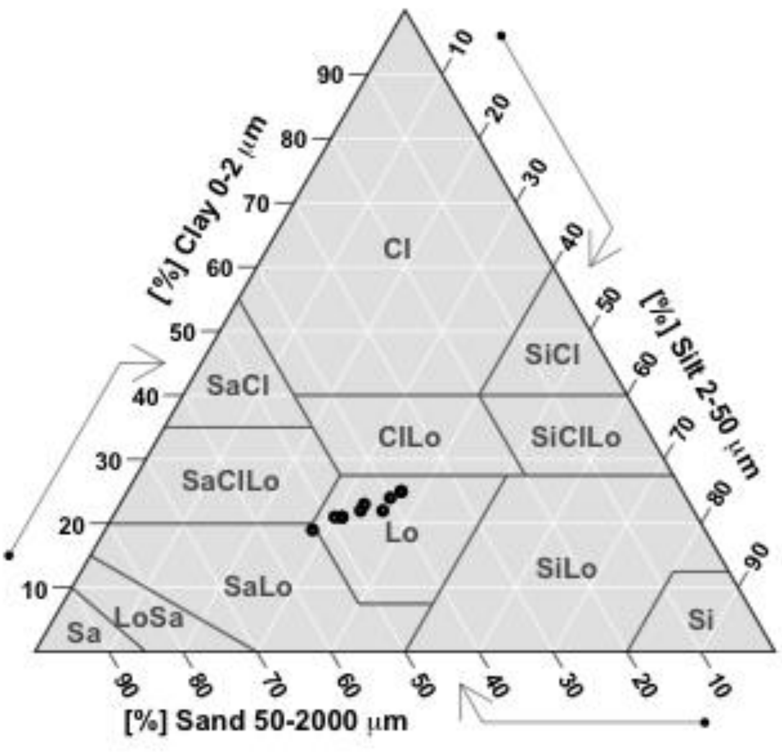


Figure 4 *The plots' textural class according to the USDA standard can be classified as loams.*

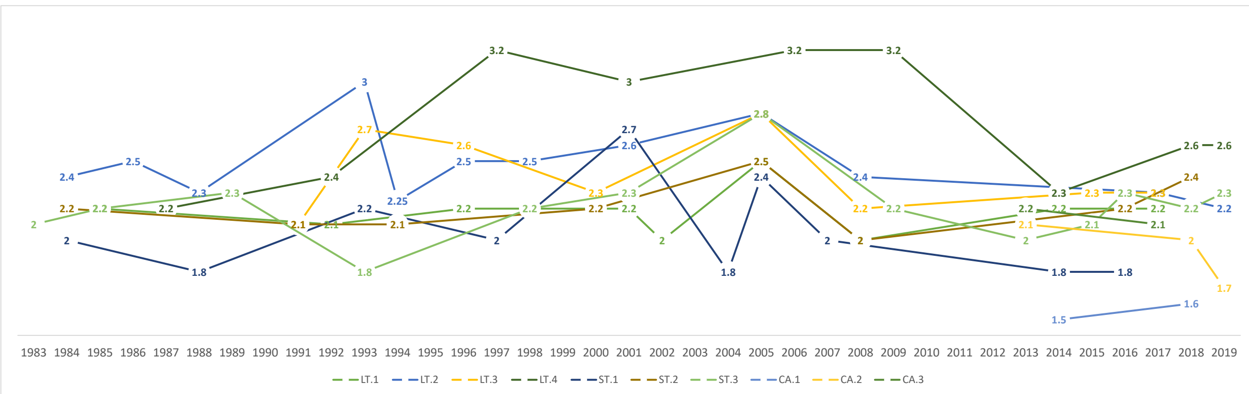


Figure 5 *Soil organic matter content of the plots under analysis through time.*

Table 5 *Crop rotation in the different plots. LT.1, LT.2, LT.3 and LT.4 are in regenerative agriculture for 10 years. The plots ST.1, ST.2, ST.3 are in regenerative agriculture for 5 years. CA.1, CA.2, and CA.3 are managed in conventional agriculture. The plots marked with * were followed by a cover crop.*

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
LT.1	Brown bean	Wheat	Potato*	Wheat	Onion*	Wheat*	Soya	Potato	Wheat*	Carrot	Wheat
LT.2	Brussel sprouts	Potato	Wheat	Green pea	Wheat*	Potato*	Wheat	Onion	Brown bean	Potato	Wheat*
LT.3	Poppy seed	Brussel sprouts	Potato	Wheat	Brown bean	Onion	Oats	Potato	Wheat*	Field peas*	Onion*
LT.4	Potatoes	Barley	Brussel sprouts	Wheat	Potato*	Wheat	Brown bean	Sugar beet*	Potato*	Wheat*	Onion
ST.1	Brussel sprouts	Wheat	Potato*	Wheat*	Onion	Wheat	Potato	Wheat*	Brown bean	Onion	Potato
ST.2	Grass seed	Grass seed	Brussel sprouts	Potato	Wheat	Brown bean	Onion*	Wheat*	Potato*	Wheat*	Carrot
ST.3	Potato	Brussel sprouts	Wheat	Onion	Brussel sprouts*	Wheat	Potato	Wheat*	Onion	Brown bean	Potato
CA.1	Brown bean	Wheat	Onion	Wheat	Potato	Brown bean	Sorghum	Oats*	Potato*	Wheat*	Onion*
CA.2	Wheat	Potato	Wheat*	Onion	Sugar beet*	Sugar beet	Wheat	Brown bean	Onion	Potato	Wheat*
CA.3	Wheat	Onion	Green pea*	Potato	Wheat	Sugar beet	Wheat	Potato	Wheat*	Onion	Carrot*

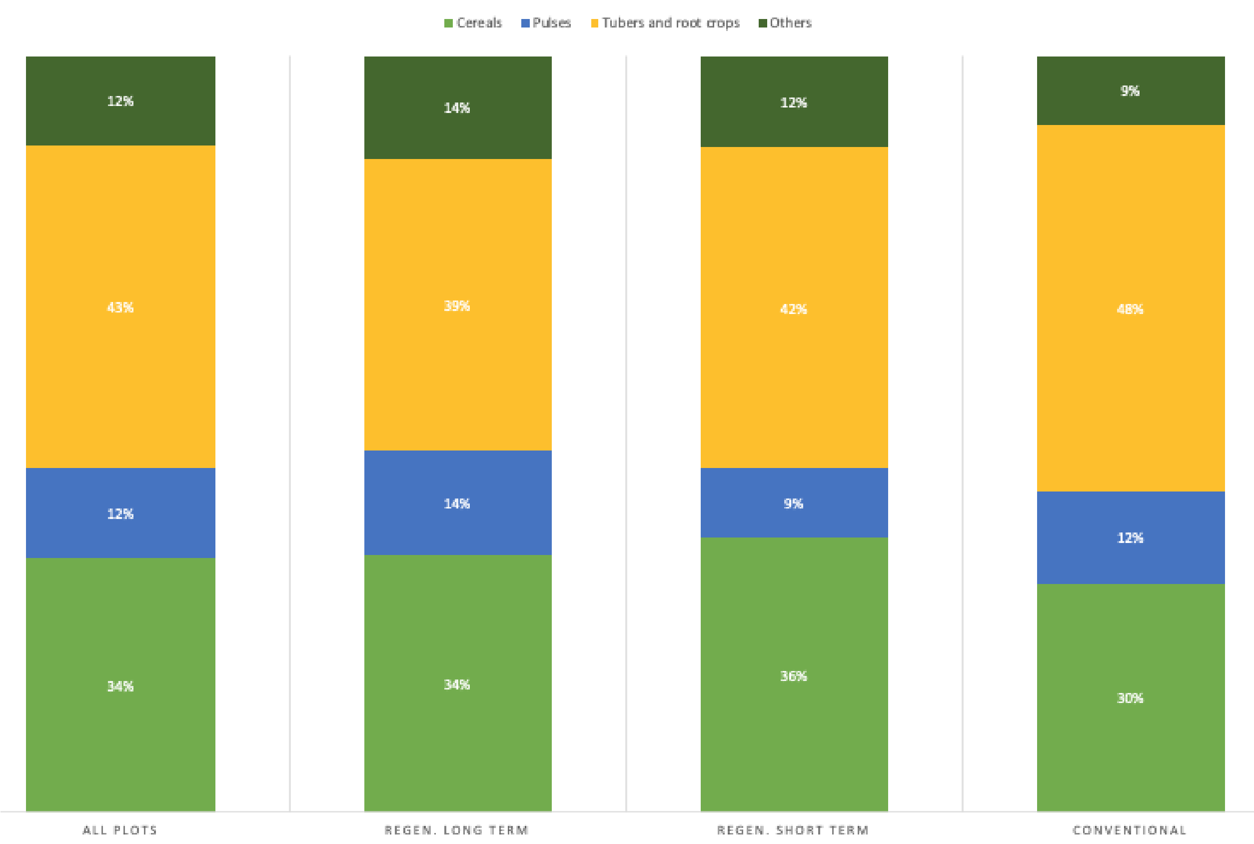


Figure 6 *Distribution of crops (classified as cereals (green), pulses (blue), tubers and root crops (yellow), and others (dark green)) on the different management types in the farm.*

The conventional management of plots in the region (as explained by the local farmer) includes the removal and sale of plant residues (particularly with wheat straw), as well as the application of pig slurry as a fertilizer. A rate of 30 tons per hectare is usual for this practice. After the introduction of regenerative agriculture, plant residues are no longer removed. In cases of excess of plant material, they may be mulched to accelerate decomposition. Instead of using pig slurry, composted amendments are applied to the plots. A usual rate is to use 15 tons per hectare of green compost, composed of plant clippings, and 15 tons per hectare of solid cow manure. In all cases, amendments are broadcasted into the fields, usually before sowing cover crops (pers. comment Jeroen Klompe, 2021). Table 3 includes information on the composition of such organic amendments.

Regarding the use of tillage, the farmer on the studied farm from the Hoeksche Waard is replacing conventional deep tilling (ploughing at a depth of 30 centimetres), for eco-ploughing. The eco-plough works at an approximate depth of 10 centimetres, therefore not contributing to the formation of a plough pan, which is a common issue in this area. The transition from intensive to shallow tillage or no tillage is considered an important step for farmers, not only because it represents a substantial investment in new equipment, but also due to the substantial change in management practices. Furthermore, the farmer in Klompe Landbouw is testing the use of a direct seeder, phasing out tillage altogether.

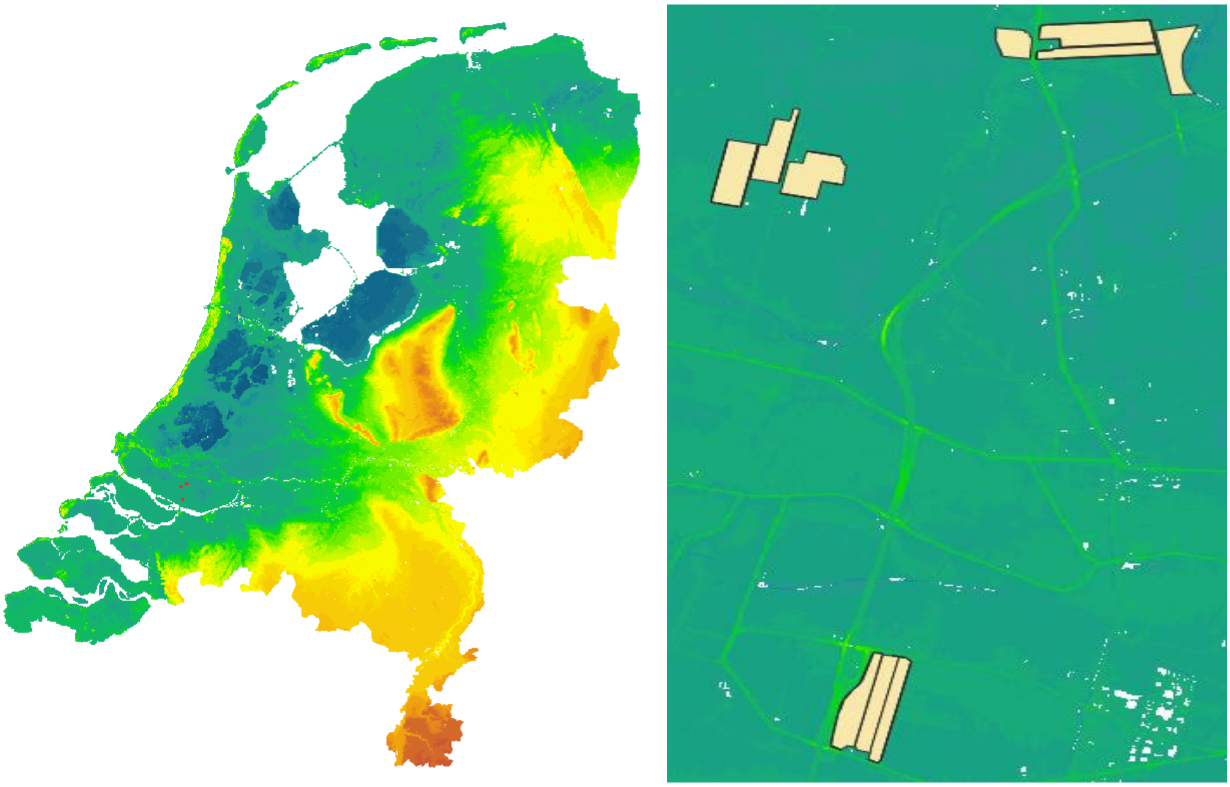


Figure 7 *The study area is located in the Hoeksche Waard in the western part of the Netherlands. The agricultural fields are located at three different locations in this area. The fields in the North (LT group) are regenerative fields for a long time, the fields located in the West (ST group) are regenerative fields since 2015. The fields in the South (CA group) are still conventional fields. The locations are plotted on the AHN2 5m map (source: PDOK).*

5.2 Field data collection

5.2.1 Cover crops

The fields have been sampled for many years (some already since 1983) and therefore the temporary changes in OM content became visible. Besides, an intensive field campaign in 2017 gave insight in other soil characteristics, like the CN-ratio and the content of micronutrients in the soil.

In the 2019/2020 winter period, four plots were sown with cover crops. Samples were taken from them to have an estimate of the produced biomass. Every time they are sown in Klompe Landbouw, cover crops are mulched and left as plant residues, they are never exported. The calculated dry matter for aboveground biomass of these cover crops is:
- LT.3: 4.05 tn DM/ha (DSV Solarigol)
- LT.4: 3.16 tn DM/ha (DSV Solarigol)
- CA.1: 7.37 tn DM/ha (Viterra multikulti)
- ST.2: 5.35 tn DM/ha (Viterra Universal + DSV Solarigol)

The species present in the mixtures used on this year are:
- DSV Solarigol: 35% common vetch, 20% black oat, 15% niger, 14% Daikon radish, 7% flax, 6% berseem clover, 2% Ethiopian mustard, 1% camelina
- Viterra multikulti: 33% persian clover, 28% lacy phacelia, 16% berseem clover, 10% daikon radish, 7% yellow mustard, 3% fodder radish, 3% common vetch
- Viterra universal: 47% lacy phacelia, 37% berseem clover, 16% black oat

5.2.2 Soil

In October 2019 field descriptions, measurements and sampling of the soil were performed by trained WEnR staff. Sampling locations were selected manually well 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[4]. As input to this zoning algorithm the 1:50.000 soil map of the Netherlands[5], the AHN3[6], available satellite imagery[7] and the field borders were used. The algorithm produces a specified number of spatially coherent and as homogeneous as possible zones per field. If needed the results can be further improved by adding more, relevant input data as yield maps, soil sensor data, NDVI maps. On all 30 sampling locations (depicted on Figure 8, Figure 9, Figure 10) penetrologger measurements and soil profile descriptions were made (green, yellow and red dots in the figures). On 24 locations samples were taken for lab analysis on soil texture, nutrients, organic matter fractions, 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). Furthermore 40 clusters of 4 topsoil samples in a line with 1 meter distance in between were taken and analysed on loss on ignition to measure the baseline of soil organic matter content on all fields with the possibility to determine short distance and longer distance variation (smaller blue dots in the figures). A full overview of all performed measurements is provided in **Fout! Verwijzingsbron niet gevonden.**. The location of the samples is depicted in Figure 8, Figure 9, Figure 10.

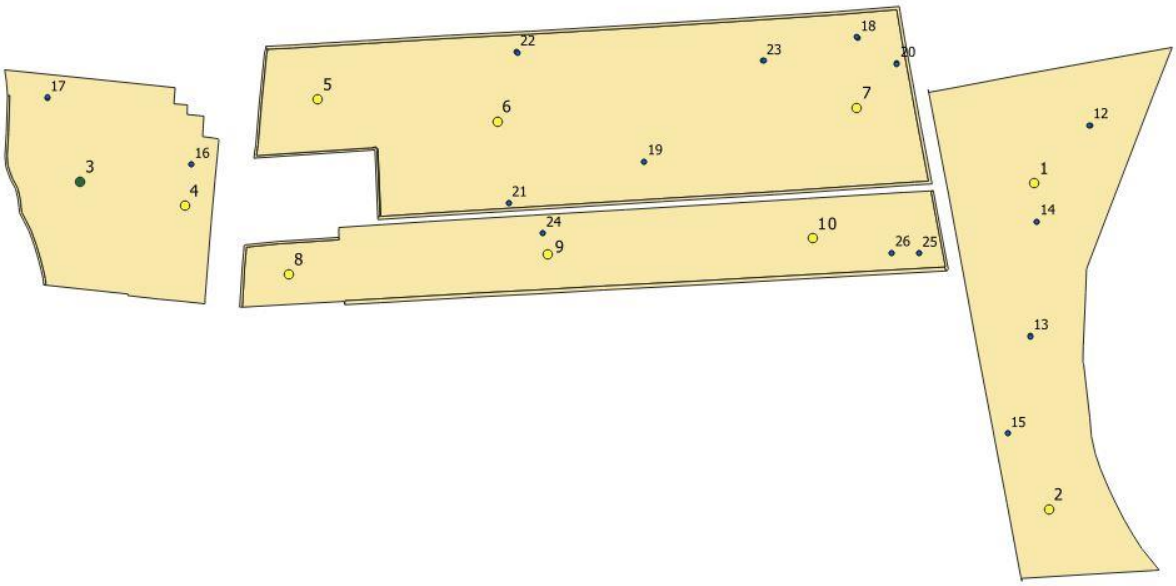


Figure 8 *Map of the plots LT.1, LT.2, LT.3 and LT.4 with datapoints. Labels indicate sample number. Red points; only soil profile description and penetrologger measurement. Yellow: Also includes texture and SOM measurements. Green: also includes soil physics measurements. Smaller blue: clusters for soil organic matter analysis of topsoil.*

4 Kempenaar, C., van Dijk, C., Hermans, G., Steele-Dun, S., van de Sande, C., Verschoore, J., van der Wal, T., Roerink, G., Visser, J., Kamp, J., Blok, P., Polder, G., van de Wolf, J., Jalink, H., Bulle, A., Meurs, B., Michielsen, J-M., van de Zande, J., Hoving, I., ... Pot, A. (2019). *Op naar precisielandbouw 2.0: eindrapport PPS PL2.0 2015-2019 topsectorproject AF-14275*. (Rapport WPR; No. 921). Stichting Wageningen Research, Wageningen University & Research. https://doi.org/10.18174/501552

5 https://www.wur.nl/nl/show/Bodemkaart-1-50-000.htm

6 https://www.ahn.nl/en

7 Sentinel 2 image of 25 February 2018, TriSat image of 26 July 2018, TriSat image of 1 September 2018.

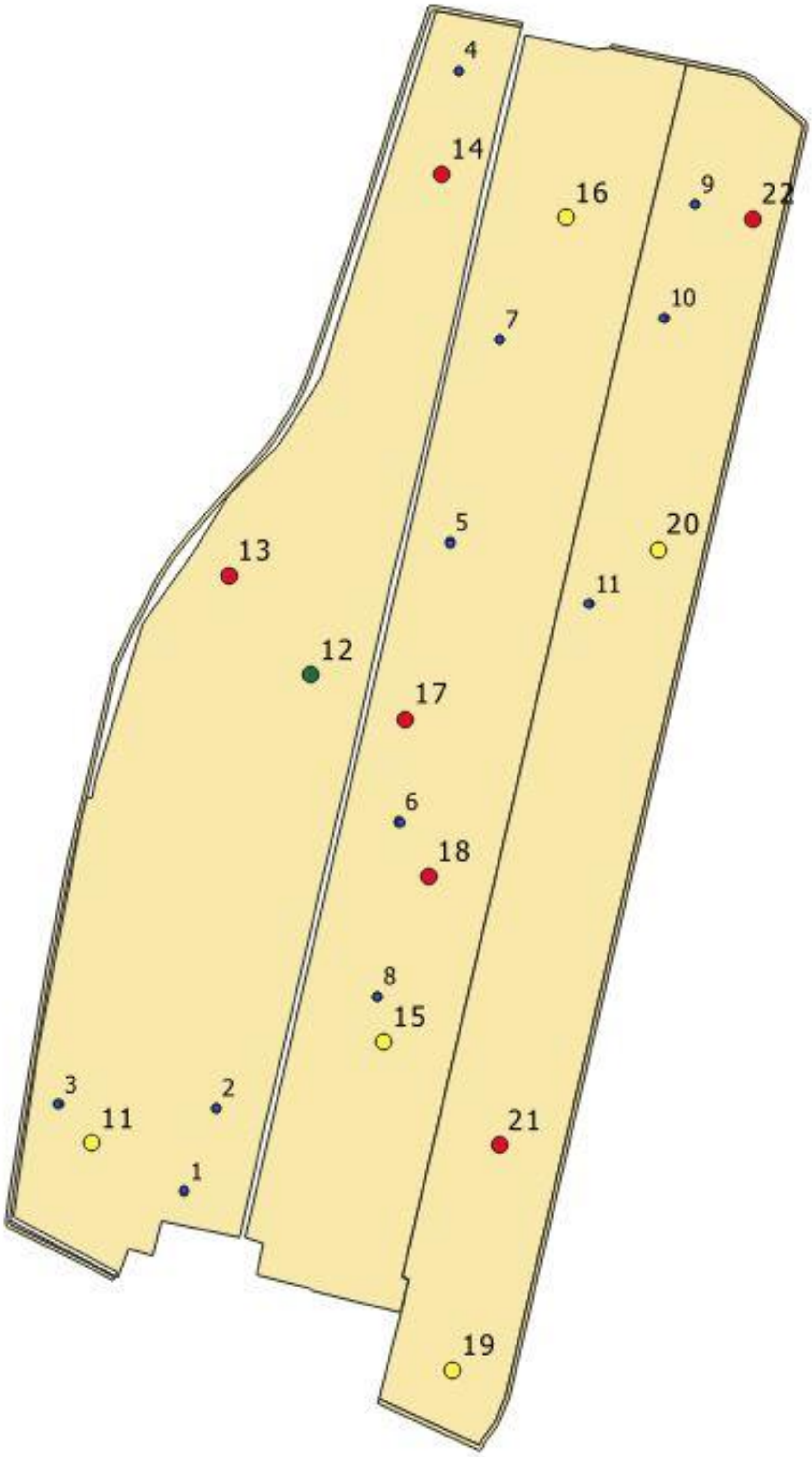


Figure 9 *Map of the plots CA.1, CA.2 and CA.3 with datapoints. Labels indicate sample number. Red points; only soil profile description and penetrologger measurement. Yellow: Also includes texture and SOM measurements. Green: also includes soil physics measurements. Smaller blue: clusters for soil organic matter analysis of topsoil.*

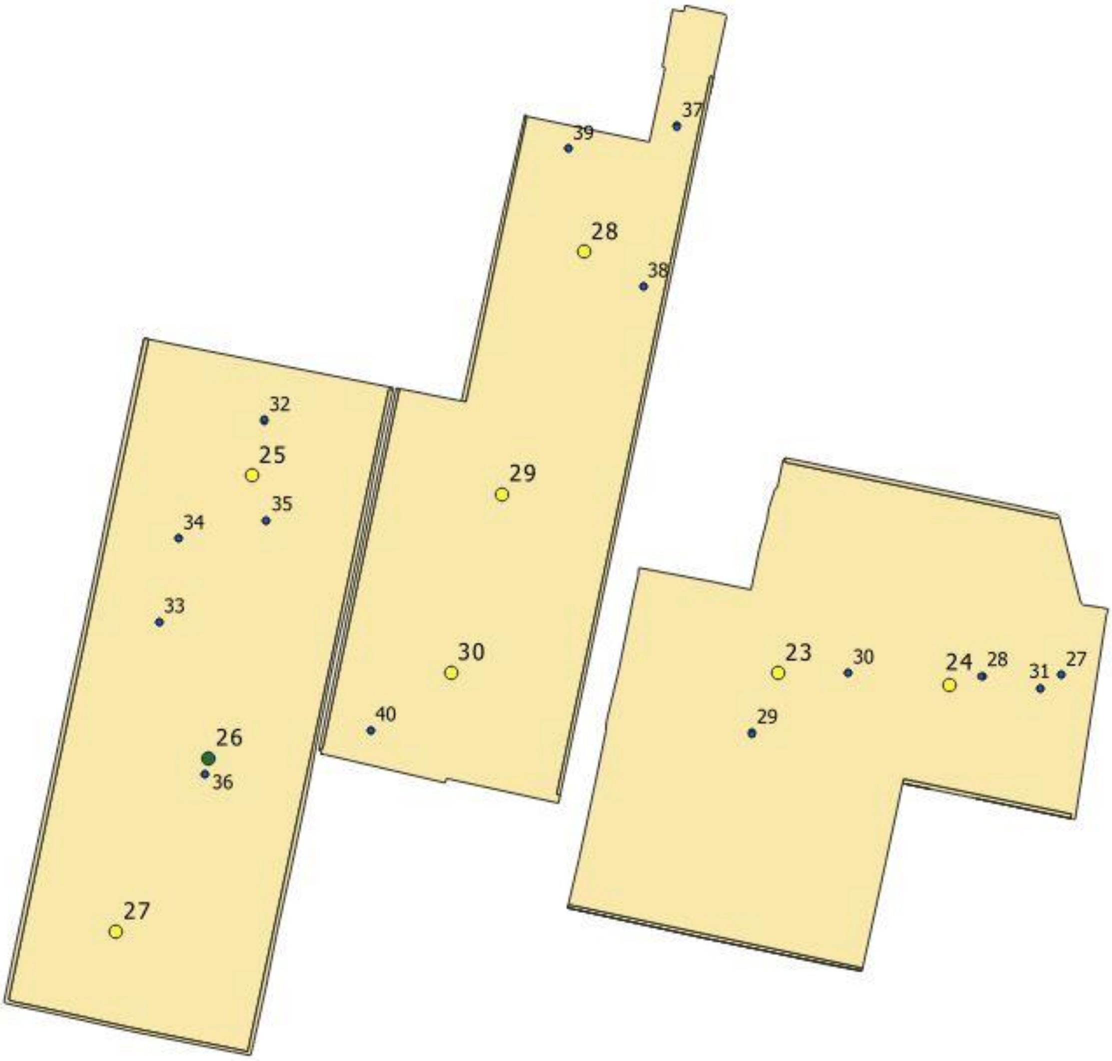


Figure 10 *Map of the plots ST.1, ST.2 and ST.3 with datapoints. Labels indicate sample number. Red points; only soil profile description and penetrologger measurement. Yellow: Also includes texture and SOM measurements. Green: also includes soil physics measurements. Smaller blue: clusters for soil organic matter analysis of topsoil.*

Some relevant field and lab results are elaborated in Figure 11 to Figure 16. The results of the soil organic matter measurements show that differences exist between the sample locations, but in general the loss on ignition of the topsoil is about 3 to 5% with some exceptions below and above. This translates to about 1 and 3% soil organic matter after correction for clay content. The lab soil texture analysis was not available yet at the time of writing of this report, hence the values in loss on ignition. Most organic matter is present in the topsoil and a clear decrease is visible in the subsoil to 0,5 to 1% soil organic matter. When the lab measurements depicted in Figure 12 are compared with the field estimates the high value for 2LG1 and 6LG2 and the low value for 6LG1 cannot be verified. It is possible that 6LG1 and 6LG2 have been switched in the lab but this cannot be verified anymore. Topsoil soil organic matter content seems to be higher in the LT block compared to the CA block, the ST block shows lower values. It should be noted that these results are preliminary. The results from the cluster analysis for soil organic matter in Figure 13 show that the short distance differences vary between 0,1 to 1,4% organic matter. This is smaller than longer distance differences but still considerable.

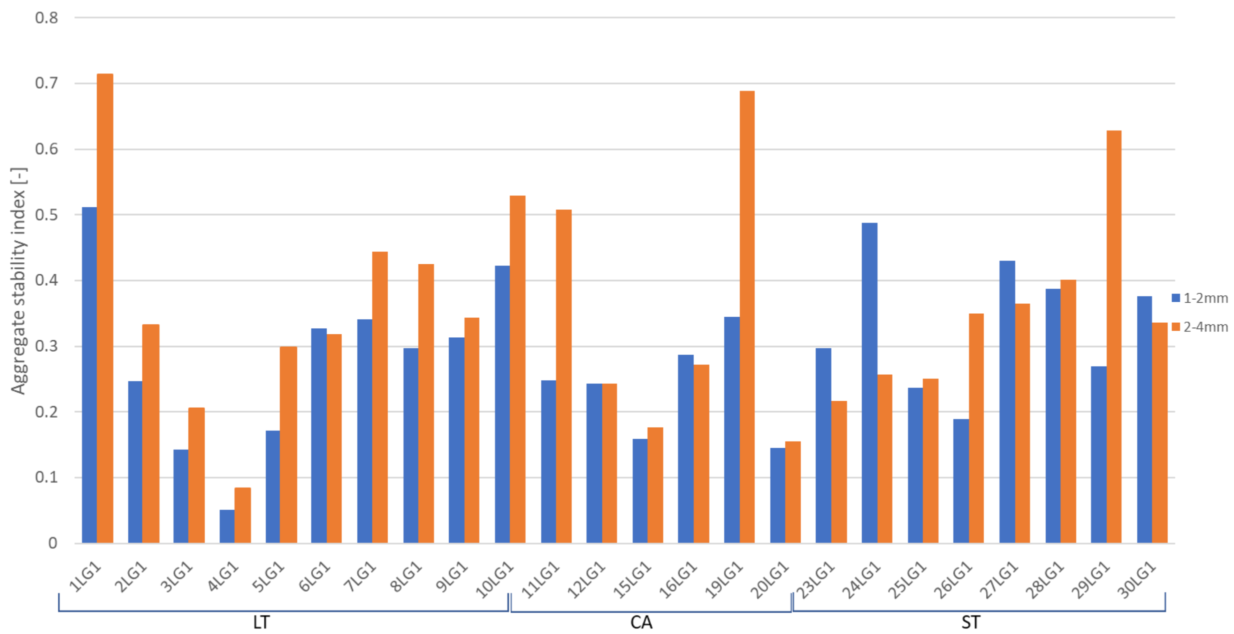


Figure 11 *Aggregate stability in the fine and coarser fractions depicted per sampling location and grouped per block of fields.*

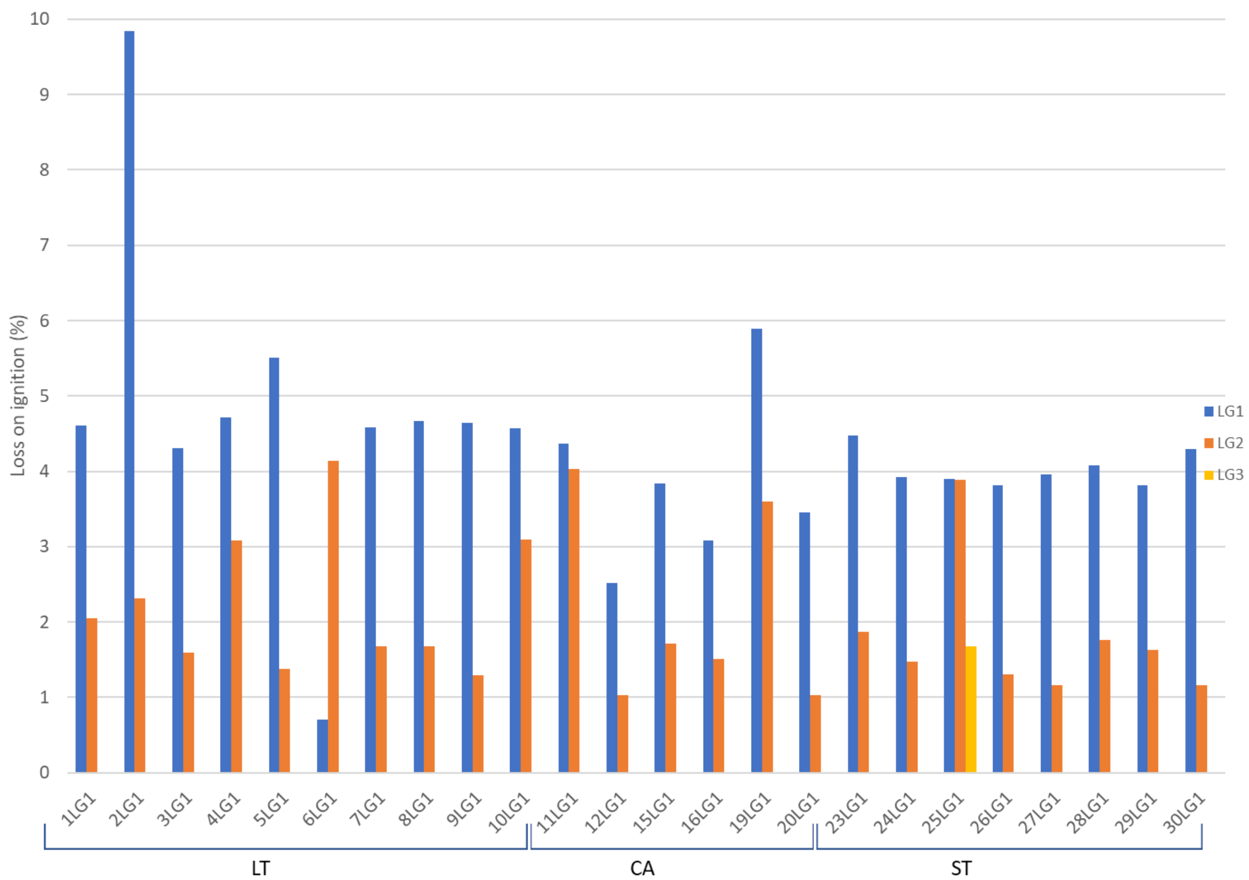


Figure 12 *Loss on ignition per horizon (LG1, 2, 3) and sampling location, grouped per block of fields. Horizons are dependent on the horizon description and can vary in depth. Note: possibly sample 6LG1 and 6LG2 have been switched in the lab, the results do not reflect field estimates. The high value for 2LG1 is also not confirmed by field measurements. Note2: loss on ignition is not corrected for soil clay content yet.*

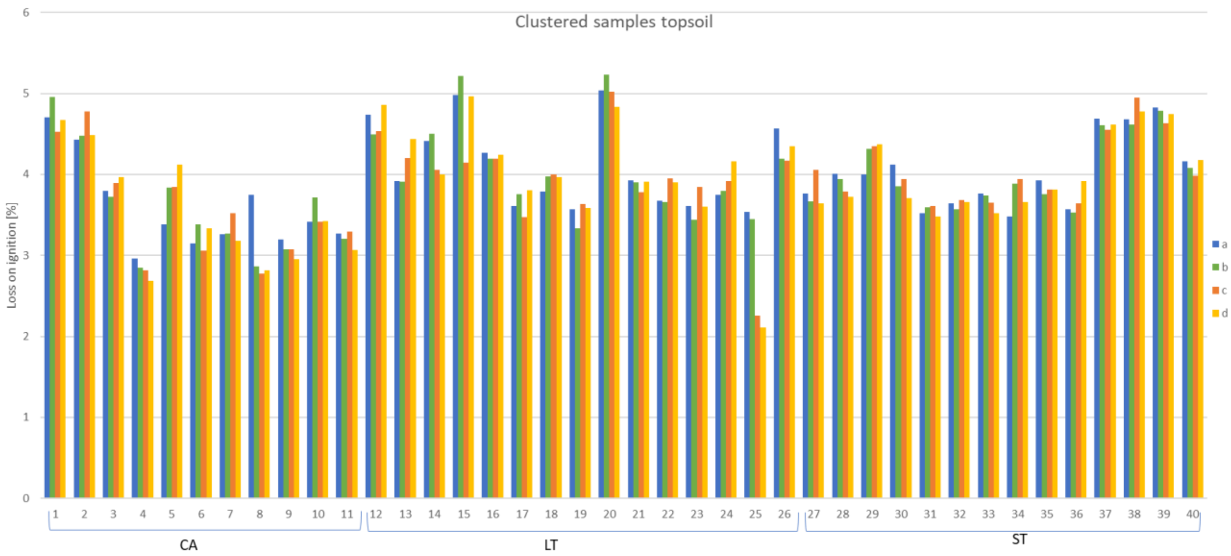


Figure 13 *Loss on ignition per cluster number with the 4 repetitions (at each 1 m distance) per cluster indicated with different colours. Note2: loss on ignition is not corrected for soil clay content yet.*

The soil profile descriptions per block show some differences in topsoil depth and clay percentages in top and subsoil, the presence of a peat layer or organic matter rich layer at greater depth. The thickness and composition of the tillage layer largely comparable. The penetration resistance plots show clear differences between blocks with a natural profile in the LT profile in Figure 14 and a compacted soil in the CA profile in Figure 15. The ST profile does show some compaction but less than CA and at greater depth. Differences between the two measurement years are relatively small although field circumstances differed (dry in 2019 and field moist in 2020).

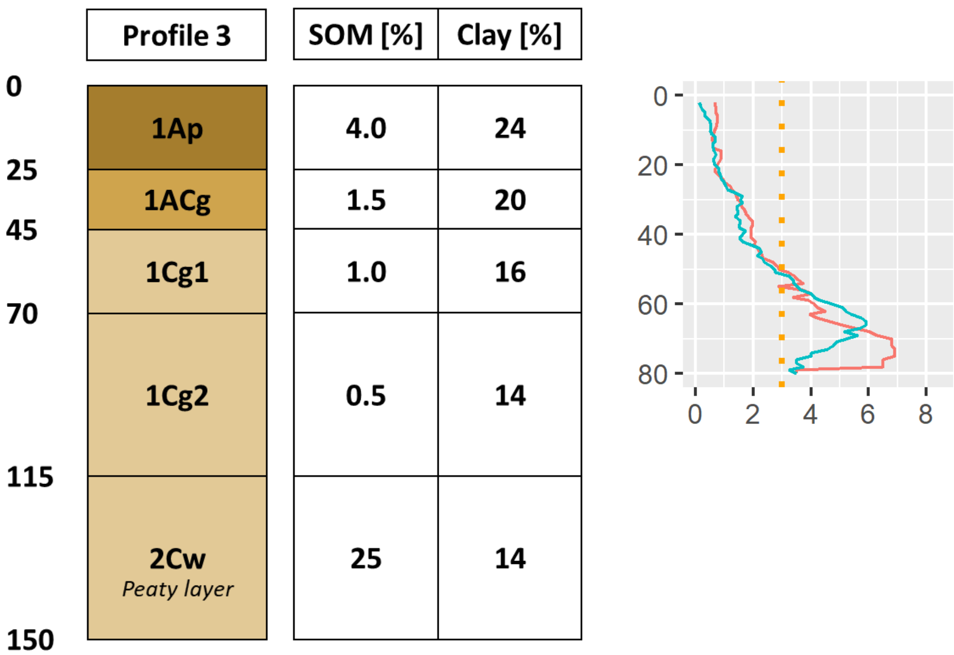


Figure 14 *Profile description according to the Dutch Soil Classification system of sampling location 3 in the LT group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y axis soil depth from soil surface is depicted. To the right the penetrologger measurements 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.*

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

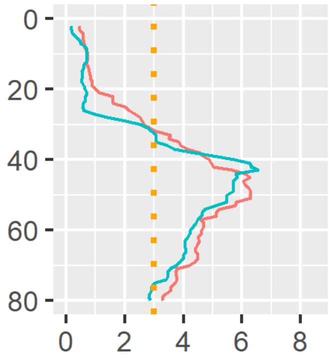


Figure 15 *Profile description according to the Dutch Soil Classification system of sampling location 12 in the CA group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y-axis soil depth from soil surface is depicted. To the right the penetrologger measurements 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.*

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

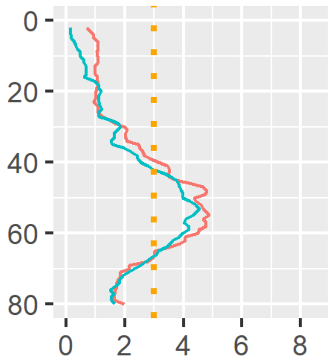


Figure 16 *Profile description according to the Dutch Soil Classification system of sampling location 26 in the ST group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y axis soil depth from soil surface is depicted. To the right the penetrologger measurements 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.*

5.2.3 Weather

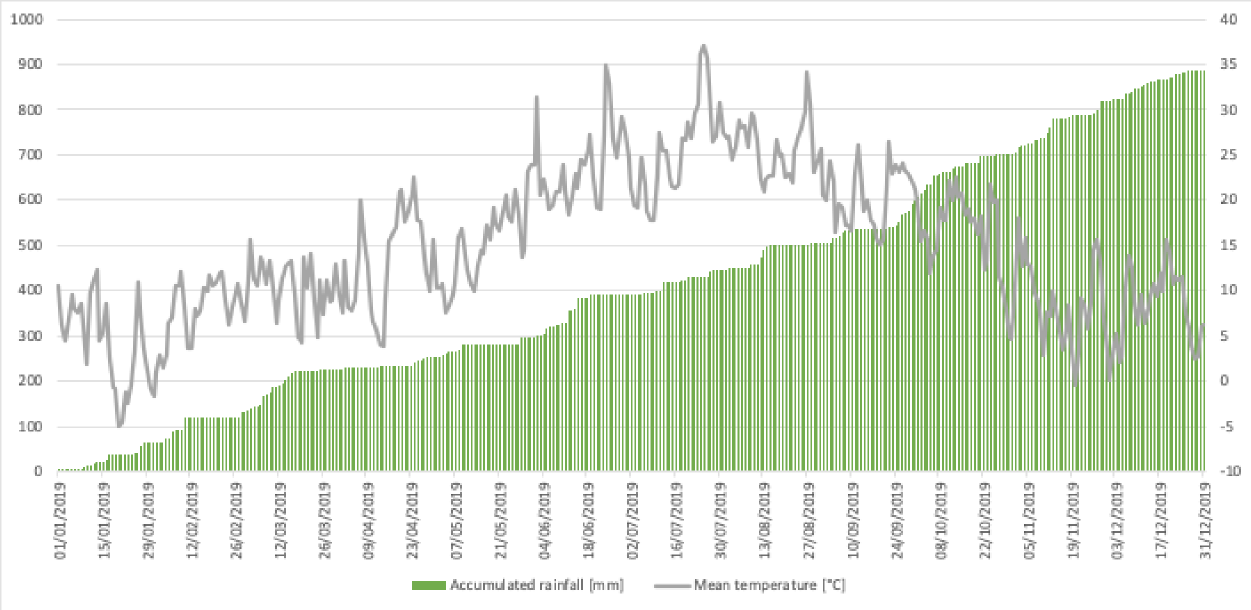


Figure 17 *Source: KNMI.*

5.2.4 Qualitative field observations

For the fields in longer transition some qualitative observations can be noted (2019/2020):

- **Improved soil structure:** airy, less compacted soils, with better infiltration.
- **Improved water holding capacity:** despite dry summer(s), no/almost no irrigation required and high(er) yields (and high-quality crops); this means a big upside in terms regenerative results, as a related downside, decreased workability of the fields must be reported.
- **Improved soil life:** most visibly by high counts of worms and the presence of fungi structures throughout the soils.

5.3 Modelling soil organic carbon content

Besides field measurements, we can also make use of models that assess changes in the soil organic carbon content. The advantage of running a model is that different scenarios can be compared and the potential carbon sequestration can be assessed. This chapter explains the model and input data that were used in this study, followed by a description of the scenarios that were tested.

5.3.1 Model description

There are many computer models that can predict carbon stock changes (Lesschen et al., 2020). This study uses the deterministic RothC model. This model was originally developed for the purpose of modelling soil organic carbon turnover (Coleman and Jenkinson, 1996). It is suitable to use for mineral soils, it requires limited input data and it is widely acknowledged and used by scientists throughout the globe. The model has been validated and calibrated in the temperate region using data from the long-term Rothamsted experiments.

The input data required by the model are easy to obtain and most of these data were collected during this study. Data that were not collected could be obtained through literature or had to be based on assumptions. The model requires weather data, soil data, and farm management data on the carbon inputs. When the input data are complete, the model splits the soil organic carbon that enters the system into four active compartments (or pools) and one inactive compartment (inert organic matter, IOM). The four active compartments are: Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass

(BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with a related decomposition rate. The priming action is taken to be zero and the proportion of an input of organic matter that is decomposed in a given time is taken to be independent of the amount added. The IOM compartment is resistant to decomposition.

Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For most agricultural crops and improved grassland, we use a DPM/RPM ratio of 1.44, i.e. 59% of the plant material is DPM and 41% is RPM. All incoming plant material passes through these two compartments once. Both, DPM and RPM decompose to form CO_2, BIO and HUM. The proportion that goes to CO_2 and to BIO and HUM is determined by the clay content of the soil. The BIO and HUM is then split into 46% BIO and 54% HUM. Animal manure is more decomposed than normal crop plant material. Different types of animal manure decompose in different carbon pools in a ratio: DPM 49%, RPM 49% and HUM 2%. Compost decomposes slightly different in a ratio: DPM 15%, RPM 70% and HUM15%. Details on the calculations are provided by Coleman and Jenkinson (2014).

5.3.2 Modelling the current situation

For each field input data were obtained for the years 2010 to 2019. Monthly weather data were available from 2010 to 2019 from the Royal Netherlands Meteorological Institute (KNMI) (Table 6).

Table 6 *The annual weather data that are used as input for the model.*

	Annual average temperature (˚C)	Precipitation (mm)	Annual average evapotranspiration (mm)
2010	7.8	948	574.7
2011	9.8	916	558.5
2012	9.3	1030	562.9
2013	9.1	916	557.1
2014	11.0	896	595.7
2015	9.9	999	566.9
2016	9.8	949	579.3
2017	9.9	1041	563.8
2018	10.5	733	648.2
2019	10.4	980	602.6

Data on the clay and soil organic carbon content were obtained from analysed soil samples, and data on the bulk density were derived from pedotransfer functions. For clay soils, the pedotransfer function of Wösten (2001) is used and for sandy soils the function of Hoekstra and Poelman (1982). Data on farm management were available for 2019, but historical data and some other input data had to be based on assumptions:

- Crop yield data of 2010 – 2018 were based on Central Bureau of Statistics (CBS) data. Yields of the selected province Zuid-Holland were used. Yields of vegetables were obtained from the Food and Agricultural Organization (FAOSTAT), because these data were not available from CBS.
- No data on crop yield were available in the CBS database for the crop blue-moon seeds. Therefore, a yield of 1.5 t dm/ha was assumed (Tönjes, 2019).
- The model includes 42 crops and therefore some crops had to be aggregated; legume crops were categorized as pulses and vegetables like carrots were categorized as vegetables. Furthermore, there is assumed that wheat and barley are winter crops, potatoes are consumption potatoes, and beet is sugar beet.
- All fields mulch crop residues into the soil. During harvest some crop residues will be lost. There is assumed that 80% of the crop residues can be mulched. The Harvest Index of each crop was used to assess the amount of crop residues.
- Images of Landsat 7 were analysed to check whether a cover crop was sown after harvest between 2000 and 2019. The type and performance of the cover crops could not be detected. Therefore, the average yield of the cover crops that were measured in 2019 was used as input for the other years which corresponds to 6 t dm/ha. In general, cover crops were sown after wheat and legume crops.

- The fertilizer application of 2019 was known; 20 t/ha green/worm compost. There is assumed that the fields long-RA (LT) receive since 2010 every 2 years 20 t/ha green/worm compost, the fields short-RA receive since 2015 every two years 20 t/ha green/worm compost and the fields with CA do not receive any green/worm compost. The composition of the green/worm compost was analysed. The product consisted for 90% of 711 g/kg dry matter (19.5% of the dry matter is organic matter) and for 10% of 255 g/kg dry matter (58.6% of the dry matter is organic matter). To convert the organic matter content to C content, a conversion factor of 0.58 was used.
- For the years no green/worm compost is applied, the fields long-RA receive 15 t/ha solid manure since 2010. The fields short-RA (ST) receive until 2014 15 t/ha slurry manure, and since 2015 the fields receive 15 t/ha solid manure for the years no green/worm compost is applied. The fields with CA receive each year 15 t/ha slurry barn manure.
- Throughout the years, soil samples were analysed on clay and organic carbon content. The model runs from 2010 and therefore soil samples that were taken around 2010 were used as input for the model.
- The amounts of crop residues were calculated using the harvest index and the fraction of crop residues that is generally being removed (high for vegetables, low for straw crops).
- Carbon content and balances were modelled for the upper 25cm.

The input data of the model can be found in Appendix A. Running the model provides insight in the carbon changes that occurred over a time span of 10 years. These results were used to estimate the average carbon sequestration in each field. The CO_2 sequestration can be calculated by taking the average carbon balance over 2010 – 2019 and multiplying it by 3.67 to get the CO_2 sequestration in t CO_2/ha/year.

5.3.3 Scenario 1: All fields under regenerative agriculture

Insights in the carbon changes per field over the past 10 years provides opportunities to test different scenarios. In the first scenario we assume that all fields are under Regen Ag since 2010. The input data need to be adapted accordingly:

- Fields that had no cover crop after legumes, wheat and onion will receive a cover crop in this scenario.
- The fields receive since 2010 15 t/ha of solid manure in one year and 15 t/ha of high-quality green/worm compost in the other year.
- Crop residues are left on the field (like it was assumed in the baseline).

An effect of Regen Ag on the yield is assumed to take longer and therefore the crop yields and the amount of residue that will remain on the field will not change. Reduced tillage to minimize aeration of the soil is also typical for Regen Ag. However, this is not yet included in the RothC model. The model runs with these slightly adapted input data and differences between the current situation and this scenario will be analysed.

5.3.4 Scenario 2: All fields under conventional agriculture

The second scenario assumes that all fields are managed in a conventional way since 2010. The input data were adapted to a typical conventional farming system in the Hoeksche Waard. The changes that were made include:

- Crop residues of straw crops are baled and removed from the field, including wheat, barley and oats. A removal fraction of 0.8 was used instead of 0.5, which means that only some below ground plant residues will remain.
- All fields receive 30 t/ha slurry barn manure per year.
- No cover crops are sown after harvest. In the Netherlands, cover crops are only obligatory on sandy soils after maize cultivation. Because no maize is cultivated on this farm, it is not necessary to grow a cover crop.

Tillage up to 30 cm depth is a common conventional agricultural practice. However, this effect cannot be included in the RothC model. The model runs with these adapted input data and differences between the current situation and this scenario will be analysed.

5.4 Sensor use

In order to initiate the models and to evaluate the carbon sequestration of a soil, the initial and subsequent SOC or SOM content needs to be known or measured. A prerequisite for a measurement in the Soil Heroes context is that it should be trustworthy, affordable, of sufficient accuracy, of the targeted support (xyz footprint) and preferably easy to carry out, possibly without interference of the farmer.

5.4.1 Soil Organic Matter/Carbon

At present the most obvious choice for soil organic matter or carbon measurements using sensors is by using infrared reflectance or absorbance in the visible, near and or mid infrared wavelengths (VNIR: 200-2500 nm; MIR: 400-6000 nm). The electromagnetic light interacts with the chemical composition of the soil, such as (in)organic compounds, texture etc. resulting in a spectrum that can be read as the spectral signature or fingerprint of that soil. By creating a library of spectra and lab measured soil properties of the same samples, models can be derived that can predict or estimate soil properties from newly measured spectra in the same area. The quality of the result depends on the quality and applicability of the library, the quality of the spectrometer used, the conditions (field or lab) and the predictability of the soil property. In general, properties like SOC, SOM, TC, clay, silt, sand, pH, carbonates, CEC, TN, extractable Ca, P sorption predict well. The quality of prediction for nutrients is variable. VNIR and MIR instruments suitable for soil analysis exist for lab and handheld field application. Typically, lab-based measurements have higher accuracy due to removal of noise caused by moisture, surface roughness or the presence of (dry) vegetation remains. MIR instruments are reported to give higher accuracies than VNIR. This can be related to the direct absorption features present in the MIR range. VNIR instruments on towed equipment or on a cone inserted into the soil also exist, and can be applied on drone, airplane and satellite applications if bare soil is visible. The penetration depth of all instruments is less than 1 cm. The choice of instrument is a balance between accuracy, measurement condition requirements, the presence of a library and cost.

5.4.2 Penetration resistance and bulk density

For other relevant soil properties various sensors exist as well. A penetrologger, such as built by Eijkelkamp[8], measures the penetration resistance of a soil up to 80 cm depth, which can be associated with rooting depth. This measurement is influenced by moisture content and the (strength and consistency of the) operator. It is advised to carry out measurements when the soil is at field capacity (field moist) to lessen the moisture effect. Measurements are always performed in fivefold. A rule of thumb that is often applied is that roots are hindered if the penetration resistance is more than 3 MPa.

The MS-Rho [9]sensor measures field moist or actual bulk density every 5 cm up to 100 cm depth. This can be corrected with a soil moisture measurement to derive dry bulk density. The measurement is based on attenuation of gamma radiation by matter over a known volume. The adjusted design of the sensor up to 100 cm depth has been validated preliminarily (van Egmond et al., in press).

5.4.3 Soil Moisture

In the past few years an increasing array of in situ soil moisture sensors have become available. Most are based on a specific measure of the di-electric constant of soil although the methods differ, with different accuracies and application possibilities as a result.

Time Domain Reflectancy is generally acknowledged as the most accurate method. It measures the change in signal between two rods pushed into the soil and relates that to the amount of moisture present. It uses a frequency that is relatively insensitive to other possible influences in signal like texture, salts, etc. The two rods (5-30 cm) of the sensor are pushed into the soil at the desired depth and connected to a data logger.

8 https://en.eijkelkamp.com/products/field-measurement-equipment/penetrologger-set-a.html
9 https://en.eijkelkamp.com/products/field-measurement-equipment/penetrologger-set-a.html

Electrical Conductivity or Electromagnetic Induction based sensors (Dacom, SensoTerra, etc.) measure the conductivity of a signal in the soil and relate that to water content, if possible after calibration between field capacity and wilting point. Calibration is meant to rule out the effect of texture and porosity or bulk density on the signal. Bigger changes in salt concentration are assumed to not occur in Dutch circumstances, some caution in interpreting readings after applying manure is advised however. Because the measurement is conducted in a rod or tube, often several depth slices are measured at the same time, thus providing a 'profile view' of soil moisture.

Frequency Domain Reflectancy is based on the same principle as TDR but optimises the frequency to the signal response, which is indicative for moisture content. A tensiometer measures the soil water suction or pressure using a ceramic hull that establishes an equilibrium with the soil moisture surrounding the sensor. This measure is relevant as an equivalent to the suction or effort a plant needs to exhibit to extract water from the soil. Both a FDR as a tensiometer are usually installed at a given depth in the soil and connected to a data logger.

Next to in situ measurements also more and more options are becoming available to measure soil moisture spatially. Some are operated from a quadbike, drone or airplane, others on a satellite. The measurement principle of Synthetic Aperture Radar (SAR) used on satellites like Sentinel 1 is based on radar, meaning that an electromagnetic signal is emitted, reflects on an object, is this case the soil or earth surface, and the reflection is received again by the antenna. The received signal, in case of bare soil, is influenced by surface roughness and soil moisture. SAR has several bands with different frequencies, each having different penetration characteristics. Typically a signal from a satellite penetrates about 5 cm into the soil. Resolution on a satellite platform will be limited and higher on an airplane.

Several indices and models exist to derive soil moisture estimates form visible and infrared satellite imagery. Thermal satellite imagery is also increasingly used for soil moisture indications. The basic principle is that a moist soil has a lower temperature that a dry soil. It does have disadvantages, for instance the influence of clouds on soil temperature. Passive and active microwave scattering are also increasingly used. Each has their advantages and disadvantages. The main principles and estimation techniques are illustrated by Zhang and Zhou, 2016. For all satellite based or airborne methods, the penetration depth of the signal in the soil is limited to the first one to five centimetre.

5.4.4 Soil texture and profile

In this study we not only use measurements to estimate the current status of the soil for ecosystem services, we also model the past, present and future soil processes that contribute to soil ecosystem services and the influence of regenerative agriculture practices on these services. For realistic modelling for instance soil organic carbon processes in the soil not only the soil organic carbon content itself but also properties like soil texture and soil profile descriptions are needed. Several sensing methods exist that can supply detailed spatial information on these properties. (van Evert, 2018; Castrignano et al. 2020).

Gamma-ray spectrometry is a passive measurement of the gamma radiation that is naturally emitted from the soil. Its amount and composition (frequencies) depend on the amount and composition of radionuclides that are present in the soil. The presence of radionuclides depends on the provenance of the parent material of the soil, or mineralogy, and soil texture. After deconvolution and regional calibration, the spectra measured by a gammaspectrometer can be translated to soil texture maps of the top 30 cm of the soil. Radiation originating from larger depths does not reach the soil surface due to attenuation by overlying soil. Gammaspectrometers can be applied using a quadbike, car, UAV or airplane. (van der Klooster et al, 2011; van Egmond, 2019).

Ground Penetrating Radar (GPR) is an active measurement device that can be used while walking or driving over soil. It usually consists of two antennas, one transmitter and one receiving antenna. The electromagnetic radar signal is sent into the soil and part of the signal will reflect back the receiver, influenced by the di-electric properties of the soil. This means that (abrupt) changes in texture, porosity, moisture are visible on the resulting xz radar image or reflectogram. To attribute the visible layers to specific texture classes and to improve the depth estimation calibration with (simple) soil profile descriptions is advised. The depth estimate is relatively precise (compared to EMI techniques) and depends on the frequency of the signal. The higher the frequency the higher the depth resolution but the lower the penetration depth. For soil profile or obstacle measurement typically a frequency of 300 to 500 MHz is used.

Electromagnetic induction measurement (EMI) measure the secondary current that is occurs when creating a magnetic field in the soil by two coils at the soil surface. The distance between the coils determines the measurement depth. Electrical conductivity (EC) measurements create an electrical field in the soil through discs that function as electrodes. The change in signal is measured and recorded. Both EMI and EC measurements provide a xz image of the conductivity or resistivity of the soil which is influenced by moisture, texture, porosity/bulk density and salt concentration. Which property determines the variability visible in a certain measurement needs to be determined through calibration using (simple) soil profile descriptions although ballpoint figures are available that relate the signal to texture. It is advised to be careful in interpreting the patterns in relation to (uneven) manure applications or storage. The depth resolution of both methods increases when multiple coils or discs are used at varying distances. Both measurements are carried out while walking or driving over the soil.

5.4.5 Vegetation

In paragraph 5.4.1 the use infrared reflectance or absorbance in the visible and near infrared wavelengths (VNIR: 200-2500 nm) is described for estimating soil organic matter, carbon, texture and other soil parameters. The same principle applies to sensing plants and is even easier and more applied than sensing of soil with VNIR. Especially green vegetation has a very distinct spectral signature (Figure 18) with a strong jump between 680 and 730-750 nm, also called the red edge. The ratio between the reflectance at 750 nm (near infrared light) and 650 nm (red light) is often used in vegetation indices to provide an estimate of the greenness of the crop, the maturity or growth stage and amount of biomass.

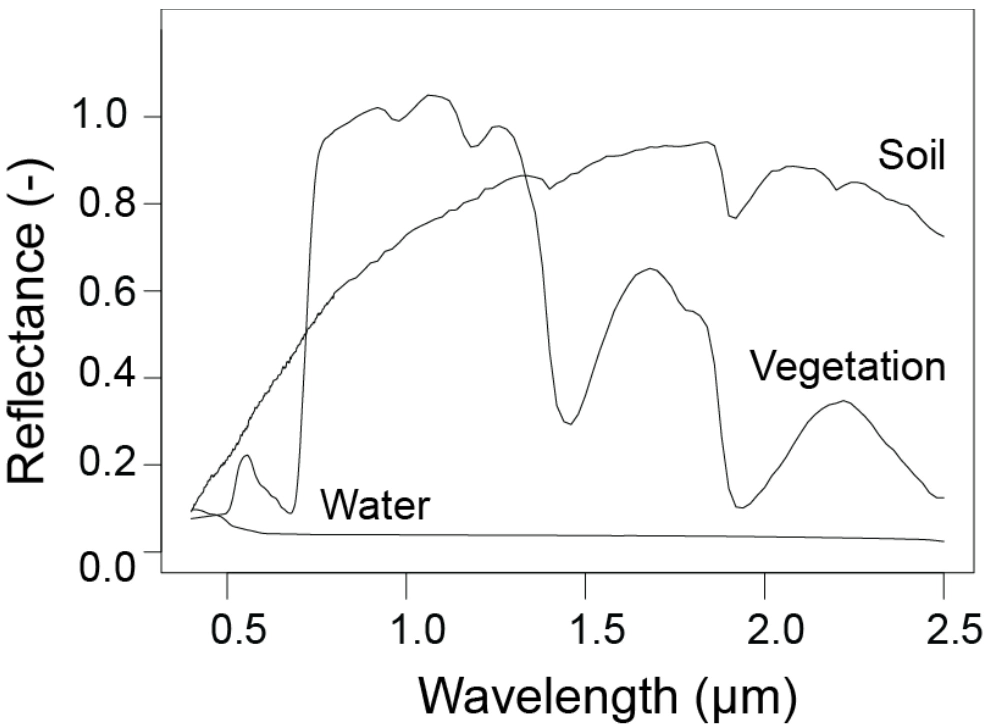


Figure 18 *spectral signatures of water, vegetation and soil. Source: Mulder, V. L. (2013), Spectroscopy-supported digital soil mapping, 188 pp, PhD thesis, Wageningen University, Wageningen.*

The most used vegetation index is the Normalised Difference Vegetation Index (NDVI), calculated by NDVI = NIR-R/NIR+R. NIR and R being the reflectance in the near infrared and the red region or band respectively. Values range between -1 and 1, with negative values usually being snow or clouds, 0 being water surface, 0,1 - 0,2 being bare soil and 0,3-0.9 or even 1 being vegetated areas, the higher the NDVI the more green the vegetation generally is. The NDVI does not increase linearly with greenness of vegetation and tends to saturate at 0.8 – 0.9 and Leaf Area Indices (LAI) above 3. Therefore, also other indices have been developed that can be more suitable but generally also a bit more difficult to calculate.

VNIR reflectance of vegetation can be measured using a wide range of sensors and platforms, from a handheld, very detailed measurement (ASD Fieldspec etc.), to on-the-go sensors (Yara N-Sensor, Crop Circle, GreenSeeker etc.) UAV measurements (EBEE, DJI etc.), airborne measurements and a large range of satellite imagery. The most suitable device and platform will depend on the spatial and spectral resolution needed, cost, availability and the need to measure at a specific time in the growing season and the presence of clouds (in temperate regions this is a severe downside of satellite imagery). Measurements can be used to monitor the development of a crop, growth stage, LAI, biomass, variation within and between fields due to the soil, field management and possible diseases, Nitrogen content etc. An easy platform in the Netherlands to monitor crops is www.groenmonitor.nl which includes all freely available corrected and processed satellite data to NDVI maps throughout the year. If that resolution is too coarse various sensors exist that can be mounted on a tractor, booms or other.

5.5 Modelling the soil organic carbon content

5.5.1 Current situation

At the moment, the plots that are longest under Regen Ag receive most carbon inputs and the fields that are still under CA receive least (Figure 19). The fields under Regen Ag do not receive any compost and solid manure, whereas the other fields do. The ST fields only received slurry manure in the years 2010-2014, because these fields became regenerative in 2015. Because the LT fields receive every 2-years 15 t/ha solid manure, and the CA fields receive every year 15 t/ha slurry manure, the average C input from manure is quite equal (i.e., solid manure contains almost twice as much C compared to slurry manure). The CA fields also mulched the crop residues, which is not often done under CA.

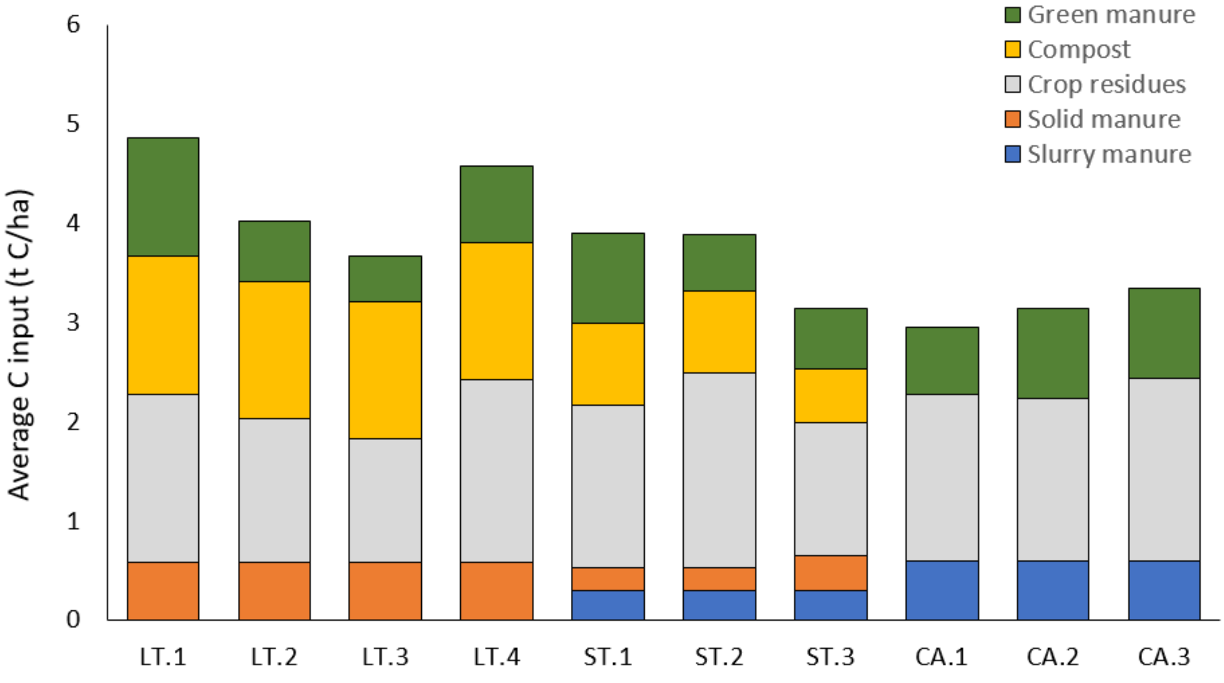


Figure 19 *The carbon (C) inputs of the different fields of the SoilHeroes farm in Hoeksche Waard.*

The model run for the years 2010-2019 to test whether differences between the LT fields, ST fields, and CA fields can already be modelled (Figure 20) and carbon sequestration (Table 7). All fields showed a slightly positive trend in the C content. On average, the carbon balance is slightly more positive in the LT fields (0.22 t C/ha), compared to the ST fields and the CA fields (0.19 and 0.18 t C/ha respectively). It is interesting to see that LT fields have highest initial C content, whereas CA fields have lowest. It is difficult to draw conclusions from the ST fields, although field ST.1 showed a steeper increase in C content after 2015 (when the fields started the transition towards Regen Ag). The other ST fields probably need more time to observe a significant effect of Regen Ag on the soil organic carbon content. Highest increase in C-content was observed at the field LT.1 which also received highest amount of C input. Hardly any change in C content was observed in ST.3 and CA.1, the two fields that received lowest C inputs.

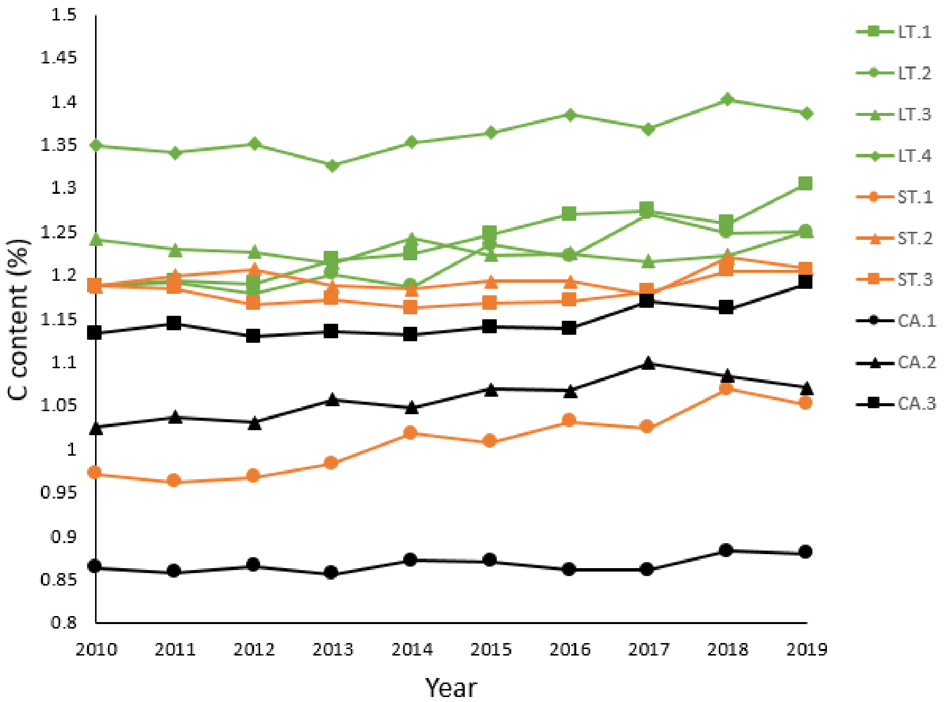


Figure 20 *The modelled carbon content between 2010 and 2019 for the ten fields (LT: green, ST: orange, CA: black).*

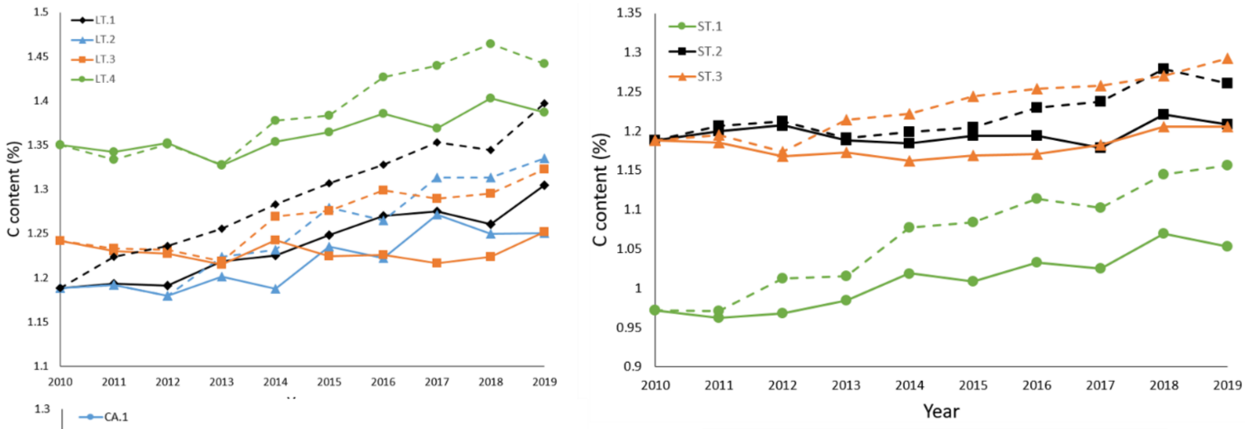
Table 7 *The initial C content, the average C input over 2010 - 2019, and the average annual carbon sequestration during this period.*

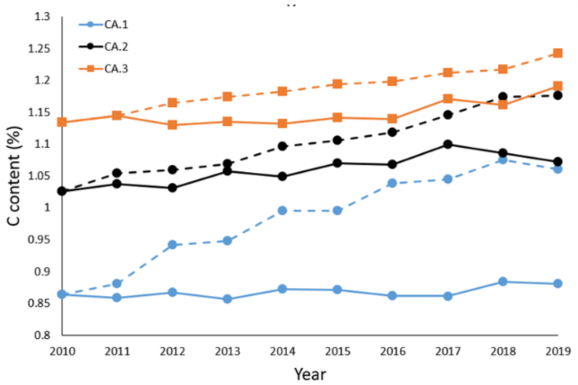
Field	Treatment	Initial C content (%)	Average C input (t C/ha/yr)	C_{seq} (t CO_2/ha/yr)
LT.1	Long term RA	1.19	4.87	1.27
LT.2	Long term RA	1.19	4.02	0.68
LT.3	Long term RA	1.24	3.67	0.37
LT.4	Long term RA	1.35	4.57	0.97
ST.1	Since 2015 RA	0.97	3.9	1.12
ST.2	Since 2015 RA	1.19	3.89	0.9
ST.3	Since 2015 RA	1.19	3.14	0.04
CA.1	CA	0.86	2.95	0.81
CA.2	CA	1.03	3.15	0.54
CA.3	CA	1.13	3.34	0.58

The results of the model can be compared to the measured carbon contents. The deviation of the modelled OM content from the measured OM content is lowest in LT.3 (1%) and highest in CA.2 (9%).

5.5.2 Scenario 1: All fields under regenerative agriculture since 2010

Growing a cover crop after legumes, wheat and onions, and replacing slurry manure by solid manure and green compost will positively influence the soil organic carbon content (Figure 21). It turned out that due to this management change, all fields showed a more positive trend in C-content. The results show that the effect of changing towards Regen Ag becomes visible after a couple of years. In most LT fields the effect of growing more cover crops after harvest clearly had an effect on the C-content. An immediate effect is visible at the field LT.1, because this field now receives nine times a cover crop after harvest instead of four. The field ST.3 and ST.2 are responding quite similar on the changes in management, whereas the field ST.1 showed a steeper increase in C content after 2014. Largest responses on the management change are, as expected, at the CA fields. Especially the field with lowest initial C content has potential (CA.1). On average, an increase of 0.34 t C/ha in the C-balance and 1.25 t CO_2/ha/year was predicted.



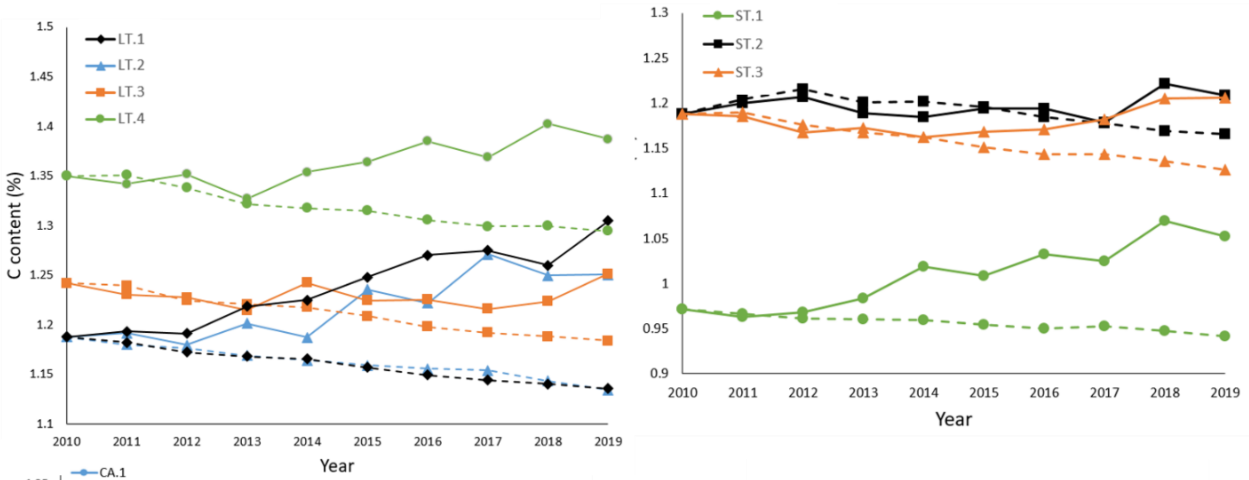


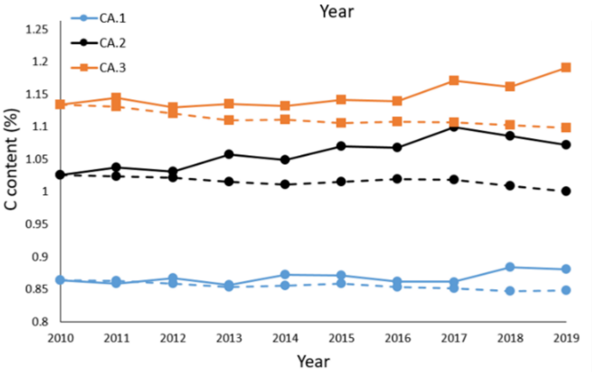
	Increase in C-balance (t C/ha)	Increase in Cseq (t CO2/ha/yr)
LT.1	0.32	1.17
LT.2	0.29	1.06
LT.3	0.24	0.90
LT.4	0.17	0.63
ST.1	0.44	1.61
ST.2	0.12	0.44
ST.3	0.39	1.44
CA.1	0.71	2.59
CA.2	0.41	1.50
CA.3	0.32	1.17

Figure 21 *The potential increase in C content (dotted lines) compared to the baseline (solid line) when the fields Long-RA (A), Short-RA (B) and conventional agriculture (C) switched to regenerative agriculture since 2010. Also the increase in C-balance and carbon sequestration (C_{seq}) compared to the baseline is given.*

5.5.3 Scenario 2: All fields under conventional agriculture since 2010

For the baseline scenario, even the fields under conventional agriculture mulched the crop residues into the soil. Removing all crop residues, not sowing any cover crop after harvest and only applying slurry manure has an effect on the C-content. The C-content declined most in the LT fields. Probably because these fields have highest initial C-content and the decrease in C-input compared to the baseline is highest. At the fields ST.2 and ST.3, the effect of this management change only showed an effect after 2015 (Figure 21). Smallest effect, but also smallest changes in management were observed in the CA fields. On average, a decrease of 0.35 t C/ha in the C-balance and 1.29 t CO_2/ha/year was predicted.





	Decrease in C-balance (t C/ha)	Decrease in Cseq (t CO2/ha/yr)
LT.1	-0.56	-2.04
LT.2	-0.37	-1.34
LT.3	-0.31	-1.13
LT.4	-0.47	-1.71
ST.1	-0.43	-1.57
ST.2	-0.33	-1.22
ST.3	-0.25	-0.90
CA.1	-0.27	-0.99
CA.2	-0.23	-0.86
CA.3	-0.31	-1.13

Figure 22 *The decrease in C content (dotted lines) compared to the baseline (solid line) when the fields Long-RA (A), Short-RA (B) and conventional agriculture (C) used a conventional management strategy since 2010. Also the decrease in C-balance and CO_2 emission (C_{seq}) compared to the baseline is given.*

5.5.4 Sensitivity analysis

A sensitivity of the model on the different carbon sources was carried out to test the effect of each carbon source on the C balance. One carbon source was changed at the time and therefore we could test the effect of: (i) more cover crops, (ii) replacing slurry manure for solid manure and green compost, (iii) growing no cover crops, (iv) removing crop residues from the field, and (iv) applying slurry manure instead of solid manure and green compost (Table 8). Sowing more cover crops after harvest has a larger effect on the carbon content in the soil compared to the application of solid manure and green compost instead of slurry manure. For scenario 2, removing the crop residues had strongest effect on the carbon balance and least effect on the application of 30 t/ha slurry manure and no solid manure or green compost. The amount of slurry manure that was applied in this scenario was twice as much compared to the baseline. Because all other variables stayed the same, some fields showed a positive effect. The effect of not sowing a cover crop after harvest depend on the number of years a cover crop was already sown in the baseline.

A sensitivity analysis on the RothC model showed that the soil moisture content, soil depth at which the model runs, and crop residues that are left in the field are most sensitive (Lesschen et al., 2020). The soil moisture content influences the carbon decomposition rate. Decomposition rate increases with soil moisture content. The RothC model was initial calibrated at a soil depth of 23 cm. Increasing the soil volume, also increases the volume at which decomposition takes place. Therefore, a smaller soil depth results in a stronger increase of the C-balance. The decomposition rate of crop residues and the amount of crop residues that are left in the field influence the C-balance as well. Changing the initial carbon content has limited effect on the C-balance. A high C content results in general in a lower C-balance because more C can mineralize and therefore higher amounts of C needs to be added to compensate for the mineralization. C-sources with a high C:N-ratio result in higher carbon balances and the clay content of the soil has limited effect on the C-balance.

Table 8 *Sensitivity of the model on the carbon sources. The values represent the percentage difference in carbon content when one variable changed (according to the scenarios) compared to the baseline.*

	More cover crops	Replacing slurry manure for solid manure and green compost	Removing crop residues	No cover crop	Applying more slurry manure instead and no solid manure and green compost
LT.1	4.2	0	-3.3	-2.7	-0.9
LT.2	2.8	0	-3.2	-1.4	-0.9
LT.3	2.6	0	-2.3	-0.2	-0.1
LT.4	2.1	0	-3.3	-1.1	-0.1
ST.1	3.5	1.2	-4	-2.9	1
ST.2	2.1	1	-4.3	-0.3	0.9
ST.3	3.2	2.2	-2.9	-1.2	1.2
CA.1	8	2.2	-4.1	-0.5	2.1
CA.2	3.3	1.7	-4.7	-2.8	1.6
CA.3	3.8	1.7	-3.9	-1.9	1.5

6 Discussion and recommendations

Regenerative agriculture is a rapidly growing but at the time of writing (2021) not a widely adapted farm management strategy in the Netherlands or abroad. However, the fact that there is no clear definition of regenerative agriculture or the availability of other terminology that indicates this way of farming, makes it difficult to assess and compare the effect and uptake of regenerative agricultural practices. Other studies often focus on a single practice, whereas regenerative agriculture focusses on improving the resilience of the farming system as a whole in a sustainable way. Making use of the network regenerativefarming.nl as a platform to exchange experiences with (aspects of) regenerative agriculture can stimulate the adoption.

This study showed that it is important to look at all aspects of the farming systems, because increasing the soil organic matter content is and can be influenced by multiple elements. For example, the introduction of more non-intensive crops in the crop rotation can reduce soil disturbance and higher amounts of crop residues that are left on the field. This is not only attractive for soil organic carbon build-up, but also for soil biota and pest and disease reduction. The slow decomposition rate of organic fertilizers with a high C:N-ratio can be another strategy to increase the soil organic matter content steadily.

The farm in Hoeksche Waard showed positive carbon balances on all fields, which is quite exceptional compared to other agricultural systems in the Netherlands (Hoogmoed et al., 2021). If no crop residues were left on the fields, eight out of ten fields would have had a negative C-balance. Leaving crop residues in the field has a positive effect on the soil quality and biodiversity (Rietberg et al., 2013), but the effect depends on the type of crop residue (Hanegraaf et al., 2010). Residues with high C contents and low N contents (e.g., straw crops) decompose much slower compared to residues with a low C content and high N content (e.g., beet leaves) (CBAV, 2013). Therefore, it is recommended to consult the Handboek Bodem & Bemesting (CBAV, 2013) to check the effective organic matter (i.e., the amount of C that remains in the soil after one year) of crop residues, cover crops and organic fertilisers before changing the farm management.

When applying pig slurry manure only 9% of the carbon that was applied remains in the soil, while this is almost 70% for GFT-compost and green compost (CBAV, 2013). Besides, slurry manure contains 40-80% of the N in the ammonium form, whereas this number is much lower for solid manure (Misselbrook et al., 2016). Ammonia (NH_3) and methane (CH_4) emissions will also reduce by 4 to 20 times when applying solid manure instead of slurry manure (IPCC, 2006). Large manure surpluses in the Netherlands makes it difficult for farmers to switch towards other types of organic manure. There are opportunities to process pig slurry into organic fertiliser products that are attractive for arable farmers to use (Egene et al., 2021). The carbon content in the soil can, for example, be improved by a P-poor OM-rich soil enhancer. Circular agriculture is enhanced by processing pig manure and it was proven that the processed products behave similar compared to mineral fertiliser (Chojnacka et al., 2020).

In the Netherlands, it is only obligatory to sow cover crops after maize harvest on sandy soil. This study showed the potential of growing cover crops more often. Many studies confirm the positive effects of cover crops on the organic matter content in the soil, however they also note that cover crops should be sown before October (Rietberg et al., 2013). It is therefore recommended to include crops after which a cover crop can be sown in the crop rotation. When no cover crops were sown, the C-balance of the fields LT.3, ST.3, CA.2, CA.3 would have turned out negative.

In this study the use of sensors to measure the spatial patterns or point values of soil properties was limited to the penetrologger (paragraph 5.2.2 and 5.4.2). The measured average penetration resistance profiles show clear differences between the blocks of fields, which is an indication of differences in rooting depth that can be incorporated in model runs and is useful information for the farmer. Other sensors have not been applied but would allow to spatialise the model runs or provide additional data on evaluation of model results. The current technologies can supply supporting information for the model runs but it is advisable to only use lab based measurements for model evaluation, either based on conventional or IR methods.

For each field, the organic matter content was measured at two or three moments in time (2010-2019). The reliability of the soil organic carbon modelling can be validated by measurements. The baseline scenario only showed 1 to 9% deviation from the measurements. Observing changes in the organic matter content takes time and no measurements are available yet to validate the scenarios. Although we ran a widely acknowledged carbon model that was validated and calibrated thoroughly using historical data of the Rothamsted Experiment, the model still has its uncertainties. The model requires limited input data, which means that some processes were simplified. For example, above and below ground biomass were estimated by a ratio, and biological decomposition was not considered. Even when using a model that requires a relatively limited amount of input data, it was challenging to obtain the data without making assumptions. The uncertainty of the input data is therefore another factor that could have affected the results. For example, data on crop and cover crop yield were only measured in 2019. For the other years, data on crop yield were obtained from CBS and the average cover crop yield of 2019 was used for modelling. The effect of these and other assumptions is unknown. It is recommended to continue collecting data on the C inputs (crop residues, green manure, organic manure, compost) and soil parameters, to minimize the assumptions that need to be made for the modelling. Another recommendation is to run multiple carbon models. Each model has its strengths and weaknesses. By running multiple models, a range of potential outcomes can be given and the results no longer rely on a single value.

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Annex 1 Input data for the RothC model

Field	Treatment	Area (ha)	Input	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
LT.1	Long-RA	6.0	Crop	Pulses	Winter wheat	Consumption potatoes	Winter wheat	Onions	Winter wheat	Pulses	Consumption potatoes	Winter wheat	Vegetables
			Yield (t ds/ha)	2.6	0.9	12.2	0.9	5.7	0.9	2.7	12.6	0.9	7.5
			Crop residues left in field	0.8	0.5	3.0	0.5	0.0	0.5	0.8	3.2	0.5	0
			Cover crop	0.0	0.0	6.0	0.0	6.0	6.0	0.0	0.0	6.0	0
			Organic manure type	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type	Green/ worm compost	Green/ worm compost	Green/ worm compost	Green/ worm compost	Green/ worm compost	Green/ worm compost	Green/ worm compost	Green/ worm compost	Green/ worm compost	Green/ worm compost
			Compost quantity (t/ha)	20	0	20	0	20	0	20	0	20	0
			Clay content (%)	21									
			Organic matter content (%)	2.2									
LT.2	Long-RA	9.1	Crop	Blue-moon seed	Vegetables	Consumption potatoes	Winter wheat	Pulses	Onions	Oats	Consumption potatoes	Winter wheat	Pulses
			Yield (t ds/ha)	1.5	0.6	12.2	0.9	2.7	6.1	2.4	12.6	0.9	2.7
			Crop residues left in field	0.8	0.0	3.0	0.5	0.8	0.0	1.3	3.2	0.5	2.7
			Cover crop	0.0	0.0	6.0	0.0	6.0	6.0	0.0	0.0	6.0	3.2
			Organic manure type	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15

Field	Treatment	Area (ha)	Input	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
			Compost type		Green/ worm compost		Green/ worm compost		Green/ worm compost		Green/ worm compost		Green/ worm compost
			Compost quantity (t/ha)	0	20	0	20	0	20	0	20	0	20
			Clay content (%)	2.3									
			Organic matter content (%)	25									
LT.3	Long-RA	17.6	Crop	Vegetables	Consumption potatoes	Winter wheat	Pulses	Winter wheat	Consumption potatoes	Winter wheat	Onions	Pulses	Consumption potatoes
			Yield (t ds/ha)	0.7	12.4	0.9	2.6	0.9	10.8	0.9	6.4	1.5	13.2
			Crop residues left in field	0.0	3.1	0.5	0.8	0.5	2.7	0.5	0.0	0.5	3.3
			Cover crop	0.0	0.0	0.0	0.0	6.0	0.0	6.0	0.0	0.0	0.0
			Organic manure type	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type	Green/worm compost		Green/worm compost		Green/worm compost		Green/worm compost		Green/worm compost	
			Compost quantity (t/ha)	20		20		20		20		20	
			Clay content (%)	24									
			Organic matter content (%)	2.2									
LT.4	Long-RA	11.7	Crop	Consumption potatoes	Winter barley	Vegetables	Winter wheat	Consumption potatoes	Winter wheat	Pulses	Sugar beet	Consumption potatoes	Winter wheat
			Yield (t ds/ha)	12.0	4.4	0.6	0.9	12.2	0.9	2.7	24.0	10.6	8.3
			Crop residues left in field	3.0	2.4	0.0	0.5	3.1	0.5	0.8	4.8	2.7	4.5
			Cover crop	0.0	0.0	0.0	0.0	6.0	0.0	0.0	6.0	0.0	3.2
			Organic manure type	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)

Field	Treatment	Area (ha)	Input	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type		Green/ worm compost		Green/ worm compost		Green/ worm compost		Green/ worm compost		Green/ worm compost
			Compost quantity (t/ha)		20		20		20		20		20
			Clay content (%)	25									
			Organic matter content (%)	2.5									
ST.1	Short-RA	14.5	Crop	Vegetables	Winter wheat	Consumption potatoes	Winter wheat	Onions	Winter wheat	Consumption potatoes	Winter wheat	Pulses	Onions
			Yield (t ds/ha)	0.7	0.9	12.2	0.9	5.7	0.9	10.4	0.9	1.5	7.2
			Crop residues left in field	0.0	0.5	3.0	0.5	0.0	0.5	2.6	0.5	0.5	0.0
			Cover crop	0.0	6.0	0.0	6.0	0.0	6.0	0.0	6.0	6.0	0.0
			Organic manure type	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type						Green/ worm compost		Green/ worm compost		Green/ worm compost
			Compost quantity (t/ha)						20		20		20
			Clay content (%)	21									
			Organic matter content (%)	1.8									
ST.2	Short-RA	11.3	Crop	Grass seed	Grass seed	Vegetables	Consump-tion potatoes	Winter wheat	Pulses	Onions	Winter wheat	Consumption potatoes	Winter wheat
			Yield (t ds/ha)	7.5	7.5	0.6	11.6	0.9	3.0	5.0	0.9	10.6	8.9
			Crop residues left in field	6.0	6.0	0.0	2.9	0.5	0.9	0.0	0.5	2.7	4.8
			Cover crop	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	5.4

Field	Treatment	Area (ha)	Input	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
			Organic manure type	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type						Green/ worm compost		Green/ worm compost		Green/ worm compost
			Compost quantity (t/ha)						20		20		20
			Clay content (%)	22									
			Organic matter content (%)	2.2									
ST.3	Short-RA	14.0	Crop	Consumption potatoes	Vegetables	Winter wheat	Onions	Vegetables	Winter wheat	Consumption potatoes	Winter wheat	Onions	Pulses
			Yield (t ds/ha)	12.0	0.6	0.9	5.7	0.6	0.9	10.4	0.9	3.6	3.1
			Crop residues left in field	3.0	0.0	0.5	0.0	0.0	0.5	2.6	0.5	0.0	0.9
			Cover crop	0.0	0.0	6.0	0.0	0.0	6.0	0.0	6.0	0.0	8.3
			Organic manure type	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)	Solid manure (every 2 years)
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type							Green/ worm compost		Green/ worm compost	
			Compost quantity (t/ha)							20		20	
			Clay content (%)	22									
			Organic matter content (%)	2.2									
CA.1	CA	13.5	Crop	Pulses	Winter wheat	Onions	Winter wheat	Consumption potatoes	Pulses	Sorghum	Oats	Consumption potatoes	Winter wheat
			Yield (t ds/ha)	2.6	0.9	6.8	0.9	12.2	3.0	2.4	4.3	10.6	9.0
			Crop residues left in field	0.8	0.5	0.0	0.5	3.1	0.9	1.3	2.3	2.7	4.9

Field	Treatment	Area (ha)	Input	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
			Cover crop	0	0	0	0	0	0	0	6.0425	0	7.37
			Organic manure type	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type										
			Compost quantity (t/ha)										
			Clay content (%)	23									
			Organic matter content (%)	1.6									
CA.2	CA	11	Crop	Winter wheat	Consump-tion potatoes	Winter wheat	Onions	Sugar beet	Sugar beet	Winter wheat	Pulses	Onions	Consump-tion potatoes
			Yield (t ds/ha)	0.9	12.4	0.9	5.7	23.5	22.8	0.9	3.0	3.6	11.5
			Crop residues left in field	0.5	3.1	0.5	0.0	4.7	4.6	0.5	0.9	0.0	2.9
			Cover crop	0	0	6.0425	0	6.0425	0	6.0425	0	0	0
			Organic manure type	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type										
			Compost quantity (t/ha)										
			Clay content (%)	19									
			Organic matter content (%)	1.9									
CA.3	CA	10.0	Crop	Winter wheat	Onions	Pulses	Consump-tion potatoes	Winter wheat	Sugar beet	Winter wheat	Consumption potatoes	Winter wheat	Onions
			Yield (t ds/ha)	0.9	7.6	2.6	11.6	0.9	22.8	0.9	12.6	0.9	6.5
			Crop residues left in field	0.5	0.0	0.8	2.9	0.5	4.6	0.5	3.2	0.5	0.0
			Cover crop	0	0	6.0425	0	0	0	6.0425	0	6.0425	0
			Organic manure type	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure	Liquid manure

Field	Treatment	Area (ha)	Input	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
			Organic manure quantity (t/ha)	15	15	15	15	15	15	15	15	15	15
			Compost type										
			Compost quantity (t/ha)										
			Clay content (%)	20									
			Organic matter content (%)	2.1									

Annex 2 Soil analysis

Table A2.1 *Sample id, Field names, sample category for soil description and sampling locations (locations indicated in Figure 8, Figure 9, Figure 10) (excluding clusters).*

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

Table A2.2 *soil analyses per sample category.*

Soil analysis	**1**	**2**	**3***	**clusters**
Soil profile description	x	x	x	
Field estimates of soil texture and organic matter (part of the soil description)	x	x	x	
Penetrologger measurement (5 fold)	x	x	x	
Aggregate stability		x	x	
Dry Bulk Density rho(d) (undisturbed samples) (T=105 dgr.C)			x	
Evaporation (Wind) (h=-50 until -700cm) (fixed > 20 points)			x	
Loss on ignition (OS) (T=550 dgr.C)			x	x
Pressure Plate (h=-10^3 until -10^4cm)			x	
Sandbox (h=0 until -100cm)			x	
Saturated Hydraulic Conductivity Ksat (h=0)			x	
PW (SFA-CaCl2) PO4		x	x	
fine size particle size distribution (pipette method, <2, <16, <50, > 50 mu)		x*	x	
pH		x	x	
K (F-AES, K-Cl extraction)		x	x	
POXC (mg/kg)		x	x	
Ntot (H2SO4-Se destruction-Kjeldahl) (g/kg)		x	x	
Ptot (H2SO4-Se destruction) (g/kg)		x	x	
Ctot (LECO, Dumas) (g/kg)		x	x	
Corg (LECO, Dumas) (g/kg)		x	x	

*' Multiple depths.

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Report 3251
ISSN 1566-7197

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ISSN 1566-7197

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