



Possibilities for monitoring CO₂ sequestration and decomposition of soil organic matter on dairy farms

Jan Peter Lesschen, Theun Vellinga, Sanne Dekker, Annelotte van der Linden, Rene Schils



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Emissions and sequestration of carbon in soils are not yet accounted for in the carbon footprint of dairy farms. The purpose of this study is to develop a reliable and transparent monitoring and accounting system for soil carbon sequestration and emissions at dairy farms. The scientists worked with study groups of dairy farmers, data analysis and model development. A monitoring system based on measurements of OM contents in existing soil analyses is not supportive enough at present to reliably estimate carbon sequestration in soils. However, a monitoring system based on a combination of soil sampling analyses, registration of activities and model calculations of changes in soil carbon quantities is technically possible. The uncertainties in these calculations are currently still too large to link these to a reliable penalty or reward system at farm level.

Keywords: soil, dairy farming, carbon balance, peat soils, sequestration, emissions

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Foreword

There is a need within the Dutch dairy sector to allow carbon sequestration in agricultural soils to contribute to the climate objective. However, the potential contribution is still uncertain and it is not yet clear how carbon sequestration in soils should be monitored. The project 'Importance of soil carbon sequestration for greenhouse gas mitigation' was therefore started in 2018. This project is funded by the Agri & Food top sector and by FrieslandCampina. The authors would like to thank everyone who contributed to the realisation of this report. First of all, our thanks go to the 37 dairy farmers who were willing to take part in this pilot project, who made their data available and who took an active part in the study groups. We would also like to thank Hans Dirksen and his staff at Dirksen Management Support B.V. for the contacts with the dairy farmers and for organising the study groups. Pieter Rooijackers and Kevin Klaver both undertook a graduate course as part of this project and, in doing so, made an important contribution to the collection of data. And lastly, several of our colleagues at WUR contributed their ideas and commented on the report.

Jan Peter Lesschen and Theun Vellinga

Summary

In the Netherlands, two-thirds of the national agricultural greenhouse gas emissions originate from the dairy sector, mainly methane and nitrous oxide emissions. The Dutch dairy production chain (production of raw materials, dairy farmers and dairy processing) emitted a total of 22.4 Mt CO₂-eq of greenhouse gases in 2017. The ambitions formulated by the Climate round table on agriculture and land use, as well as the recent EU climate policy for 2021-2030, emphasise the importance of reducing CO₂ emissions from peat soils and sequestering carbon through organic matter (OM) in agricultural soils. However, these emissions and sequestration are not yet accounted for in the carbon footprint of dairy farms, even though there is a need among dairy farmers to start accounting for carbon sequestration in their soils.

In order to realise these ambitions and demonstrate the effects, a reliable and transparent system is required to monitor soil carbon sequestration and emissions and related soil management. The main focus of this Top Consortium for Knowledge and Innovation (TKI) project 'Importance of soil carbon sequestration for greenhouse gas mitigation' was on developing such a system. This project was conducted by Wageningen Research and was financed by the Dutch Ministry of Agriculture, Nature and Food Quality and FrieslandCampina. The main goal was to develop a reliable and transparent monitoring and accounting system for soil carbon sequestration and emissions at dairy farms. In this project, the scientists worked with study groups of dairy farmers, data analysis and model development. Data regarding soil sampling, land use and farm management practices, such as manure application, grassland improvement and grazing, was collected from 37 dairy farms.

The build-up and decomposition of organic matter is a dynamic process and as a result, large spatial variation of organic matter can occur in soils caused by factors such as differences in soil texture, land use and water management. Also, farm management influences the amount of soil organic matter (SOM), for example through the choice of temporary versus permanent grassland or arable land. The SOM balance is the outcome of OM supply via crop residues, manure, green manure, compost and other organic manure and decomposition of the organic material in the soil.

Analyses of soil samples of the 691 fields at the participating dairy farms showed that SOM was the highest in permanent grassland (7.8% on average), followed by temporary grassland (6.5%) and arable land (5%). For a limited number of fields – 14 out of 76 with sufficient available data – a significant change of OM was found in the course of time. The average carbon (C) fraction of SOM based on the dataset was 0.53, which is somewhat higher than the frequently used value of 0.50 for the conversion factor. The large variation in SOM, in terms of both time and space, the limited availability of soil samples and the limited accuracy of the sampling show that it is difficult to monitor changes in soil carbon based only on soil sampling at farm level.

Modelling changes in carbon stock is a good alternative, as soil sampling over a long period (ten years at least) is required in order to assess carbon sequestration (or losses). In this study, the internationally acknowledged and widely used RothC model was used to simulate changes in soil carbon stock in mineral soils (sand and clay). This dynamic model calculates the changes in carbon stock based on climate data, OM content, clay content and supply of organic material such as manure and crop residues.

In total, data was collected for 691 fields at the 37 dairy farms, of which 48% was sandy soil, 30% clay soil and 22% peat soil. The average carbon supply to the soil of the 37 farms was 6.4 tonnes C/ha, but this varied between 4-10 tonnes C/ha. Crop residues, mainly from grassland, contributed most to the supply (4 tonnes C/ha), followed by animal manure which contributed on average 2.4 tonnes C/ha. The large variation showed that by focusing actively on animal manure, crops and grassland management, it should be possible to influence the carbon balance. Model results showed that on average 0.4 tonnes C/ha/year was sequestered on grassland. Green maize and other arable

crops, however, produced a negative soil carbon balance of -0.5 tonnes C/ha/year and -0.6 tonnes C/ha/year respectively. Fields on clay soils generally showed a higher carbon sequestration of +0.4 tonnes C/ha/year compared to fields on sandy soils with +0.1 tonnes C/ha/year. Results showed a large variation but in general a higher carbon supply corresponded with a relatively stronger positive carbon balance. On soils with higher OM content it is harder to maintain a positive carbon balance due to greater decomposition. Model calculations can predict the long-term potential of carbon sequestration or breakdown of OM at field level. The sensitivity analysis of the RothC model showed three factors that strongly influenced the final soil carbon balance: 1) climate data, mainly precipitation; 2) soil depth over which the OM balance was computed; and 3) amount of crop residues supplied from grass.

In this study we also looked at the effect of including soil carbon in the Carbon Footprint (CFP) calculation. The average CFP of 33 farms on mineral (sand and clay) soils was reduced by 2% from 1.19 to 1.17 kg CO₂-eq/kg FPCM (Fat and Protein Corrected Milk). However, the variation was large. In some cases, the CFP decreased by a maximum of 12%, but in other cases the CFP increased by a maximum of 15%. The CFP can be further reduced by implementing measures that reduce the decomposition of SOM or increase the input of organic material to the soil. The main measures for the Dutch dairy sector are to optimise land use, minimise grassland renewal and maximise the use of green manure and catch crops.

The RothC model is not suitable for peat soils and peaty soils. In order to calculate CO₂ emissions from these soils, calculation rules from the national Pollutant Release and Transfer Register were used. To calculate the CO₂ and N₂O emissions, information on the groundwater level classes, the presence of a clay or sand topsoil layer and the trophic level (mineral richness) of the peat soils was used. The average emissions of peat soils for the twelve dairy farms was estimated at 12.5 tonnes CO₂/ha, with 7.0 tonnes CO₂/ha for peaty soils. As a result, the average CFP of these farms increased by 19% from on average 1.31 to 1.57 kg CO₂-eq/kg FPCM. The increase in CFP of the farms varied between 8% and 31%.

Based on data from the participating farms complemented with literature, we conclude that a monitoring system based on OM analyses using existing soil sampling is not supportive enough at present to reliably estimate SOC sequestration. However, a monitoring system at field and farm level based on a combination of soil sampling analyses, registration of activities and model calculations of changes in soil carbon is technically possible. The uncertainties in these calculations are currently still too large to link these to a reliable penalty or reward system at farm level.

Three parallel streams are identified to realise a future monitoring system of soil carbon for the Dutch dairy sector: 1) calculation of the changes in SOM stock in agricultural soils, 2) more frequent monitoring of OM contents via soil sampling on a large number of fields, in order to validate the calculations, 3) linking the results of validated calculations to the national Pollutant Release and Transfer Register for the purpose of reporting under the UNFCCC, EU and Dutch Climate Agreement.

1 Introduction

1.1 Background

In 2018, a start was made by the Dutch government to further develop the Dutch climate policy until 2030. This process is being organised in the Climate round tables, which includes a round table for agriculture and land use. In 2017, agriculture contributed 9.5% (18.9 Mt CO₂-eq) and land use 2.8% (5.6 Mt CO₂-eq) to national greenhouse gas emissions in the Netherlands (NIR, 2019). Dairy farming provides a major contribution to the formation of greenhouse gases from the agricultural sector. Two-thirds of the 18.9 Mt CO₂-eq mentioned above originates directly from nitrous oxide and methane in the dairy sector. The Dutch dairy production chain (production of raw materials, dairy farmers and dairy processing) emitted a total of 22.4 Mt CO₂-eq of greenhouse gases in 2017. Both the government and the dairy industry are focused on reducing greenhouse gas emissions in dairy farming. The Sustainable Dairy Chain (DZK) programme has set targets for this purpose for 2020 (20% reduction compared to 1990) and a further reduction of 1.6 Mt CO₂-eq for 2030.¹ FrieslandCampina is working with its farmers to reduce greenhouse gas emissions in the chain by developing monitoring and remuneration tools that support this process, by introducing sustainable products on the market and by innovating at its dairy farms and factories.

To date, CO₂ emissions from peat soils and carbon sequestration in soil organic matter (SOM) have not been included in the monitoring of greenhouse gas emissions in the dairy chain. They do, however, form part of the national Pollutant Release and Transfer Register for the LULUCF (Land Use, Land Use Change and Forestry) sector, based on land use maps, the soil map and emission factors. The current national emission reporting on changes in carbon quantities in agricultural soils is based on a Tier 1/2 approach: a constant quantity of soil C is ascertained per type of land use and soil type. In current reporting, the changes in carbon stock in mineral soils are only affected by changes in land use. There is as yet no procedure in current reporting for basing the calculation of the carbon quantities on soil and grassland management, such as the supply and removal of organic matter and the ploughing up of grassland.

In the plans put forward by the Climate round table on agriculture and land use², as well as in the new EU climate policy for 2021-2030 as set out in the Effort Sharing Regulation (ESR) and the regulation on land use (2018/841), the CO₂ emissions from, and sequestration in, agricultural soils are mentioned explicitly. Dairy farmers themselves would also like to see carbon sequestration included in the monitoring. Calculating the changes in carbon quantities entails a transition to a higher Tier (2 or 3) in the IPCC method. This type of transition is subject to criteria and requires scientific substantiation. A model approach will require a scientifically substantiated model that can calculate changes in organic matter based on available data regarding grassland and arable land management and measurements of organic matter in soils.

In the ESR, each member state has been set the task of reducing emissions until 2030. This should be done by reducing emissions in various economic sectors, including agriculture, although part of this may be achieved by sequestering carbon in forest soils and agricultural soils and by reducing emissions from peat soils. This so-called flexibility is described in detail in the ESR (see Box 1). The objectives set out in the Dutch Climate Agreement³ that was presented on 28 June 2019 are in line with those of the ESR. An objective has also been agreed in the Climate Agreement regarding the reduction of emissions from agricultural soils and an increase in carbon sequestration by 0.4-0.6 Mt of CO₂ per year by 2030.

¹ <https://www.nzo.nl/wp-content/uploads/2018/07/NZO-Rapport-Klimaatverantwoorde-zuivelsector-in-Nederland-december-2018.pdf>

² <https://www.klimaataakkoord.nl/landbouw-en-landgebruik>

³ <https://www.klimaataakkoord.nl/documenten/publicaties/2019/06/28/klimaataakkoord>

It is known from literature that there is a large variation in soil organic matter content in terms of both space and time (De Wit et al., 2018). At the same time, many farmers have high expectations when it comes to the potential of reducing CO₂ through sequestration in soil organic matter. There are also high expectations among many non-agricultural parties. Farmers are willing to adapt their business processes and hope to see these efforts reflected in higher levels of organic matter. It must therefore be possible to monitor the relationships between effort and result, which must be apparent from the data on measured soil organic matter. Due to the large variation in organic matter content, there is a clear chance that it may not be easy to demonstrate this relationship based on the data of individual fields. How can a relationship be made apparent and can it be determined reliably? Should the collected data be supported with model calculations with which to eliminate the variation between fields and years? Or should the field data be aggregated to averages at farm level or an even higher level of aggregation? The national emission registration of the sequestration and decomposition of carbon in agricultural soils is primarily focused on changes in land use, but does not yet take into account the management of the soil.

Box 1

In the EU's Effort Sharing Regulation (ESR) (2018/842), the Netherlands has been set a reduction target for the non-ETS sectors of 36% by 2030 in relation to their 2005 levels. The Committee states that there must be a linear decrease in emissions during that period. The regulation refers to three forms of flexibility:

- A slight deviation from the linear decrease in emissions is allowed. If too little emission reduction is achieved in a year, this can be made up for in a subsequent year (Article 5).
- Part of the emission reduction may be offset against emissions from the ETS sectors (Article 6).
- Part of the emission reduction may be achieved via the land use sector (LULUCF) through carbon sequestration in forest and agricultural soils or through reduction of emissions from peat soils (Article 7).

For the Netherlands, this last form of flexibility may amount to a (cumulative) maximum of 13.4 Mt of CO₂-equivalents over 2021-2030. The reduction of CO₂ in the atmosphere that can be achieved in this way does not have to be accomplished via other mitigating measures. This type of flexibility can be implemented by land users in the Netherlands, i.e. the agricultural sector (particularly dairy farming and arable farming), site management organisations (such as Nature Monuments, State Forest Management, Provincial Nature Conservation Society etc.) and other landowners.

The ambitions of the Climate round table on agriculture and land use are in line with the possibilities set out by the ESR. The Draft Climate Agreement sets out 0.5 Mt per year for carbon sequestration in mineral soils and other agricultural lands and a reduced emission of one Mt per year for peat soils. This increased sequestration in mineral soils and reduced decomposition on peat soils call for significant changes in the management and use of agricultural lands and the possible conversion of agricultural land into forests.

Careful consideration of the pros and cons and the potential of including soil emissions based on the activities of dairy farmers or arable farmers is desirable, both in terms of implementing the Dutch climate policy and making use of the flexibility in the ESR and for the agricultural sector itself. The question of whether it is possible to develop a reliable and transparent monitoring system plays an important role in this consideration. Without effective monitoring at farm, regional or sectoral level, it will not be possible to capitalise the contribution of soil carbon to emission reduction in the Dutch climate policy and the ESR. There is therefore an urgent need for a reliable and transparent system that can monitor the sequestration and emission of carbon and the corresponding soil management. Although this report takes dairy farming as its input, this issue is also important for arable farming sectors in the Netherlands. When it comes to the dairy sector, it is important to know what the effects are of incorporating the CO₂ emissions from peat soils and the sequestration or decomposition of carbon in sandy and clay soils on the emissions in the dairy chain, as described in the sector report 'Sustainable Dairy Chain' and the climate module of the Annual Nutrient Cycling Assessment (ANCA - KringloopWijzer).

A system for monitoring carbon sequestration in, and carbon emissions from, agricultural soils can be regarded as a coherent interconnection between a) measurements of organic matter quantities (and thus carbon (C) in the soil); b) the collection of data relating to land use, management, supply and removal of organic matter; c) calculations of organic matter balances and consequent changes in organic matter in agricultural soils; and d) a procedure that describes the level of aggregation (field, farm, area or sector) at which the results of the monitoring are displayed and can be used.

1.2 Objective

This TKI project entitled 'Importance of soil carbon sequestration for greenhouse gas mitigation' has therefore formulated the following goals:

- To develop a reliable and transparent system to monitor and calculate carbon sequestration in, and carbon emissions from, soils on dairy farms. Monitoring and calculation must: a) be sufficiently reliable; b) make use of data on dairy farms that is available in practice.
- To test the system of monitoring and calculation on a number of dairy farms in order to arrive at a practicable system of data collection and interpretation by dairy farmers.

These goals have been translated into the following research questions:

- Is it possible to draw up a clear classification that determines whether a field is categorised as mineral soil or peat soil?
- Reliability of the measurements as performed in practice: how large is the variation in the measurements of soil organic matter and how useful are they for monitoring the sequestration of organic matter?
- Calculating the development of organic matter content: is it currently possible to develop a reliable calculation model for the sequestration and emissions of carbon in agricultural soils?
- How can a reliable system be created? Can monitoring be based on soil sampling only or is a combination of sampling and modelling needed to ensure that monitoring is sufficiently reliable?
- What data sources should be accessed for reliable monitoring and to what extent is that feasible?
- Does the monitoring system developed in this project offer sufficient perspective for dairy farmers to take action in demonstrating and improving their carbon sequestration? And can the measures taken by dairy farmers to improve sequestration and reduce decomposition be recorded reliably?
- What does the inclusion of the soil carbon sequestration or emission mean for greenhouse gas emissions in the dairy chain and for the carbon footprint for milk?

Reliability of the monitoring system is a key condition. In this study, reliability means that the prediction of the organic matter content should at least indicate the correct trend – the net sequestration or decomposition of organic matter – with a high degree of certainty and indicate the extent of the sequestration/decomposition with a reasonable degree of certainty. It is important for the dairy farmer's perspective for action to know whether he or she is taking the correct action.

1.3 Approach

The key aim of the project concerns the development of a reliable and transparent monitoring system. It is not the soil-related issue of calculating organic matter that is the main concern, but rather the procedure and how it can be used and whether it produces sufficiently reliable results to be used in practice at farm or sector level. The work in this project is therefore based on four tracks: a) study groups involving dairy farmers; b) data analysis; c) model development and d) packages of measures.

Study groups of dairy farmers The dairy farmers in the study groups make the following data available: all data relating to the organic matter in all fields, going back in time to before 2000 where possible, together with a reconstruction of their land use (grassland, arable land, reseeding etc.) The question here is what data is available and to what extent is a reconstruction of land use possible up until the time that this information was registered centrally. At the same time, the dairy farmers act as

a sounding board group for the data analysis, the model development and the development of a set of measures for further sequestration of organic matter.

Data analysis The data from the dairy farmers is used to investigate whether an accurate reconstruction can be made regarding the changes in soil organic matter based on sampling at field level. This would enable the creation of a simple procedure which could be used to determine the sequestration of carbon without having to sample the soil every year.

Model development Field tests have shown that there can be a large variation in organic matter content within fields and between years. In anticipation of a conclusion from the data analysis, an existing calculation model is already being expanded, to be used in conjunction with soil sampling for the purpose of setting up a more reliable monitoring system. An important aspect that is relevant to both field data and model calculations is whether the results can be used for monitoring and benchmarking at field level, farm level or sector level.

Packages of measures A variety of measures have emerged from test field research. In addition, dairy farmers have their experiences of reseeded grassland, practising crop rotation between grassland and arable land (usually maize) and of using green manure or compost. This knowledge is bundled to create a set of practical measures that contribute to increasing organic matter content.

2 Organic matter in soils

2.1 Introduction about sequestration and decomposition of carbon in soil

Much of the knowledge relating to carbon sequestration in grassland and arable land is known and described in reports. The report by Conijn and Lesschen (2015) provides an overview regarding the status of this knowledge.

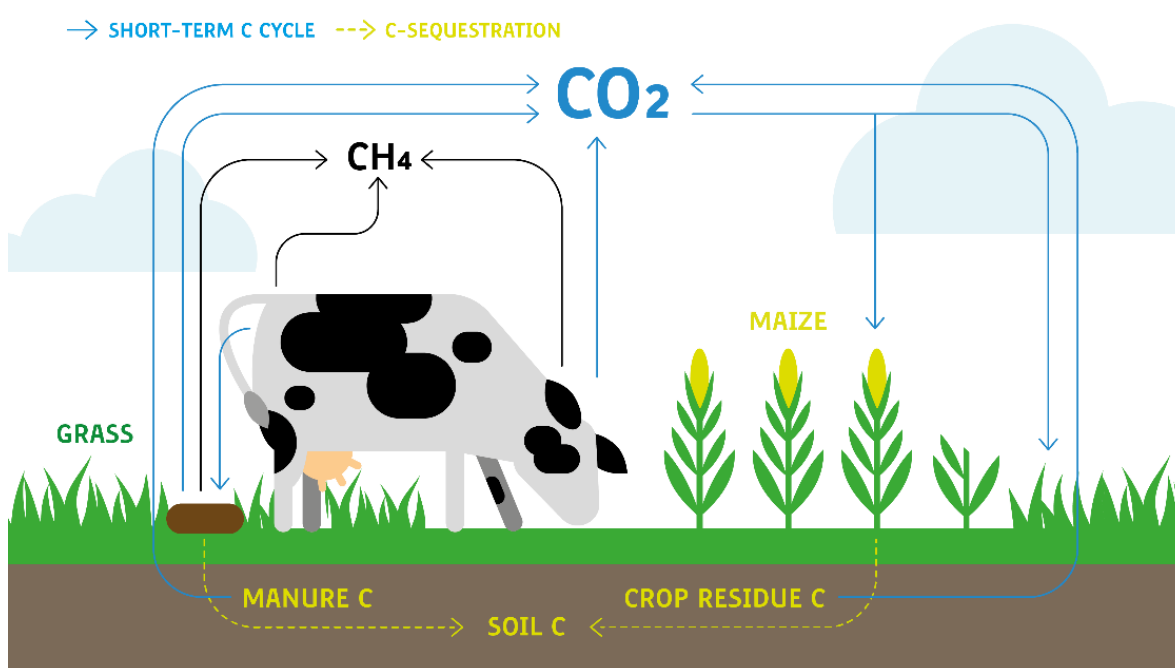


Figure 1 Schematic overview of the carbon cycle (© FrieslandCampina).

The carbon cycle starts with the process of photosynthesis: CO₂ is converted by sunlight into plant material (biomass), a wide range of organic compounds, about half of which consists of carbon. This process makes oxygen available again. The biomass can be used in a variety of ways. In dairy farming, the biomass consists of grass, green maize and various other plant-based products that are eaten by the livestock and converted into milk, meat and manure. CO₂ is produced again when cows respire; in addition, methane (CH₄) is released from the rumen of cows. When using the crops as feed, there are always crop residues, particularly roots, that are left out in the field. Manure and urine from the animals are also returned to the land as fertiliser. This organic matter (also biomass) serves as food for soil life and is converted into stable organic matter (humus) and CO₂. However, stable soil organic matter can also be broken down.

Organic matter is subject to decomposition by micro-organisms such as fungi and bacteria. The decomposition can be described as a first order reaction. Some of the decomposed organic matter disappears as CO₂, some of it is sequestered in micro-organisms and some of it is converted into a more resistant form with a lower decomposition rate. This means that organic matter is always being passed on. The extent to which organic matter is converted into more resistant material is known as the humification coefficient. This process of decomposition also includes the organic matter that remains after being applied in a previous year. Organic matter that is a year old may break down more slowly than new organic matter but it is broken down nonetheless. It also means that the

decomposition of organic matter is dependent upon the supply of new organic matter and the presence of older organic matter.

This soil organic matter is made up of around 50% carbon (C). This is referred to as soil carbon (an exact value is provided later on in this report). The carbon that is converted into biomass and which is then used by humans and animals, including the manure that is produced, is described in the 'short-term carbon cycle'. This is carbon that is removed from the air but which returns as CO₂ within a reasonable period as a result of the respiration of people and animals as well as the digestion of manure and crop residues by larger and smaller soil organisms. Part of the biomass remains present in the soil as humus for a longer period of time and is only broken down slowly. This forms part of the 'long-term carbon cycle' as the carbon is removed from the atmosphere for a longer period. Fossil fuels such as oil and coal also form part of the long-term cycle. This carbon was once removed from the atmosphere and is now returned.

The carbon in biomass from crops is not counted as carbon sequestration as it is only present in that form for a short while. The permanent vegetation present in forests is, however, considered to be part of the long-term carbon cycle. In forests, there is a large amount of carbon above ground. In grassland, this amount is limited in relation to the amount of carbon that is sequestered in soil organic matter. The IPCC has drawn up rules that include all these quantities in the calculations relating to CO₂ emissions and carbon sequestration in land use and any relevant changes (Lesschen et al., 2012). These consist of a subdivision into three relevant land use categories (forest, grassland and arable land) and set carbon stocks per land use type and soil type. (See Annex 1 for details.)

The build-up and decomposition of organic matter is a dynamic process and a large spatial variation of organic matter can often occur in soils. This is largely determined through:

- Soil origin: soils are either organic or mineral. Organic soils are mainly composed of accumulated organic matter from a distant past. Much more organic matter (i.e. carbon) is stored here than in mineral soils such as sandy and clay soils. The organic matter contents in mineral soils are much lower than in peat soils. In peat soils, it is difficult to distinguish between organic matter from the centuries-old process of peat formation and the organic matter from the dead stubble and roots from plants that have recently died and from manure applications. Mineral soils are composed of mineral components: sand and clay particles. In these soils, the organic matter that has been added through land use can be clearly measured. In mineral soils, the organic matter content usually decreases with increasing depth. Almost all crops grow roots in the 0-30 cm layer, with a limited number of deeper roots. The supply of organic matter mainly occurs in the topsoil. Transport does, however, take place to deeper layers (Braakhekke et al., 2011 and 2013). These authors describe a progression in organic matter in a forest soil where much more than half of the organic matter is stored in the 0-30 cm layer. They also explain that organic matter decomposition also occurs in the deeper layers.
- Soil texture: sandy soils often have lower OM levels than clay soils since clay soils are better at binding the organic matter in stable clay-humus complexes.
- Land use: grasslands have a higher OM content than arable land. This is due to the greater supply of organic matter from stubble, roots and manure and less disruption of the soil from activities such as ploughing.
- Moisture: organic matter contents are often higher in wet conditions than in dry conditions.
- Temperature: higher temperatures result in faster decomposition of organic matter. It is therefore harder to achieve high organic matter contents in warmer regions.

In the Netherlands, the amount of carbon in mineral soils averages around 93 tonnes of carbon per hectare in the 0-30 cm layer and in peat soils averages 191 tonnes of carbon per hectare (Conijn and Lesschen, 2015). However, there is a high degree of variation which depends on the above factors. Farm management also influences the amount of organic matter in the soil. In addition to the choice between temporary or permanent grassland or arable land, the organic matter content is mainly determined by the organic matter balance: the supply of organic matter via crop residues, manure, green manure, compost and other organic fertilisers and the decomposition of the organic material present in the soil. Crop residues are broken down more quickly than manure while compost is broken down more slowly than manure. At the same time, there is also a difference in the organic matter

content and the rate of decomposition between manure types and crops. Depending on the quality of the material supplied, 5-80% of it will remain in the soil after one year. The rest returns to the atmosphere as CO₂.

Soil organic matter is an important measure of soil quality/fertility due to factors such as the effect on soil structure, the moisture-retaining properties of the soil, the use of nutrients and the nitrogen-producing capacity of the soil. However, the organic matter content required must be weighed up against the required soil functions (Schröder et al., 2016). Every soil function is associated with an optimum amount of soil organic matter. Above this optimum level, more organic matter does not lead to better performance of that soil function. It may even lead to contradictory effects. For example, high levels of organic matter can have a negative effect on the success of pesticides and there is also a risk of higher nitrate leaching and N₂O emissions. However, not much research has as yet been carried out into quantifying these possible 'trade-offs'.

Properly validated models are available in agricultural research that can be used to calculate the influence of management measures on the change in speed of sequestration (or of release) (Conijn and Lesschen, 2015; Vellinga et al., 2004, Schröder et al., 2018). Most of the models work with similar principles as regards the supply and decomposition of organic matter. An overview can be found in Lesschen et al. (2020), in which a comparison is made between various soil carbon models and their suitability for use as practical models within Dutch agriculture.

2.2 Land use in Dutch dairy farming

The Netherlands has a total land area of 3.37 million hectares (CBS, 2019). Of this land, 54% (1.8 million hectares in 2019) is being used by the agricultural sector as cultivated land. The majority of agricultural land is used for grassland – 0.98 million hectares of permanent, temporary and natural grassland. This is followed by arable land (including fodder crops) at 0.73 million hectares. The remaining 0.18 million hectares of agricultural land is used for activities such as horticulture, including greenhouse horticulture, and fruit cultivation. In 2017, the Dutch dairy farming sector had 0.85 million hectares in use. Figure 2 shows that the total land used for agriculture has decreased by 9% since 2000 but that the area being used by dairy farming has increased by 5% during the same period. Over this period, the total number of dairy farms has fallen by 30% (CBS, 2017). As a result, the average amount of land used per dairy farm has risen from 37.8 hectares in 2000 to 54.2 hectares in 2017. However, milk production per hectare rose by 27% between 2000 and 2016 (WECR, 2018). For each kilogram of milk, the amount of land required has therefore fallen in recent years.

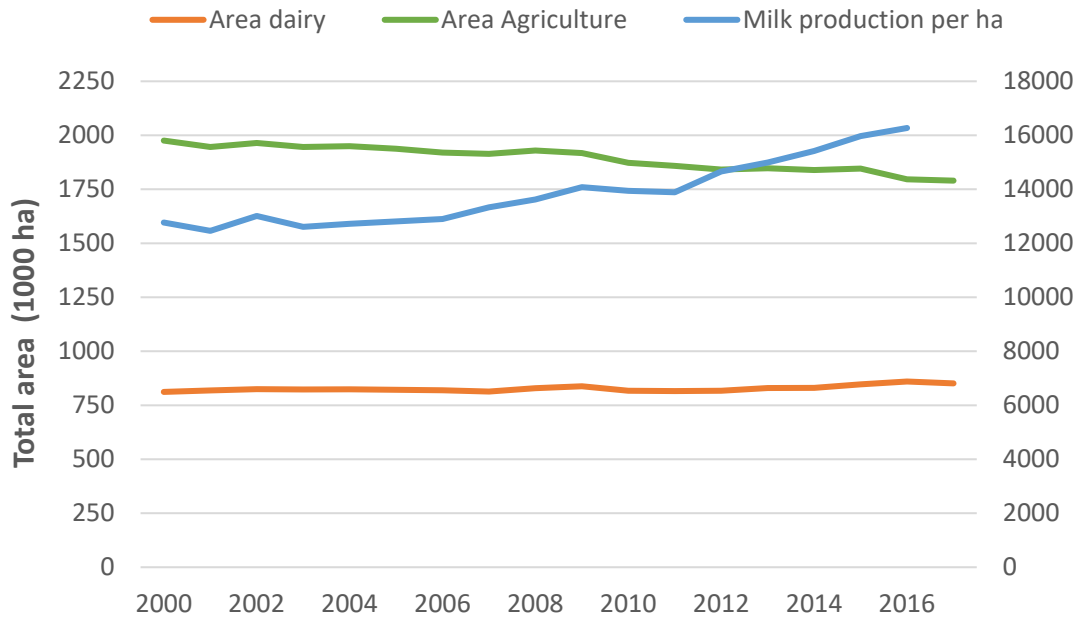


Figure 2 Development of total land use for Dutch agriculture and dairy farming and milk production per hectare. Source: www.agrimatie.nl.

According to data from the Annual Nutrient Cycle Assessment (ANCA) for 2017, the dairy farmers of the FrieslandCampina cooperation had around 638,000 hectares of agricultural land in use, of which the majority was grassland (83%), followed by maize land (13%) and other arable land (4%); see Figure 3. Based on the carbon stocks in the top 30 cm layer of the soil, as calculated by Conijn and Lesschen (2015), the carbon in these soils amounts to 71 Mt of carbon, or 261 Mt of CO₂. These calculations are based on the division of soils into the main groups sand, clay and peat. The average amount of organic matter is known for each soil type and type of land use; see also Annex 1. These values are multiplied by the hectares per soil type/land use combination. In addition, there is more carbon stored in the subsoil, particularly in peat soils.

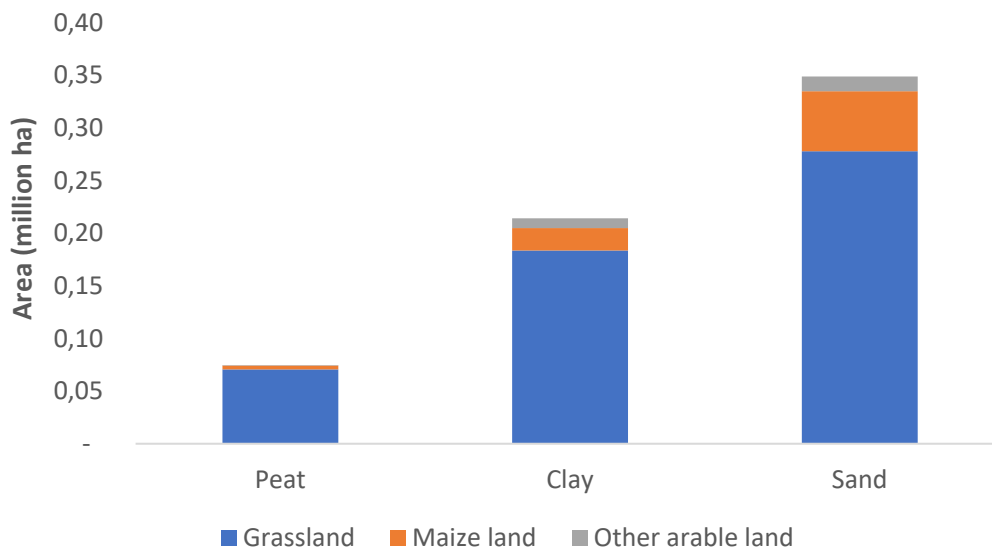


Figure 3 Areas of land use of the dairy farms in the FrieslandCampina cooperation.

This study does not consider the potential to sequester carbon in agricultural soils that are indirectly used to grow purchased feed. The amount of land used indirectly depends on the crop yield per hectare of the purchased feed consumption per kilogram of milk. The average concentrate application per kilogram of milk produced in the Netherlands has not changed significantly between 2000 and 2017 and fluctuates over the years between 25 and 28 kg of feed per 100 kg of milk. Earlier LCA studies show that land use for milk is around 1 m² per kg of FPCM (Fat and Protein Corrected Milk) (De Vries and De Boer, 2010). Roughly a third of this land is indirectly used for growing concentrate feed and, in almost all cases, is located outside the dairy farm. Over the past twenty years, not only has there been a decrease in the total area of grassland but also an increase in the proportion of this area used for temporary grassland. There has been a more intensified exchange between grassland and maize land in recent years, as well as the exchange of land between arable farms and dairy farms. At the same time, this has not led to a visible decrease in the organic matter contents of grassland, as can be seen in Figure 4.

2.3 Organic matter in agricultural soils

The organic matter content of the topsoil is measured on farms with a certain degree of regularity. This is done at least once every four years since OM content is one of the parameters of the standard soil analysis that is mandatory for retaining derogation. An analysis of the soil samples from Eurofins shows that, on average, the organic matter content under grassland and maize land in the Netherlands has more or less remained constant over the past thirty years (Figure 4). There have, however, been fluctuations between the years. These fluctuations were caused by the different fields over all the years, although there may also be differences in measured levels within a single field between years (Ehlert et al., 2018). The organic matter content of maize land is lower than that of grassland. It is therefore possible to observe very different trends relating to organic matter content on an individual farm or field.

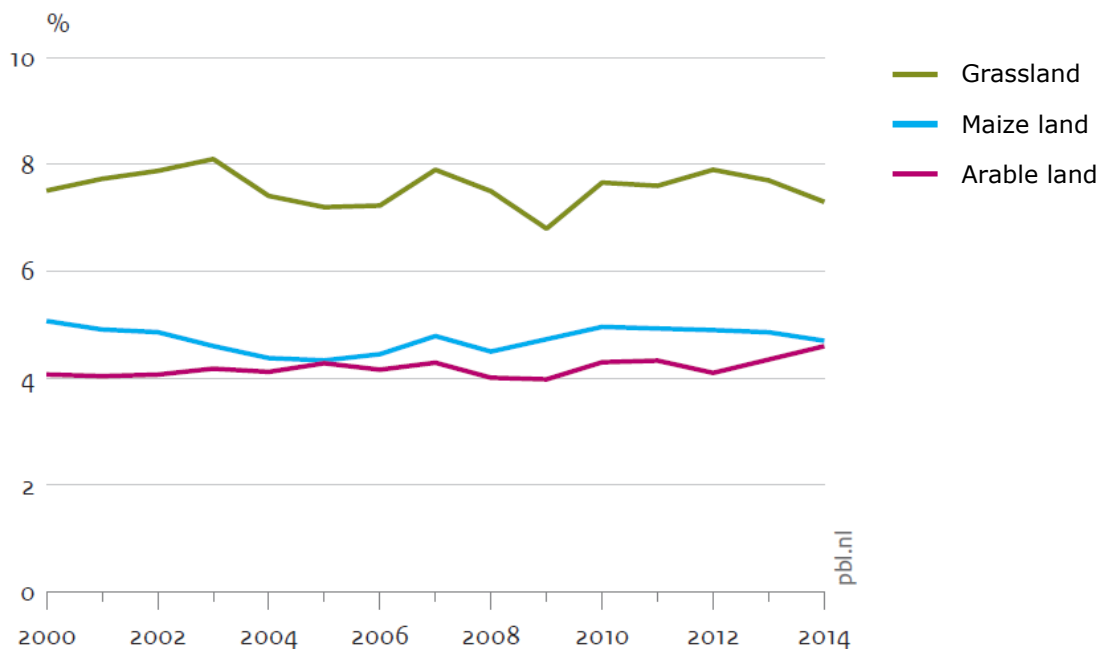


Figure 4 Changes in the content of soil organic matter under grassland, maize land and arable land in the Netherlands during the period 2000-2014 based on Eurofins data (Van Grinsven and Bleeker, 2016).

3 Materials and methods

3.1 Collection of farm data

To gain insight into the real-life data available, data was collected from 37 working farms relating to soil analyses, operational management, such as land use (grass, maize, crop rotation etc.), use of fertilisers (what type, how much, green manure, compost), grassland improvement and grazing.

Selection of working farms

The following criteria were used to select the 37 working farms:

- Only dairy farmers can participate. They supply to dairy companies in the Netherlands.
- Farms are evenly distributed over sand, clay and peat. Loess was not taken into consideration because of its limited surface area.
- There must be a representative selection of dairy farmers, to include dairy farmers from the group already motivated and actively working on soil data and thinking about measures to promote organic matter sequestration as well as dairy farmers not yet doing so.
- Dairy farmers must be prepared to share data with the researchers and to discuss their activities with one another.
- There is variation on the farms based on:
 - the presence of grassland for nature conservation objectives (management agreement or designated for nature)
 - the distribution of permanent and temporary grassland
 - the percentage of grassland and arable land
 - the number of cattle
 - ditch water levels, in the case of peat soils
 - biological and conventional production methods
 - whether or not grazing is carried out.

The farms were selected in collaboration with Dirksen Management Support based in Beusichem. The distribution of the farms in the Netherlands is shown in Figure 5.

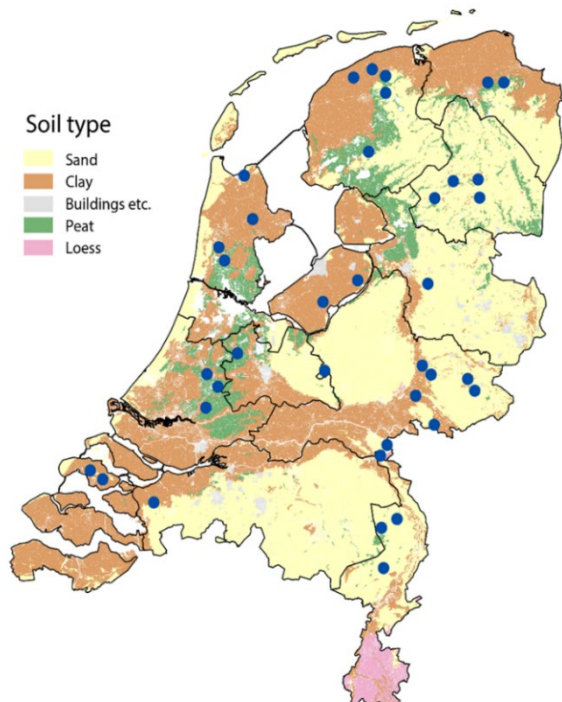


Figure 5 Location of the participating dairy farms.

Collection of data

Data was collected on the farms relating to:

- Organic matter contents on all fields, from the most recent data (2017) and all information available for previous years from the dairy farmers themselves. This concerns data from soil analyses that were carried out on the instruction of the dairy farmer. This data comes from analyses that are undertaken at regular intervals (once every four years); in some cases the analyses are connected to a change in land use.
- Characterisation of fields. For the purpose of analysis, it is important to know whether the fields are composed of sand, clay or peat. A detailed description is provided in one of the following sections on how fields are categorised according to soil type.
- A reconstruction of the land use over the years (grassland, arable land, reseeded etc.). This was carried out based on records made by the dairy farmer via their own accounts or specifications for the ANCA, registration for the Netherlands Enterprise Agency (RVO), data that is available in the 'Boer & Bunder' (Farmer and his plot) database (<https://boerenbunder.nl/>) and based on the memory of the persons concerned. Much of the data for the period prior to 2009 was retrieved from memory.
- Operational management, as regards fertilisation and grazing based on data in the ANCA for the 2016 and 2017 financial years.

Study groups

The study group meetings served several purposes:

- To provide an overview of the data collected for individual farms and for groups of farms.
- To check and supplement the data.
- To discuss the collected data and the analysis results. What conclusions can be made for the researchers and the dairy farmers? What could this mean for monitoring of organic matter sequestration and for the perspective for dairy farmers to take action?
- To discuss possible measures that contribute to organic matter sequestration in the soil.

The study groups were supervised by the project team, together with Dirksen Management Support.

3.2 Classification of field soil types

As different model calculations are needed to calculate emissions and carbon sequestration, the soil group – sand, clay, peaty or peat – has been determined for each field. It is important to have good criteria for the purpose of classifying soil samples according to soil types. Peat soils and peaty soils have a different structure to sandy soils and clay soils. The latter two consist of mineral particles (silicates) of different sizes, while the peat soils and peaty soils are made up of preserved plant residues. It is not true that peat soils consist of 100% plant debris. It is often mixed with clay and sometimes with sand. Peaty soils are soils with a thin layer of peat (less than 40 cm).

The relevant data from the data set comprises the following variables: organic matter content, soil type from the soil analysis report and soil type based on the national 1:50000 soil map⁴. The maps that are used as underlay for *Boer en Bunder* do not distinguish between peat soils and peaty soils and are therefore not suitable for this purpose. The first step is a classification based on organic matter content. A soil with 20% or more organic matter in the soil analysis is counted as an organic soil. However, fields with an organic matter content lower than 20% may still need to be considered as organic soils as peat layers can also start deeper in the profile, especially with grasslands in which samples are only taken from the top 10 cm. Soils with an organic matter content lower than 20% are therefore subjected to an additional analysis with the help of the soil map. This is shown by the dotted line in Figure 6.

The second step for organic soils is to make a distinction between peat soils and peaty soils based on the soil map. With mineral soils, the classification is based on the soil analysis, in which the levels of lutum (clay particles) and sand are specified. This classification is illustrated in Figure 6.

⁴ <https://www.wur.nl/nl/show/Bodemkaart-1-50-000.htm>

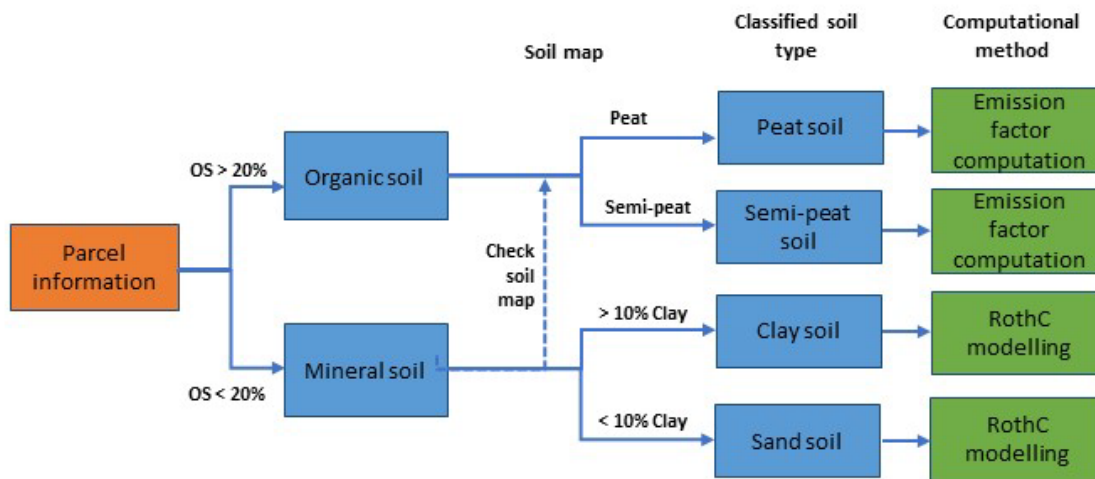


Figure 6 Classification diagram for soil type per field.

3.3 Modelling carbon dynamics of mineral soils

In order to determine the sequestration (or losses) of organic carbon in the soil, soil measurements are required over a longer period. Soil carbon sequestration in the form of organic matter is a relatively slow process as it always involves small changes in quantity in relation to a large stock. In addition, there is a significant spatial variability in organic matter and considerable differences can occur even within the same field. In order to reliably determine organic matter content, many soil samples are needed, with a high frequency over time and with an individual analysis of all samples. This makes it very expensive to perform accurate monitoring of changes in carbon stock. Due to the significant variation – which is also found in test fields – even this method of sampling and analysis does not yet produce reliable results in the short term (<5-10 years). The alternative is to model changes in carbon stock.

3.3.1 Model selection

Over the years, many soil carbon models have been developed worldwide that are often similar to one another in terms of structure (Smith et al., 1997). However, there are only a limited number of models that are used in the Netherlands for calculating organic matter dynamics in agricultural soils and which are scientifically documented (Table 1).

Table 1 Overview of soil carbon models used and published in the Netherlands.

Model	Reference	Strengths	Weaknesses
RothC	Coleman et al., 1997; Smith et al., 1997; Byrne and Kiely, 2009; Conijn and Lesschen, 2015	Differentiates between five OM pools, relation to moisture, temperature and organic matter balance, applied and acknowledged internationally	Little explicit distinction between grassland and arable land
International Carbon Balance Model (ICBM)	Vellinga et al., 2004; Kätterer and Andr�en, 1999	Differentiates between two OM types, alternation of grassland and arable land	Works with average years, no detailed OM balance
EOM balance	Schr�oder et al., 2018	Detailed organic matter balance for the input side	Standard decomposition factor, annual balance only, not linked to OM development over time.

Various researchers may have simple simulation models that have not been documented but which would qualify for use as a monitoring instrument. Organic matter models have been developed for other countries (such as DAYCENT, Del Grosso et al., 2009), but these have not been calibrated for conditions in the Netherlands. An analysis was recently conducted by Lesschen et al. (2020) of various soil carbon models and their suitability for use as a practical tool in the Netherlands. One of the models selected is the RothC model.

The RothC model describes the sequestration of carbon based on climate, organic matter content, clay content and the supply of organic material such as manure and harvest remnants (Coleman and Jenkinson, 2014). Another model, the ICBM (Kätterer and Andren, 1999; Vellinga et al., 2004), focuses primarily on the alternation between grassland and arable land and on the reseeding of grassland. This model only distinguishes between sandy soils and clay soils. Both the RothC and ICBM models are able to calculate organic matter development for a period of many years. The Effective Organic Matter (EOM) model by Schröder et al. (2018) describes the organic matter balance (= carbon balance) based on the supply of organic matter and decomposition rates. The EOM model uses this to calculate how much organic matter remains after one year. The calculation is repeated for a subsequent year, but the amount of organic matter remaining from the previous years is not included. The EOM model is therefore not suitable for long-term monitoring.

However, none of these models can calculate the large variation within fields and between years in detail since this type of modelling requires a tremendous amount of soil data; after all, the spatial variation in clay, sand, moisture, organic matter supply etc. needs to be entered. This detailed data is not available on a practical scale.

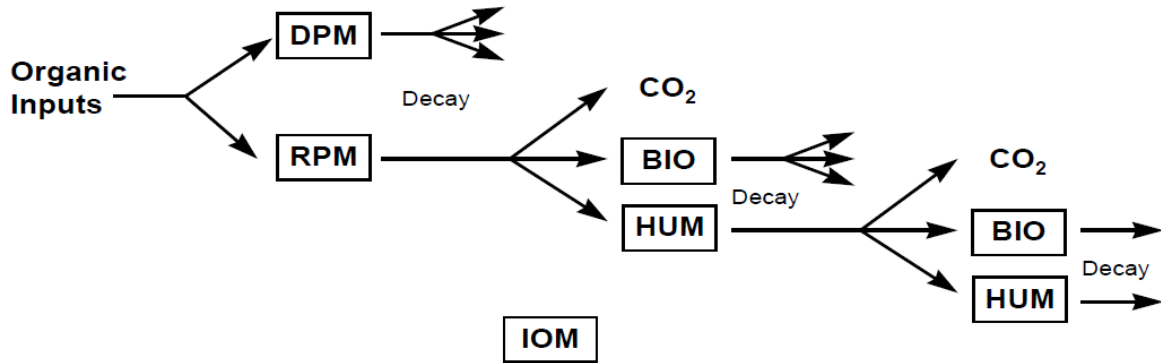
There are a number of reasons why it was decided to further develop the RothC model as the model to be used to simulate changes in the soil carbon stocks on farms with grassland and/or arable land in the Netherlands. The model is better at distinguishing between organic matter groups and makes more detailed use of soil properties (a sliding scale between sand and clay) and can take into account weather conditions (temperature and moisture). The model also works with smaller intervals than the ICBM model and EOM model. This model is also used on a wide international scale and is described in many scientific publications. The availability of the required data does not present a problem for use of the RothC model as all the required data is relatively easy to obtain. The knowledge and insights gained from the ICBM and EOM models can be used to improve the RothC model. The RothC model has been used on a national scale for the Netherlands before (Conijn and Lesschen, 2015) and will probably be used for the national Pollutant Release and Transfer Register in future. In this way, the monitoring outcomes and the resulting calculations at farm level can be incorporated into the national Pollutant Release and Transfer Register to make mitigation efforts apparent and count towards the national reduction target.

3.3.2 RothC model description

The RothC model is a dynamic model for the conversion of organic carbon in mineral soils. The model is widely used internationally and is frequently documented (including by Coleman et al., 1997; Smith et al., 1997; Byrne and Kiely, 2009). The model takes into consideration the effects of soil type, temperature, moisture content and soil cover on the decomposition of organic carbon. The model uses monthly intervals to calculate changes in the organic carbon stock on a time scale from one year to several centuries. This project uses version 26.3 of the RothC model as described by Coleman and Jenkinson (2014).

In the RothC model, the carbon is split into four active compartments and a small amount of inert organic matter. The four active compartments/pools are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM); see Figure 7. Each of these compartments has its own specific decomposition coefficient (the decomposition is a fraction of the amount present), except for the IOM compartment in which organic matter is no longer broken down. The decomposition coefficient for each compartment is influenced by texture, temperature, moisture and soil cover. The decomposition is described as a first order reaction in most soil carbon models, including the RothC model. The decomposition constants are 10 for the

DPM compartment, 0.3 for the RPM compartment, 0.66 for the BIO compartment and 0.02 for the HUM compartment. This means, for example, that an average of 2% of the organic carbon in the HUM compartment breaks down each year while 30% of the carbon is broken down in the RPM compartment. The decomposition constant of 10 indicates that all the material is broken down well within a one-year period. These decomposition constants are determined on the basis of the long-term experiments conducted in Rothamsted and are not usually changed for the purpose of using the model.



RPM : Resistant Plant Material
DPM : Decomposable Plant Material
BIO : Microbial Biomass
HUM : Humified OM
IOM : Inert Organic Matter

Figure 7 Schematic overview of the carbon compartments in the RothC model.

The RothC model uses the following data on a monthly basis (averages or totals):

- total amount of precipitation (mm)
- total open water evaporation (mm)
- average air temperature (°C)
- clay content of the soil (%)
- extent of soil covered by a crop (%)
- soil depth used in calculations
- supply of plant debris and green manure (tonnes of C per ha)
- supply of organic fertilisers, such as animal manure and compost (tonnes of C per ha)
- decomposition rate of the plant debris (RPM/DPM ratio)

The carbon content of the soil can be specified as a start value but can also be calculated based on the equilibrium value that is achieved in the long run. The RothC model is available as a standalone Windows version in which input can be changed via text files. This process is automated for the purpose of calculating all the fields and farms, which is why the calculation rules of the RothC model have been converted to a different programming language (GAMS in this case) so that simulations can easily be performed for all fields and so that the input data can automatically be read in from Excel files (or other possible data files).

3.3.3 Input data

Climate data

The model requires the following monthly climate data: average air temperature, precipitation and evaporation. Modelling is based on the use of a data set of measurements provided by the Royal Netherlands Meteorological Institute (KNMI). This data set contains monthly climate data per KNMI zone for the period 1983-2017. The farms are linked to these fourteen KNMI zones. The meteorological year 2017 was used to calculate the soil carbon balance since most of the other input

data was also collected for this year. This year was also average in terms of precipitation. In addition, a calculation of all meteorological years has been included for the sensitivity analysis.

The KNMI data for evaporation is based on the reference crop evapotranspiration according to Makkink's formula (Makkink, 1957). The reference crop evapotranspiration is the amount of water that evaporates from a grass field that receives a good supply of water and nutrients. However, the RothC model makes use of open water evaporation. To obtain this, the Makkink evapotranspiration is multiplied by 1.25 (Feddes et al., 2003).

Soil data

The RothC model uses organic matter content, clay content and soil density in its calculations. Organic matter content and clay content are parameters that are also determined in standard soil analyses. This data has been requested from participating farmers for each field (see also Section 3.1). For future implementation in the entire dairy farming sector, this soil data can, in principle, be retrieved from the 'My fields' web application and is therefore also available for automation.

It has been assumed for the calculations that organic matter consists of 50% carbon on average (Pribyl, 2010), although practical analyses show a large variation ranging from 30% to 70%. The determination of organic carbon is a separate determination in addition to the determination of organic matter. As determination of organic carbon is by no means always carried out, the average value has been used. The actual organic carbon content can be used in the eventual monitoring process if this information has been determined. If organic carbon has not been determined, the standard value can be used.

Correction of organic matter content to 0-25 cm

The sampling depth for soil analyses depends on the crop being grown. Soil analyses for fertilisation recommendations on grassland are conducted using the top 10 cm layer while the sampling depth on arable and maize land is 25 cm. This means that the organic matter contents on grassland and arable land are not directly comparable; the same applies to the amounts of organic matter (and carbon) that are stored in the soil. In order to combine all the data on organic matter, everything has been converted to the 0-25 cm layer. However, the conversion factor depends on soil type and land use. Based on the data sets used to calibrate the RothC model, conversion factors have been derived (Table 2). This shows that the organic matter contents in the top 10 cm are higher than in the layer underneath. There is little difference when it comes to arable land and temporary grassland. This is because the soil in these fields is ploughed several times and the soil layer is relatively homogeneous over 25 cm.

Table 2 Conversion factors to convert organic matter contents in the 0-10 cm layer to organic matter contents in the 0-25 cm layer.

Land usage	Soil type	Conversion factor
Permanent grassland	Clay	0.67
	Sand	0.81
Temporary grassland and arable land	Clay	0.97
	Sand	

Soil density

To convert carbon content to carbon stock, the density of the soil must be known. This is a parameter that is not normally measured as part of soil sampling and for which no farm-specific data is thus available. This is far too expensive. However, there are formulas available for calculating density, often on the basis of organic matter content and soil texture. Clay soils use the formula devised by Wösten (2001) and sandy soils use the formula by Hoekstra and Poelman (1982). Soil densities are currently being updated and new measurement techniques and sensors are being developed. The main factor that can cause deviations is soil compaction caused by heavy machines.

$$\text{Density}_{\text{clay}} = 0.6117 + (0.003601 * \text{clay content}) + (0.002172 * (\text{OM content})^2) + (0.01715 * \log(\text{OM content}))$$

$$\text{Density}_{\text{sand}} = 0.667 + (0.021 * \text{OM content})$$

Organic manure supply

The supply of carbon from organic manure is based on the farm-specific supply specified in the Annual Nutrient Cycle Assessment (ANCA). The ANCA distinguishes between ten different types of manure (Table 3). However, the data for this is only available in terms of nitrogen and phosphate, and not for carbon. That is why the amount of nitrogen in the manure used is converted to carbon using the C/N ratio in Table 3. If no farm-specific N content is available, the standard content as shown in Table 3 is used.

However, the manure supply shown in the ANCA is only available at farm and crop group level and not per field. In that case, an average manure supply is used in calculations, taking into account the application standards for N and P. The supply of carbon from pasture manure is only attributed to fields for which it is indicated that they are used for grazing.

Table 3 Properties of the different manure types (Schröder et al., 2018).

Manure type	N content (g/kg)	C/N ratio	Humification coefficient
Pasture manure from grazing livestock	4.0	8.9	0.7
Liquid manure from grazing livestock	4.0	8.9	0.7
Solid manure from grazing livestock	7.7	10.1	0.7
Liquid manure from confined livestock	7.0	5.7	0.33
Solid manure from confined livestock	34.1	6.2	0.33
Compost	7.0	15.1	0.9
Thin fraction	4.9	3.6	0.5
Thick fraction	9.2	8.3	0.5
Artificial fertiliser substitute	7.3	1.5	0.33
Digestate	5.6	3.0	0.9
Other manure	5.6	3.0	0.9

Supply of crop residues

The supply of carbon from crop residues is often the main source of carbon to the soil, especially for a permanent crop such as grassland with a dense root system. However, it is difficult to measure this supply. In grassland, there is year-round decomposition of plant residues and growth of roots and new shoots. To make a good estimate of this supply, long-term experiments have been used to determine what the contribution of crop residues in grassland must have been.

The carbon supply from crop residues has been calibrated for each treatment within each data set, taking into account the clay content of the soil, the average weather during the period concerned and the carbon supply from animal manure. The results for grassland show an average carbon supply from crop residues of 5.1 t C/ha for treatments that are exclusively mown without supply of animal manure and of 3.7 t C/ha for treatments that are also grazed and treated with animal manure. The supply of carbon calculated from crop residues ranges from -0.5 to 7,6 t C/ha (Figure 8). Annex 2 contains a more detailed description of how this calibration is performed for grassland and maize.

Based on this data, it is not possible to infer a relationship between the grass yield above ground and the supply of crop residues (mainly roots) to the soil. This is also consistent with other literature (Poeplau, 2016; Poeplau et al., 2018) in which no fixed shoot-root ratio can be found for grassland. Grass with large quantities of manure often has shallow roots while unmanured grassland has more roots that are also deeper. This is why a set carbon supply of 5.1 t C/ha was ultimately assumed for all permanent grassland based on Figure 8.

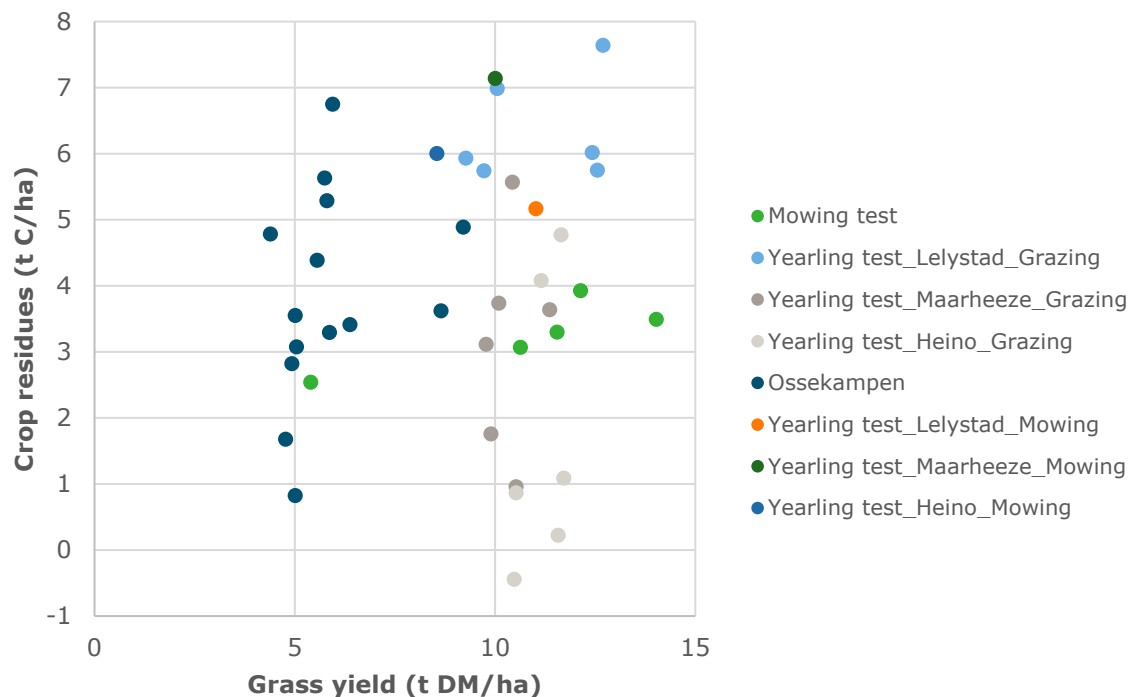


Figure 8 Calibrated carbon supply from crop residues in relation to the grass yield above ground.

There is less uncertainty when it comes to maize and other arable crops as these are single-season crops with less root system renewal. A supply of 1.1 tonnes of C/ha was calculated for green maize (see Annex 2), and for arable crops, a calculation was made of what the carbon supply should be based on the yield and the ratio between harvested biomass and total biomass of the crop. The supply of carbon from crop residues is summarised in Table 4.

Table 4 Supply of carbon from crop residues for grassland, green maize and catch crops.

Land use	Carbon supply from crop residues (tonnes/ha)
Permanent grassland	5.1
Temporary grassland	3.4
Green maize	1.1
Catch crop	1.0

3.4 Modelling the decomposition of organic soils

All fields of the participating farms are designated as 'peat', 'peaty' or 'mineral'. Grass stubble, roots and plant debris also die off on peat soils, but this is indistinguishable from the peat soil itself. The decomposition of drained peat soil is greater than the sequestration from crop residues. The calculations on peat soils are therefore concerned with the decomposition of organic matter and how it can be reduced.

Emissions were subsequently calculated for the peat and peaty fields. To perform this calculation, the groundwater level class, the presence of a clay or sand topsoil layer and the trophic level (mineral richness) of the peat were ascertained for each field using the soil map.

The groundwater level class is related to the expected drop in ground level for a peat field. This is estimated based on a combination of the ground water level class and the soil properties of the top layer of a field (see Table 5 from Kuikman et al. (2005)). Here, the groundwater level classes were subdivided into poorly drained, reasonably drained and well drained. Groundwater level classes (Gt) I and II fall under poor drainage, Gt IIb, III and IIIb fall under reasonable drainage and all Gt IV classes

and above fall under good drainage. The calculation is now based on the presence or absence of a clay cover and on three drainage classes, which results in six classes for which measurements are known. To calculate the CO₂ emission from the peat fields in kg per ha, use was made of the following formula (Kuikman et al., 2005) that is also used for the national emission reporting (Arets et al., 2019).

$$CO2_{em} = S_{mv} * \rho_{so} * fr_{os} * fr_c * \frac{44}{12} * 10^4$$

Where:

$CO2_{em}$ = CO₂ emissie (kg CO₂ ha⁻¹ jaar⁻¹)

S_{mv} = snelheid jaarlijkse daling van het maaiveld (m jaar⁻¹)

ρ_{so} = bulkdichtheid van ongerijpt veen (kg m⁻³)

fr_{os} = organisch stof fractie in veen (-)

fr_c = koolstof fractie in organisch stof (-)

Following on from Kuikman et al. (2005), a standard measurement of 140 kg soil m⁻³ has been used for the bulk density of peat. 0.8 has been used as the standard value for the organic matter fraction in peat and 0.55 as the standard value for the carbon fraction in organic matter. The factor 44/12 is the conversion from C to CO₂.

For the N₂O emission related to peat oxidation, the trophic level of the peat is also important and gives an indication of the mineral richness of the peat. Oligotrophic peat (legend symbols on soil map ..Wp, ..Vp, ..Vs) has grown under nutrient-poor conditions, often raised bogs, while mesotrophic and eutrophic peat (legend symbols on soil map ..Wz, Vz ..Vc,..Vb,..Vd,..Vr,..Vk) have grown under moderate to nutrient-rich conditions, often fens. The trophic layer of the peat is based on the legend symbols of the Soil Map of the Netherlands (scale 1:50,000). Mesotrophic and eutrophic peat have a C/N ratio of 15-30 and oligotrophic peat has a ratio of 40-70. The emission calculations are based on a single C/N ratio of 20 for eutrophic and mesotrophic peat and 40 for oligotrophic peat (Kuikman et al., 2005).

The N₂O emissions from peat (tonnes of CO₂-eq ha⁻¹ yr⁻¹) are calculated using the following formula:

$$N_2O_{em} = \left(\left(S_{mv} * \rho_{so} * fr_{os} * fr_c * \frac{1}{C/N} * 10^4 \right) * 0.02 \right) * \frac{44}{28} * 298$$

Where:

N_2O_{em} = N₂O emissie (ton N₂O ha⁻¹ jaar⁻¹)

S_{mv} = snelheid jaarlijkse daling van het maaiveld (m jaar⁻¹)

ρ_{so} = bulkdichtheid van ongerijpt veen (kg m⁻³)

fr_{os} = organisch stof fractie in veen (-)

fr_c = koolstof fractie in organisch stof (-)

Here, too, a standard value is used for bulk density (140 kg/m³), organic matter fraction (0.8) and carbon fraction (0.55). The factor 0.02 is the emission factor for N₂O from peat soils and the factor 44/28 is the conversion from N to N₂O. These calculations are used to calculate the amount of CO₂ and N₂O emissions per hectare. This is multiplied by the size of the field. Ultimately, this calculates the emissions from a field composed of peat soils.

4 Results

4.1 Farm data

4.1.1 Land use

In total, data was collected for 691 fields at the 37 dairy farms, of which 48% was sandy soil, 30% clay soil and 22% peat soil. Farms can have several types of soil within the farm.

Table 5 *Distribution of fields and farms* among soil types.*

Soil type	Number of fields	Number of farms
Clay	204	21
Peat	158	12
Sand	329	22

* There are 37 farms in total but a farm can have several types of soil

Soil analyses are available digitally for almost all fields from 2004 to 2015. Only limited data is available for the period prior to these years. In some cases, it was possible to retrieve data going back forty years. Each farm has an average of eighteen fields, with an average of three and a maximum of eight observations per field.

The land use of the fields can be seen in Table 6. In 56% of the fields, the land was used for permanent grassland, nearly a quarter was used for temporary grassland and a fifth was used as arable land. Maize was cultivated on 60% of the arable land and more than a quarter was used for growing root crops (potatoes, beets or bulbs).

Table 6 *Registered land use of all fields in the period 2004-2017.*

Category	Subcategory	Number of fields
Arable land	Green maize	661
	Potatoes	161
	Cereals	84
	Flower bulbs	75
	Sugar beet	68
	Other crops	78
Total for arable land		1,127
Nature	Woodland	9
Permanent grassland	Permanent grassland	3,173
Temporary grassland	Temporary grassland	1,383
TOTAL		5,692

4.1.2 Soil properties

Within a particular type of soil, there is a large variation in the sand, silt and lutum fractions, as well as in the levels of organic matter and carbon matter. The organic matter content averages 8.3% on clay soils, 34% on peat soils and 6.3% on sandy soils. The variation is greatest in clay soils with a variation coefficient of 0.8. At 0.3, the C/N ratio in the organic matter is the lowest variation coefficient of the various soils properties (Table 7). The determination of organic carbon was introduced only recently, which is why there is less data available.

Table 7 Soil sampling results for fields at the 37 participating farms, subdivided into soil type.

Ground type [-]		Number	Minimum	Maximum	Average	Stand. dev.	Variation coefficient
Clay	OM [%]	660	1.2	38.9	8.3	6.4	0.8
	OC [%]	39	1.4	11.4	6.3	3.2	0.5
	N Total [mg N/kg]	682	91	15,910	3,763	3,013	0.8
	C/N ratio	479	6.0	44.9	10.6	3.2	0.3
	Lutum [%]	489	1.0	52.0	23.4	12.0	0.5
	Silt [%]	102	10.0	43.0	28.7	7.7	0.3
	Sand [%]	175	9.0	95.0	41.1	20.3	0.5
Peat	OM [%]	595	5.9	65.1	34.1	13.8	0.4
	OC [%]	32	5.0	18.8	11.6	3.6	0.3
	N Total [mg N/kg]	484	396	25,590	11,342	5803	0.5
	C/N ratio	391	8.0	43.6	12.6	3.4	0.3
	Lutum [%]	396	1.0	44.0	25.9	9.6	0.4
	Silt [%]	139	5.0	40.0	18.1	6.3	0.3
	Sand [%]	149	2.0	81.0	32.4	23.7	0.7
Sand	OM [%]	1,087	1.6	33.1	6.3	3.2	0.5
	OC [%]	58	1.5	8.8	3.3	1.6	0.5
	N Total [mg N/kg]	940	140	11,562	2,169	1,212	0.6
	C/N ratio	790	5.7	35.0	15.7	3.9	0.2
	Lutum [%]	392	1.0	25.0	3.7	2.5	0.7
	Silt [%]	153	4.0	47.0	15.6	8.9	0.6
	Sand [%]	207	24.0	90.0	75.7	9.6	0.1

If the fields are subdivided into land use (permanent and temporary grassland and arable land), there are visible differences between the average contents (Table 8). Organic matter content is highest on permanent grassland followed by temporary grassland. Organic matter content is lowest on arable land. There is also a significant variation within every group of soil type/land use.

Table 8 Organic matter contents of fields at the 37 participating farms, subdivided into land use.

Soil type	Crop group	Minimum	Maximum	Average	Stand. Dev.
Clay	Arable land	1.2	21.9	4.0	2.9
	Permanent grassland	2.1	23.5	9.4	4.9
	Temporary grassland	1.3	21.9	7.2	4.9
Peat	Arable land	5.9	25.5	17.0	6.6
	Permanent grassland	6.5	59.8	30.1	13.1
	Temporary grassland	6.3	57.9	18.9	11.0
Sand	Arable land	2.2	19.8	5.7	2.8
	Permanent grassland	2.3	20.6	6.8	3.6
	Temporary grassland	2.1	33.1	5.7	3.3

A large variation in organic matter contents between fields is to be expected. The subdivision into sand, clay and peat is in itself a simplification of complex soil factors and the history and land use of farms is often quite different.

4.1.3 Variation within farms and across farms

Although a large variation in organic matter contents can be found within a soil type, the variation in levels within farms is often smaller than across farms. Table 9 shows the organic matter contents of permanent grassland for the farms with sandy and/or clay fields only, which were sampled between 2014 and 2017. It appears that the variation between fields within one farm is often smaller than the variation of all fields belonging to a group of farms.

Table 9 Organic matter contents of permanent grassland on farms with sandy and/or clay fields only.

Farm	Number of fields			Standard deviation for organic matter content			Organic matter content (%)		
	Clay	Sand	Total	Clay	Sand	Total	Clay	Sand	Total
1		12	12		0.79	0.79		4.39	4.39
2		1	1		0.00	0.00		4.00	4.00
3	10		10	1.86		1.86	5.10		5.10
4	8	9	17	2.33	1.29	2.01	6.26	4.74	5.46
5		23	23		1.10	1.10		3.68	3.68
6		25	25		7.47	7.47		8.62	8.62
7	13		13	1.03		1.03	3.22		3.22
8		30	30		1.45	1.45		6.76	6.76
9	12		12	1.39		1.39	4.09		4.09
10		12	12		1.19	1.19		4.97	4.97
11		22	22		1.80	1.80		5.98	5.98
12		24	24		1.01	1.01		4.28	4.28
13	7	10	17	1.11	1.83	1.58	4.17	4.55	4.39
14	9		9	2.76		2.76	12.31		12.31
15	7		7	1.00		1.00	2.97		2.97
16		10	10		1.59	1.59		5.07	5.07
17	4	21	25	1.21	0.93	1.01	3.70	4.41	4.30
18		33	33		2.20	2.20		8.80	8.80
19		2	2		0.50	0.50		3.60	3.60
2	12		12	0.80		0.80	6.02		6.02
21	12	2	14	1.53	0.05	1.79	6.57	3.45	6.12
22		5	5		1.07	1.07		4.98	4.98
23	11		11	1.26		1.26	3.55		3.55
24	15		15	1.09		1.09	4.75		4.75
25		15	15		1.37	1.37		5.67	5.67
26		9	9		1.50	1.50		6.49	6.49
27	8		8	0.56		0.56	3.46		3.46
28		44	44		1.55	1.55		7.32	7.32
Total	128	309	437	2.72	3.07	3.00	5.13	6.09	5.81

Statistically, the larger numbers could lead to a lower standard deviation, but this effect is negated by the large variation between farms. In the case of the farms taking part in this project, these are also spread out over the whole of the Netherlands. The smaller variation within farms is an indication, however, that a focused aggregation of fields into a single group based on soil characteristics can limit the variation of the organic matter content measured.

4.1.4 Trend in changes relating to organic matter content

Within the fields, there is a large variation over time. From the large group, all fields with permanent grassland and a sufficiently long series of organic matter data were selected. Based on field research and the resulting calculations (Soussana et al., 2004; De Wit et al., 2018), you might expect the organic matter content of permanent grassland to increase over time. A very simple regression analysis was conducted to check whether this is indeed the case and whether it can be demonstrated reliably. If the organic matter content increases over time, this can be calculated with the formula:

$$OM(t) = a + b*t$$

where a is the start quantity in the first year, b is the average change in content and t is the time expressed in years. If the value of b is greater than zero, this indicates an increase in organic matter content. All fields with a sufficiently long series of measurements were assessed to see whether the slope of the line deviates significantly from zero. The results in Table 10 reveal that only a limited number of fields display a significant change in organic matter content over time. Out of the total

number of 76 fields, it can only be demonstrated in 14 cases that organic matter content changes over the course of time. Less than half show an increase, with the rest displaying a decrease. If all fields are taken together, a very simple linear regression shows that there is no change in organic matter contents over time. In all cases, the standard deviation is much greater than the value of gradient b .

Table 10 Overview of the number of fields for which it can be significantly demonstrated that organic matter content on permanent grassland changes over time.

	p < 0.1		Insignificant		Average value b	Standard deviation
	Number	%	Number	%		
Clay	7	47	8	53	-0.25	-1.76
Peat	3	9	29	91	-0.04	-0.13
Sand	4	14	25	86	-0.01	0.58

Comparable situations can be found in the fields used as arable land for the entire time. It means that the variation in one and the same field is already very large over time and is barely usable for determining changes in organic matter quantities on individual fields. The variation on working fields may arise from the fact that samples are not always taken from the same places in a field. However, another possibility is that the grassland has been ploughed up and immediately sown again, with the sod containing the high organic matter content now ploughed under. It is often difficult to find out the usage history.

Exact usage is known, however, for test fields as more homogeneous fields are often chosen, the test fields are small (15 m² for mowing trials, 1000 m² for grazing trials) and sample-taking is conducted following a detailed protocol. In addition, the trial treatments are often repeated two to four times and the frequency of the determination is often much higher than in real-life, sometimes even once a year. This is expected to significantly reduce the spatial variation that results from sample-taking. This hypothesis can be tested by means of test fields in four locations, two of which are monitored for a period of sixteen and seventeen years and the other two for a period of more than twenty years.

Figure 9 is derived from the multi-year phosphate test fields of Wageningen UR (Ehlert et al., 2018). During the testing period, all test fields are used as permanent grassland without reseeding of grass turf or any tillage activities. One phosphate treatment is chosen, the values shown are an average of the 0-5 cm and 5-10 cm soil layers combined, an average of the 10-20 cm and 20-30 cm soil layers combined and of the repetitions that are made in the trial. This data shows that there is also a significant variation over time under highly conditioned and controlled conditions.

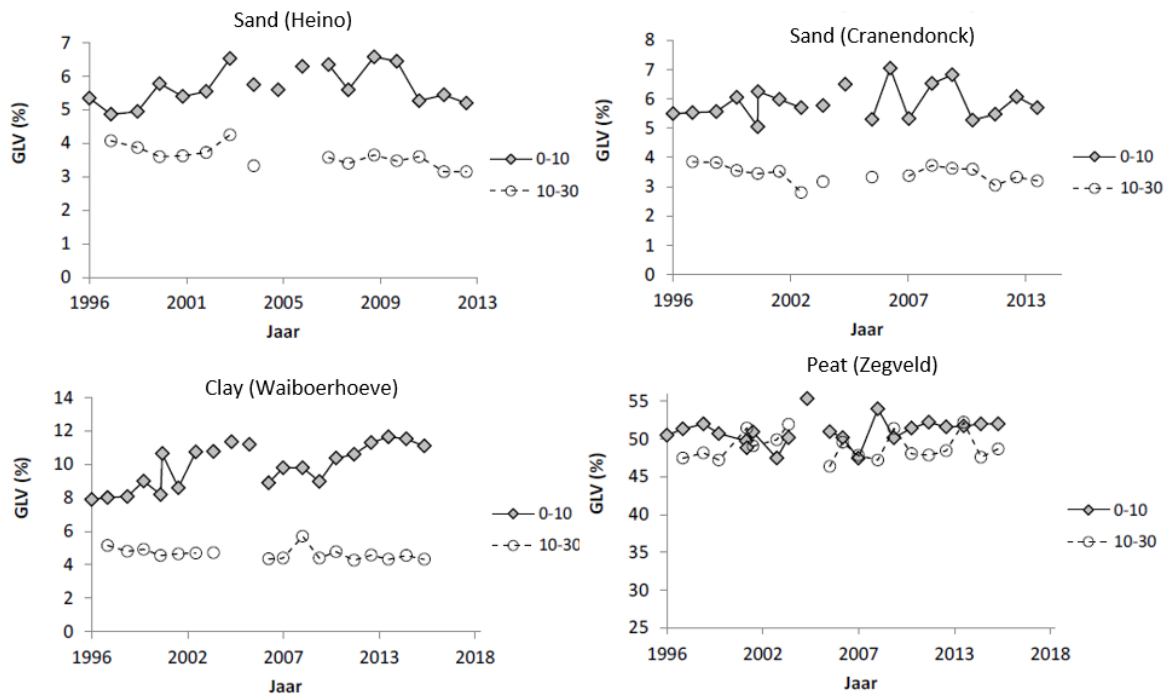


Figure 9 Change in organic matter content (GLV = LOI = loss on ignition) since 1996 in 0-10 cm and 10-30 cm soil layers with equilibrium fertilisation (0-10 cm determined as the average of 0-5 cm and 5-10 cm; 10-30 cm determined as the average of 10-20 cm and 20-30 cm). (Source: Ehlert et al., 2018.)

The measurements on the working farms reveal that the variation in data is so great that it is not feasible to make reliable claims regarding changes in organic matter contents in relation to land use (grassland or arable land). A large spatial and temporal variation also exists in the measurements conducted on highly controlled test fields. This indicates that measurements on working fields alone are not sufficiently accurate to be able to demonstrate changes in organic matter contents reliably. With larger data series, such as those determined on test fields, statistical methods can be used to demonstrate a reliable change (Ehlert et al., 2018). This cannot be achieved for working fields.

It is difficult for dairy farmers to retrieve and/or reconstruct historical supporting data on land use and the reseeded of grassland and earlier measurements relating to organic matter content. This was only possible in a limited number of cases. The collection of historical data at company laboratories may offer prospects for obtaining longer data series, but without detailed information on use and management.

4.1.5 Organic matter and organic carbon

Carbon forms part of the organic matter. In fresh plant material, 40-45% of the organic material consists of carbon (C) while this percentage is often much higher in soil organic matter. The literature review carried out by Pribyl (2010) puts forward an average value of 0.5 for the carbon content of organic matter. In a limited number of cases (107), the organic carbon was determined in addition to the organic matter for the available data set of the soil analyses. The results of this analysis can be found in Table 11.

Table 11 The carbon fraction of organic matter (without dimensions) at the participating working farms, subdivided into sand, clay and peat.

	Average carbon fraction of organic matter	Maximum	Minimum	Standard deviation	Number of samples
Total	0.54	0.76	0.33	0.05	107
Clay	0.53	0.57	0.47	0.03	40
Peat	0.53	0.61	0.46	0.04	24
Sand	0.56	0.76	0.33	0.06	43

This shows that on the basis of this data set the average carbon fraction of soil organic matter is slightly higher than the frequently used value of 0.5 for the conversion factor. For the time being, this study uses 0.5 as the factor for converting organic matter into organic carbon, but this factor may need to be amended for the Netherlands in future on the basis of further measurements.

4.2 Modelling of carbon sequestration and decomposition in mineral soils

4.2.1 Carbon supply at farm level

Based on data from the ANCA on manure applications and yields, the average carbon supply per farm has been calculated for 37 farms (Figure 10). A distinction was made between carbon supply from crop residues, animal manure, pasture manure and compost. Most of the carbon supply originates from animal manure and crop residues. The carbon supply from crop residues varies between 2.4 and 5.1 tonnes C/ha/year per farm and averages 4.0 tonnes C/ha/year. The carbon supply from animal manure is subdivided into solid manure, pasture manure and liquid manure (incl. thin fraction). The average carbon supply from animal manure is 0.4 tonnes C/ha/year from solid manure, 0.2 tonnes C/ha/year from pasture manure and 1.8 tonnes C/ha/year from liquid manure. Compost is used on four farms, resulting in an average supply of 0.4 tonnes C/ha/year. All this data represents an average value for all fields per farm. There is no data available in the ANCA for field-specific applications.

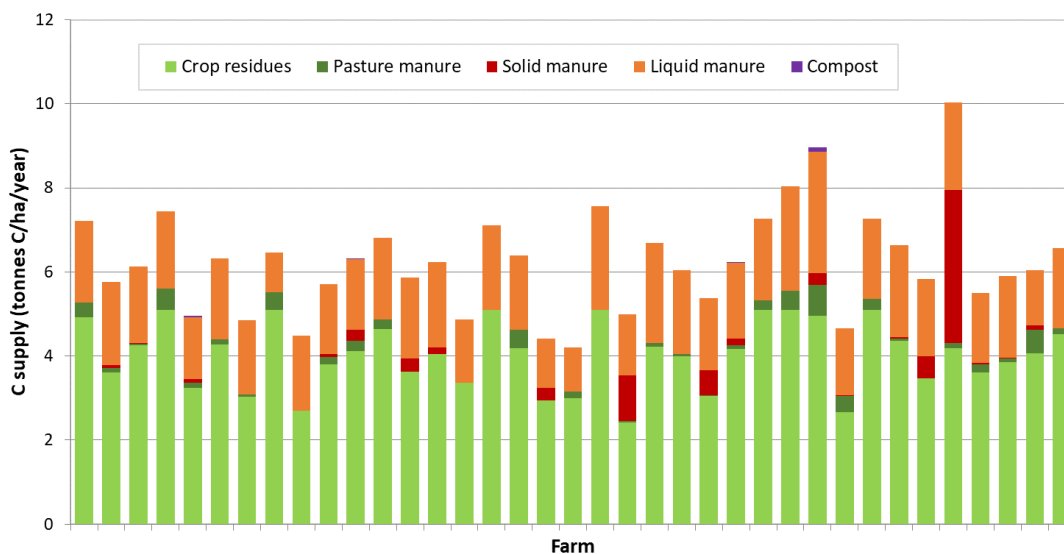


Figure 10 Average supply of carbon to the soil per farm, based on data from the Annual Nutrient Cycle Assessment.

4.2.2 Carbon balance per land use and soil type at field level

The calculation in this section is only applicable for sandy soils and clay soils since the RothC model is not suitable for calculating the decomposition on peat soils and peaty soils. The organic matter that is present and that is supplied is subjected to decomposition processes. Of all the organic matter that is supplied, a part of it still remains after a year. This is determined by the distribution of organic matter over the different compartments (see Figure 7), their decomposition rates, the soil properties and the weather conditions. The net result of the supply and the decomposition of carbon that is supplied and present is called the soil carbon balance.

As the fields vary in organic matter content and clay content, the results of the carbon balance are calculated at field level. Figure 11 shows the modelled carbon balance for all fields on mineral soils. The model results show that on average 0.4 tonnes C/ha/year is sequestered on grassland. On the other hand, green maize and other arable crops display a loss of soil carbon on average, with -0.5 tonnes C/ha/year and -0.6 tonnes C/ha/year respectively. When we look at soil type, the fields on clay soils generally show a higher carbon sequestration than fields on sandy soils. The average carbon balance of the clay soils is +0.4 tonnes C/ha/year, while the average carbon balance of the sandy soils is +0.1 tonnes C/ha/year.

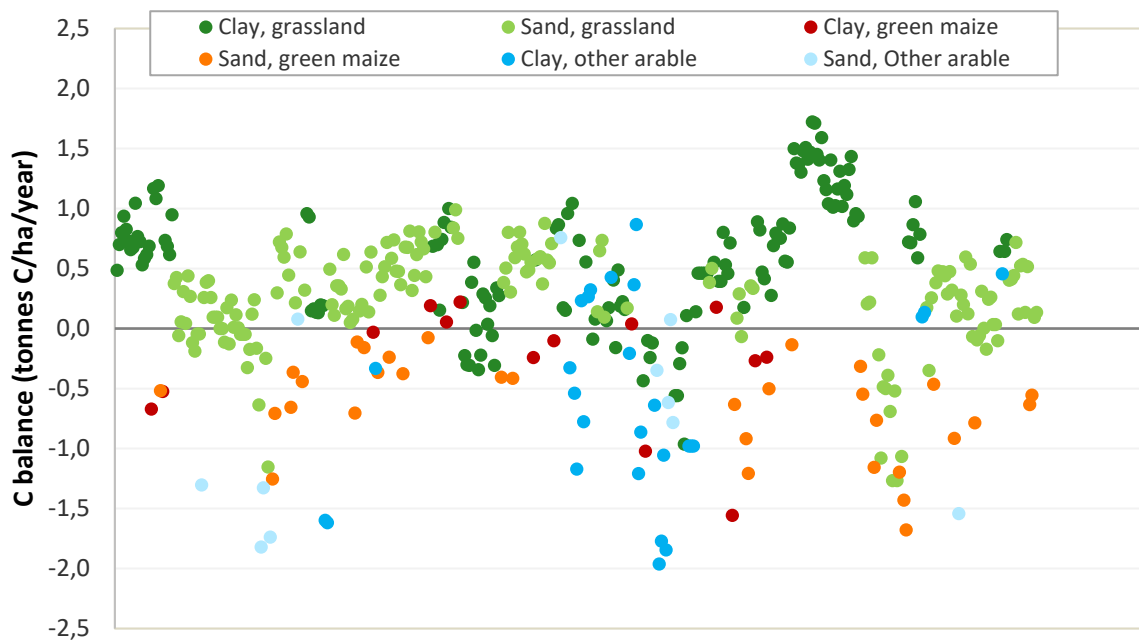


Figure 11 Modelled carbon balance for all fields per land use and soil type (the X axis shows all fields arranged per farm).

To determine the relationship between the carbon balance and the carbon supply to the soil, the average supply of carbon per field is set against the modelled carbon balance for the relevant field (Figure 12). The results show a considerable variation but, in general, a higher carbon supply corresponds with a relatively stronger positive carbon balance. Of the three categories of land use, the arable fields show the largest variation in carbon supply. The carbon supply on these fields varies from 0 to 8 tonnes C/ha/year. The carbon balance on these fields varies from -2.0 to 0.9 tonnes C/ha/year. On average, the grassland fields have the most positive carbon balance and the highest supply. The carbon supply of the grassland fields varies between 4.9 and 9.1 tonnes C/ha/year and the carbon balance varies from -1.3 to 1.7 tonnes C/ha/year. The carbon supply of the green maize fields varies between 1 and 4 tonnes C/ha/year and the carbon balance varies between -2.0 and 0.2 tonnes C/ha/year.

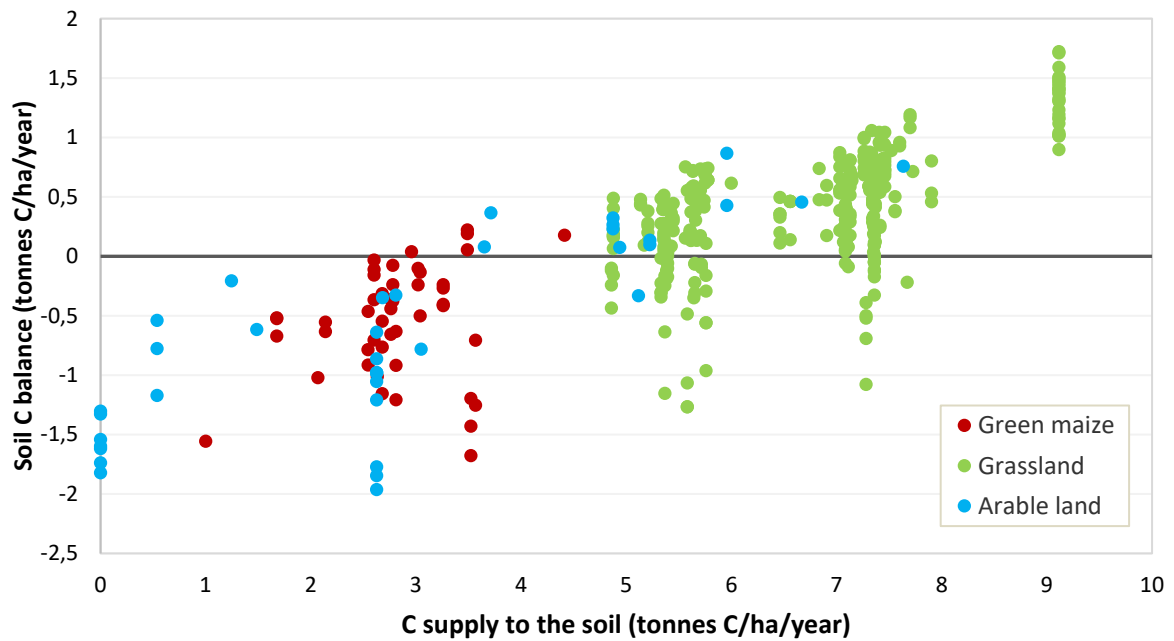


Figure 12 Carbon balance in relation to carbon supply to the soil at field level. The results are subdivided according to land use.

In addition to the relationship between the carbon balance and carbon supply, we also looked at how the modelled carbon balance relates to the measured soil organic matter content. The results of the fields are subdivided into soil type in order to investigate whether there is a difference between sandy soils and clay soils when it comes to the relationship between the carbon balance and soil organic matter content. Figure 13 shows a large dispersion but, in general, the carbon balance of the fields decreases as organic matter content increases. This can be explained by the fact that more decomposition occurs with a higher organic matter content, which eventually leads to a balance between supply and decomposition. It can also be seen that the average carbon balance of the clay soils is higher than that of the sandy soils, especially with higher organic matter contents. This means that organic matter can be sequestered more easily in clay soils. This is completely in line with the findings of Hassink (1995) who attributes this to better physical protection of organic matter in clay soils.

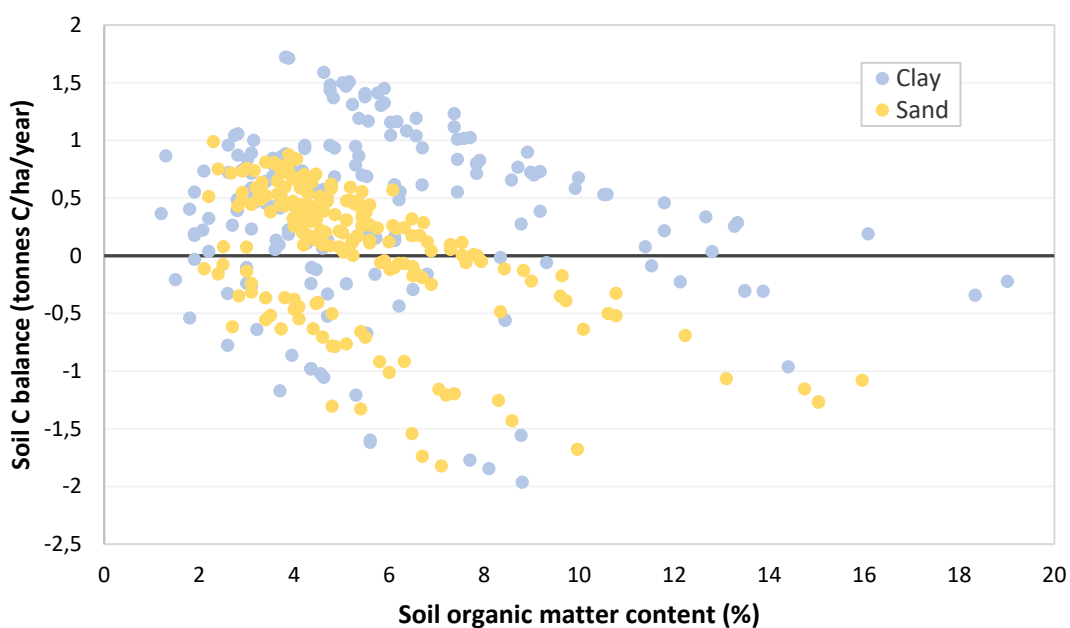


Figure 13 Carbon balance of clay and sandy soils in relation to the organic matter content of these soils: the data is displayed at farm level.

4.2.3 Comparison with historical data

In order to assess the calculated soil carbon balance, a comparison was also made with the historical data on the organic matter contents of participating farms. Figure 14 shows the comparison between the historical soil data and model results for two farms. The graph shows the organic matter contents measured historically up to 2017 together with the modelled organic matter contents for 2017 and, twenty years later, for 2037. The results for 2037 are based on the assumption that the farm concerned continues its management practices applied in 2017 for the next twenty years. In order to compare the model data with the historical data, the trend was determined for both data sets. The results for farm A show a departure from the trend (Figure 14A). The soil organic matter contents measured over the past 31 years show a decrease while the results based on the model show an increase in organic matter content for the next twenty years. Farm B, on the other hand, shows a continuation of the trend (Figure 14B). From 1997 to 2017, an increase in the organic matter contents measured can be seen. The modelled organic matter contents from 2017 and 2037 also show an increase. For most farms in the pilot group, the trend lines of the historical data were reasonably similar to the calculated trend from the soil carbon balance. However, this approach must be regarded as an indication at most, given that the historical trend, in particular, is highly uncertain due to a limited number of measuring points, a considerable variation between fields and the lack of sufficient information about historical usage.

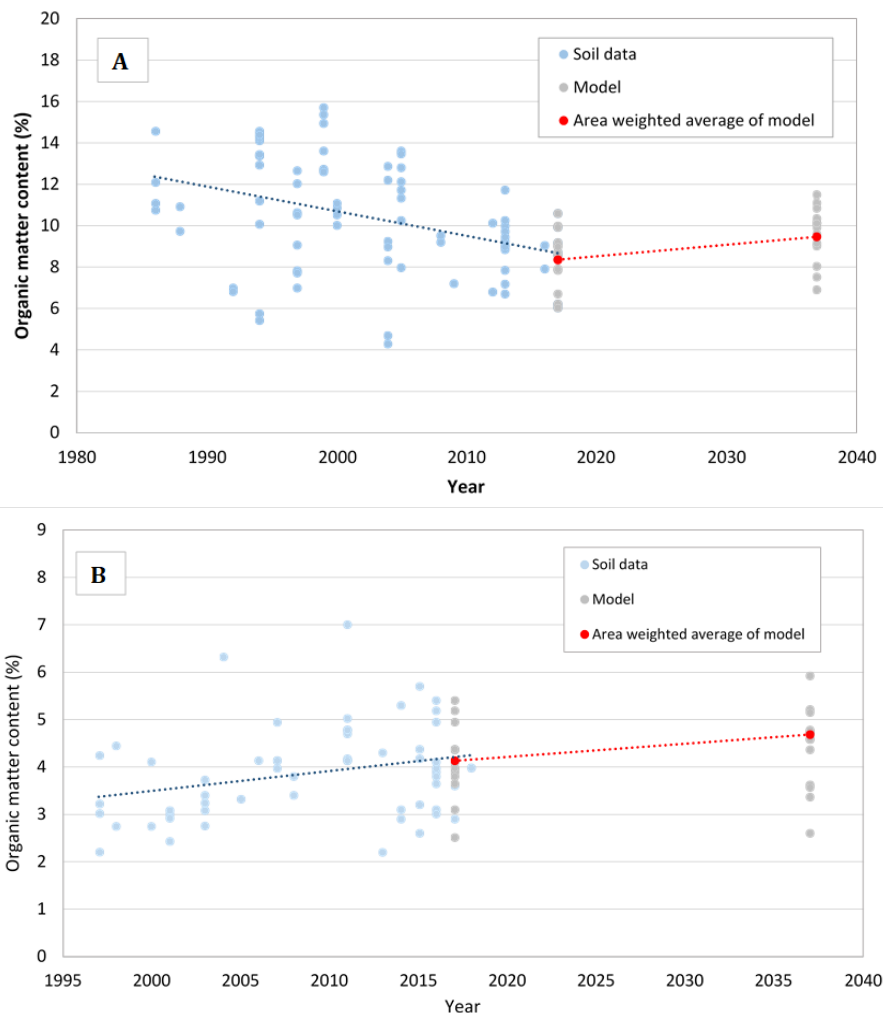


Figure 14 A comparison of the modelled organic matter contents with historical measurement data for farms A and B.

The model calculations can signify a trend for mineral soils in the sequestration and/or decomposition of organic matter at field level. The calculation makes use of specific data per field (texture, organic matter, land use) and average values per farm (amount of organic manure, compost and other additives). This calculation is based on implementation of current land use and land management practices.

There is also a large variation when modelling the organic matter content over time; this is due to variation in the carbon supply from crop residues and the use of average (not farm-specific) values for the application of animal manure and artificial fertiliser. Because of this variation, it is not possible to check the calculated values at farm level based on measurements in the field. When monitoring is started, calculations and validation will enable a continuous process of model improvement. Only on this basis can accurate conclusions be made about the margin of error.

4.3 Carbon decomposition in organic soils

The calculation of CO₂ emissions from peat soils is based on the expected drop in ground level; this depends on the groundwater level class, the presence of a sandy or clay topsoil layer and the peat type. The emissions from peaty soils are calculated based on the groundwater level class, which is an indicator of the extent of drainage. A total of twelve farms with peat soils and peaty soils took part in this pilot study. The expected drop in ground level of the peat fields varies from 3 mm to 12 mm per year. These drops in ground level result in CO₂ emissions ranging from 6.8 to 27.1 tonnes of CO₂/ha/year. The CO₂ emissions from the peaty fields vary between 6.0 and 17.6 CO₂ tonnes/ha/year. The N₂O emissions from the mineralisation of peat soils is not included since they are already included in the current footprint calculation in the ANCA.

Figure 15 shows the average CO₂ emission from peat soils and peaty soils per farm. At farm level, the CO₂ emission from peaty soils varies between 6.0 and 10.4 CO₂ tonnes/ha/year, with an average of 7.2 CO₂ tonnes/ha/year. The CO₂ emission from peat produces a higher average per farm of 12.5 CO₂ tonnes/ha/year and varies from 6.8 CO₂ tonnes/ha/year to 23.4 CO₂ tonnes/ha/year. The average emission from participating farms for peat soils and peaty soils is lower than the national average which is 12 tonnes CO₂/ha/year for peaty soils and 18 tonnes CO₂/ha/year for peat soils.

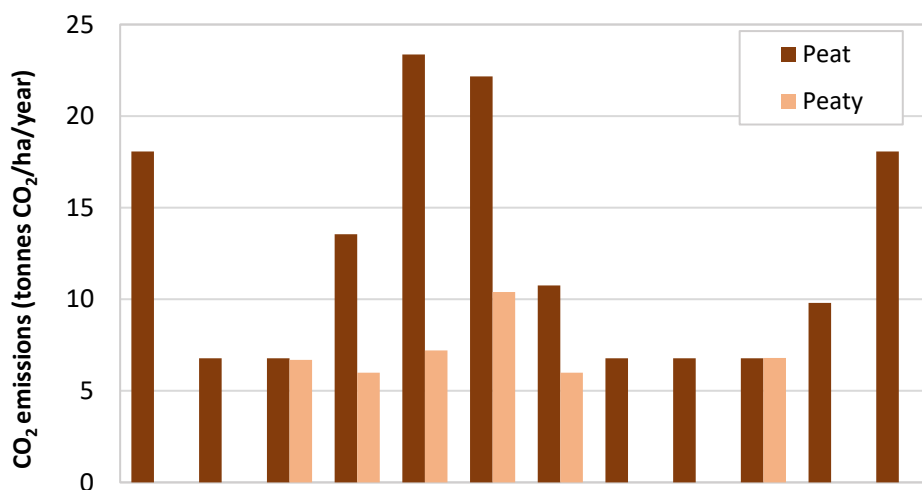


Figure 15 CO₂ emissions from peat soils and peaty soils calculated per farm.

4.4 Effect of carbon sequestration and decomposition on the carbon footprint for milk

Mineral soils

The Carbon Footprint (CFP) specified in the ANCA and the CFP including soil carbon sequestration are shown in Figure 16. Of the 37 participating farms, 33 had fields with a mineral soil. Of these 33 farms, the average CFP, without calculating soil carbon sequestration, was 1.19 kg CO₂-eq/kg of FPCM. The influence of carbon sequestration on the CFP varies widely per farm. The results show that the CFP decreases by a maximum of around 12% compared to the CFP in which soil carbon sequestration is not included. However, in some cases, the CFP also increases if the farm has a negative carbon balance on average. The maximum increase is 15%. In general, the average soil carbon sequestration calculated results in a decrease in the CFP to an average of 1.17 kg CO₂-eq/kg FPCM. There is an average of 24 grams of CO₂-eq between the calculation with sequestration and the calculation without. For a farm with one million kg of milk and 50 hectares, this equates to 24,000 kg CO₂ sequestration per year at farm level and 480 kg CO₂ per hectare. In order to provide participants with more insight into the effect of soil carbon balance per field on the CFP, a waterfall chart has been created for each farm. Figure 17 shows an example of the effect of sequestration and decomposition in fields on the total CFP for a farm. Soil carbon sequestration occurs in nine of the eleven fields on this farm. These fields contribute to a decrease in the CFP. By contrast, two fields have a negative carbon balance and produce an increase in the CFP.

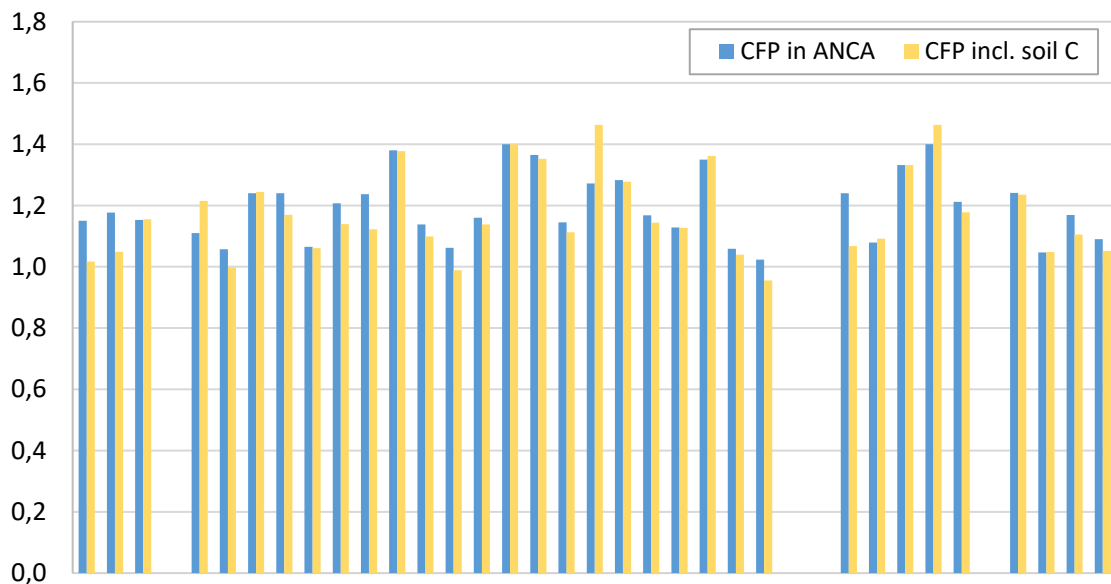


Figure 16 Comparison between the carbon footprint in the ANCA and the calculated carbon footprint including carbon sequestration and decomposition in mineral soils (missing data is for farms with organic soils only).

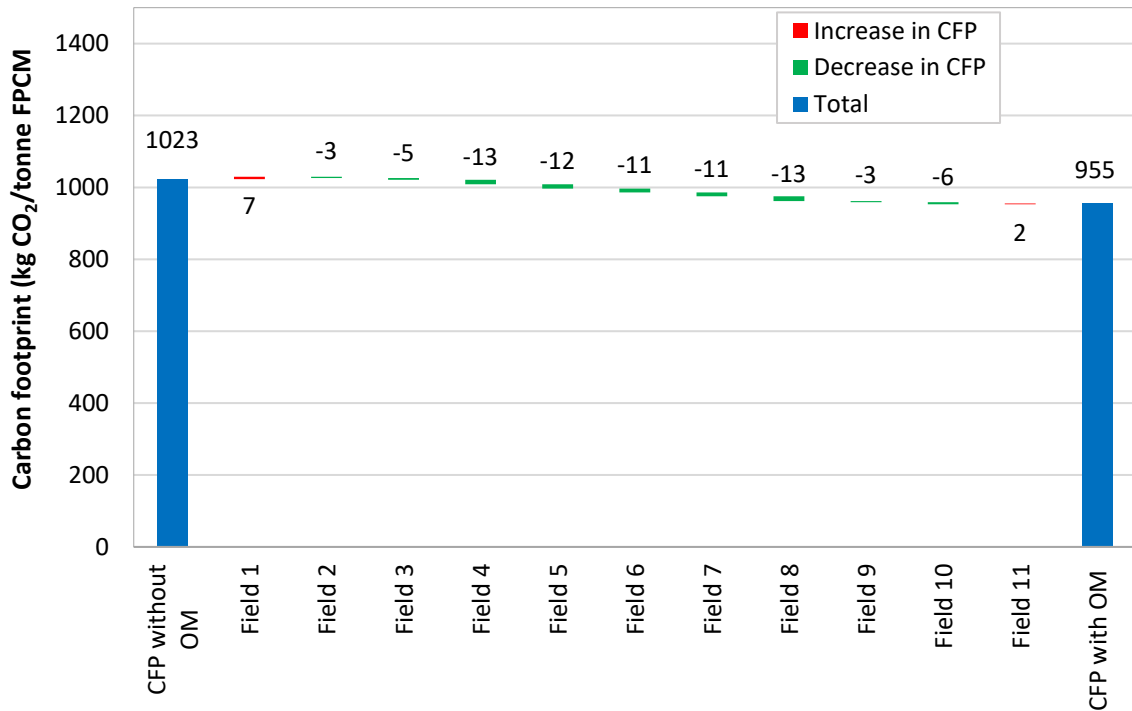


Figure 17 Example for one dairy farm that shows to what extent each field contributes to the average carbon footprint of milk through the emission (red) or sequestration (green) of soil organic matter in the field.

Organic soils

The effect of CO₂ emissions from organic soils on the CFP is shown in Figure 18. The average CFP of the farms with organic soils is 1.31 kg CO₂-eq/kg FPCM. The calculated carbon decomposition on these farms produces an average increase in the CFP of 19% (ranges from 8% to 31%). This results in an average CFP of 1.57 kg CO₂-eq/kg FPCM. Since a number of these farms also have mineral soils, the effect on the average footprint is smaller. For example, a dairy farm with one million kg milk and 50 hectares of land will produce 260 tonnes CO₂-eq of emissions from organic soils per year, which is 5.2 tonnes of CO₂ per hectare. Farms that lie entirely on peat soil will produce emissions nearing 15 to 20 tonnes CO₂-eq per hectare per year, as shown by the values in Figure 15.

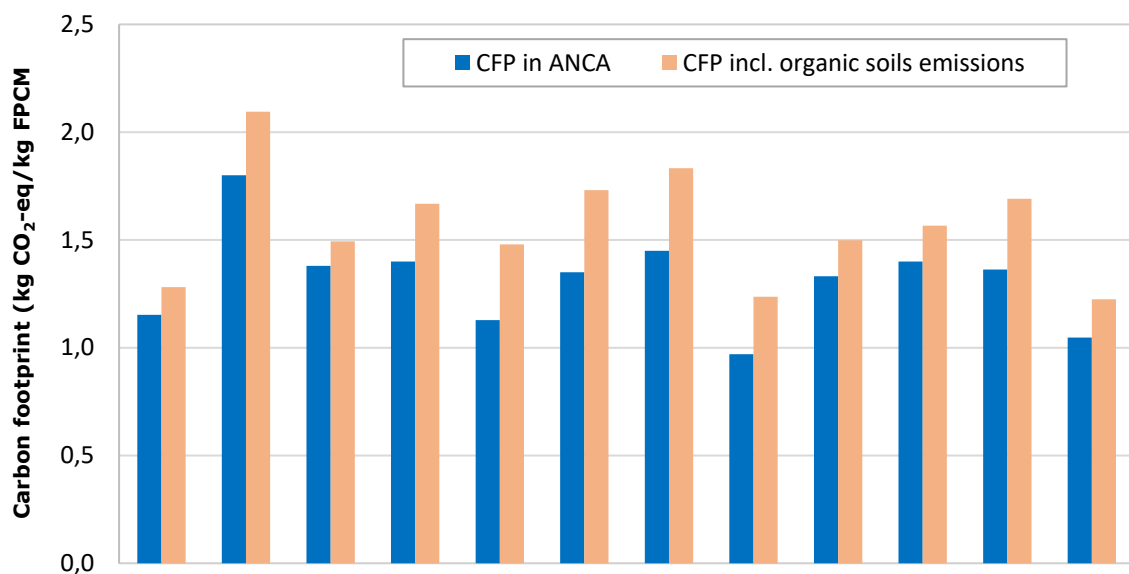


Figure 18 Carbon footprint specified in the ANCA in comparison with the calculated carbon footprint including CO₂ emissions from organic soils for the participating dairy farms with organic soils.

5 Discussion and conclusions

The importance of organic matter and its increased sequestration in mineral soils and reduced decomposition in peat soils has become more apparent with the Climate Agreement and the focus on soil quality. A good monitoring system and knowledge of measures have therefore become urgent. The characteristics of a monitoring system are described as follows:

A system for monitoring carbon sequestration in, and carbon emissions from, agricultural soils can be regarded as a coherent interconnection between a) measurements of organic matter quantities (and thus carbon (C) in the soil); b) the collection of data relating to land use, management, supply and removal of organic matter; c) calculations of organic matter balances and consequent changes in organic matter on agricultural soils; and d) a procedure that describes the level of aggregation (field, farm, area or sector) at which the results of the monitoring are displayed and can be used.

In order to develop a tested, reliable and transparent system, a number of research questions were formulated. These questions will be discussed in this chapter.

5.1 Monitoring based on existing soil analyses carried out for fertilisation recommendations

In order to measure the effect of changes in soil management and other management practices on soil carbon, measurements are needed over a longer period of time given that carbon sequestration is a relatively slow process and because it involves small changes in relation to a large existing stock. In addition, there is often a significant spatial variation in organic matter content, even within the same field, that is associated with factors such as small differences in height, differences in drainage and the presence of peat layers.

For monitoring at farm level, data from soil analyses carried out for fertilisation recommendations is usually available. Many farmers have their fields analysed for fertilisation recommendations and dairy farmers registered for derogation also have a legal obligation to take a soil sample at least once every four years. This soil data from commercial laboratories such as Eurofins could provide the basis for monitoring at farm level.

A study by Goidts et al. (2009) for Wallonia reveals that there is considerable uncertainty regarding the determination of soil carbon stocks at landscape level (20%). This uncertainty is mainly due to the heterogeneity of the landscape as well as to the resampling within a field. This last aspect also became apparent during a test by the journal *De Boerderij* in which the same soil sample was sent to different laboratories and there were considerable differences in organic matter content between laboratories.⁵ In addition, there is also the margin of error on the soil analyses in the laboratory which can amount to 5-10% of the measured value. This means that an organic matter content of 3% could also be 2.85% or 3.15%; these are large differences when converted into tonnes of CO₂ per hectare. The relative error is larger for soils with a low organic matter content. De Wit et al. (2018) concluded on the basis of an analysis of organic matter build-up under permanent grassland that there is a significant variation in the measurements, as a result of which only 20-25% of the variation in organic matter content can be explained by the age of the grassland. The values of the organic matter measurements on the fields of the participating dairy farms show the presence of a similar variation but indicate that the variation is smaller within farms than between farms. It would be wise to consider the best way to aggregate data.

⁵ <https://www.boerderij.nl/Home/Achtergrond/2018/7/Grote-verschillen-Pw-getal-bodem-mengmonster-306309E/>

Most measures that promote soil carbon result in a potential sequestration of roughly 1-2 tonnes of CO₂ per hectare (Lesschen et al., 2012). This means an increase over ten years of 2.7 to 5.4 tonnes of carbon per hectare which corresponds to a relative increase in organic matter content by 3% to 6%. This therefore lies within the error margin for the soil carbon measurements. It is only possible to establish a change with greater certainty if measurements are conducted over a period longer than ten years or if a greater number of soil samples are analysed.

In addition, the limited sample depth for grassland (0-10 cm) makes it difficult to monitor fields with temporary grassland and arable land accurately given that samples are taken from arable land at 0-25 cm and it is not clear what happens in the deeper layer of permanent grassland. A long-term phosphate trial on grassland shows that the organic matter content on clay soil increases significantly in the 0-10 cm layer but decreases in the 10-30 cm layer, which limits the overall increase (Van Middelkoop, 2017).

In an Austrian pilot project⁶ conducted on working sites, the carbon sequestration that is achieved is paid out based on soil carbon measurements. However, in this project, almost a third of the costs for soil carbon sequestration are spent on monitoring, such as for the costs of soil analyses carried out specifically for the project. In addition, the test in Austria involves the application of very large quantities of compost to arable land, which leads to relatively large changes in organic matter contents in a short space of time.

Based on the data from the group of farms participating in this study and on the literature, it can be concluded that a monitoring system based on data from existing commercial soil analyses is not supportive enough at present to reliably estimate carbon sequestration in the soil and to pay out credits on that basis. Due to the significant spatial and temporal variation, there is also considerable uncertainty with regard to use of these analyses at a higher aggregation level.

5.2 Calculating the development of organic matter content

5.2.1 A clear procedure for classifying fields according to soil type

It proves difficult in practice to make a clear distinction between the different soil types. There are several sources of data that also contradict one another at times. Data from the soil analyses is only relevant for the top 10 cm layer in grassland or the 25 cm layer in arable land. For peat soils with a sand or clay cover, the analysis does not have to show that it is a peat soil, which means that a check of the soil map is still necessary. It is especially difficult for peaty soils as these are not categorised as a separate soil type in the soil analyses and in the soil type map for the manure policy. However, this category of soil does require a different type of calculation than peat soils. Although the proposed method involving use of the soil map provides a good indication, it can still deviate from reality at farm level since the soil map has a scale of 1:50,000 which limits its accuracy at field level. The distinction between clay soil and sandy soil has no further relevance for the calculation since the clay content is used for the model calculation. It is useful, however, to make this distinction if results are aggregated to regional or national level. There are also clear differences in the possibilities for carbon sequestration between clay soils and sandy soils.

In future, a better map for peat soils and peaty soils will be needed that contains information about the current water level, since water level, in particular, determines the amount of the emissions. There are also soils with a high organic matter content, particularly clay soils, which are not peat soils or peaty soils and which cannot therefore be calculated reliably using the RothC model. However, there is still no scientifically tested model available for use in practice that can accurately calculate emissions from peat soils and peaty soils. A number of these fields were also included in this pilot group and are therefore not included in the analysis. There can also be considerable variation within the field, particularly at the boundary between peat and mineral soils, which makes it difficult to clearly identify

⁶ <https://www.oekoregion-kaindorf.at/index.php?id=623>

the type of soil in a field. Further research is required to find out exactly how to deal with this group. However, it is possible to advise dairy farmers to keep fields containing a high organic matter content under permanent grassland as much as possible in order to maintain this high content.

5.2.2 Annual sampling at a set depth and set time

Grassland and arable land are sampled at different depths. Samples with a layer thickness of 10 cm are taken from grassland, and in the years prior to 2000, samples were even taken at a depth of 5 cm (Reijneveld et al., 2009). Arable land is still sampled over the 0-25 cm layer. These different layer thicknesses make it necessary to convert these depths to the same layer. A depth of 25 cm is now used for the calculations. For a reliable conversion, measurements should be taken at both 0-10 cm and 0-25 cm based on field research so that a better conversion factor can be established. The changes in soil organic matter content depends on land use and any rotation therein. Old grassland will mainly have a high organic matter content in the topmost 5-10 cm and a significantly lower content beneath the top 10 cm. If the grassland is ploughed and reseeded regularly, then a proportion of the organic matter will be shifted to a slightly deeper layer and mixed and the distribution over the 0-25 cm layer will be different. It is highly recommended to use the same layer thickness when measuring soil organic matter content on both grassland and arable land.

There is also some variation in the measurements of organic matter content during the course of the year. The supply of organic matter and the conditions for decomposition (temperature and moisture) play a major role in this. To ensure that this variation is excluded during measurements as much as possible, it is recommended to use a set sampling time. The best time for sampling is in autumn or winter when no manure is applied. On many fields, measurements are now carried out once every four years. An annual measurement would be much better for accurate measurements and comparison with calculations. This would be expensive, however, so it may be worth considering doing this on a limited number of fields or investing in new measuring methods that are faster and cheaper (see also Section 5.2.6).

5.2.3 Calculation model

In view of the above problems associated with monitoring soil carbon using measurements, a system of settlement based on measures taken is likely to be more attractive in the short term. In order to attribute the climate benefits gained due to the measures taken, it is also necessary to quantify carbon sequestration. There are two possible approaches: 1) farm-specific quantification based on a soil carbon model, 2) use of standard 'fixed' values for carbon sequestration. A brief description of both approaches is given below.

Given the long-term effect and the uncertainties associated with soil carbon measurements, the use of models to quantify the effects of measures on soil carbon stocks is a logical alternative. There are various scientific soil carbon models and tools specifically for use in practice that could be used for this purpose. After making a comparison, it was decided to employ the internationally applied RothC model (Coleman et al., 1997). Every calculation model will always be based on a start value for organic matter content. The most recently measured organic matter content of the field for which the calculation is being performed can be used for this purpose. Information is also needed regarding use of the field (grassland or arable, type of crop), application of organic matter, crop residues and other field management practices. The advantage of this calculation method is that you can work on a field-specific basis to some extent, although data will not always be available at field level.

The advantage of the model calculations is that farm management practices are included when calculating sequestration (or decomposition) of carbon in the soil. This offers the dairy farmers a more direct perspective for action. The consequence of land use, manure application and soil management can be calculated on an annual basis. This is also possible when monitoring via measurements but the results cannot be determined for each year afterwards. In practice, the current measuring frequency is often once every four years. Increasing this frequency would lead to an increase in monitoring costs but would provide better insight into the changes in soil organic matter.

Although the model calculations produce a single value as outcome, it has already emerged during calibration of the calculation model that the estimation of organic matter supply from crop residues on grassland is a source of great uncertainty. This means that using models for the settlement of carbon sequestration at field level also causes some uncertainty. This uncertainty mainly relates to the absolute level of organic matter content and, to a lesser extent, to the trend over time. It therefore provides a better estimation of the organic matter quantities over time than a set of successive observations at field or farm level.

The uncertainty of the calculated result is still so significant, however, that use of the model results for settlement/rewards at field and farm level is not yet suitable. Nevertheless, it does offer more and better possibilities for assessing the development of the organic matter quantities on a larger scale (groups of farms). An important advantage of using a model calculation is that a direct link can be made to activities on the dairy farm.

5.2.4 Data availability

The data that is used to calculate the development of organic matter content relates to a) land use and crop type, b) the application of organic fertilisers in particular, c) the management of the field and d) soil information.

Land use refers to the choice between grassland and arable land. With arable land, further details are needed regarding the crop that is being cultivated. This data is available every year as it is also needed within the context of the manure legislation. This data is nationally and publicly available in the *Basisregistratie Gewaspercelen* (Basic register for crop fields) (BRP) to which it can automatically be linked. The type of land use and crop determine the amount of organic matter that remains on the land from crop residues.

In addition to crop residues, the application of organic fertilisers is also important. The amount of organic matter and the amount of carbon present in each fertiliser is taken into account. All manure types are registered in the Annual Nutrient Cycle Assessment (ANCA) together with the organic matter contents and the levels of N, P and K. The application of these fertilisers is not registered per field but is registered in the ANCA at farm level. Registration at farm level means that it is only possible to use average dosages. Information at farm level would be desirable. In principle, it would be possible to register the dosage of organic manure applied at field level but this does require an increase in the amount of data entered as well as changes to the ANCA. Furthermore, it is difficult to check this data at field level, certainly for fields that are merged or split up over time.

Management of the field relates to a) the cultivation of green manure, b) the possible removal of crop residues and c) in the case of grassland, whether or not the land is reseeded and the amount of grazing. The cultivation of green manure and the production of this manure is not currently recorded in monitoring systems such as the ANCA. The cultivation of a green manure can be recorded in a simple yes/no report, but the amount of organic matter to be recorded is difficult to estimate and almost impossible to verify. The removal of crop residues is especially important with cereal crops, as straw is often used in stalls and added to manure to make it stackable. This means that in addition to the uncertainty in the calculations due, among other things, to the estimation of crop residue recycling, the input data that is used is not always verifiable. This is particularly important if the straw is removed from the farm. If it is used within the farm, it is regarded as an internal item. This is easy to register.

It is also easy to register the reseeded of grassland at farm level. However, this is an observation carried out by the dairy farmer himself and is not therefore checked. Fields are often reseeded by agricultural contractors and this activity could therefore be registered via their work slips. Grazing is already registered in the ANCA, although at farm level. For more accurate calculations, it should also be recorded at field level, preferably with the type and duration of grazing. An initial step would be to specify which fields are used for grazing so that a better estimation can be made of the amount of pasture manure per field.

5.2.5 Sensitivity analysis

The model calculations of changes in the amounts of soil organic matter (and therefore carbon) are based on measurements of the supply and quality of that organic matter and on measurements of the decomposition of that matter in field tests and pot tests. A number of factors have a clear influence on the extent of the decomposition and therefore on the final carbon balance: the net change in carbon stock. The standard situation in the calculations shown in Figure 19 is a net increase of 0.35 tonnes of carbon per hectare per year. There are three factors that have a strong influence on the final carbon balance: the availability of moisture, the depth over which the organic matter is calculated and the amount of crop residues brought in from grass. In a dry year, the decomposition of organic matter is strongly inhibited and a greater amount of organic matter remains. By contrast, in a wet year, more organic matter is broken down than supplied. This makes the annual decomposition process very sensitive to the availability of moisture in the soil. A calculation over a smaller depth (20 cm compared to 25 cm) leads to a stronger increase than a calculation over a greater depth (30 cm compared to 25 cm). At a greater depth, there is a larger volume where decomposition can take place. The supply of crop residues from grass also has a significant influence. A 10% increase in the supply of grass (more than 500 kg of carbon) leads to a stronger increase of 130 kg of carbon in the carbon balance.

A slightly higher or lower organic matter content has a limited effect on the final carbon balance. A higher organic matter content leads to a lower value for the carbon balance. This is because the carbon present is also subject to decomposition. Manure that is richer in carbon (a higher C/N ratio) results in a higher value for the carbon balance. While the clay content of the soil does have some influence, a 20% increase or decrease in clay content only results in a difference of 20 to 30 kg of carbon per hectare per year in the carbon balance.

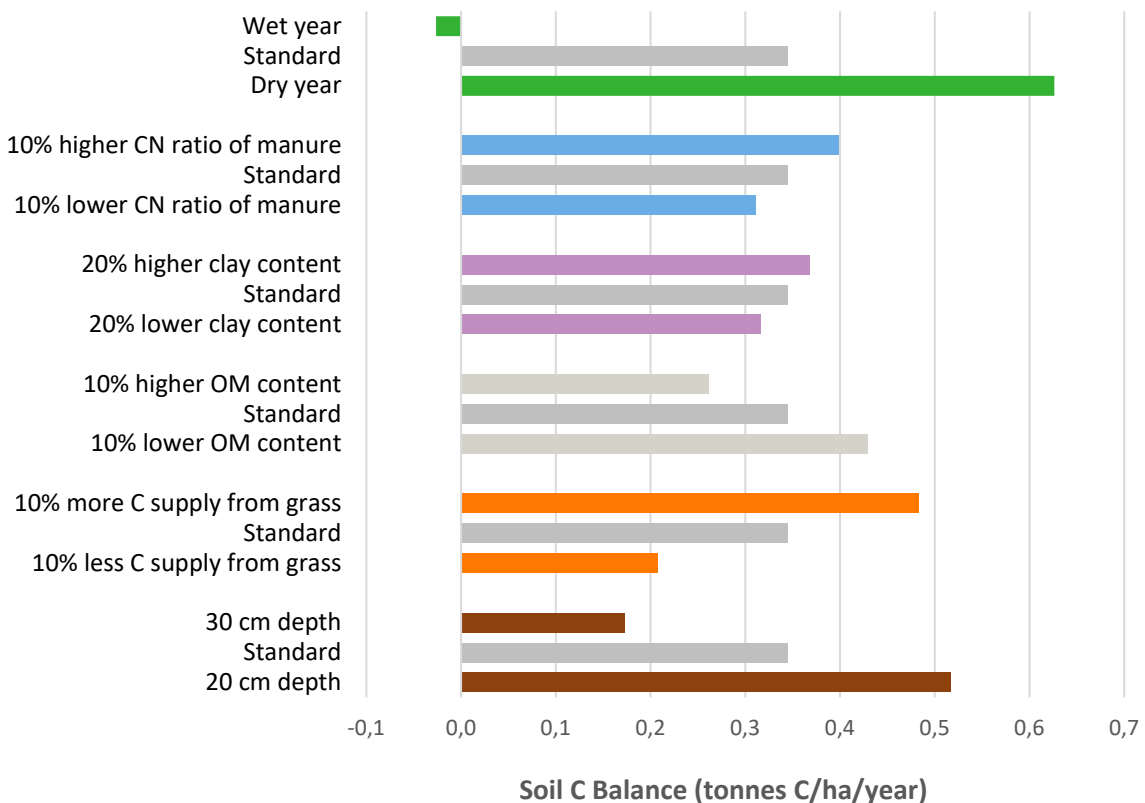


Figure 19 Results of the sensitivity analysis for a number of important input parameters. Results are based on the average soil carbon balance of all 37 participating dairy farms.

5.2.6 Validation and verification

A model-based approach will also require final verification. This could be carried out on the basis of the long-term monitoring of soil carbon, possibly at national level. This could be used to validate the models as well as to verify the trend in soil carbon for the nationally aggregated results of all farmers combined. The question remains as to what type of monitoring should be used for verification purposes. There are various systems available:

- Practical data: grassland and arable land fields are usually sampled once every four years. Often, some of the fields are analysed every year. This means that complete verification is not possible every year. Moreover, verification is made difficult by the variation in organic matter contents between years (as found on the test fields, Ehlert et al., 2018).
- National soil carbon monitoring: within the framework of the climate budget, monitoring was conducted on a national scale in 2018, whereby 1,100 sites used to validate the national soil map (national sample survey of soil map units, LSK) for the period 1995-2000 were re-sampled and analysed for soil carbon and organic matter contents (Tol-Leenders et al., 2019). The preliminary results show that the total organic matter stock in the Netherlands has decreased by a significant difference. This decrease is caused by a reduction in peat soils and peaty soils. This result is also consistent with the new soil map published in 2014 which shows that large areas of peat soils and peaty soils have disappeared. If we only look at mineral soils, there is a small, insignificant increase in organic matter content. However, there is a considerable degree of uncertainty with regard to these results. Based on the current number of sampled sites, it is highly unlikely that a difference in the order of magnitude of the required target will be established. This is partly because of uncertainties in the analysis due to differences in methodology between both samples and error margins in the measurements. It may be possible to demonstrate this with more extensive monitoring that includes a greater number of locations.

There may well be more possibilities for measurements and validation in future. Various new sensors have recently been brought onto the market, which can be used to determine soil characteristics on site based on near infrared (NIR) or mid infrared (MIR) technology. In combination with precision agriculture, these sensors could also be installed on tractors and used to map out the organic matter content for a field. Since many measurements could then be carried out, it would be possible to determine a more accurate average organic matter content for a field and thus make it suitable for monitoring. Further development would, however, be needed when it comes to sensors, their use on grassland and questions on how to deal with varying moisture content, differences in ploughing depth and soil structure and the presence of plant debris.

Another possibility is via remote sensing, in which use is made of satellites. The EU is investing heavily in new sensors and applications via the Copernicus programme and these may also be useful for monitoring soil carbon. Direct monitoring of soil carbon does not appear to be possible yet since this would only be possible for soils without crop cover. Remote sensing also offers the possibility of checking whether farmers apply certain measures. It would then be possible to properly monitor measures such as applying catch crops and green manure and not ploughing up grassland. The current version of the *Groenmonitor* (Green monitor)⁷ is already partly suitable for this purpose.

5.3 Perspective for action for dairy farmers

5.3.1 The effect of changes in soil carbon on the footprint for milk

It is important to know to what extent changes in organic matter content affect the footprint for milk. Even if the effects on a litre of milk are only small, an effect that occurs in 14 billion kg of milk (roughly the milk production of the Netherlands in 2019) could be worthwhile on a national scale.

The calculations in Section 4 show that the difference for this group of dairy farmers on mineral soils is a reduction in footprint by about 24 grams of CO₂-eq per kg of milk. This amounts to 2% for an average footprint of 1,190 grams of CO₂-eq per kg of milk. Although this may not seem like much, the

⁷ <http://www.groenmonitor.nl/>

experiences within the study groups of dairy farmers show that a reduction in the footprint for milk requires several small steps. There have been no measures as yet that immediately reduce the footprint by several hundred grams. Furthermore, there is currently no specific focus on measures to increase carbon sequestration which means that there is greater potential for reducing the footprint. Based on the estimation that 88% (based on data from the FrieslandCampina companies) of the milk is produced on mineral soils, it would still be an effect of 0.24 Mt of CO₂ per year that could be achieved now without specific measures.

The effect is stronger on peat soils where the decomposition of peat increases the footprint of milk by an average of 260 grams of CO₂-eq per kg of milk, based on the limited collection of dairy farms on peat soils and peaty soils. There is no additional sequestration on peat soils but rather a deceleration in decomposition. Vellinga et al. (2018) calculate an achievable reduction of 2 Mt per year in the long term through a combination of measures such as raising groundwater levels, underwater drainage and the removal of peat soils from agricultural production. If a quarter of this can be achieved in the short term, this would represent 0.5 Mt of CO₂-eq per year.

Although the above calculations simply provide an indication, they do show that determining the development of organic matter contents in mineral soils and the decomposition of peat in organic soils is important for both the sector and for the Netherlands as a whole. While this is not news, it is an important observation for the dairy sector and possibly justifies the perceived need to monitor developments in organic matter contents more closely.

5.3.2 Soil carbon measures for the dairy farming sector

Relevant soil carbon measures for the dairy farming sector can be found in Table 12. Further information about these measures can be found in the *Handleiding voor goed koolstofbeheer* (Manual for good carbon management) (Staps et al., 2017) and, specifically for the dairy farming sector, in the *Carbon Valley-rapport* (Carbon Valley report) (van Eekeren et al., 2018).

Table 12 *Relevant soil carbon measures for the dairy farming sector.*

Measure	Description	Simulation in RothC possible
Optimum land use	Land use that is optimised for commercial interests and for soil carbon consists of 60% permanent grassland, 20% maize and 20% clover, with the latter two included in a three-year rotation. The three year maximum enables the clover to become well established and loss of nitrogen is limited after the land is ploughed up.	Yes
Minimising grassland renewal	Ploughing up grassland for grassland renewal or conversion to arable land speeds up the decomposition of carbon. In addition, large amounts of nitrogen are released, which can lead to high emissions of nitrous oxide. Increasing the age of grassland by postponing grassland renewal is an effective measure for building up organic matter.	Yes
No-till farming	No-till farming disrupts the soil less than ploughing which means that less organic matter is broken down. This measure is particularly effective when there is already a significant amount of carbon in the soil but is less effective as a build-up measure.	Yes, with modification
Manure processing and higher dosage of solid fraction	The application of solid manure, the solid fractions from manure separation or carbon-rich fertilisers from manure processing leads to more carbon in the soil when compared to liquid manure.	Yes
Application of compost	Compost has a higher C/N ratio and is less easily broken down and so contributes to the build up of carbon in the soil.	Yes
Green manure/catch crops	Growing and incorporating catch crops/green manure after or between the main crop can increase the organic matter content in the soil. It can also limit nitrogen losses. Sow as soon as possible. Opt in the long term for fodder crops or other crops that provide sufficient space for green manure at the end of the growing season.	Yes
Grass undersown in maize	Grass undersown in maize also serves as a catch crop but as it is undersown, it is far more developed when the maize is harvested, which makes it more effective for the absorption of nitrogen and the sequestration of carbon in the soil.	Yes, but more info about carbon supply required
Deeper rooted grass types	Deeper rooted grass types can contribute to carbon sequestration in the subsoil; up to now, distribution has mainly focused on biomass above ground, but attention is now being paid to grass types that have more underground biomass and which therefore make a greater contribution to the build up of organic matter.	Not yet, requires further research
Herb-rich grassland	A herb-rich grassland can include types that grow deeper roots and have more underground biomass, contributing to extra carbon sequestration. The final contribution greatly depends on the composition and can have either a negative or positive effect.	Not yet, requires further research
More grazing	With grazing, there are more grazing losses (due to trampling) which leads to greater supply of crop residues to the soil. However, scientific studies do not yet show a clear effect.	Not yet, requires further research
Agroforestry	Agroforestry is the combination of arable crops or grassland with trees or bushes. The combination of different crops can lead to ecological and economic interactions that produce an effect that is greater than the sum of the monocrops. Extra carbon sequestration can take place in both the biomass and in the deeper subsoil due to the deeper rooted trees.	Not yet, requires further research

There is sufficient perspective for action for farmers to stimulate carbon sequestration in view of the possible measures as presented in Table 12. In calculating this, management-related data is required, such as the use of organic fertilisers, the reseeded of grassland and the cultivation of green manure. The major advantage of calculating organic matter development is that the effects of most measures are taken into account and made visible each year and an important point is that they can be recorded reliably. Some of the measures, such as herb-rich grassland, deeper rooted grass types, more grazing and agroforestry require multi-year experimental field research in order to determine proper quantification of the contribution to carbon sequestration. Some of the other measures, such as greater use of processed manure – including solid manure – and adding straw to manure application compost, result in the movement of the organic matter. This organic matter would otherwise be used

elsewhere and lead to an increase in soil organic matter. The greatest gains are therefore to be found in measures that prevent or significantly inhibit the decomposition of organic matter and in the production of extra organic materials. In particular, these are the measures that relate to optimisation of land use, minimisation of grassland renewal and maximum use of green manure and catch crops. Extra sequestration of carbon is often not possible in mineral soils that already have a high organic matter content and it is especially important to maintain the existing carbon stock. In this case, an important measure is to retain permanent grassland (minimise grassland renewal).

An alternative is to use pre-defined values for soil carbon sequestration for various measures. Based on literature and/or model results, a fixed value can be determined per measure. For example, the measure to leave straw behind on the field leads to a carbon sequestration of 500 kg C/ha/year. A distinction could also be made according to soil type and/or current organic matter class. The advantage of this type of system is that it is easier to check and farmers are already familiar with fixed values in the manure policy. The disadvantage is that it is less farm-specific and perhaps does less justice to the actual carbon sequestration given that average values are used. In addition, there is a need for greater flexibility so that more payments can be based on results (actual soil carbon sequestration) instead of payments based on means-oriented regulations.

5.4 Recommendations for setting up a monitoring system

Based on the data collected from the participating farms, the literature review and the model calculations, it can be concluded that a monitoring system at field and farm level is technically feasible in the form of a combination of measures, registration of activities and calculations of the changes in organic matter quantities. This approach is also in line with a recently proposed strategy for monitoring, reporting and verifying soil carbon (Smith et al., 2020).

To fully realise the potential for carbon sequestration in soils, three parallel tracks are needed (see also Figure 20):

- Calculating the change in organic matter stock that is recorded under agricultural soils
- Monitoring the organic matter contents via measurements on fields, to validate the calculations
- Linking the results of the validated calculations to the national Pollutant Release and Transfer Register for the purpose of reporting under the UNFCCC, EU and Dutch Climate Agreement.

These will be worked out in more detail individually.

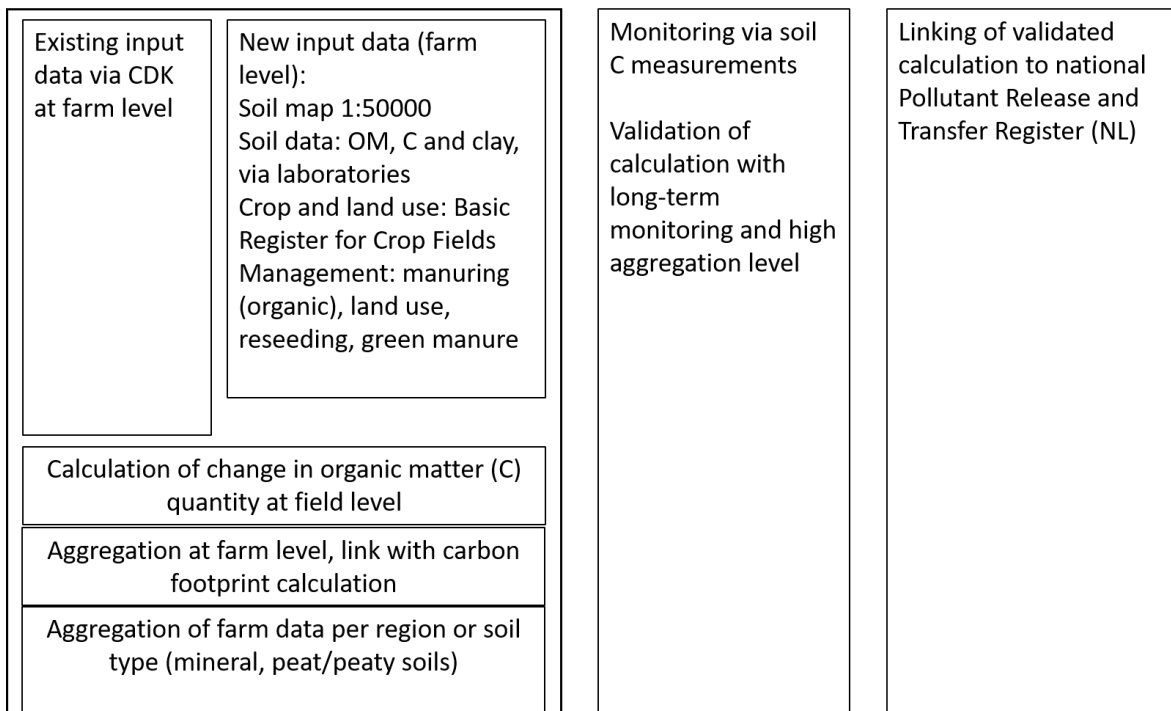


Figure 20 The three parallel tracks for monitoring and registering the sequestration of organic matter (and carbon) in agricultural soils: farm calculations, validation via soil carbon measurements and link/coordination with the procedure in the national Pollutant Release and Transfer Register (CDK stands for 'Centrale Database Kringloopwijzer' (ANCA Central Database)).

5.4.1 Calculating the change in organic matter stock

The monitoring system requires data, some of which is already collected in the ANCA Central Database (CDK). This data mainly relates to manure applications and the levels of organic matter and minerals in manure. This is good quality data that is supplied automatically. Field data about land use and crops is also available from the *Basis Registratie Percelen* (Basic register for crop fields) and can be linked. It has also become possible recently to link the soil data from soil analyses carried out by three soil laboratories with the ANCA. Soil data, such as organic matter content, could therefore also be included in the calculations automatically.

The data that is not yet registered mainly concerns information relating to measures and soil management at farm and field level. A large part of this data cannot be collected automatically as it relates to activities that do not involve automatically registered product flows, such as whether or not grassland is ploughed up or green manure is sown. It is also more difficult to check this data. An investigation should be carried out into whether any of this data could in some way be included in the ANCA via automatic or other type of registration. The data that cannot be registered automatically would therefore require random checks.

5.4.2 Validation of the calculations

The uncertainty of the proposed monitoring system is too great to assess farms individually on the change in soil organic matter quantities. However, it does provide dairy farmers with useful feedback on the effect of the measures taken at the farm. On a larger scale, the average results can be used to assess the changes in organic matter quantities in the soil. The variation within farms and between farms shows that a simple aggregation of data (lumping everything together) does little to improve accuracy. Within farms, the variation is smaller. This indicates that a smart aggregation of data could solve the problem of few observations without greatly increasing the distribution due to spatial variation. This approach requires further elaboration of the smart combination of soil information, farm information, land use and management and the systematic application of statistical methods.

In the beginning, it will be necessary to verify the monitoring system every few years in order to create a reliable system. On the one hand, it may be possible to use the large number of analyses of agricultural fields carried out by soil laboratories for this purpose and, on the other hand, it may be possible to use data from national monitoring, such as the LSK/CC-NL, which may be repeated in future. The results of the verification can indicate whether calculations and observations are still in line with one another. At the same time, measuring techniques could be used that make it possible to perform large numbers of observations quickly, as described in Section 5.2.

5.4.3 Alignment with the national Pollutant Release and Transfer Register

The project described in this report looked at the possibilities for monitoring from the perspective of soil science and agriculture: what farm data is available and what happens on farms that has an influence on the change in organic matter quantities in agricultural soils? Reference has been made to the need to collect reliable data and to scale up this data so that reliable claims can be made at levels higher than the farm (i.e. regional to national).

The development of the monitoring system must be linked to the activities of the national Pollutant Release and Transfer Register. This requires further modification of the procedure for calculating the LULUCF emissions for this national register. The requirements for reliable monitoring and the procedure in the organic matter calculation must comply with IPCC and UNFCCC guidelines.

5.4.4 Recommendations

Based on the project, the following recommendations have been drawn up. Make sure that the monitoring system, the validation and the integration with the national Pollutant Release and Transfer Register are developed in parallel.

As far as the monitoring is concerned, set up a pilot project in which the monitoring system is configured as above. This entails:

- a. incorporating the data collection in the ANCA
- b. incorporating calculation of the soil carbon balance in the ANCA, and
- c. providing dairy farmers with feedback on the results.

On the one hand, this pilot project provides a learning process for the calculation method, but it is also beneficial for dairy farmers to register the required data and obtain insight into the effect of their land use and land management practices.

As regards validation:

- a. Analyse the practical data available from organic matter measurements combined with soil and land use data in conjunction with soil analyses from laboratories. A statistical analysis of this must provide insight into the appropriate method of data aggregation.
- b. Explore the possibilities for a uniform depth for both grassland and arable land for the purpose of determining organic matter content in agricultural soils.
- c. Make sure that historical land use data is recorded per field, in combination with the recording of historical data on organic matter.
- d. Work on developing measurement techniques that make it possible to use soil analyses with a high frequency (at least once a year), together with detailed spatial information. This process can be linked to the development of precision agriculture.
- e. Study the relationship between organic matter and its carbon content and soil density on a regular basis in order to improve estimations of the amount of carbon sequestered.
- f. Make sure that new insights in monitoring and validation are incorporated in the monitoring strategy and adapt calculation rules in the soil carbon model where necessary.

As regards the link with the national Pollutant Release and Transfer Register:

- g. Submit the results of this study to the LULUCF working group that is concerned with the emissions and sequestration of carbon for the national Pollutant Release and Transfer Register.
- h. Involve the working group for emissions registration in the monitoring and validation activities. Methods to be developed must be discussed and agreed upon beforehand so that work is based on the same methods and assumptions and practical data can also be used for the national Pollutant Release and Transfer Register.

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Annex 1 Summary of NIR method for changes in soil carbon stock

Below is a brief summary of two detailed documentation reports:

- Arets, E.J.M.M.; van der Kolk, J.W.H; Hengeveld, G.M.; Lesschen, J.P.; Kramer, H.; Kuikman, P.J. & Schelhaas, M.J. (2019) Greenhouse gas reporting of the LULUCF sector in the Netherlands. Methodological background, update 2019
- Lesschen, J. P., H. I. M. Heesman, J. P. Mol-Dijkstra, A. M. van Doorn, E. Verkaik, I. J. J. van den Wyngaert and P. J. Kuikman. (2012). *Mogelijkheden voor koolstofvastlegging in de Nederlandse landbouw en natuur*. Alterra report 2396. Alterra Wageningen UR, Wageningen, The Netherlands. <http://edepot.wur.nl/247683>.

Both reports are an elaboration of the standardised reporting as defined by the IPCC:

- IPCC. (2003). Good Practice Guidance for Land Use, Land-Use Change and Forestry. IPCC National Greenhouse Gas Inventories Programme. Published by the Institute for Global Environmental Strategies (IGES), Kanagawa, Japan.
- IPCC. (2006a). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1, General Guidance and Reporting. IPCC National Greenhouse Gas Inventories Programme. Published by the Institute for Global Environmental Strategies (IGES), Kanagawa, Japan.
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- IPCC. (2014). 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol. In T. Hiraishi, Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G., editor. IPCC, Switzerland.

The quantities of carbon in and on soils is calculated on the basis of:

- Land-use type
- Carbon present in above-ground and underground biomass and organic matter in soils

In this way, a carbon amount per hectare is determined per combination of land-use type and soil type. This is multiplied by the number of hectares that are present in the Netherlands for each combination. The emissions from land use and any changes associated with it are only based on areas and not on activities.

For land-use type, IPCC distinguishes between the following categories:

- Forest land
- Cropland
- Grassland
- Wetlands
- Settlements
- Other land

The categories 'grassland' and 'cropland' are especially relevant for dairy farming in the Netherlands. The main category 'grassland' encompasses all grassland for agricultural use, recreation and nature, all nature areas that do not fall under the definition of grassland and lastly, all orchards with grass undergrowth.

The carbon stocks of grassland are monitored following the Tier 1/2 approach, which means that fixed quantities of carbon are assumed regardless of type of management (mowing, grazing, fertilisation, etc.). The amount of organic carbon in agricultural soils is determined using the LSK measurement, whereby the amount of organic matter is determined at 1400 locations over five different layers. On this basis, the amount of carbon is determined in the organic matter found in the top 30 cm layer. Lesschen et al. (2012) have subdivided this further based on the LSK determination and data on land use into carbon stocks per land use/soil type combination. These are shown in Figure A1.1.

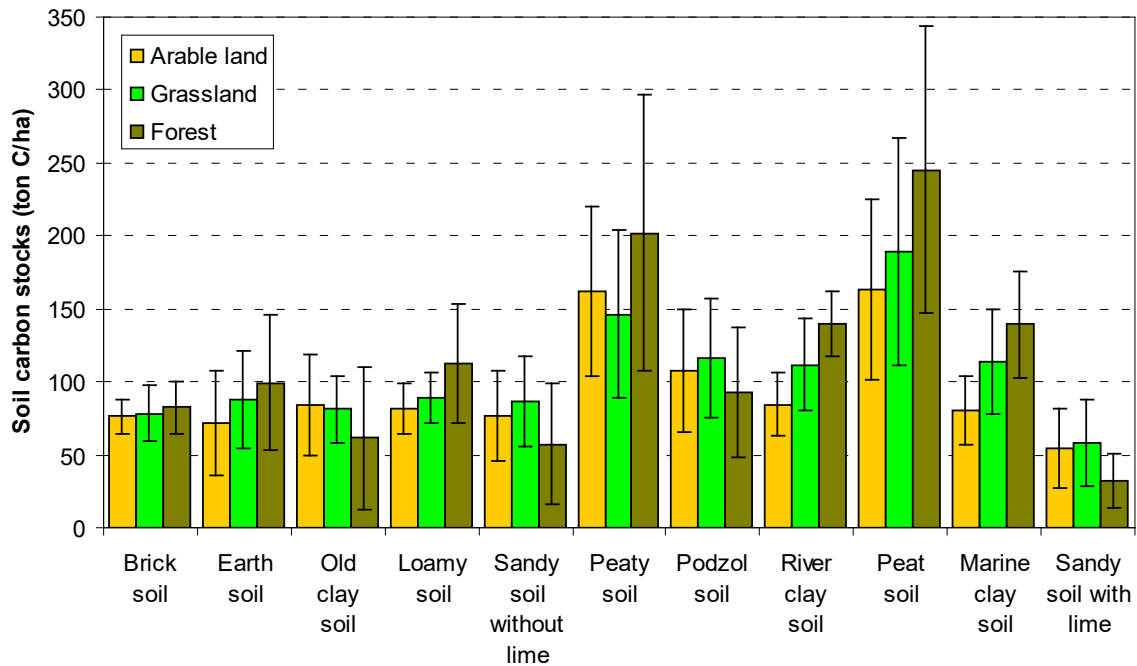


Figure A1.1 Average soil carbon quantities per combination of land use and soil type. The error bars show the standard deviation (Lesschen et al., 2012).

Change in carbon quantities in the Netherlands

Annual records are kept of the land use in the Netherlands and the changes made to it. An overview of this information is created in the 'land use change matrix' and all changes in land use are reported. This matrix is used to perform an annual calculation of carbon quantities. If a field switches from one type of land use to another, the change in carbon quantity is spread over twenty years. The report from Arets et al. (2019) provides a detailed table showing the annual changes.

Organic soils

Peat soils are reported separately as a large proportion of the soil consists of organic matter. In the Dutch report, peat soils have a peat layer of at least 40 cm within the 0-120 cm layer, while peaty soils have a peat layer of 5-40 cm within the 0-80 cm soil layer. The calculation of the decrease in organic matter and carbon is described in Section 3 of the report. The decomposition of peat soils is determined based on the drop in ground level and averages 19 tonnes of CO₂ per hectare per year.

Annex 2 Calibration of crop residues

A2.1 Calibration of crop residues on grassland

The contribution of crop residues on permanent grassland was calibrated using three data sets (Table A2.1).

Mowing test (Schils et al., 2004)

The test field was a newly sown field of permanent grassland with twenty treatments that consisted of a combination of crop (grass or grass/clover), nitrogen release (0 to 400 kg N/ha/year) and phosphate release (0 to 105 kg P/ha/year). The test field was not treated with animal manure and was mown only. At the start and end of the study, the soil contained 79 t C/ha on average. Afterwards, the carbon stock varied from 77.5 to 80.5 t/ha, but there was no clear effect from the treatments.

Yearling test (Van Middelkoop et al., 2016)

The yearling test is an ongoing study that is being carried out on three sites. In 1997, six treatments were applied to permanent grassland, consisting of combinations of two nitrogen surpluses (180 and 300 kg N/ha) and three phosphate surpluses (0, 20 en 40 kg P₂O₅/ha). The test fields are mown and grazed by yearlings alternately and are treated with liquid cattle manure in addition to artificial fertiliser. On these pasture fields, the carbon stock has changed from 0.5 to -0.6 t C/ha/year. In 2002, the test was expanded to include a mowing field for mining phosphate, with a nitrogen surplus of 300 kg N/ha and a phosphate surplus of -100 kg P₂O₅/ha. The carbon stock on these mowing fields changed from 0.3 to -0.8 t C/ha/years.

Ossekampen (Korevaar & Geerts, 2015)

The test field consists of six grazed and sixteen mown fields of species-rich grassland with a varied, highly diverse supply of nitrogen, phosphate and potash. Only the mown fields were used for this study. On average, the carbon stock decreased from 94 to 84 t C/ha. The end stock varied from 60 to 116 t C/ha.

Table A2.1 Overview of data sets for calibration of permanent grassland.

Name	Ground type	Usage	Period	Year	Carbon (t/ha)		Sequestration (t C/ha/year)
					Start	End	
Mowing test, Lelystad	clay	mowing	1994 - 1998	5	79	79	0.0
Yearling test, Lelystad	clay	mowing	2002 - 2015	14	106	100	-0.4
		grazing	1997 - 2015	19	109	118	0.5
Yearling test, Heino	sand	mowing	2002 - 2012	11	80	71	-0.8
		grazing	1997 - 2012	16	76	67	-0.6
Yearling test, Cranendonck	sand	mowing	2002 - 2013	12	67	70	0.3
		grazing	1997 - 2013	17	72	72	0.0
Ossekampen, Wageningen	clay	mowing	1958 - 2016	59	94	89	-0.1

The carbon supply from crop residues has been calibrated for each treatment within each data set, taking into account the clay content of the soil, the average weather during the period concerned and the carbon supply from animal manure (manure application and excretion in the pasture by grazing cattle). The results show an average carbon supply from crop residues of 5.1 t C/ha for treatments that are exclusively mown without supply of animal manure and of 3.7 t C/ha for treatments that are

also grazed and fertilised with animal manure. The supply of carbon calculated from crop residues ranges from -0.5 to 7,6 t C/ha (B2.1).

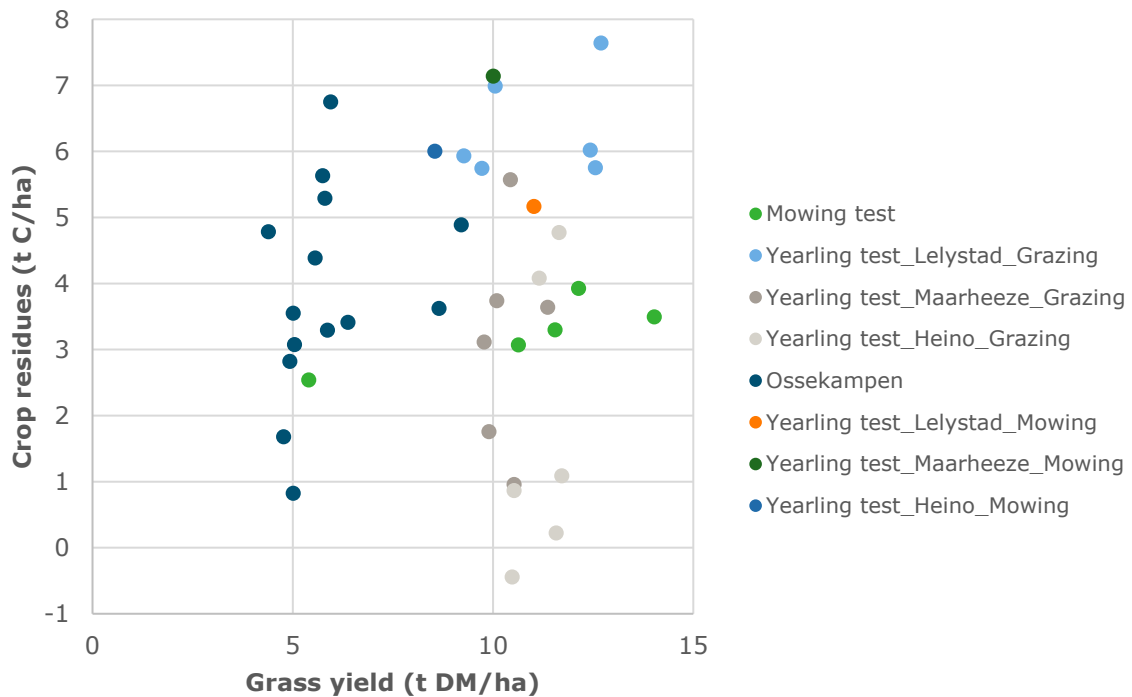


Figure A2.1 Calibrated carbon supply from crop residues in relation to the grass yield above ground.

A2.2 Calibration of maize crop residues

According to the *Handboek Bodem & Bemesting* (Soil & Fertilisation Handbook)⁸, the contribution of green maize crop residues is 2000 kg of organic matter per hectare, which corresponds to one tonne of carbon per hectare. We assessed this value using three data sets (Table A2.2).

Wintergewassen (Schröder et al., 1992 and Van Dijk et al., 1995)

In a seven-year field test conducted at the Aver Heino test farm, green maize was cultivated continuously without winter crop (fallow), with rye stubble or with grass undersowing. The three main treatments were combined with a fertilisation treatment (0 or 35 tonnes of thin cattle manure/ha). Without winter crop, the carbon stock decreased by 0.6 to 0.8 tonnes/ha/year, regardless of whether or not manure was applied. Winter crops had no effect on the carbon stock on unmanured fields. Only the combination of winter crops with manure resulted in a slight increase in carbon stock (+0.1 tonnes of C/ha/year). The carbon supply from the winter crops was determined to be 1.1 tonnes of C/ha (Schröder et al., 1997).

Mest_Maarheeze (Schröder et al., 1985)

On the test farm at Maarheeze, maize was cultivated continuously for seven years with an annual dosage of thin cattle manure, rising from 50 to 300 tonnes/ha/year. The carbon stock increased annually by 0.6 tonnes/ha with the lowest manure application. As more manure was applied, the carbon stock increased further, up to 2.6 tonnes/ha/year with 300 tonnes of manure per hectare.

⁸ <https://www.handboekbodemenbemesting.nl/nl/handboekbodemenbemesting/Handeling/Organische-stofbeheer/Organische-stof/Kengetallen-organische-stof.htm>

Mest_Heino (Schröder et al., 1985)

Over a period of ten years, maize was cultivated alternatively with grass at the Aver Heino test farm. The crop rotation entailed three years of maize followed by one year of grass. The maize was fertilised every year with 0 to 300 tonnes of thin cattle manure per hectare. The grass was not fertilised. Without fertilisation, the carbon stock increased annually by 0.6 tonnes/ha with the lowest manure application. With manure dosages above 200 tonnes/ha, the stock increased by more than 1.5 tonnes/ha. For the one-year grassland, a carbon supply of 5.1 tonnes/ha was determined.

Table A2.2 Overview of data sets for validation of maize.

Name	Soil	Period	Treatments	Carbon (t/ha)		Sequestration (t C/ha/year)
				Start	End	
Continuous maize						
Winter crops, Heino	Sand	1988-1994	0 tonnes of TCM/ha Fallow land	53	49	-0.6
			35 tonnes of TCM/ha Fallow land	53	47	-0.8
			0 tonnes of TCM/ha Grass undersowing	53	47	-0.8
			35 tonnes of TCM/ha Grass undersowing	53	54	0.1
			0 tonnes of TCM/ha Rye stubble	53	48	-0.7
			35 tonnes of TCM/ha Rye stubble	53	54	0.1
Manure, Maarheeze	Sand	1976 - 1982	50 tonnes of TCM/ha	48	52	0.6
			100 tonnes of TCM/ha	48	55	0.9
			150 tonnes of TCM/ha	47	63	2.3
			200 tonnes of TCM/ha	50	64	2.0
			250 tonnes of TCM/ha	46	64	2.5
			300 tonnes of TCM/ha	48	66	2.6
Maize-Grass (3:1)						
Manure, Heino	Sand	1972 - 1982	0 tonnes of TCM/ha	73	80	0.6
			50 tonnes of TCM/ha	73	83	0.9
			100 tonnes of TCM/ha	73	89	1.4
			150 tonnes of TCM/ha	73	86	1.2
			200 tonnes of TCM/ha	73	94	1.8
			250 tonnes of TCM/ha	73	90	1.5
			300 tonnes of TCM/ha	73	91	1.6

The simulations show varying results. The model outcomes for carbon build-up with continuous maize with relatively low manure dosages show a reasonable similarity with the measurements observed (Figure A2.2). However, the model overestimates the influence of higher dosages of manure. The decomposition rate of the thin cattle manure (TCM) might be faster than the standard farm yard manure used in the model. The simulation of a 3:1 maize-grass crop rotation shows a similar effect: with increasing dosages of manure, the simulated carbon stock increases faster than the measured stock. Without the application of manure, the simulated stock is lower than the measured value. This could indicate that the intermediate year with grass supplies more carbon than is currently assumed (5.1 tonnes C/ha).

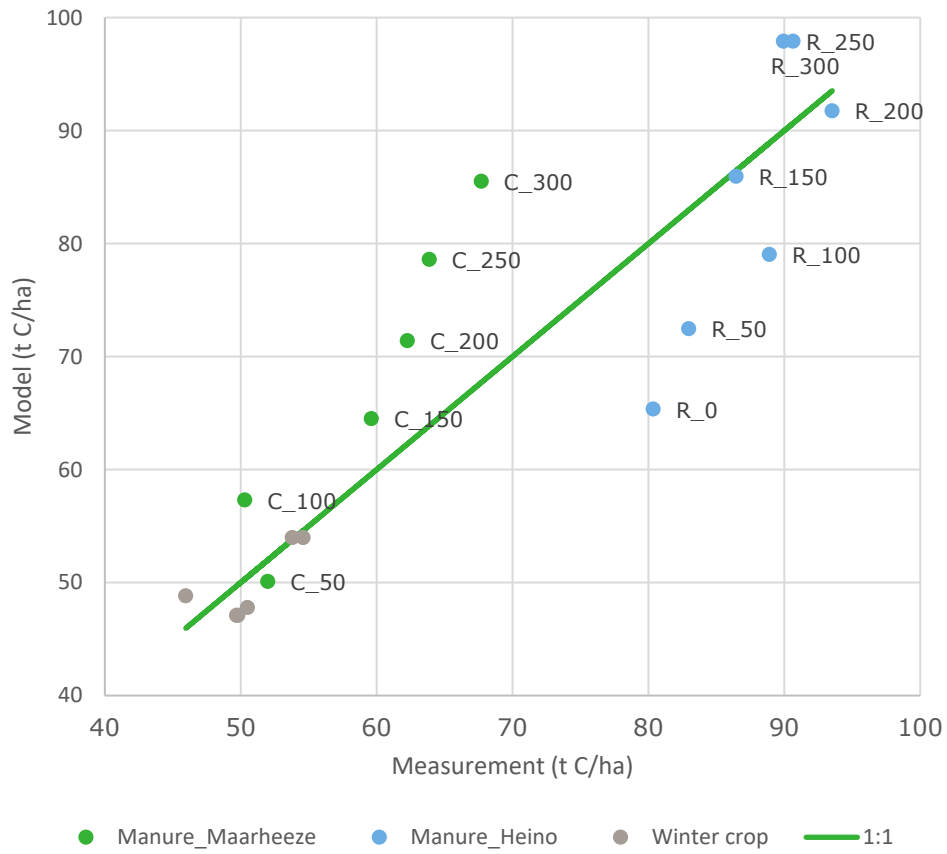


Figure A2.2 Soil carbon stock at the end of the test according to the RothC model in relation to the carbon stock observed. The label specifies the manure dosage.

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