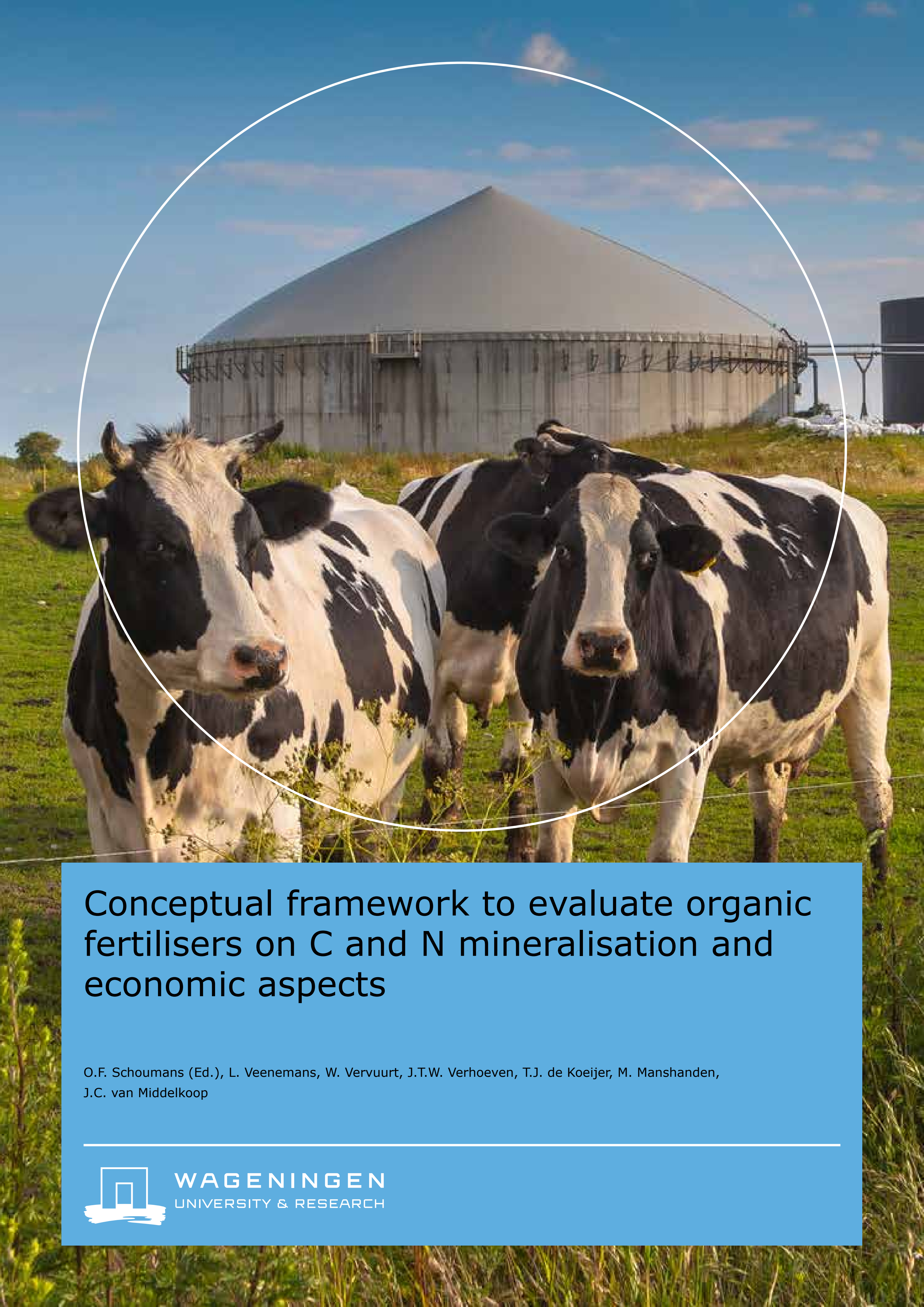

Conceptual framework to evaluate organic fertilisers on C and N mineralisation and economic aspects

O.F. Schoumans (Ed.), L. Veenemans, W. Vervuurt, J.T.W. Verhoeven, T.J. de Koeijer, M. Manshanden,
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Conceptual framework to evaluate organic fertilisers on C and N mineralisation and economic aspects

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Organische stof wordt algemeen beschouwd als een belangrijke factor om de kwaliteit van landbouwgrond te handhaven en te verbeteren. In dit rapport wordt een eenvoudige methodiek gepresenteerd om organische bemestingsproducten te evalueren ten aanzien van afbraak en koolstofopslag in de bodem. Aan de hand van uitgevoerde incubatieproeven en laboratorium analyses zijn de concepten getest en gekalibreerd qua impact op de bodemkwaliteit met betrekking tot netto C en N mineralisatie. Tevens zijn de economische aspecten nader belicht. De methodiek werkt goed voor koolstof maar de stikstofmineralisatie vraagt nog aandacht.

Organic matter is widely regarded as an important factor in maintaining and improving soil quality of agricultural land. This report presents a simple methodology to evaluate organic fertiliser products with respect to degradation and carbon storage in soil. Based on incubation trials and laboratory analyses conducted, the concepts were tested and calibrated in terms of their impact on soil quality with respect to net C and N mineralization. The economic aspects were also discussed. The methodology works well for carbon but nitrogen mineralization still requires attention.

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Preface

Assessment of the value of organic fertilisers in terms of soil quality, agronomy, environment and human health is complex, but needs more attention because of valuable biomass streams for food production will come on the market as a result of Europe's Circular Economy strategy. Therefore, Wageningen Research has started a project called: "Development of an evaluation framework for organic fertilisers". In the first phase (2019), the activities were focused on setting up a framework for the agronomic, environmental and economic evaluation, including the determination of important parameters and their measurement protocol. In the second phase (2020-2022) the approaches were tested, evaluated and used for calibration purposes. In this report the second phase is reported regarding the agronomic and economic aspects.

This study was carried out by Wageningen Environmental Research, Wageningen Plant Research, Wageningen Livestock Research, Wageningen Economic Research, and Wageningen Food Safety Research. The research was funded by the Dutch Ministry of Agriculture, Nature and Food Quality (project number KB-34-010-002).

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Summary

Different organic materials, like crop-residues, manure, co-digestates and compost are used to maintain or improve the organic matter content of the soil and the associated soil quality. Especially with the increasing variety in types of organic materials that become available for agricultural use, it is important to know the fate of organic fertilising products in the soil in terms of mineralisation (carbon (C) as well as nitrogen (N)) and long-term storage of carbon in the soil. Both aspects are relevant from an agronomic as well as from an environmental point of view.

The humification coefficient and net organic nitrogen mineralisation of organic fertilisers are commonly determined with incubation experiments. These experiments are labour intensive and time consuming, and therefore, alternative simple approaches which can predict carbon and nitrogen turnover for the short and long term would be very valuable from a practical point of view. The development and testing of such an approach was the main aim of this study.

In total 16 different types of organic products, which differ in carbon decomposition and nitrogen release (mineralisation / immobilisation), were used in incubation experiments with a sandy soil and a clay soil to measure carbon and nitrogen mineralisation. Additionally, these materials were analysed for various parameters that might help to explain the differences in the mineralisation rates of the products. The RothC model approach was used to predict C-mineralisation of the products (in both soils) in order to determine for each of the products the organic pool fraction of easily decomposable carbon material (f_{DPM}) and the organic pool fraction of resistant carbon material (f_{RPM}) where $f_{DPM} + f_{RPM}=1$.

The organic fertilisers highly vary in distribution of the two organic pools. Products with a low C measured mineralisation are described by the model as having a low fraction of decomposable carbon, while products with a high C mineralisation have a high fraction of decomposable carbon. The two-pool model approach was satisfying in predicting the measured C-mineralisation of the products in both soils (humification coefficient). Consequently, based on the differences in organic pool fractions of the organic fertilisers, the long term effect of the organic products on carbon storage in the soil can be predicted.

Furthermore, the easily decomposable fractions of the organic fertilisers are highly correlated (R^2-adj. =96.5) with a combination of the following product characteristics: the amount of total nitrogen of the product, the respiration measured after adding the product to alanine (a MicroResp parameter) and the size of fraction F1 of the product (a pyrolysis parameter). Modelling the carbon mineralisation based on the predicted decomposable carbon fraction calculated from the correlation with these three analyses gave very similar results compared to the mineralisation predicted based on the decomposable fraction as was found with calibration on incubation results. However, a follow-up validation study indicates that the MicroResp method does not give robust results. Therefore, correlations with other parameters are being investigated.

Therefore, by measuring these three organic product characteristics, enabling the determination of the easily decomposable fraction of organic fertilisers, a direct and more simple approach can be used to benchmark the products on their C decomposition characteristics (humification coefficient).

By using a fixed C/N ratio for each of the two pools also the N mineralisation can assessed based on the mineralisation of carbon. However, by using this simple approach the predicted N- mineralisation was found to be higher than the measured N mineralisation. This can be due to over-simplification or a measurement artefact if gas losses have occurred during the incubation experiment.

In a follow-up research project an independent dataset – which was not used for the calibration – will be used to validate the presented approach to predict the fate of organic fertilisers in terms of decomposition and long-term carbon storage by using rather simple laboratory tests. In addition the approach for nitrogen mineralisation will hopefully improve.

With the increase in attention given to climate change and soil quality, the application of OM has got additional added value. Besides keeping the SOM percentage at an optimal level, it also plays a role in carbon storage in agriculture. In light of the development of carbon credits OM is becoming increasingly important financially. This changes the break even points of the economic considerations in fertiliser use.

Definitions and abbreviations

Abbreviation	Description
ADF	Acid detergent fibre
ADL	Acid detergent lignin
BOD(5)	Biological oxygen demand during 5 days
BOD(7)	Biological oxygen demand during 7 days
COD	Chemical oxygen demand
C_{org}	Organic carbon
$DC_{rate,soil}$	Decomposition rate of organic matter in the soil
DM	Dry matter
DOC	Dissolved organic carbon
$DPM_{calibration}$	The decomposable plant material fraction obtained by using the incubation data in RothC.
$DPM_{regression}$	The decomposable plant material fraction obtained by using the relationship between relatively simple laboratory tests and $DPM_{calibration}$.
EC	Electrical conductivity
EOM	Effective organic matter. The amount of organic matter that remains after one year in the soil
$EOM_{prod\ i}$	Effective organic matter content of product i
$ER_{EOM,P2O5,prod\ i}$	Phosphate based effective organic matter enrichment of product i
FM	Fresh matter
$f_{P2O5,law}$	Fraction of the phosphate content of a product that has to be taken into account by law, in relation to the calculation of the amount of phosphate that is allowed per hectare by the phosphate application norm
HC	Humification coefficient. This is defined as the fraction of organic matter of the organic product that remains after one year in the soil.
HC_{2pool}	The humification coefficient obtained by applying the two-pool model to incubation data.
$HC_{regression}$	The humification coefficient obtained by using relatively simple laboratory tests and HC_{2pool}.
HC_{RothC}	The humification coefficient obtained by using RothC approach and $DPM_{regression}$ and $RPM_{regression}$ fractions
HI	Hydrogen index
HWC	Hot water extractable carbon
HWC(1)	Hot water extractable carbon, performed by the WUR laboratory of Plant Science Research
HWC(2)	Hot water extractable carbon, performed by the WUR laboratory of Animal Ecology
HWN	Hot water extractable nitrogen
$M_{OM,PN}$	The phosphate norm based maintenance value for soil organic matter, i.e. the amount of soil organic matter that needs to be maintained, relative to the maximum amount of phosphate that can be applied based on the phosphate norm.
NAC	Long term nitrogen availability coefficient
NDF	Neutral detergent fibre
$N_{min,net}$ (%) incubation	The percentage of the net organic N mineralisation of organic fertilisers relative to the organic N content, determined on the basis of incubation experiments, corresponding with 100 days of mineralisation at 20℃. For the calculation, the N min at 80 and 120 were averaged.
$N_{min,net}$ (%) regression	The percentage of the net organic N mineralisation of organic fertilisers at 100 days relative to the organic N content, obtained by using the relationship between relatively simple laboratory tests and $N_{min,net}$ (%) incubation
$N_{min,net}$ (%) RothC	The percentage of the net organic N mineralisation of organic fertilisers relative to the organic N content after 100 days of decomposition, obtained by using RothC
N_{org}	Organic nitrogen
OI	Oxygen index
OM	Organic matter
$OM_{DC,soil}$	Annual amount of organic matter decomposition in the soil
$OM_{prod\ i}$	Organic matter content of product i
PMN	Potentially mineralisable nitrogen
PN	Phosphate norm
$P_2O_{5\ prod\ i}$	Phosphate content of product i
%OM compensated	Percentage of organic matter maintenance that will be compensated by product i

1 Introduction

1.1 The overarching project

The current European policy strongly focuses on the transition from a linear economy towards a circular economy (CE Package 2015[1]) where waste is reduced to a minimum and re-use and recycling of waste materials and products is promoted. Furthermore, the use of synthetic mineral fertilisers must be reduced, because scarce sources, like natural gas and phosphate rock, are being used to produce mineral fertilisers (resp. nitrogen and phosphate fertilisers). As a result, new types of organic and organo-mineral products are coming into the agricultural market as fertilisers (both nitrogen (N) and phosphor (P)) and as soil improver. These new organic fertilising products are often produced by processing organic waste. The determination of the quality of the products and the fate in the soil system are of high importance to predict the sustainability aspects of the new biobased products in terms of agronomic- and environmental impact. However, a systemic evaluation framework was missing.

In 2019 a concept for a *framework to characterise and evaluate the impact of the use (new) organic fertilising products* has been developed with the focus on the long-term effects that organic materials may have on soil fertility (carbon, nitrogen, phosphorus and potassium), soil quality aspects (heavy metals), emissions to the air (N_2O, NH_3) and water (NO_3, P), health/environmental aspects (antibiotics, pathogens) and economic value of the soil and agricultural production (Schoumans *et al.*, 2019). Many of these aspects must be based on a mechanistic understanding of the fate of the components from organic fertilisers in the soil. However, simple analytical methods are needed which can assess the long-term agronomical impact and changes in soil quality. With respect to emissions to the air (N_2O, NH_3) and water (NO_3, P) a simple environmental approach for soil-crop combinations was developed by Schoumans *et al.* (2021). Regarding health/environmental aspects practical process information of the sorption and release of medicines in soils including the availability of medicines in soils in relation to the type of organic products. The results of this part of the project are published in a peer reviewed journal (Rietra 2023). In this report the focus is on the development of a simple C and N mineralisation approach and the evaluation of economic aspects.

1.2 C and N Mineralisation

Organic matter is widely recognised as an important factor in maintaining soil fertility, soil biological activity and soil structure. Different organic materials, like crop-residues, manure, co-digestates, and compost are used to maintain or improve the organic matter content of the soil and the associated soil quality. The increase or decrease of the amount of soil organic matter (SOM) depends on the decomposition rates of both applied organic products to the soil and already present SOM. The humification coefficient (HC) is an important parameter to express the fate of organic fertilisers at the short term (1 year). The HC is defined as the fraction of organic matter applied by an organic fertiliser that remains after one year. Effective organic matter (EOM) is defined as the amount of organic matter that remains in the soil one year after application of the organic product. The current view is that application of more stable organic matter products, as indicated by a high humification coefficient (HC), lead to higher EOM values. Very high HC-values can lead to even carbon storage in the soil at long term (e.g. after 50 years).

Organic fertilisers (with a low C/N ratio) are often applied to agricultural soils to provide nitrogen to plants during the growing season, as mineral N is released due to decomposition of the organic material. Organic fertilisers with a high C/N ratio can cause immobilisation of available mineral N in soils or a part of applied mineral N fertiliser due to the production of biomass with a lower C/N ratio (e.g. if straw is applied on soil with and without applied mineral fertiliser; (Van Groenigen and Zwart, 2007)). For efficient use of organic fertilisers, it is important to estimate the plant available nitrogen (N) of these fertilisers during growing

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[1] https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en

season. When the amount of N, that can become available during the growing season, is known, application rates can be adjusted in such way that they provide sufficient, but not excessive N to agricultural soil, therefore minimising adverse environmental impacts of nitrate leaching (Chescheir Iii *et al.*, 1986; Douglas and Magdoff, 1991). This enables agronomic correct N fertilisation to reach the target for quality (e.g. protein content in grass and grains) and crop characteristics (e.g. no excessive leaf growth in potatoes and sugar beets) as well.

The HC and net organic N mineralisation ($N_{min,net}$) of organic fertilisers are commonly determined with incubation experiments. These experiments are labour intensive and time consuming (about 100 days), and therefore, *alternative simple models in combination with simple laboratory tests, which can predict C and N turnover, would be very valuable* from a practical point of view. Such a simple approach should be able to assess the impact of different types of organic fertilisers on the amount of EOM (short term), carbon storage (long term) and N availability. Therefore, incubation experiments and laboratory analyses were carried out to test whether simple laboratory tests can explain the measured variation in C- en N-mineralisation (incubation tests) of the organic fertilising products.

In order to predict the C turnover, the results of the incubation experiments were evaluated using two models: a freely-fitted two-pool model and the already-parameterised Rothamsted Carbon Model (RothC (Coleman and Jenkinson, 1996)). Furthermore, the nitrogen mineralisation was assessed by using C/N values in combination with fitted C mineralisation found with RothC. To link laboratory analyses with the experimental and model results, the following approaches were tested:

a. Determining a parameter or a combination of parameters from the laboratory analyses which explain the HC resulting from the two-pool model (i.e. $HC_{regression}$).
b. Determining a parameter or a combination of parameters from the laboratory analyses which are useful for model initialization in RothC (i.e. $DPM_{regression}$).
c. Determining a parameter or a combination of parameters from the laboratory analyses which explain the $N_{min,net}$ resulting from the incubation experiment (i.e. $N_{min,net}$ (%) regression).

In this report the calibration of these approaches by testing 16 different types of organic products which differ in carbon decomposition and nitrogen release (mineralisation / immobilisation) is described. This gives practical information of the applicability of simple analytic protocols to assess the long-term agronomic impact of organic materials. These 16 organic products can also be used as benchmark products for the evaluation of new organic biobased fertilisers.

Objectives
The main objectives are:

- Characterisation of products by means of a long list of analytical tests. This includes an inventory of determination methods for fractions of organic matter in organic fertilisers. The challenge is to find parameters that could act as a proxy for the time-consuming determination of the humification coefficient and N-mineralisation.
- Evaluation of two mechanistic concepts (simulation models) on their ability to simulate the build-up and breakdown of organic matter in the soil and the release or immobilisation of nitrogen.

1.3 Economic aspects

The addition of organic matter to soil has several positive effects, such as improving soil life, which feeds on fresh organic matter and subsequently improves soil structure (Ten Berge *et al.*, 2019). This can result in an economic impact for farmers.

To determine the potential price for organic fertilisers an assessment framework is needed. In this report a method is proposed to determine the value of organic fertilisers, with a focus on the value of the organic matter (OM). The implementation of a carbon credit is also studied to find out how this stimulates carbon sequestration. So, the two main economic questions studied are: (a) what is the value of OM in organic fertilisers? And (b) what are the effects of subsidising carbon sequestration on the farm?

1.4 Reader

In Chapter 2, the selection procedure for organic fertilising products is discussed, together with the analytical methods used to analyse characteristics of these fertilisers and the methods to determine the decomposition of organic matter and the mineralisation and immobilisation of nitrogen from the fertilisers, which are relevant for the resilience of the soil. Furthermore, the approaches for evaluating economic aspects are described. In Chapter 3, the characterisation of organic fertilisers in terms of chemical-, physical- and biological parameters, the results of the carbon and nitrogen mineralisation experiments and models, applicability of the models and economic analyses are discussed. The report finalises with conclusions and recommendations (Chapter 4).

2 Methodology

Regarding the short- and long-term effect of decomposition of organic fertilisers two incubation tests were carried out with 16 different types of organic products applied at two soils (sand and clay), one to determine C-mineralisation and one to determine N—mineralisation/immobilisation. Based on literature study two model concepts were chosen to describe on one hand the C-mineralisation and on the other hand, N-mineralisation/immobilisation. In addition, a long list of (bio-)chemical characterisation of the products and the two soils were carried out, which is used to determine which simple parameters can be used to predict the fate of the product in soils in terms of C and N. A simple analytical procedure can help to derive a quick scan of the fate of (new biobased) organic products in soils.

2.1 Selection of organic fertilising products

For both the incubation experiments and laboratory analyses, organic fertilisers were selected. The organic fertilisers used in this research (Table 2-1) were selected based on general knowledge of humification coefficients (HC) and long-term N availability coefficients (NAC) of the different organic fertilisers. The HC is defined as the fraction (or percentage) of the applied amount of organic C (a fraction of organic matter) that is still present after one year. This is an important parameter to express the fate of organic fertilisers. The NAC is defined differently by various researchers. Most often, it is defined as the amount of N becoming available for plant uptake within the growing season relative to the total amount of N applied. Sometimes, it is also defined in terms of mineral fertiliser equivalents, which amounts to about the same, since N from mineral fertilisers usually becomes completely available during the growing season. Among others, environmental conditions determine whether the plant can take up all available N and thus whether the amount of N taken up by plants and mineral fertiliser equivalents have similar results. Both these definitions were accepted when estimating $N_{min,net}$ values based on literature. Based on expert judgement and literature study, a 3x3 matrix was filled in to obtain as many as possible combinations of degrees of humification and long term N availability (Table 2-2).

Table 2-1 *Organic fertilisers collected and analysed for this study.*

#	Organic fertiliser	Description/remarks
1	Cattle slurry	
2	Pig slurry	
3	Organic waste compost	Compost made of source-separated biowaste
4	Farmyard manure	Solid fraction of manure from organically kept dairy cattle
5	Garden peat	Garden peat from the brand Pokon
6	Straw	
7	Grass	
8	Chicken manure	Dried, heterogenous chicken manure
9	Mono-digested cattle slurry	
10	Deep litter stable manure	From dairy cattle (Remeker), in Dutch: *potstalmest*
11	Bokashi	Bokashi made from leaves
12	WWTP dairy sludge	Anaerobic sludge from a NEREDA treatment plant processing waste water from a dairy factory
13	Struvite with organic matter	Struvite produced by a waste water treatment plant processing waste water from potato industry
14	Champost	
15	Soil improver from GZV	Soil improver produced by Groot Zevert Vergisting, with P fraction removed. For more information about the production process, see Regelink *et al.* (2021).
16	Co-digestate from GZV	Co-digestate produced by Groot Zevert Vergisting (pig slurry and agro-industrial residues). For more information about the production process, see Regelink *et al.* (2021).

Pre-treatment

The 16 organic fertilisers were collected and homogenised. When organic material contained large parts (such as deep litter stable manure, which contains straw), it was cut with scissors or otherwise broken down to smaller pieces (e.g. using a jaw crusher). To enable homogenisation of grass and straw, grass was dried at 70°C and grass and straw were ground and sieved with a mesh size of 1 mm. For laboratory analyses, some material of each fertilisers was divided over several small jars and put into the freezer. Additionally, a little of each fertiliser was freeze-dried to obtain dry material for several laboratory analyses (Van Soest, total organic C and total N, N in pepsin, elemental C and H; see section 2.2 for the analytical aspects). Freeze-drying was executed instead of drying by oven to prevent loss of NH_4 and decomposition of carbonates and struvite due to high temperatures.

Table 2-2 *Matrix for the humification coefficient and N availability (during one year or growing season) coefficient of the chosen organic fertilisers, based on literature study and expert judgement.*

		Humification coefficient		
		Low	**Moderate**	**High**
		< 0.35	0.35 - 0.7	≥ 0.7
N availability coefficient	**Low** **<0.35**	Straw1)	Champost2) Farmyard manure3)	Bokashi4) Deep litter stable manure5) Garden peat6) Soil improver from GZV7) Organic waste compost8)
	Moderate **0.35 - 0.7**	Grass9) Pig slurry10) Chicken manure11)	Cattle slurry12) WWTP dairy sludge 13)	Codigestate from GZV14) Monodigested cattle slurry15)
	High **≥ 0.7**	Struvite with organic matter16)		

1) HC: 0.31 (Inagro, 2011)
N: 0.12-0.35 (Hijbeek *et al.*, 2018)
2) HC: 0.42-0.91 (Velthof, 2004; Van Dijk *et al.*, 2005; Hendriks, 2011; Conijn and Lesschen, 2015; CDM, 2017; Handboek Bodem en Bemesting, N.B.)
N: 0.25 (Straatsma, 2014)
3) HC: 0.5-0.6 (Sleutel *et al.*, 2007; Rietra *et al.*, in press.)
N: 0.15-0.3 (Sullivan, 2008; Jensen, 2013)
4) HC: 0.82 (Spijker *et al.*, 2022)
N: -
5) HC: 0.72 (van der Burgt *et al.*, 2011)
N: -
6) HC: -
N: -
7) HC: 0.7 (Regelink *et al.*, 2019)
N: -
8) HC: 0.75-0.9 (Van Dijk *et al.*, 2005; Inagro, 2011; Conijn and Lesschen, 2015; CDM, 2017)
N: 0.1 (Gutser *et al.*, 2005)
9) HC: 0.26-0.33 (Handboek Bodem en Bemesting, N.B.)
N: -
10) HC: 0.3-0.42 (Van Dijk *et al.*, 2005; Inagro, 2011; Conijn and Lesschen, 2015; CDM, 2017; Handboek Bodem en Bemesting, N.B.)
N: 0.4-0.7 (Delin *et al.*, 2012; Jensen, 2013)
11) HC: -
N: 0.55 (IRS, 2011)
12) HC: 0.4-0.7 (Van Dijk *et al.*, 2005; Inagro, 2011; Conijn and Lesschen, 2015; CDM, 2017; Handboek Bodem en Bemesting, N.B.)
N: 0.3-0.54 (Gutser *et al.*, 2005; Sullivan, 2008; Delin *et al.*, 2012; Jensen, 2013)
13) HC: -
N: 0.4 (RVO, 2018)
14) HC: -
N: 0.6-0.9 (Delin *et al.*, 2012; Jensen, 2013)
15) HC: 0.57-0.72 (Schouten *et al.*, 2012)
N: 0.6-0.9 (Delin *et al.*, 2012; Jensen, 2013)
16) HC: -
N: -

2.2 Analytical methods

All laboratory analyses conducted are listed in Table 2-3. All analyses have been executed in duplicate.

Dissolved organic carbon

Dissolved organic carbon (DOC) consists of a wide range of molecules ranging from simple acids and sugars to complex humic substances (van Dijk *et al.*, 2012). Previous studies used DOC predominantly to analyse water contamination and to a lesser extend its multifunctionality to sustain soil functions (e.g. its role in acid-basic reactions, immobilisation of heavy metals, soil aggregation, C and nutrient cycling, and as an energy source for micro-organisms). As DOC is largely a product of decomposition of litter and humus, DOC concentration indicates maturity of organic material and is therefore considered as a key functional pool which is useful for understanding C dynamics (Zmora-Nahum *et al.*, 2005). Straathof and Comans (2015) analysed the DOC concentration and quality of eleven compost types varying in their input materials and composting duration. They found that compost originating from municipal waste (containing the most nutrients and relatively a lot of C) and the shortest period composting at peak temperature had the highest DOC concentration. It is therefore likely that the preservation of C in organic material is reflected in the DOC concentration. Composts with similar inputs and lengths of decomposition did not only have similar DOC concentrations, but also had similar DOC profiles. DOC concentration reflects input materials and processing conditions and might therefore be a valuable parameter.

Dissolved organic carbon from organic fertilisers was extracted with 0.01 M $CaCl_2$, with a ratio of 1:10 (w/v). Relatively large amounts were used: 10 gram of fertiliser and 100 mL of extract to avoid deviations due to heterogeneity. The DOC content was analysed with a Segmented Flow Analyser (SFA).

Total organic C and total N

The total organic C (C_{org}) content is the amount of all carbon in organic form per kg product. Total N is the total amount of nitrogen per kg product. The amount of organic fertiliser added in the incubation experiment for C has been based on the C_{org} values of the organic fertilisers. C_{org} and total N are commonly used to calculate the C_{org}/N ratio. When an organic substrate has a C:N ratio between 1 and 15, rapid mineralisation and release of mineral N occurs, which is available for plant uptake. The lower the C:N ratio, the more rapidly nitrogen will be released into the soil for immediate crop use (Watson *et al.*, 2002). A C:N ratio > 35 results in microbial immobilisation of N, meaning that mineral N is incorporated into microbial biomass (Brust, 2019). When using the standardly used C/N ratio, it does not take into account in which form N is present. Rather than using total N, total organic nitrogen (N_{org}) can be used to calculate the C_{org}/N_{org}-ratio. Qian and Schoenau (2002) found a negative relationship between the C_{org}/N_{org}-ratio and mineralised N from manures. Total organic N can be estimated by subtracting mineral N from the total N content. This is the fraction that can decompose and form mineral N through mineralisation.

Total organic carbon and total N were measured in freeze dried material by a LECO analyser. For total N, however, it was found that the results were often lower than the measured mineral N content, which is why the results were deemed unreliable. For this reason, the total N content was re-analysed in fresh material by determination in digests according to NEN 7434. We have used the total N results from the determination in digests for our experiment.

Mineral N (NH_4)

The mineral N content is the total amount of inorganic nitrogen, in the forms of ammonium and nitrite and nitrate. This was initially measured in 1M KCl extracts at pH = 2 with a Segmented Flow Analyser (SFA). However, as the results were often higher than the total N contents of the products (see also the section above on total N), the products were analysed again but now according to NEN 7438, which is a titrimetric determination of the ammoniacal (NH_4) nitrogen content. With a Nitratesmo strip, it was determined that there was no nitrate (NO_3) present in the materials. The results for the ammoniacal nitrogen content were used in our experiment as the mineral N content.

Electrical conductivity

The application of soil electrical conductivity (EC) has its origin in the measurement of soil salinity (Corwin and Lesch, 2005). However, EC also serves as a measure of soluble nutrients (Smith and Doran, 1997) for both cations and anions. Therefore, EC is useful in monitoring the mineralisation of organic matter in soil (De Neve *et al.*, 2000; Eigenberg *et al.*, 2002), and predictive method to estimate soil nitrate (Doran *et al.*, 1996).

Electrical conductivity was measured with an EC electrode, directly in the organic fertiliser (cattle slurry, pig slurry, monodigested cattle slurry, WWTP sludge, codigestate) or in a diluted sample (1:5 w/v) for the remaining fertilisers. The EC values measured in diluted samples were multiplied by 5 to obtain the EC for the fertilisers in undiluted form.

Oxygen demand

The biological oxygen demand (BOD) and chemical oxygen demand (COD) are commonly used to quantify oxidisable pollutants in surface- and wastewater. The BOD is a parameter for carbon that is oxidised by the microorganisms present during a standardised incubation, and provides information about the decomposability of the material (Clemens and Huschka, 2001; Stowa, 2002). It is commonly used to determine the stability of composts. The COD measures the amount of oxygen consumed for the oxidation of total organic matter (Woodard and Curran, 2006; Kalamdhad and Kazmi, 2009; Tas *et al.*, 2009). The COD indirectly measures the amount of total organic matter (biodegradable and inert material). The COD is often used in conjunction with the BOD to estimate the biodegradable organic material. The ratio of COD/BOD is an estimate of the biodegradability of the organic material, and would be useful parameter for the purpose of our study.

As COD is the sum of biodegradable and inert material, COD is not expected to correlate with the C and N mineralisation. The BOD value is expected to correlate positively with the C mineralisation, because it indicates more microbial activity. Since the ratio of COD/BOD is used to estimate the biodegradability of the organic material, the ratio might correlate to mineralisation of C and N. A higher value indicates that the organic material probably contains a larger portion of organic material that is not biodegradable by ordinary microorganisms (Woodard and Curran, 2006; Kalamdhad and Kazmi, 2009; Tas *et al.*, 2009). In other words, a higher COD/BOD ratio may indicate the presence of organic matter that is harder to biodegrade, meaning microbiologically stable.

For the BOD measurement, samples were diluted to 2.5-10 g organic matter/L. 200 mL of diluted sample was added to bottles with a volume of 1L. Aerobic sludge (with approximately 10 mg of total suspended solids/L) was used as inoculum and macronutrients, micronutrients and a phosphate buffer were added as well. Nitrification was inhibited by using ATU (5 mg/L). Soda-lime pellets were used to catch CO_2 formed during the experiment. Oxygen consumption was determined by measuring the decrease in pressure within the bottles. The temperature was maintained at 20 °C, with continuous mixing at 100 rpm. The pH was maintained at 6.5-8. The test period was 7 days, during which both BOD_5 and BOD_7 were determined. The COD was determined by titration.

MicroResp

The MicroResp method is a colorimetric technique that can be used for profiling microbial respiration on various substrates providing an insight into microbial functional diversity and assess the soil biodiversity. It is hypothesised that the greater the diversity of the microbial community the wider the range of carbon source utilisation. MicroResp evaluates the maximum potential activity, not the actual activity (Sultana, 2011). The MicroResp method is commonly used to characterise functional diversity of soils.

The ability of soil microorganisms to catabolise a range of different organic substrates provides information on those involved in the carbon cycle. Sultana (2011) found that addition of slow-degradable organic fertilisers did affect the total respiration, but not the respiration responses on specific organic compounds, even after long term addition. Despite the complex relationships, a high catabolic respiration response is associated with the growth of the microbial community, higher decomposition and nutrient cycling (Sultana, 2011).

Since the focus of our study is on organic material and its dynamics in the soil, before performing the MicroResp method, organic material was added to soil samples (sandy soil, see Table 2-4) following the method used for the carbon incubation experiment (i.e. same amount of carbon added to soil) and incubated for three weeks at 20°C. Then, as part of the MicroResp procedure, the samples were incubated for 6 hours at a temperature of 25℃ at a saturation of 60%. The samples were then added to a deep-well microplate. Seven carbon substrates were added at an application of 30 mg per gram water (lignin, alanine, aminobutyric acid, N-acetyl glucosamine, D(+) glucose, alpha ketoglutarate and malic acid). A detection plate is attached on top, which detects carbon dioxide emissions with cresol red as indicator. Eventually, the CO_2 respiration per hour was determined with a spectrophotometer.

Oxitop
Oxitop is a standard method for determining the respiration in waste water and soil. Later on, it became a standard method for determining the stability of organic soil improvers as well. It determines the oxygen consumption which is a direct measure for the stability. With this method, composts are usually classified as stable, whereas champost and sludge are not stable. The oxygen consumption can be seen as a direct measure for organic matter stability. Moolenaar (2002) conclude that the C mineralisation can be derived directly from Oxitop data. Besides O_2 respiration, N mineralisation is measured in the same samples by measuring NH_4 contents. Formation of NO_3 is avoided by using an nitrification inhibitor. This way, the O_2 respiration measurements are not influence by the formation of NO_3 (Moolenaar, 2002). As Oxitop is able to assess the stability of organic material and quantify N mineralisation, the analysis could be used to examine C and N dynamics.

Samples were diluted to 2-50 g organic matter/L, depending on the expected oxygen consumption. 200 mL of diluted sample was added to bottles with a volume of 1L. Macronutrients, micronutrients and phosphate buffer were added with concentrations according to the protocol of NMI for the Oxitop method. Nitrification was inhibited by using ATU (50 mg/L). Soda-lime pellets were used to catch CO_2 formed during the experiment. Oxygen consumption was determined by measuring the decrease in pressure within the bottles over 7 days. The temperature was maintained at 30 °C, with continuous mixing at 100 rpm. The pH was maintained at 6.5-8. A sample was taken daily to determine the NH_4 content.

Pyrolysis
The Rock-Eval pyrolysis was designed for petroleum exploration to determine the type and quality of organic matter in rock samples (Sebag *et al.*, 2006). The technique can also be used to characterise (im)mature organic matter in soil samples, in particular the stability of organic matter. Application of this method on organic residues is relatively new. The method provides an extensive list of parameters, each providing information on the characteristics of the organic matter. Saenger *et al.* (2013) introduced the use of four fractions, which are distinguished based on the thermal resistance to decomposition. F1 are labile biological constituents, related to little resistant bio-macromolecules typical of fresh plant material and soil litter. F2 are resistant biological constituents, related to abundant and rather resistant biopolymers such as lignin and cellulose. F3 are immature non-biotic constituents, related to humic geo-macromolecules. F4 is the mature refractory fraction, rather well-presented in deeper soil layers. The fractions can be used to calculate the I-index and the R-index (Sebag *et al.*, 2016). The I-index is calculated using lower temperature areas representing thermally more labile OM compounds. The R-index index calculated using higher temperature areas representing thermally more stable OM compounds {Sebag, 2016 #52}{Soucémarianadin, 2018 #58}. As thermal resistance to decomposition is often seen as an indicator for the stability of organic material, it will be of interest to compare Rock-Eval parameters with incubation data. In search of simple techniques to characterise and monitor organic matter, Albrecht *et al.* (2015) assessed the I- and R-index on compost. Albrecht *et al.* (2015) found that the I-index decreased and the R-index increased with the length of composting (up to 128 days). Soucémarianadin *et al.* (2018) explored whether respired-C isolated by a laboratory soil respiration test and Rock Eval parameters correlated. As expected, a higher I-index (associated with fresh and labile C) correlated positively with respired C and a higher R-index (associated with more resistant material) correlated negatively with respired C. Although tested on compost and forest soils, the I- and the R-index are good candidates to provide insights in the C dynamics.

This lab analysis was executed with the Rock Eval at the laboratory of Deltares. Each sample was heated gradually with oxygen (aerobic) and without oxygen (anaerobic), up to 850°C. Released hydrocarbons, carbon monoxide and carbon dioxide were detected by a flame ionization detector and infra-red detectors (Sebag *et al.*, 2006).

C/H ratio
The C/H ratio is often determined for carbon-based fuels (coal, wood, gas). Compounds with a lower C/H ratio have a higher energy efficiency and emit less CO2 during combustion. The C/H ratio provides

information about the composition of a material (stoichiometry). The C/H ratio is used to indicate the level of stability and aromaticity of biochars, but usually the C_{org}/H ratio is used and not the total C/H ratio (Leifeld *et al.*, 2020). Total C and C_{org} differ in that total C includes elemental and inorganic C as well, such as graphite and (bi)carbonates.

The total C and H content was determined in freeze-dried material that was grinded to 0.2 mm by using an elemental analyser.

Van Soest analysis

The van Soest analysis was developed mainly to assess digestibility of feed for the livestock industry. Recently, acid detergent analysis has been reported to be able to evaluate decomposition properties and to determine the available nitrogen of organic materials. With the analysis, cellulose-, hemicellulose- and lignin-like fractions can be quantified. Lignin is considered as the most stable fraction, followed by cellulose and hemicellulose. The fractions are used to calculate several indices, as an indication of the stability of the material. The biodegradation potential can be estimated by: (hemicellulose+cellulose)/lignin, a lower ratio indicates material that is less susceptible to decomposition (Amery *et al.*, 2020). Lashermes *et al.* (2009) and Peltre *et al.* (2012) describe the *I*ROC indicator, which reflects the proportion of added organic material that may be retained in the soil for decades and is based on the soluble, cellulose and lignin like fractions. Another ratio that might be interesting is the lignin/nitrogen ratio, since less breakdown of highly lignified plant residues is expected in the scarcity of easy available N compounds (Mewes, 2017). The van Soest parameters have been previously tested on their usability to predict C and N mineralisation in several studies. Lashermes *et al.* (2010)conducted a comprehensive assessment in search of an indicator able to quantify the proportion of added organic material remaining in the soil over a long period of time. The lignin-like fraction is found to correlate negatively with the overall mineralised C during incubation (Lashermes *et al.*, 2009; Mewes, 2017). The cellulose-like fraction was negatively correlated to the overall mineralised C of a wide variety of organic amendments during 91d incubation in one study (Lashermes *et al.*, 2010) and positively related to the decomposition parameter of the resistant fraction in another (Thuriès *et al.*, 2002). The hemicellulose like fraction was positively correlated to the overall mineralised C during 91d incubation in the study of Lashermes *et al.* (2010), but negatively correlated to both the decomposition parameter of the labile fraction in the study of Thuriès *et al.* (2002) and the initial C mineralisation of plant materials measured at day 1-3 during incubation (Mewes, 2017). Together with C and N, hemicellulose and lignin were found to explain >90% of the decomposition parameter (*k*) of labile and resistant fractions of organic amendments (Thuriès *et al.*, 2002). In contrast, Zwart *et al.* (1999) did not find any correlations between van Soest-parameters (cellulose, hemicellulose and lignin) and the total N- and C-mineralised during a 126 week incubation, tested on various organic amendments.

The hemicellulose, cellulose and lignin fraction are determined as Neutral Detergent Fiber (NDF) by heating the material in a neutral solution. The cellulose and lignin like fractions are determined as acid detergent fiber (ADF) using a weak acid solution, and the lignin like fraction is determined by using a sulphuric acid fraction. The van Soest analysis was carried out at the ‘Chemisch laboratorium Diervoeding’, following the procedures described by van Soest (1963), van Soest *et al.* (1991), van Soest and Wine (1967) and Baars *et al.* (2021), using freeze dried material.

Hot water extractable C and N

Hot water extractable C (HWC) is used as an indicator for the labile fraction of C. Since the focus of our study is on organic material and its dynamics in the soil, organic material was added to soil samples following the method used for the incubation analysis. HWC and hot water extractable N (HWN) both quantify a labile fraction of respectively C and N, which is related to the microbial biomass (Ghani *et al.*, 2003; Curtin *et al.*, 2006). HWC is a sensitive indicator for management practices. Therefore, HWC is considered as a useful indicator to assess the soil quality (Ghani *et al.*, 2003). Ghani *et al.* (2003) found that HWC measured in soil samples was positively correlated with soil microbial biomass, microbial N, mineralisable N and total carbohydrates. HWC measured in organic material correlated well with short term C and N mineralisation (Antil *et al.*, 2011). In soils, HWC was strongly related to mineralised N (Ros, 2011). As HWC quantifies a labile C-fraction associated with microbial activity, HWC would be useful for understanding C dynamics after the application of organic matter in agricultural soils. However, Poeplau *et al.* (2018) conclude that it is difficult to use water extractable carbon as a fraction with a distinct turnover rate.

For the HWC and HWN method, soil-fertiliser mixtures were incubated for three weeks at a temperature of 20℃. The HWC was determined by extracting 4 gram of soil with 30 ml distilled water for 30 minutes. The suspension was centrifuged for 20 minutes and the supernatant discarded to remove cold water soluble fractions. Next, the sediments in the centrifuge tubes were shaken with a fresh amount of 30 ml distilled water for 10 seconds and left for 16 h in a hot-water bath at 80 °C. After filtration, part of the hot water extract was used to measure organic carbon (total minus inorganic carbon). Another subsample of the hot water extract was used to measure total soluble N (hot water extractable N, HWN), NH4-N and NO3-N.

N in pepsin extract

This analysis was designed to estimate the protein digestibility in animal feeds (Serna and Pomares, 1992). Castellanos and Pratt (1981) found that N in pepsin extract correlated well with initial mineral N + N mineralised in a greenhouse experiment. Therefore, N in pepsin can be used as a proxy for N mineralisation.

Pepsin extraction was executed on freeze-dried material. The method used was according to the protocol as given in the Benelux-Publicatieblad.[2]

Potentially mineralisable nitrogen

PMN correlates with total microbial biomass (Schipper and Sparling, 2000), which is related to the decomposition of organic material. Therefore, PMN is expected to correlate with C and N mineralisation. Potentially mineralisable nitrogen (PMN) is obtained by an incubation of waterlogged soil for 7 days at 40°C. At the end of the incubation, accumulated ammonium is measured (protocol as supplied by J. Bloem). PMN is used as an indicator for labile N, and is used as a proxy for the total microbial biomass (van den Elsen *et al.*, 2019). The amount of mineral nitrogen (NH_4-N) released is a measure of the quality (N-content and decomposability) of the organic matter (Major *et al.*, 2017).

Potentially mineralisable nitrogen was measured as the increase in NH_4^+ during one week of anaerobic (waterlogged) incubation of 8 g organic fertiliser in 40 ml water at 40°C.

Table 2-3 *List of laboratory analyses carried out on the organic fertilisers within this study.*

Parameter type	Parameter
Bulk parameters	Dry matter content
	Dissolved organic carbon (DOC) (in 0.01M $CaCl_2$)
	NH_4 (NEN 7438)
	Organic matter content (LOI)
	pH (in 0.01M $CaCl_2$)
	Total N (NEN 7434)
	Total organic carbon (C_{org}) (LECO)
Generally relevant	Cl (in $NaNO_3$)
	Electrical conductivity (EC) (in water)
	Total P, K, S, Mg, Ca
C dynamics	Biological Oxygen Demand (BOD)
	Chemical Oxygen Demand (COD)
	Hot water extractable organic C (HWC)
	MicroResp
	Oxitop
	Pyrolysis
	Total C (element)
	Total H (element)
	Van Soest analysis
N availability	Hot water extractable organic N (HWN)
	N in pepsin extract
	Potentially mineralisable N (PMN)

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[2] https://www.benelux.int/files/8513/9878/0978/2003-02-0.pdf

2.3 Incubation experiments

The aim of the N incubation experiment is to quantity the mineralisation rate of organic N from organic fertilisers. No mineral N will be applied additionally.

The aim of the incubation experiment for C is to quantify the carbon mineralisation rate of the organic fertilisers, which can be used to calculate the HC. During this experiment, additional mineral N is applied to avoid N limitation. Next, it is evaluated if the measured HC can be derived from straightforward laboratory methods.

The outcome of the laboratory analyses is used to investigate which characteristics of the fertilisers actually determine the change in soil organic matter content and/or N mineralisation (for each studied soil type). Additionally, information of both incubation experiments can be combined e.g. the HC value can perhaps be predicted based on the characteristics of the added fertiliser, soil type and the net N mineralisation.

2.3.1 Chemical, physical and biological soil parameters

For the incubation experiments a sandy soil and a clay soil were used (Table 2-4). The sandy soil and the clay soil contained 1.6 and 2.9% organic matter and 3 and 32% clay, respectively. Both soils contained less than 0.2% lime. It was required that the SOM content was low and lime was not present. A low SOM content was needed to avoid that measurements of organic carbon decomposition of the organic fertilisers were negligible compared to the SOM decomposition of the soil. No lime was allowed to be present as lime can decompose during incubation experiments, thereby releasing CO_2 to the air and interfering with the measurements of organic carbon decomposition. The soil was air dried (non-controlled at about 15-20°C) and sieved over a mesh size of 5 mm.

Table 2-4 *Characterisation of the two soil types used for the incubation experiments. Sources: Eurofins report (all parameters except for the water holding capacity) and WUR Soil Biology Lab (water holding capacity).*

Name		**Commanderij 2**	**Lange Bos**
Soil type		Sandy soil	Clay soil
Specification			Fluvial clay
Location		Wageningen	Region of Zoelen
Parameter	***Unit***	***Value***	***Value***
Silt	%	4	40
Sand	%	91	25
Clay	%	3	32
OS	%	1.6	2.9
C-org	%	0.8	1.6
CEC	*mmol+/kg*	40	223
CEC-occupied	%	100	93
Lime	%	<0.2	<0.2
Total N	*kg N/ha*	2840	1810
N supplying capacity	*kg N/ha*	50	100
C/N ratio	-	10	9
P-PAE	*kg P/ha*	12.2	1.2
Total K	*kg K/ha*	210	55
Total S	*kg S/ha*	900	295
pH-CaCl2	-	5.9	6.8
Microbial activity	*mg N/kg*	32	27
Water holding capacity	*mL/kg*	219	398

2.3.2 Carbon mineralisation

The methodology used was similar to that of Van Groenigen and Zwart (2007). Dried and sieved (5 mm) sandy soil was mixed with organic fertilisers and mineral nitrogen fertiliser (calcium ammonium nitrate (CAN), 27% N), corresponding to an addition of 3 g C from organic fertiliser per kg soil[3] and 76.9 mg N from CAN per kg soil[4]. An amount of 200 grams of mixture was added to glass flasks with a volume of 500 mL. Air was able to flow in and out of the flasks to prevent CO_2 concentration build up and therefore diffusion of CO_2 back into the mixture.

The experiment included 16 organic fertilisers and two types of blanks:

1. sandy soil with CAN fertiliser (blank BN)
2. sandy soil without CAN fertiliser (blank B)

These 18 treatments were executed in duplicate, resulting in 36 flasks in total. During the experiment, the temperature was kept at 20 °C and moisture content was maintained at 60% of WHC by regular rewetting. The CO_2 evolution from each flask was measured at day 1, 3, 6, 9, 14, 24, 41, 63, 90 and 120, by closing the flasks for 1 hour (at day 1) to a maximum of 7 hours (at day 120), depending on the expected CO_2 evolution, and measuring with a gas monitor. The mixtures were analysed for organic carbon content as well by the Kurmies method, before and after the experiment (t=0 and t=120 days).

Carbon emission from soils mixed with organic fertilisers were measured in duplicate and reported as µg C-CO_2/kg dry soil/hour (Annex 2). These values were averaged and corrected for C emissions from the blank BN sample average, resulting in C emissions originating only from the organic fertilisers. At t = day 0, a CO_2 flux of 0 mg C/kg dry matter/day was assumed. With linear interpolation, the approximate CO_2 flux (in mg C/kg dry matter/day) between measured points of time was calculated. From these velocities, the cumulative C flux (in mg C/kg dry soil) was calculated for each measured point in time.

2.3.3 Nitrogen mineralisation

The methodology that was used was similar to that of Van Groenigen and Zwart (2007). Dried and sieved (5 mm) sandy soil was mixed with organic materials. It was opted for an addition of 76.9 mg N per kg soil (i.e. 200 kg N ha^{-1}, when assuming 2.6 million kg soil ha^{-1}). However, due to unreliable N measurements of the organic materials, different quantities of N were added to the mixture (see section 3.6). We corrected for these quantities based on new measurements. 200 grams of mixture was added to oxygen permeable audiothene plastic bags. Alike the C mineralisation experiment, the 16 selected organic fertilisers and two types of blanks were used. In this case, the blank with mineral nitrogen fertiliser received ammonium nitrate, corresponding with 200 kg N ha^{-1}. For each measurement in time, the bags were removed from the experiment and brought to the lab for analysis of mineral N (NH_4 and NO_3/NO_2). The 18 treatments were executed in duplicate and, because they were to be measured at 7 points in time, in total 18*2*7 = 252 audiothene plastic bags were required. During the experiment, the temperature was kept at 20 °C and, because the audiothene plastic bags do not let through water, the moisture content was set at 60% of WHC without requiring rewetting. Mineral N analyses were performed at day 1, 3, 10, 25, 50, 80 and 120 of the experiment. The mixtures were analysed for organic carbon content as well by the Kurmies method, before and after the experiment (t=0 and t=120 days). Because in this experiment N limitation could occur as no additional mineral N fertiliser was provided, relative C mineralisation was expected to be different from the C mineralisation in the C mineralisation experiment. By executing the Kurmies analysis, this difference could be investigated.

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[3] This corresponds with 7800 kg C/ha in the topsoil of 0.2m, when 2.6 million kg soil/ha is assumed.

[4] This corresponds with 200 kg N/ha in the topsoil of 0.2m, when 2.6 million kg soil/ha is assumed.

Table 2-5 *Amount of N (g kg-1 soil) applied with each material.*

Fertilising product	Mineral N (g kg^{-1} soil)	Organic N (g kg^{-1} soil)	Total N (g kg^{-1} soil)
1. Cattle slurry	123	38	161
2. Pig slurry	184	43	227
3. Organic waste compost	19	85	104
4. Farmyard manure (cattle)	20	76	96
5. Garden peat	10	41	52
6. Straw	14	46	60
7. Grass	14	66	80
8. Chicken manure	15	66	81
9. Monodigested cattle slurry	91	68	159
10. Deep litter stable manure	49	68	117
11. Bokashi	14	78	92
12. WWTP sludge	15	117	132
13. Struvite with organic matter	46	42	89
14. Champost	9	64	73
15. Soil improver from GZV	16	61	77
16. Codigestate from GZV	127	76	203

2.4 Modelling approaches

In this section, three modelling approaches are discussed:

- C mineralisation with a simple two-pool model
- C mineralisation with RothC
- N mineralisation ($N_{min,net}$ (%)) with a new approach in RothC

2.4.1 A simple two-pool model for C mineralisation

In order to describe the mineralisation of organic fertilisers over time (net CO_2 emissions), a first order decomposition of two-pools is assumed. For one pool, the decomposition is described by:

$$\frac{dC}{dt} = -k\,C \tag{1}$$

$$\frac{1}{C}dC = -k\,dt \tag{2}$$

$$[ln\,C]_{C=Co}^{C=Ct} = [-k\,t]_{t=0}^{t} \tag{3}$$

$$ln\frac{Ct}{Co} = -k\,t \tag{4}$$

$$C_t = C_0\,e^{-kt} \tag{5}$$

C	The amount of carbon present due to the addition of organic fertilisers
t	Time
k	Decomposition rate constant
C_0	The initial amount of carbon from organic fertilisers (before decomposition), the amount of carbon at t = 0
C_t	The amount of carbon left from organic fertilisers at t = t

Equation 5 calculates how much C is still present at t = t. The cumulative amount of C that is emitted as CO_2 over time (C_{cum}) can be calculated as follows:

$$C_{cum,t} = C_0 - C_t = C_0 - C_0\;\;e^{-kt} \tag{6}$$

$$C_{cum,t} = C_0\;(1 - e^{-kt}) \tag{7}$$

If the initial amount of C (C_0) is divided over multiple pools - in our study two different organic pools - the total cumulative emission of these two pools can be estimated by means of:

$$C_{cum,t} = C_1 * (1 - e^{-k_1 t}) + C_2 * (1 - e^{-k_2 t}) \tag{8}$$

with C_0 being equal to C_1+C_2. The parameters C_1 and k_1 concern a fast pool of decomposable C and C_2 and k_2 are related to a more slowly decomposable pool of C. Eq. 8 can be rewritten into:

$$C_{cum,t} = C_1 * (1 - e^{-k_1 t}) + (C_0 - C_1) * (1 - e^{-k_2 t}) \tag{9}$$

Or as fraction of the amount applied:

$$\frac{C_{cum,t}}{C_0} = f_1 * (1 - e^{-k_1 t}) + (1 - f_1) * (1 - e^{-k_2 t}) \tag{10}$$

This initial amount of carbon C_0 is the same as the amount of carbon added with organic fertilisers. In our incubation experiment, approximately 3 g C from organic fertiliser was added per kg soil. The value for C_0, therefore, is assumed to be equal to 3000 mg/kg. Three unknown variables remain: f_1, k_1 and k_2. By using EXCEL-SOLVER and minimising the difference with the cumulative C values found with linear interpolation, the optimal values for f_1, k_1 and k_2 were found per organic fertiliser. This overall simple two pool model will be used to fit the optimal curve of the measured mineralisation of each organic product. In fact, not only the fraction size of the two pools (f_1 and f_2) will differ between the organic products but also the associated decomposition rate (k_1 and k_2) of the two pools will differ between the organic products. This does not matter for fitting purposes of the mineralisation experiment, but this method therefore does not give information of on forehand-defined pools with specific characteristics and their own specific decomposition rates.

Furthermore, the determined fraction of the pools in the organic products (f_1 and f_2), via this freely parametrised two pool approach (Eq. 10), differ between the two incubation tests (with a sand soil and a clay soil). Therefore, a more general and conceptual approach is used (as described by RothC model) to determine the size of the specific pools of the organic products independent on with soil type they will be applied (section 2.4.2).

The HC_{2pool} was derived from the data obtained by incubation experiment, following the approach described by van der Burgt *et al.* (2011). In order to recalculate the carbon decomposed during the incubation experiment (120 days) to the fraction that will be left at the end of the year under field conditions (HC), data needs to be corrected for the duration of the experiment and temperature. The incubation experiment was executed by 20℃, and recalculated to field conditions by the correction factor F. The correction factor F was described by van der Burgt *et al.* (2011) based on Janssen (2002), and formulated as follows:

$$F = 2^{(T-9)/9} \tag{11}$$

One year decomposition under field conditions (Netherlands 9℃) then equals 156 days decomposition at 20℃. We used the two-pool-model to estimate the carbon remaining at day 156 to calculate the HC_{2pool} for each material. During the fitting of the incubation tests the parameters C_1, k_1, k_2 were optimised for each fertiliser separately at once by using EXCEL-solver.

2.4.2 RothC

Over the last few decades, several models have been developed to simulate C and N dynamics in agricultural soils. Some of these models share the same principles when it comes to C decomposition or N mineralisation and immobilisation. Comparisons of such models have been made by Lesschen *et al.* (2020), De Willigen *et al.* (2008) and Heinen and de Willigen (2005). Aiming at the development of a conceptual framework to evaluate organic fertilisers, Schoumans *et al.* (2019) propose to adjust the RothC model to make it suitable to predict the C and N dynamics after the application of organic materials, taking into account the variable characteristics of the organic materials. In the next sections the RothC model approach is described in more detail.

RothC is commonly used to forecast organic carbon dynamics in agricultural soils. RothC uses five carbon pools, based on their resistance to decomposition (Coleman and Jenkinson, 2014). A visualisation of the model pools and turnover processes is discussed in more detail in the next section. Originally, parameter values were obtained by iterative fitting based on data derived from long-term field experiments in Rothamsted (Jenkinson *et al.*, 1987; Jenkinson *et al.*, 1992). Standard values are set for decomposition and efficiency parameters, and pool sizes are obtained by an equilibrium run. Establishing RothC partition coefficients based directly on measurements would facilitate the simulation of the long-term effects of a wide range of organic materials, considering their very variable composition and decomposability depending on their origin. Before selecting parameters presented in section 2.2, it is essential to gain a basic understanding of the RothC pools and the opportunities to improve the pool-concepts explored by others.

2.4.2.1 RothC pools

RothC divides soil organic matter into five different pools: decomposable plant material (DPM), resistant plant material (RPM), humified organic matter (HUM), microbial biomass (BIO) and inert organic matter (IOM). An overview of RothC pools and turnover flows is visualised the next figure and the decomposition rates are listed in Table 2-6.

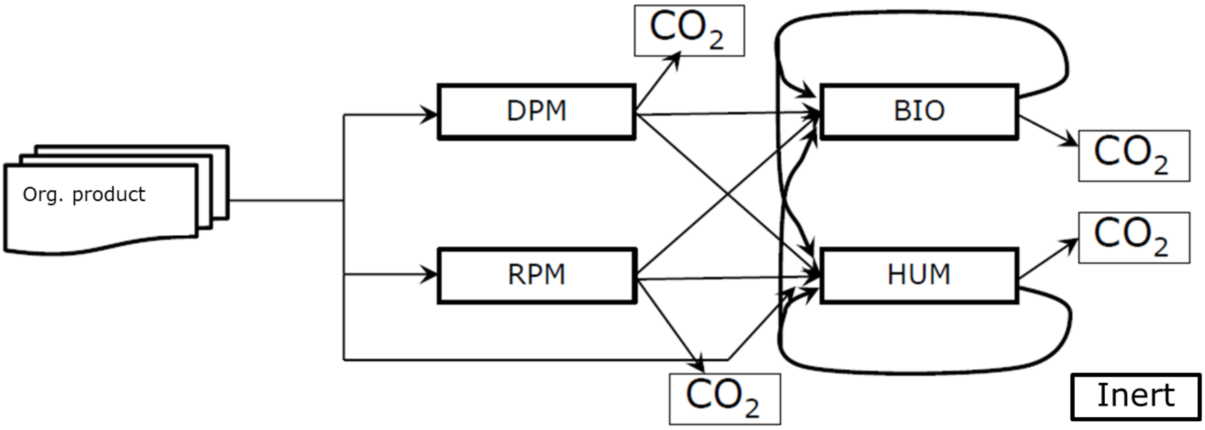

Figure 2-1 *Turnover of organic matter pools as distinguished by RothC.*

Table 2-6 *RothC pools and their decomposition factors (k) as defined by Coleman and Jenkinson (1996).*

RothC pools	**Abbreviation**	**k-value**
Decomposable Plant Material is characterised by a high decomposition rate constant	DPM	10
Resistant Plant Material is characterised by a low decomposition rate constant	RPM	0.3
Humus represents the humified organic matter in the soil, and is characterised by the lowest decomposition rate constant.	HUM	0.02
Microbial biomass represents the soil microbes, and decays to CO2 and humus.	BIO	0.66
Inert Organic Material is resistant to decomposition.	IOM	-

The initial soil carbon pools are calculated based on the formulas shown in Table 2-7. The mentioned average abc-value is a factor that takes into account the local conditions of the soil (monthly temperature, moisture and soil cover). This factor was in our approach set to an average 0.75, based on average temperature, rainfall and evapotranspiration for the province of Gelderland and the assumption of soil cover.

After establishing the initial soil pools, incoming plant material is divided into the DPM and RPM pools. The ratio DPM/RPM is an estimate of the decomposability of the applied material. In RothC application of plant material only consist of DPM and RPM, while manure application consist of a small part HUM (2%). The formulas used in RothC for dividing input material over pools are given in Table 2-8. Decomposition of each of the fractions (DPM, RPM, BIO and HUM) is modelled with a first order process. BIO and HUM (and inert organic matter) are assumed to be inherently present in the soil. DPM and RPM are only ‘produced’ in the soil by addition of an organic product with a specific fraction of DPM and RPM. The decomposed DPM and RPM will partly emitted as CO_2 and will partly turnover in the BIO and HUM pools. The factor X is defined as the ratio of produced C as CO_2 and the amount that in turned over into the BIO+HUM pool, which depends on the clay content of the soil (as used in RothC):

$$X = \frac{CO_2}{(BIO + HUM)} = 1.67 * (1.85 + 1.60 * e^{-0.0786 * \%Clay}) \qquad 12$$

The assimilation fraction (β) determines which part of the total decomposition becomes part of the BIO and HUM pools. So, the assimilation fraction (β) is defined as:

$$\beta = \frac{(BIO + HUM)}{(BIO + HUM + CO_2)} = \frac{1}{1 + X} \qquad 13$$

Consequently, the fraction C emitted as CO2 is defined by:

$$f_{CO2} = \frac{CO_2}{(BIO + HUM + CO_2)} = \frac{X}{1 + X} \qquad 14$$

The sum of β and f_{CO2} is always 1. The influence of the clay content of the soil on the assimilation fraction (β) and the fraction emitted as CO_2 is shown in Figure 2-2. At higher clay contents the net mineralisation is reduced (fraction CO_2 emitted are lower). However the impact is limited.

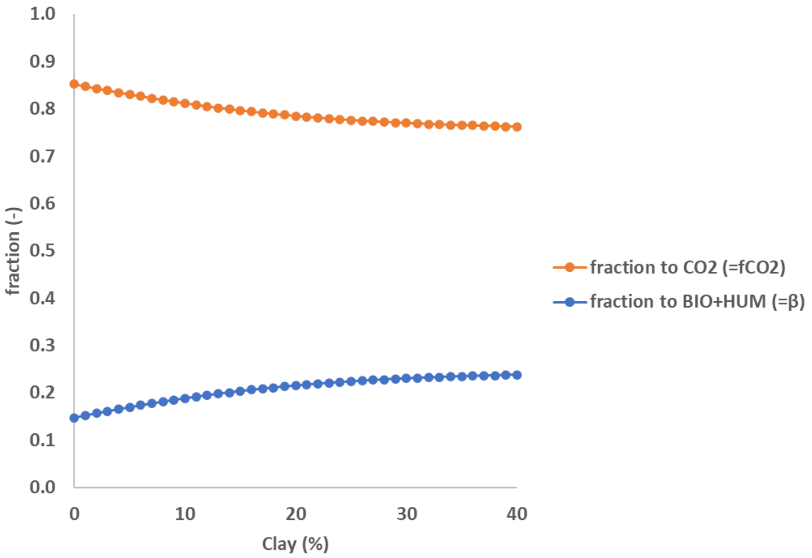

Figure 2-2 *Influence of the clay content of the soil on the fraction of decomposed material that will be emitted as CO_2 and the fraction that becomes part of the (BIO+HUM)-pool.*

The fraction f is the distribution fraction that determines how much of the produced BIO+HUM is attributed to the BIO pool. Consequently, the fraction 1-f is the fraction of produced HUM out of (BIO+HUM). As described by Groenendijk (2016), the turnover rate of each fraction can be described by the following matrix of equations as shown in Figure 2-3. Unfortunately, there is no direct analytic solution of this equation, therefore ‘SOLVER’-function in Excel (iteration) has to be used to find the optimum combination.

$$\begin{pmatrix} \frac{d\,DPM}{dt} \\ \frac{d\,RPM}{dt} \\ \frac{d\,BIO}{dt} \\ \frac{d\,HUM}{dt} \end{pmatrix} = \begin{pmatrix} -k_1 & 0 & 0 & 0 \\ 0 & -k_2 & 0 & 0 \\ f\beta k_1 & f\beta k_2 & -(1-f\beta)k_3 & f\beta k_4 \\ (1-f)\beta k_1 & (1-f)\beta k_2 & (1-f)\beta k_3 & -(1-(1-f)\beta)k_4 \end{pmatrix} \begin{pmatrix} DPM \\ RPM \\ BIO \\ HUM \end{pmatrix}$$

Figure 2-3 *Matrix process rate description of the RothC pools, based on Groenendijk et al. (2016). With k= decomposition rate, f = distribution fraction between BIO and HUM, and β = the fraction of decomposing organic matter that goes to in the BIO and HUM pools.*

Table 2-7 *Description of the initial organic pool sizes in the soil in RothC (Coleman and Jenkinson, 2014; Hendriks et al., 2021).*

Initial pool	**Formulae**
IOM	$IOM = 0.049 * SOC^{1.139}$
DPM_{ini}	$DPM_{ini} = \frac{DPM_{inp}}{k_{DPM} * abc_{average}}$
RPM_{ini}	$RPM_{ini} = \frac{RPM_{inp}}{k_{RPM} * abc_{average}}$
$(BIO+HUM)_{ini}$	$(BIO + HUM)_{ini} = SOC_{ini} - (DPM_{ini} + RPM_{ini} + IOM)$
BIO_{ini}	$BIO_{ini} = \frac{(BIO + HUM)_{ini}}{1 + \frac{k_{BIO}}{k_{HUM}}}$
HUM_{ini}	$HUM_{ini} = \frac{(BIO + HUM)_{ini}}{1 + \frac{k_{HUM}}{k_{BIO}}}$

Table 2-8 *Input pools over which yearly input of organic matter is divided in RothC.*

Input pool	**Input material**	**Formulae**
DPM_{inp}	Plant material	$DPM_{inp} = C_{inp}*0.59$
	Manure	$DPM_{inp} = C_{inp}*0.49$
RPM_{inp}	Plant material	$RPM_{inp} = C_{inp}*0.41$
	Manure	$RPM_{inp} = C_{inp}*0.49$
HUM_{inp}	Manure	$HUM_{inp} = C_{inp}*0.02$

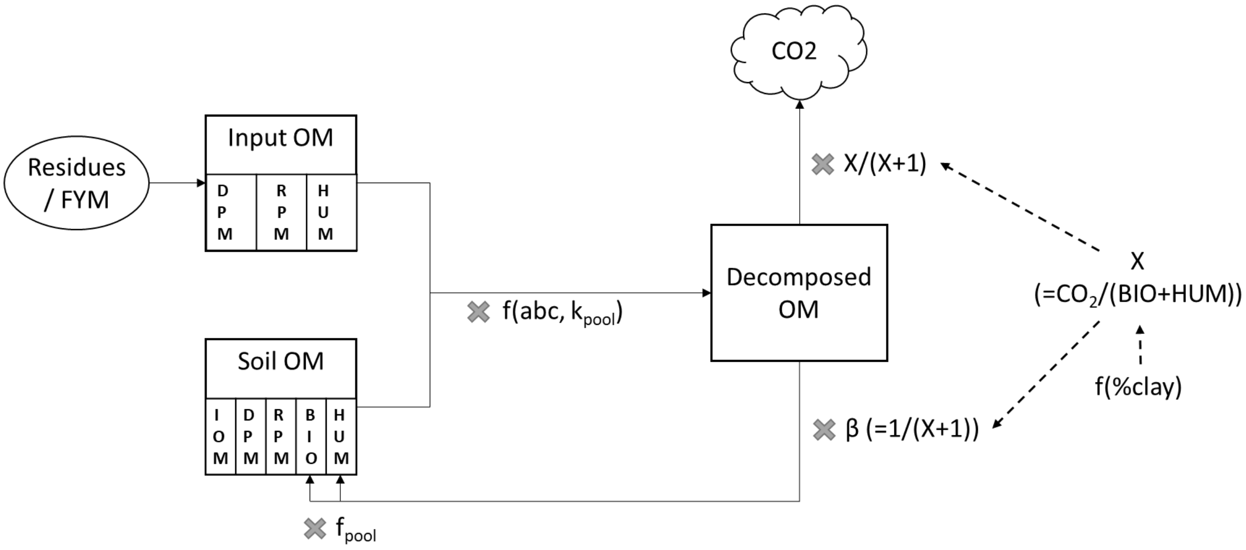

Figure 2-4 *Visual representation of the RothC model per time step. FYM = farmyard manure, OM = organic matter, DPM = decomposable plant material, RPM = resistant plant material, HUM = humified organic matter, IOM = inert organic matter, BIO = microbial biomass, abc = a correction factor for temperature, moisture and soil cover,* k_{pool} *= the decomposition rate of that pool, X = the ratio between the production of* CO_2 *and BIO and HUM pools, %clay = the percentage of clay in the soil, which influences X, ß = the fraction of decomposing organic matter that goes to in the BIO and HUM pools, and* f_{pool} *= distribution fraction between BIO and HUM (*$f_{BIO} = 0.46$*,* $f_{HUM} = 0.56$*).*

Since the model conception, RothC pools have been evaluated and discussed for being based on qualitative concepts rather than measurable entities (e.g., Senapati *et al.* (2013)). In many studies, the concept of the pools have been questioned, and methods are explored, developed and tested to define the pool sizes. In some studies, measurement data were tested as RothC parameters (e.g. (Zimmermann *et al.*, 2007; Peltre *et al.*, 2012; Senapati *et al.*, 2013; Poeplau *et al.*, 2018; Lee *et al.*, 2021)).

A method introduced by Bodemkundige Dienst van België and Universiteit Gent (2006), taking into account the stability of incoming organic material, is to distribute C to DPM and RPM on the basis of the humification coefficient (HC), by the following formula: DPM/RPM-ratio = -2.174 x HC + 2.02 (see 3.2.3.1 for a short evaluation with our data).

To conclude, several attempts have been made to make a link between the RothC pool concepts and measurable parameters (e.g. (Skjemstad *et al.*, 2004; Zimmermann *et al.*, 2007; Peltre *et al.*, 2012; Senapati *et al.*, 2013; Poeplau *et al.*, 2018; Lee *et al.*, 2021). This was done either by making a direct link keeping the RothC parameters constant, by calibrating the RothC pool sizes, or by calibrating the decomposition values. Poeplau *et al.* (2018) conclude that a suitable set of parameters has not been found.

2.4.2.2 Determination of the pool size of the organic products

In the RothC model the application of an organic fertiliser is characterised by three pools, namely DPM, RPM and HUM (see section 2.4.2.1). Each pool fraction (f_{DPM}, f_{RPM} and f_{HUM}) will decompose with a pool-specific decomposition rate (k_{DPM}, k_{RPM} and k_{HUM}). In RothC the decomposition rate factor is multiplied with the monthly abc-factor. The a-factor is the rate modifying factor for monthly air temperature, b-factor is the modifying factor for topsoil moisture deficit of each month and c-factor is the modifying factor soil cover. Since the incubation tests have no moisture deficit and no vegetation, the factors b and c have a value of 1. As a result only the temperature factor is included in the equations, by using the same equation as described in section 2.4.1.

In line with Eq. 10 and Eq.11, the mineralised fraction of the applied amount of organic fertiliser (after a certain time and at an average temperature T) can be assessed by:

$$\frac{C_{min,i}}{C_{tot}} = \left(f_{DPM,i} * \left(1 - e^{-k_{DPM}*t*2^{\frac{T-9}{9}}}\right) + \left(1 - f_{DPM,i} - f_{HUM,i}\right) * \left(1 - e^{-k_{RPM}*t*2^{\frac{T-9}{9}}}\right) + f_{HUM,i} * \left(1 - e^{-k_{HUM}*t*2^{\frac{T-9}{9}}}\right)\right) \tag{15}$$

The RothC standard decomposition rate of each pools are given in Table 2-6, resulting into

$$\frac{C_{min,i}}{C_{tot}} = \left(f_{DPM,i} * \left(1 - e^{-10*t*2^{\frac{T-9}{9}}}\right) + \left(1 - f_{DPM,i} - f_{HUM,i}\right) * \left(1 - e^{-0.3*t*2^{\frac{T-9}{9}}}\right) + f_{HUM,i} * \left(1 - e^{-0.02*t*2^{\frac{T-9}{9}}}\right)\right) \tag{16}$$

Furthermore, it is assumed that the applied organic products do not have a HUM pool with a very low decomposition rate 2% per year (0.02 y^{-1}), resulting into a simple two pool approach with fixed decomposition rates of the two pools DPM and RPM:

$$\frac{C_{min,i}}{C_{tot}} = \left(f_{DPM,i} * \left(1 - e^{-10*t*2^{\frac{T-9}{9}}}\right) + \left(1 - f_{DPM,i}\right) * \left(1 - e^{-0.3*t*2^{\frac{T-9}{9}}}\right)\right) \tag{17}$$

The fraction of mineralised C (after 1 year at a temperature of 9°C) of an organic fertiliser added to the soil can be assessed by:

$$\frac{C_{min,i}}{C_{tot,i}} = f_{DPM,i} * (1 - e^{-10}) + \left(1 - f_{DPM,i}\right) * (1 - e^{-0.3}) \approx f_{DPM,i} + \left(1 - f_{DPM,i}\right) * 0.2591178 \tag{18}$$

As a result, the percentage of C (as applied by the organic fertiliser) that will decompose in the soil (after one year and at average temperature of 9 °C) will vary between 25.9% and 100% at resp. $f_{DPM,i} = 0$ and $f_{DPM,i} = 1$. Similarly, the fraction of C of the product that remains in the soil (known as humification coefficient) becomes:

$$HC = 1 - \frac{C_{min,i}}{C_{tot,i}} = 0.74081822 * (1 - f_{DPM,i}) \tag{19}$$

and this HC will vary between approx. 0% and 74.1% (at resp. $f_{DPM,i} = 1$ and $f_{DPM,i} = 0$). With this assessment the nett accumulation in the HUM- and BIO-pools is excluded.

This means that for rather stable organic products with a low mineralisation (less than 25.9% of applied C), the predicted DPM and RPM fraction will be poorly predicted with the two pool system based on the fractions RPM and DPM (Eq. 14). In that case, it would be better to assume DPM = zero and predict a value for the fractions RPM and HUM (in line with Eq. 14):

$$\frac{C_{min,i}}{C_{tot}} = \left(f_{RPM,i} * \left(1 - e^{-0.3*t*2^{\frac{T-9}{9}}}\right) + \left(1 - f_{RPM,i}\right) * \left(1 - e^{-0.02*t*2^{\frac{T-9}{9}}}\right)\right) \tag{20}$$

With this equation low percentages of mineralisation (2.0% – 25.9%) of organic fertilisers product can be predicted (HC values between 74.1% and 98.0%).

However, in our study the two-pool approach of RothC with DPM and RPM, as expressed by Eq. 14, is used to determine the DPM fraction of all organic products.

The incubation tests were carried out with an application 3 gram organic C (C_o value) per kg dry soil and at a constant temperature (T) of 20°C. So for each organic product the f_{DPM} can be assessed and consequently, f_{RPM} becomes 1-f_{DPM}.

Since the fractions of DPM and RPM in an organic product are product-specific and not depending on external conditions (temperature, clay content, moisture deficit etc), differences in net mineralisation (in fact emitted as CO_2) of the products in different soil types should be due to (1) changes assimilation factor (β) which depends on the clay content, but that influence is inherently limited (Eq. 12 and 13; Figure 2-2) and (2) abc-factor; the decomposition rate modifying factor. Of the abc-factor, only factor b (top soil moisture deficit factor) is dependent on soil type (clay content). Because there is no moisture deficit during the incubation tests, however, there is no influence of the soil type (clay content) due to the abc-factor. Since the reduction in mineralisation in the clay compared to the sand soil cannot be explained by the difference in assimilation factor (β) alone, in our study one of the decomposition rate factors is adjusted. In our study the decomposition rate of easily decomposable carbon pool (DPM) is kept at 10 (y^{-1}) for both soils (sand and clay) in line with the standard value of RothC. For the decomposition rate of the RPM pool in sandy soils also the standard value of RothC is used (0.3 y^{-1}), while for clay soils an adjusted value (0.08) is used in order to the predict the reduced net mineralisation of the organic products in clay soils compared to sandy (as measured in the incubation experiments).

Table 2-9 *Input parameters RothC used in our approach for model initialization.*

Parameter	Soil type (if relevant)	Value	Source
k_{DPM}		10	Coleman and Jenkinson (1996); (Coleman and Jenkinson, 2014)
k_{RPM}	Sandy soil	0.3	Coleman and Jenkinson (1996); (Coleman and Jenkinson, 2014)
	Clay soil	0.08	Adjusted, based on parameterisation with experimental incubation data of this study
k_{BIO}		0.66	(Coleman and Jenkinson, 2014)
k_{HUM}		0.02	(Coleman and Jenkinson, 2014)
β	Sandy soil	0.16	Based on the clay percentage[5]
	Clay soil	0.23	Based on the clay percentage
α		2.33	Based on temperature[6]
Clay content (%)	Sandy soil	3	Measured
	Clay soil	32	Measured
OM content (%)	Sandy soil	1.6	Measured
	Clay soil	2.9	Measured
Temperature (T)		20	-

2.4.3 Determining $N_{min,net}$ incubation

$N_{min,net}$ is commonly defined as the amount of organic N of exogenous organic material that becomes available as mineral N. In Dutch research, N mineralisation of an organic product is commonly determined at 28, 42, 84 or 120 days (Velthof, 2003; Smit *et al.*, 2004; Van Groenigen and Zwart, 2007; Zwart, 2007; Reuland *et al.*, 2022), by analysing mineral nitrogen content at time t=t and correcting for t=0 days and for the blank (i.e. the N mineralisation of the soil without organic product). Because N mineral was not measured in our experiment at t=0, the values of t=1 day were used instead for calculating the mineralisation over time. We determined $N_{min,net}$ (%) incubation by averaging the N that had become available after 80 at 120 days during the incubation. (~ available N at 100 days). Corrected for the blank, $N_{min,net}$ (%) incubation can be calculated with the following formula:

$$N_{min,net}(\%\ N_{org}) = \frac{N_{min(t=x)} - N_{min(t=0)}}{N_{org}} * 100\% \tag{21}$$

2.4.4 Modelling nitrogen mineralisation based on RothC pools

Van Faassen and Lebbink (1994) integrated N mineralisation in RothC, arising from the challenge to synchronise N supply of organic manure with crop demand in integrated farm systems. The distribution of C and N over the pools is done on the basis of the C/N-ratio. The underlying assumption is that the stability of a pool, expressed in its constant decomposition rate k, corresponds to its C/N-ratio. The C of the organic material was distributed over DPM and RPM so that the summed turnover by the model fits the given humification coefficients (Van Faassen and Lebbink, 1994). The N in organic material is then distributed on the basis of the set C/N-ratios of each pool. The C/N ratios are 80, 4, 12 and 12 respectively for RPM, BIOM (=BIO), POM (defined by Van Faassen and Lebbink (1994) as young humus, and is similar to the HUM pool that we have described before), COM (=IOM) and the remainder of residue C and N was put into the DPM

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[5] β =1/(1+1,67*(1,85+1,6*EXP(-0,0786*clay percentage))).

[6] $\alpha = 2^{(T-9)/9}$

pool. Decomposition rates (k) are 0.35, 0.15, 0.005, 0.12 and 0 for DPM, RPM, POM, BIOM and COM respectively. These values were determined by iterative fitting, based on empirical humification coefficients. These humification coefficients were 0.35 for stubble, straw and old roots, and 0.50-0.85 for very persistent organic matter. N turnover is derived from C turnover: N released from decomposed organic matter inputs (equal to the C/N ration) minus N immobilised in products formed equals net N mineralisation or net immobilisation of mineral-N (Van Faassen and Lebbink, 1994). The article mentions that gross N immobilisation is based on model calculations, but does not provide equations.

Based on similar assumptions, Coleman *et al.* (2017) included N mineralisation in RothC. To determine initial values for HUM+BIO+IOM, the model was run to equilibrium until the modelled C_{org} matches the initially measured C_{org}. The authors based the initial values of the nitrogen pools on the C/N ratios of each pool. For BIO-N and HUM-N, the C/N ratio was fixed at 8.5. Additional temporary pools for dissolved organic carbon (COD) and nitrogen (DON) were created, and 4.6% of the added FYM is put directly to DOC and DON and is lost by leaching and/or runoff immediately before entering the SOC and SON pools. Decomposition and efficient parameters were not mentioned in Coleman *et al.* (2017) and Muhammed *et al.* (2018). Most likely, they used the values set by Coleman and Jenkinson (1996). Nitrogen in each pool that is mineralised or immobilised was calculated on the basis of C dynamics and the C/N ratio.

In our study we used a simple approach similar to Coleman *et al.* (2017) and Van Faassen and Lebbink (1994), deriving N turnover from C turnover.

In the first place, for each of the organic materials the DPM and RPM fractions were derived from the incubation tests measurements (RothC fitting approach).

Secondly, the C/N ratio of DPM was calculated by (adapted from Bonten *et al.* (2016)):

$$CN_{DPM} = \frac{DPM_{in}}{N_{in} - \frac{RPM_{in}}{CN_{RPM}}} \tag{22}$$

where

CN_{dpm} and CN_{rpm} = C/N ratios of resp. decomposable and recalcitrant plant material in the organic material (-)

DPM_{in} and RPM_{in} = input of decomposable and recalcitrant plant material via the organic material (kg yr^{-1} C)

N_{Iin} = input of total N via the organic material (kg yr^{-1} N)

The C/N ratios of RPM and BIO were derived from literature (Van Faassen and Lebbink, 1994; Bonten *et al.*, 2016; Coleman *et al.*, 2017). The C/N ratios for RPM, BIO and HUM were set to 100, 8.5 and 8 respectively. Furthermore, for each RothC pool the parameters of turnover processes were set as described in section 2.4.2.

Thirdly, the soil organic matter content of the topsoil (sand as well as clay) was divided over the five RothC pools as presented in Table 2-7.

Finally, the net N mineralisation or immobilisation is calculated by the difference of (1) N released over time from the decomposition of applied organic materials (calculated from DPM and RPM and their C/N ratio) and (2) the N that accumulates in the organic pools of the soil (HUM & BIO).

Since the N release of the decomposition of the products is always positive, the net N immobilisation of the product applied to the soil is highly dependent on the distribution of the soil organic matter content over the pools and the mineral N content in the soil.

2.4.5 Correlations

In order to find relatively easy methods to predict C and N turnover, we examined to which extent (sets of) parameters obtained by laboratory analyses could explain the variation with the modelled C and N turnover. The following approaches were tested:

a. A parameter or a combination of parameters from the laboratory analyses which explain the HC_{2pool}.
b. A parameter or a combination of parameters from the laboratory analyses which explain the $N_{min,net}$ resulting from the incubation experiment.
c. A parameter or a combination of parameters from the laboratory analyses which are useful for model initialization in RothC.

Parameters were tested individually on linear and non-linear correlations. On the basis of these results in combination with the hypotheses formulated in paragraph 2.2, parameters were selected, clustered and tested by for- and backward stepwise regression, by using the ‘bestmodel’ procedure in R. The following formula was used:

$$y = constant + a\ (parameter\ 1) + b\ (parameter\ 2) + c\ (parameter\ n) \tag{23}$$

The y-variables investigated were the HC resulting from the two-pool model, $N_{min,net}$ and the DPM fraction of RothC. The regression analysis input was due to the best model procedure limited to 12 parameters in total. The parameter values were expressed per kg C_{org}.

2.4.6 Model application in crop rotations

The RothC model, using DPM and RPM values as found in this study and supplemented with a nitrogen turnover module, was applied on common crop rotations in the Netherlands to predict C and N mineralisation, both for common fertilising schemes as well as for the assessment of relatively new organic materials. The common crop rotations and fertilising schemes are described by van Rotterdam *et al.* (2021), the most relevant are selected and listed in 0. The relatively new organic materials were integrated by replacing slurries with either solid manure, processed manure or struvite with organic matter (fertiliser products), and compost with either garden peat, bokashi, WWTP sludge, champost, or soil improver GZV (soil improving products). The total applied P_2O_5 was kept constant and the total applied N was kept between legal limits. The approach enables a comparison between the current common fertilisation, and a realistic assessment of new organic materials.

2.5 Approaches for evaluating economic aspects

The impact of organic matter applications on economic aspects has been investigated with two approaches: i) the capability of the organic fertiliser to maintain the soil organic matter content (SOM; or soil organic carbon, SOC) and ii) carbon credits for carbon sequestration.

2.5.1 Value of organic matter to maintain SOM

In a meta-analysis by Renske Hijbeek (Hijbeek *et al.*, 2016) the effect of soil organic matter on yield was studied under conditions where sufficient nutrients were supplied by mineral fertilisers. Across 20 experiments the mean additional yield effect was not significantly different. However, for some crop types, such as potatoes (7%), sugar beet (7%), maize (4%) and spring sown cereals (3.4%), the effect was significant on sandy soils. After consultation several colleagues researchers and the outcome of a recent study (Moinet et al, 2023) these numbers do not seem to be suitable to calculate the economic break-even point of SOM-content in a specific soil to produce optimal yield. Therefore, the analysis has focused on the amounts of an organic fertiliser required to maintain the organic matter content of the soil and the associated costs. In order to maintain income, these costs need to be compensated by e.g. increasing the yield, reduction in the use of mineral fertilisers, less costs related to soil / crop management of the field.

In the first place, the annual SOM decomposition needs to be calculated. Secondly, the capacity of the applied organic fertiliser to compensate SOM decomposition has to be estimated by taking into account the legislative aspects for the application of nutrients. Finally, the associated price of the organic fertilisers has to be taken into account.

The annual amount of organic matter decomposition in the soil ($OM_{DC, soil}$) can be calculated by:

$$OM_{DC,soil} = (DC_{rate,soil}/100) * (SOM/100) * d * \rho * 10^4$$

where

$OM_{DC, soil}$	= annual organic matter decomposition of the soil	(kg OM per ha)
$DC_{rate,soil}$	= organic matter decomposition rate in the soil	(%)
SOM	= soil organic matter content	(%)
d	= top layer thickness	(m)
ρ	= bulk density	(kg m^{-3})

In The Netherlands, on most arable land a maximum of about 50 kg P_2O_5 per ha (P norm; PN) may be applied if the P status of the soil is neutral. This is often the limiting factor for application of most organic fertilisers. Consequently, the higher the OM-P ratio of an organic fertiliser, the more OM can be applied. The amount of SOM that needs to be maintained, relative to the amount of P norm (PN) that can be applied as maximum, is called the PN based maintenance value ($M_{OM,PN}$) expressed in kg OM per kg P_2O_5:

$$M_{OM,PN} = OM_{DC,soil} / PN$$

This amount of organic matter decomposition in the soil has to be compensated by the application of an organic fertiliser. Since a part of the organic fertiliser will decompose in the short term, the effective amount of organic matter (EOM) that remains in the soil after a year is often used to calculate the 'organic matter enrichment' of the soil. The humification coefficient (HC) is defined as the fraction of the amount of applied OM that is left over after a year. The EOM of a specific product, $EOM_{prod\ i}$, is therefore equal to the organic matter content of the organic product ($OM_{prod\ i}$, in kg OM per kg product) multiplied with the HC value. Consequently, if the EOM content of the organic product ($EOM_{prod\ i}$) is the divided by its P_2O_5 content ($P_2O_{5\ prod\ I}$, in kg P_2O_5 per kg product), the P_2O_5 based EOM enrichment of organic product i ($ER_{EOM,P2O5,\ prod\ I}$, in kg EOM per kg P_2O_5) can be calculated:

$$ER_{EOM,P_2O_5,prod\ i} = \frac{HC_{prod\ i} * OM_{prod\ i}}{P_2O_{5_{prod\ i}}} = \frac{EOM_{prod\ i}}{P_2O_{5_{prod\ i}}}$$

However, in the Dutch manure act for some organic products (compost based) only a fraction of the amount the phosphate has to be taken into account in relation to the calculation of the amount of P_2O_5 applied P norm according to the P norm (PN) of 50 kg P_2O_5 per ha. The main reason is that also a large part of an amount of soil is applied as product. We will call this fraction ($f_{P2O5,\ law}$). Currently, a value of 0.25 is used for two types of compost (VFG compost and green compost) while for other organic fertilisers a value of 1 will be used.

In general, the percentage of organic matter maintenance that will be compensated by an organic fertiliser i is defined as:

$$\%OM_{compensated} = \left(\frac{ER_{EOM,P_2O_5,prod\ i}}{f_{P_2O_5,law}}\right)/M_{OM,PN}$$

Besides this product maintenance fraction of the organic fertiliser also the costs of the product need to be taken into account in relation to the maximum application of 50 kg P_2O_5 per ha (PN), leading to the price in euros per hectare:

$$Price_{prod\ i,field} = \frac{PN * Price_{prod\ i}}{f_{P_2O_5,law} * P_2O_{5_{prod\ i}}}$$

In the Netherlands the prices of manure are currently negative, which means that arable farms will get money if they accept manure as organic fertiliser on their farm. This is an artefact of the current manure market in The Netherlands. Since there is no information of the prices to be paid to the farmer for each of the long list of types of manure, it is assumed that the market price of dairy slurry will become €5 per ton in the future. This is not unrealistic since the livestock density and manure production is decreasing rapidly nowadays. Dairy slurry is set as reference since dairy slurry is highly accepted as organic fertiliser on arable farms because of the nutrient rations in dairy slurry. The prices of other manure types are related to the price of dairy slurry based on the relative OM ratio of the two products. E.g. the OM-content of pig slurry is 7.9% and dairy slurry 7%, so the price of pig slurry becomes 5 * (7.9/7.1) =€5.55. To illustrate the economic aspects an intercomparison will be made for several organic fertilisers in terms of capability to maintain organic matter content of the soil and by taking into account the costs of the organic fertilisers. However, this is an oversimplification of the price setting, because in practice also the nutrient content of the organic fertilising products will be taken into account.

Another remark has to be made. The effective organic matter after one year (EOM) is used in this approach. In fact, after one year still a part of the EOM will decompose. In fact, it is assumed that the decomposition of EOM will largely become part of the humus and biomass pool, but this will likely not be the case for products with a low humification coefficient (HC). In those cases the compensation fraction will be overestimated. However, in agricultural practices the EOM values of organic products are frequently used as an organic matter indicator to maintain the organic matter content of the soil.

2.5.2 Carbon credits

In order to determine the economic value of organic fertilisers in terms of carbon credits, a bio-economic farm model 'Farmdyn' (Britz *et al.*, 2014) has been used. Farmdyn is a detailed linear programming model which simulates the economic decision-making process of individual farmers. The model calculates optimal farm management and income. With this model the economic value of organic fertilisers can be calculated based on optimal farm management and income in a scenario without and a scenario with the possibility to use organic fertilisers. The difference between the calculated incomes in the two scenario's is used for the determination of the economic value of the used organic fertiliser and the value of the organic matter content in this fertiliser.

The model is used for an analysis of the effect of carbon credits on the cropping plan and on the use cattle slurry and green compost. This scenario rewards the environmental service of storing carbon in soil by subsidizing carbon sequestration, with the intend to motivate farmers to adapt their farming practice towards a practice that results in more soil organic carbon (SOC) at the long term. The effects on cropping plan, income and the organic matter balance are based on comparison to a base scenario without the use carbon credits.

For the carbon credits two scenarios are simulated:
1. €30 per ton CO_2
2. €200 per ton CO_2

In both scenarios the basis of the model is the same as the base scenario that is used to calculate the value of organic fertiliser. In the scenarios of €30 and €200 the farmer is subsidized for CO_2 stored. This is a broad range since real prices for C-storage are not published. In Europe the carbon credits prices are currently (19 October 2023) about 80 Euro[7]. In the calculations the amount of CO_2 stored is calculated by dividing total effective organic matter by two, as 50% of organic matter consists of carbon. This is multiplied by a factor that determines the weight of carbon as part of carbon dioxide (44/12). The scenarios will show the effect of a carbon credit and the difference in effect between a credit of €30 and €200. The decision that are possible in the model are the same as the basic model.

A second approach is based on the contribution of an organic fertiliser on the long-term carbon storage (after 50 years). Based on the HC values of the organic fertiliser, the size of each of the Roth-C pools has been determined and used to determine long term storage.

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[7] https://carboncredits.com/carbon-prices-today/

3 Results and discussion

3.1 Product characteristics

A wide range of organic materials were selected, varying in terms of humification coefficients (HC) and long term N availability (see section 2.1). Results of the lab-analyses of the studied organic fertilising products and the correlation matrix are shown in 0.

Most manures, both raw and processed, had a relatively low dry matter content (~10%), whereas the straw, (dried) grass, chicken manure and struvite were higher in dry matter (~80-90%). The pH of the materials ranged from 3 to 9 (garden peat and farmyard manure).

Garden peat, straw, grass and soil improver from GZV had the highest organic matter contents expressed in dry matter (~90-100%), whereas WWTP dairy sludge and struvite had the lowest OM content (~30%). This corresponds, as expected, quite well with the measured C_{org} contents: the soil improver from GZV and garden peat had the highest C_{org} content (543 and 499 g/kg DM, resp.), whereas organic waste compost, WWTP dairy sludge and struvite were lowest in C_{org} (178, 121 and 107 g/kg DM, resp.). Raw manure and processed manure all had similar C_{org} contents. Materials with a lower C content in the dry matter were also found to have a low proportion of neutral detergent fibre (NDF) obtained by the van Soest analysis.

The EC, total N content and mineral N content in the dry matter were higher in the manures, with the highest values for pig slurry and codigestate from GZV, and lowest in soil improvers (compost, peat, straw, bokashi). The EC was related to both the total N content (R2=0.79) and mineral N content (R2=0.83). The DOC content and HWC showed a similar but less distinctive trend, with lower correlations with N content, among others due to a relatively high value for grass for both DOC and HWC.

The C_{org}/N ratio was low for most manures, WWTP dairy sludge and struvite (~2-8), and higher for straw, peat and soil improver from GZV (~40-90). Taking the C_{org}/N_{org} ratio resulted in similar results except for more average instead of low values for the manures (~10-25). Low C_{org}/N ratio is somewhat associated with a high HWN (see Figure 3-1) and high PMN, indicating a high level of available nitrogen. The relationship between HWN or PMN and C_{org}/N is, however, not linear.

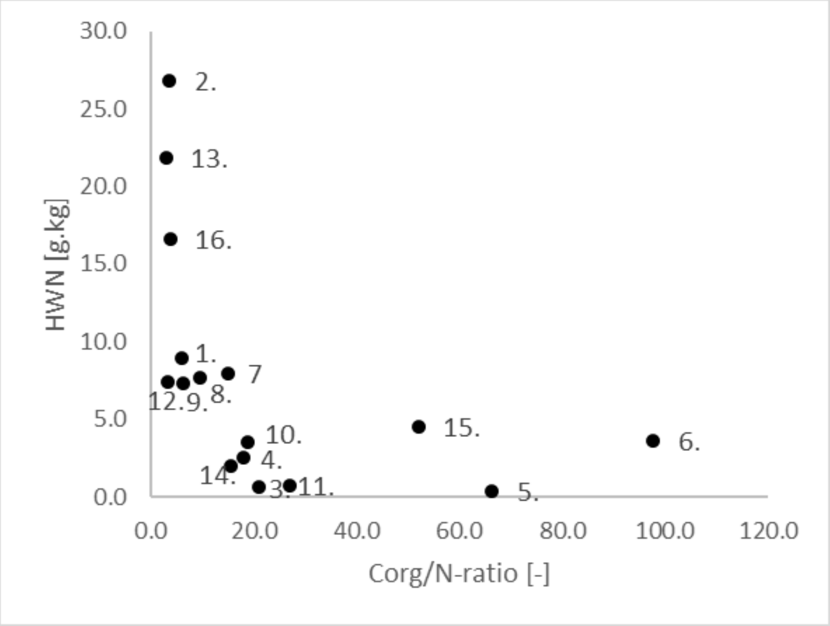


Figure 3-1 *HWN versus Corg/N-ratio of all 16 organic materials assessed in this study.*

The HWC, Oxygen Index (OI), Hydrogen Index (HI), Oxitop and the I-index are all expected to describe the more labile fraction of C. Contrary to the expectations, these indicators, expressed per amount of organic C, do not seem to be related to one another (see 0). Furthermore, these indicators are not (linearly) correlated to the amount of organic carbon decomposed in this study after 120 days at 20C. Therefore these fractions are describing distinctive characteristics of the materials instead of a similar fraction present in the product.

The MicroResp. consists of several indicators, and a sum of all (the total respiration). A high total catabolic respiration response would be associated with the growth of the microbial community and higher decomposition (Sultana, 2011). Expressed per amount of organic carbon in the product, the respiration on struvite was generally the lowest. The highest respiration levels were found for grass and pig slurry. Especially for respiration on Alanine, a high correlation was found with the cumulative amount of decomposed carbon in the incubation experiment at 120 days at 20 C (R2=0.76).

Parameters such as the R-index and COD/BOD ratio are expected to describe the more stable fraction of C in the organic materials. A higher COD/BOD ratio may indicate the presence of organic matter that is harder to biodegrade, meaning microbiologically stable. Organic materials with a high COD/BOD ratio were garden peat, soil improver from GZV, champost, bokashi and farmyard manure. Grass, chicken manure and struvite had a low COD/BOD ratio. The R-index was high for WWTP dairy sludge, struvite, champost and garden peat and low for cattle slurry and straw. These parameters do not indicate similar trends. When relating the results to the cumulative carbon breakdown after 120 days at 20 C, the correlation is weak for both parameters (R2=0.36 for COD/BOD and 0.28 for R-index).

Parameters that seem to correlate include COD and the MicroResp. indicators. This may be a result of the type of analyses, since all of those measure respiration on C fractions of the products. These indicators also seem to correlate with Total H. Furthermore, the MicroResp. parameters seem to correlate with the van Soest parameters. This may be due to the fact that materials with a low C fraction are low in lignin and cellulose fractions (as mentioned above), and therefore induce low respiration rates.

The correlation matrix shows that some analyses might be related, however, since there are no strong linear relations, it can be deduced that the analyses indicate different aspects of organic material.

3.2 Carbon

The data obtained from the incubation experiments are presented in 0 and Figure 3-2, the model parameters derived are presented and discussed in section 3.2.2 and 3.2.3 and experimental results and model results are compared in section 3.2.4.

3.2.1 Incubation experiment results

Figure 3-2 (data points) shows a large variation in C decomposition between organic fertilisers. Fresh plant material (grass and straw) and animal slurry (both cattle and pig) showed the largest decomposition, while solid cattle manures showed a slower decomposition. Cattle slurry and grass are characterised by a high initial decomposition, while farmyard manure decomposed more steadily. Highly processed materials (such as champost and bokashi) generally showed a low decomposition.

Most of the materials showed a higher decomposition when applied to sandy than to clay soil (except for garden peat and champost), but followed a similar decomposition pattern. Some materials behaved differently when applied to a clay or sandy soil. Organic waste compost, for example, had a relatively high initial decomposition when applied to a sandy soil, which did not occur when applied to a clay soil. For slurry, both for cattle and pig, the initial decomposition was higher in clay soils but the final decomposition was higher in the sandy soil.

By including additional mineral N in the C incubation experiment and not in the N experiment, the effect of N application could be investigated (C*N interaction). When N is not limiting (optimal availability of N), the minimum value of the HC per fertiliser is expected. For example, Van Groenigen and Zwart (2007) found a

HC of 16% for applied straw with an addition of mineral N fertiliser and of 32% for applied straw without an addition mineral N fertiliser. This implies that limitation of mineral N (in soil + N mineralised) reduces the decomposition of the organic product and results into a higher humification coefficient. The actual decomposition (no N addition; effect of soil + fertiliser) can be compared with the maximum/potential decomposition (excess N; effect of soil + fertiliser at excess N levels). However, the analysis performed as to compare the final carbon content of the soils in both experiments, the Kurmies analysis, proved insufficiently precise to measure small differences in carbon content. Therefore, it was not possible in this study to compare the actual and the potential decomposition.

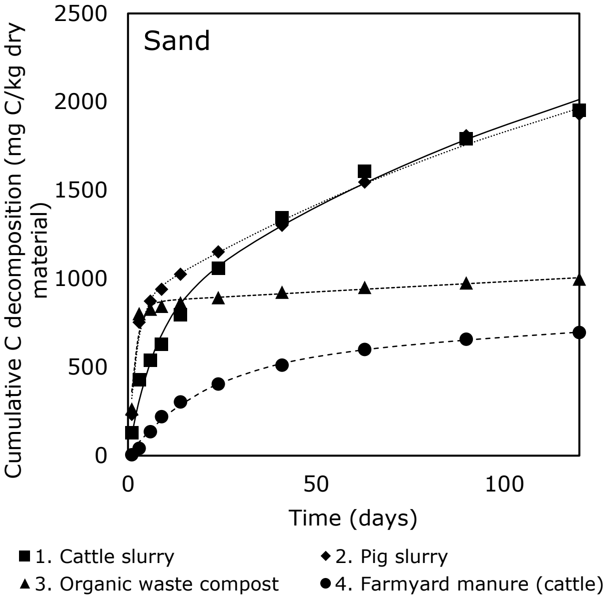
3.2.2 Two pool model for carbon mineralisation

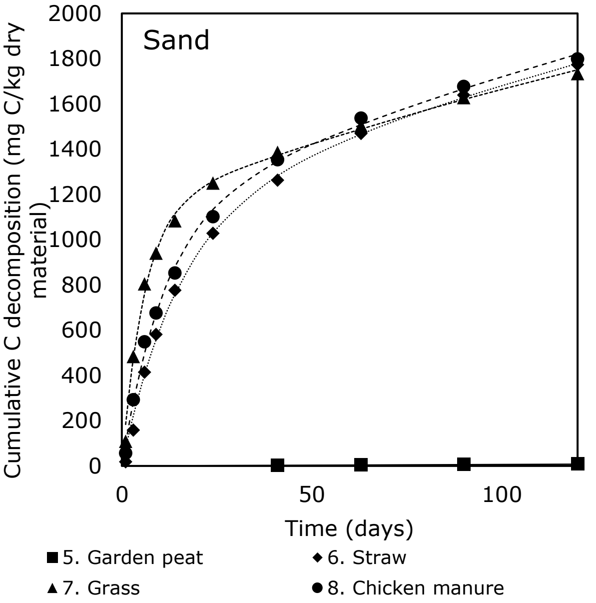
The two-pool model was applied to the carbon incubation experiment. The parameters found are presented in Table 3-1, the corresponding C decomposition is presented in Figure 3-2. As can be derived from the figures, the two model was able to describe the measured decomposition data. Compared to other organic materials, the deviation between plotted and measured datapoints was relative high for cattle- and pig slurry. For clay, the model tends to overestimate the decomposition in day 0-14, underestimates between day 14-90 and overestimates the decomposition again after >90 days. For sand, the deviation for cattle slurry originates from the divergence of measured datapoints. For pig slurry the deviation is due to day 1, the plotted and measured data for day 3-120 show a good fit.

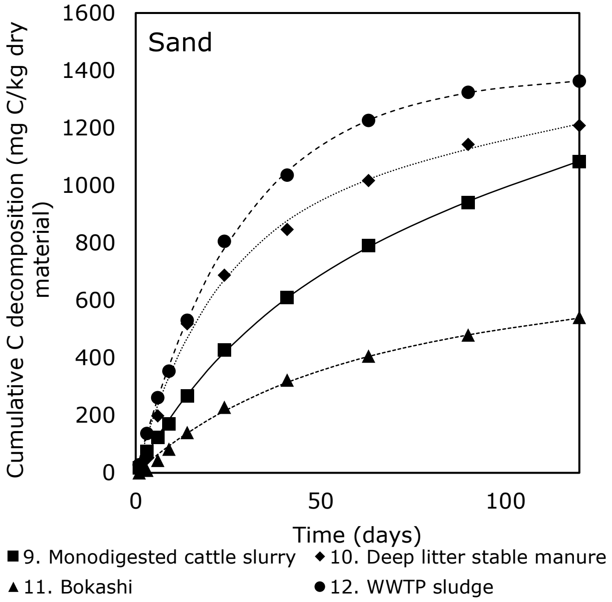
The sum of squared errors (SSE) is used to find the best fits with EXCEL function SOLVER. The errors between measured and modelled values are squared and summed. With SOLVER, the parameters C_1, k_1 and k_2 were adjusted to find the lowest values for the SSE, where C_2= 100%-C_1 Since the values for each organic fertilising product are not relative to each other, and the SSE increases with higher C mineralisation values, the values of the SSE cannot be compared between organic fertilising products.

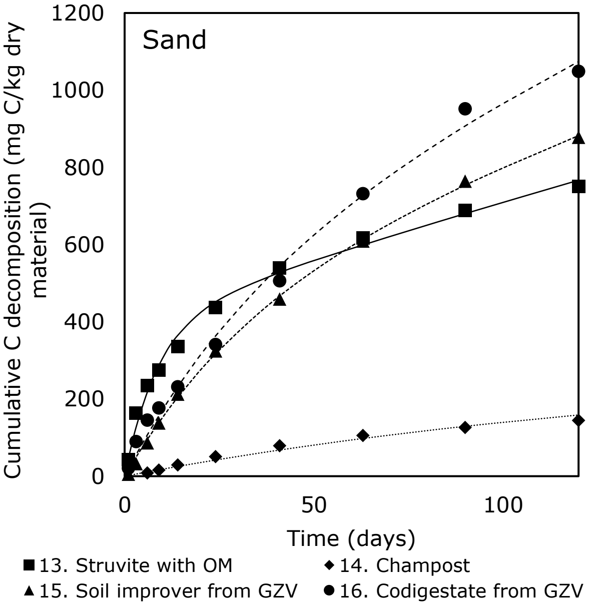
Table 3-1 *Results from the two pool model applied on the results of the C incubation. C_1 (i.e. fast pool) is the amount of carbon assigned to the pool with the highest decomposition parameter (k_1), and C_2 (i.e. slow pool) is the amount of carbon assigned to the pool with the lowest decomposition parameter (k_2). The value of C_2 is set as 100%-DPM. HC_{2pool} is the predicted HC of the organic fertiliser after t=156 days of incubation at 20°C (which equals to 365 days at 9°C as average annual temperature in The Netherlands).*

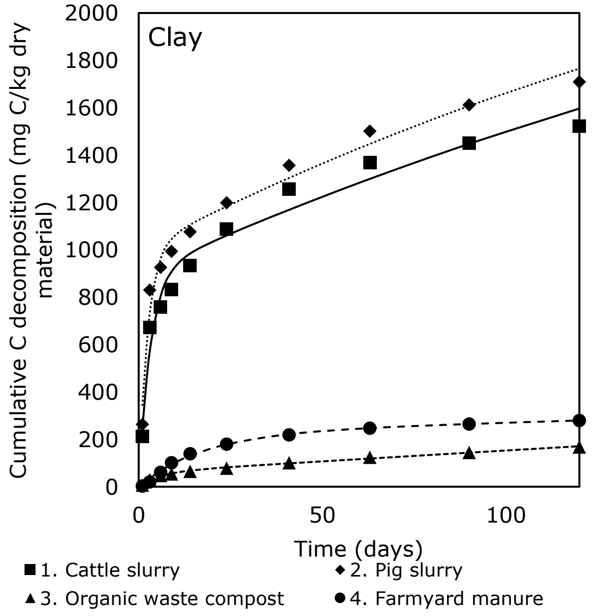
	k_1	C_1	k_2	C_2	HC_{2pool}	
	fast pool	**fast pool**	**slow pool**	**slow pool**		**SSE**
	(day^{-1})	**(%)**	**(day^{-1})**	**(%)**	**(-)**	
Sand						
1. Cattle slurry	6.3E-02	25.0	2.9E-03	75.0	0.26	30761
2. Pig slurry	1.9.E-01	28.6	2.6E-03	71.4	0.28	19429
3. Organic waste compost	2.3E-01	28.9	2.4E-04	71.1	0.65	21989
4. Farmyard manure (cattle)	2.1E-02	17.8	2.5E-04	82.2	0.75	2575
5. Garden peat	1.2E-05	97.4	0.0E+00	2.6	1.00	193
6. Straw	2.9E-02	35.4	1.7E-03	64.6	0.35	8928
7. Grass	7.3E-02	37.8	1.4E-03	62.2	0.37	9333
8. Chicken manure	3.9E-02	35.9	1.7E-03	64.1	0.34	8142
9. Monodigested cattle slurry	1.3E-02	19.8	8.4E-04	79.2	0.59	418
10. Deep litter stable manure	2.0E-02	29.4	6.1E-04	70.6	0.56	13189
11. Bokashi	7.3E-03	21.9	0.0E+00	79.1	0.81	1525
12. WWTP sludge	1.5E-02	45.8	2.6E-05	54.2	0.54	1430
13. Struvite with organic matter	4.2E-02	13.3	5.4E-04	86.7	0.72	4104
14. Champost	3.6E-03	8.6	0.0E+00	91.4	0.94	321
15. Soil improver from GZV	1.3E-02	13.4	7.5E-04	86.6	0.66	846
16. Co-digestate from GZV	1.2E-02	13.4	1.1E-03	86.6	0.58	7838
Clay						
1. Cattle slurry	1.4E-01	29.9	1.4E-03	70.1	0.41	40691
2. Pig slurry	1.8E-01	33.3	1.7E-03	66.7	0.36	30257
3. Organic waste compost	7.3E-02	2.0	1.4E-04	98.0	0.93	96
4. Farmyard manure (cattle)	2.5E-02	7.5	7.2E-05	92.5	0.90	546
5. Garden peat	2.3E-05	17.3	1.7E-05	82.7	0.99	55
6. Straw	2.1E-02	31.5	2.9E-04	68.5	0.62	12156
7. Grass	5.4E-02	31.5	3.4E-04	68.5	0.61	7681
8. Chicken manure	3.8E-02	31.5	6.0E-04	68.5	0.55	5163
9. Monodigested cattle slurry	1.4E-02	11.9	7.8E-05	87.9	0.86	760
10. Deep litter stable manure	1.4E-02	28.6	2.8E-05	71.4	0.71	13194
11. Bokashi	6.1E-03	11.6	5.4E-05	88.4	0.90	306
12. WWTP sludge	1.4E-02	19.2	2.1E-04	80.8	0.75	525
13. Struvite with organic matter	8.8E-02	6.5	9.6E-04	93.5	0.66	843
14. Champost	4.1E-02	4.2	1.2E-04	95.8	0.92	111
15. Soil improver from GZV	1.2E-02	21.5	1.9E-04	78.5	0.74	6664
16. Co-digestate from GZV	1.3E-02	13.1	2.8E-04	86.9	0.79	725

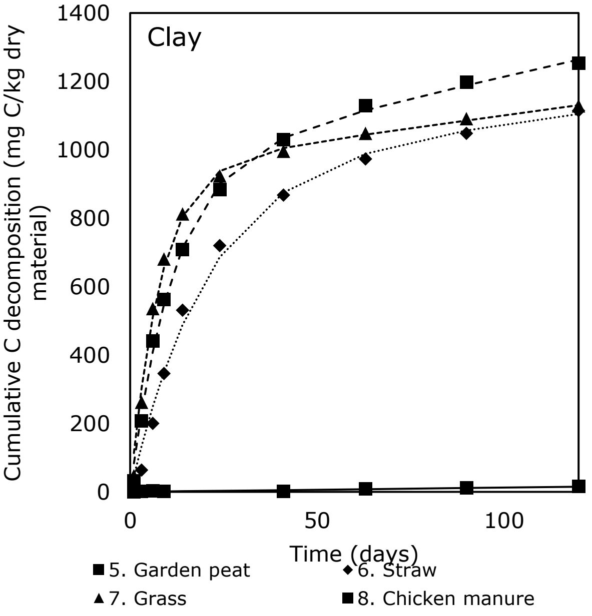

Sand
Cumulative C decomposition (mg C/kg dry material)
0
500
1000
1500
2000
2500
0
50
100
Time (days)
■ 1. Cattle slurry
◆ 2. Pig slurry
▲ 3. Organic waste compost
● 4. Farmyard manure (cattle)


Sand
Cumulative C decomposition (mg C/kg dry material)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
50
100
Time (days)
■ 5. Garden peat
◆ 6. Straw
▲ 7. Grass
● 8. Chicken manure


Sand
Cumulative C decomposition (mg C/kg dry material)
0
200
400
600
800
1000
1200
1400
1600
0
50
100
Time (days)
■ 9. Monodigested cattle slurry
◆ 10. Deep litter stable manure
▲ 11. Bokashi
● 12. WWTP sludge


Sand
Cumulative C decomposition (mg C/kg dry material)
0
200
400
600
800
1000
1200
0
50
100
Time (days)
■ 13. Struvite with OM
◆ 14. Champost
▲ 15. Soil improver from GZV
● 16. Codigestate from GZV


Clay
Cumulative C decomposition (mg C/kg dry material)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
50
100
Time (days)
■ 1. Cattle slurry
◆ 2. Pig slurry
▲ 3. Organic waste compost
● 4. Farmyard manure


Clay
Cumulative C decomposition (mg C/kg dry material)
0
200
400
600
800
1000
1200
1400
0
50
100
Time (days)
■ 5. Garden peat
◆ 6. Straw
▲ 7. Grass
■ 8. Chicken manure

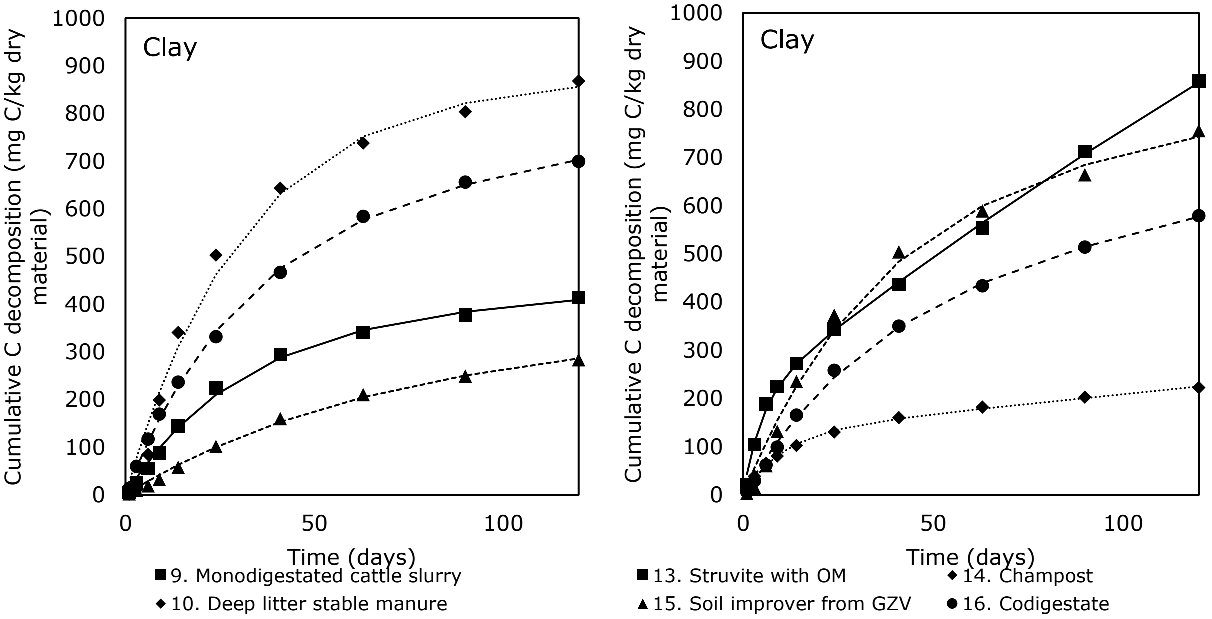


Figure 3-2 *Results of measured data (data points) and the two-pool model (lines): cumulative C decomposition. Mind the y-axis-ranges.*

It seems that in most cases the C-mineralisation can be well described (Table 3-1; Figure 3 2). However, because three variables were fitted, there is a chance that more answers are possible to retrieve the best fit. Furthermore, the ‘fast’ pool can still also be very slow, as is the case for garden peat. Only a small part of this pool has been emitted at t=120 days, whereas for other fertilisers most C of the fast pool was already released at t=120 days.

Based on the differences in predicted parameters of the decomposition of organic fertilisers during the incubation test, we can conclude the following: 1) pig slurry and organic waste compost have the highest values for k_1, which indicates that the quick pool of these fertilisers is very easily decomposable; 2) cattle slurry and pig slurry have the highest values for k_2, which indicates that these fertilisers continue decomposing relatively rapidly also at relative long term; 3) garden peat has very low values for both k_1 and k_2, indicating relative (very) low decomposition.

Furthermore, the expected HC values of the products (see Table 2-2) differ from the HC values of the products found with the two-pool model (Table 3-1). These results are further discussed in section 3.2.4.

3.2.2.1 Correlations

In order to enable quick estimations of the HC of divergent organic materials, it was tested whether parameters obtained by relatively easy lab analyses could explain the HCs that were found on the basis of incubation experiments. Both single parameters and a combination of parameters were tested.

Single parameter

The proportion of variation associated with the correlations is shown in Table 3-2. Correlations between the HC_{2pool} and Microresp. parameters provided relatively high R^2 values. The best fit was obtained by Alanine, which is presented separately in Figure 3-3. Materials with a high HC_{2pool} (5. garden peat; 14. champost) show the largest deviation, along with cattle slurry (1.). Although it was hypothesized that the HC_{2pool} would correlate well with HWC, the Rock Eval parameters and PMN, the data did not support these hypotheses. Strong correlations (R^2>0,5) were mainly found for the Microresp. parameters and for the lignin like fraction (van Soest). A non-linear fit was tested for each parameter, but did not improve the R^2 values.

Table 3-2 Correlations between the characteristics of the organic fertilisers and HC2pool.

	Parameter	**Unit**	**R^2**	
			Sand	**Clay**
	Total N	[g/kg C_{org}]	0.05	0.16
	NH4	[g/kg C_{org}]	0.14	0.30
	H	[g/kg C_{org}]	0.02	0.11
	C/H	[-]	0.03	0.11
	DOC	[g/kg C_{org}]	0.42	0.54
	N_{org}	[g/kg C_{org}]	0.00	0.00
	C_{org}/N	[-]	0.01	0.02
	C_{org}/N_{org}	[-]	0.00	0.00
	EC	[mS/cm]	0.07	0.20
	BOD(5)	[g/kg C_{org}]	0.15	0.20
	BOD(7)	[g/kg C_{org}]	0.17	0.20
	COD	[g/kg C_{org}]	0.39	0.53
	COD/BOD	[-]	0.37	0.24
	HWC(1)	[g/kg C_{org}]	0.07	0.17
	HWC(2)	[g/kg C_{org}]	0.08	0.23
	HWN	[g/kg C_{org}]	0.01	0.12
	N in pepsin	[g/kg C_{org}]	0.01	0.11
	N in pepsin/TN	[-]	0.05	0.11
	PMN	[g/kg C_{org}]	0.22	0.13
Microresp.	Lignin	[ug/g C_{org}/h]	0.62	0.50
	Alanine	[ug/g C_{org}/h]	0.73	0.60
	Aminobutyric acid	[ug/g C_{org}/h]	0.58	0.41
	N-acetyl glucosamine	[ug/g C_{org}/h]	0.65	0.43
	D(+) glucose	[ug/g C_{org}/h]	0.65	0.42
	Alpha ketoglutarate	[ug/g C_{org}/h]	0.05	0.01
	Malic acid	[ug/g C_{org}/h]	0.22	0.11
	Total respiration	[ug/g C_{org}/h]	0.56	0.36
Rock Eval	F1	[%]	0.35	0.29
	F2	[%]	0.20	0.23
	F3	[%]	0.44	0.32
	F4	[%]	0.18	0.13
	I-index	[-]	0.27	0.28
	R-index	[-]	0.31	0.22
	OI	[-]	0.12	0.03
	HI	[-]	0.11	0.16
Van Soest	NDF	[g/kg C_{org}]	0.07	0.00
	ADF	[g/kg C_{org}]	0.17	0.27
	ADL	[g/kg C_{org}]	0.54	0.50
	ADF-ADL	[g/kg C_{org}]	0.05	0.00

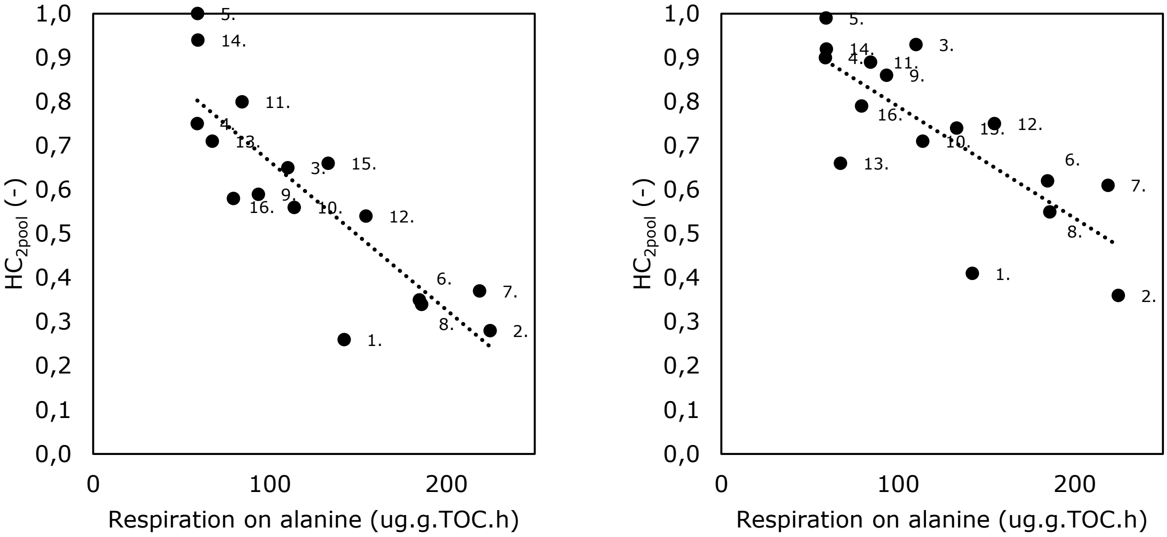


__Figure 3-3__ Correlation between the respiration of the sixteen organic products on alanine (MicroResp.) and the HC_{2pool} obtained in a sand soil (left) and clay soil (right).

Combination of parameters

Various combinations of parameters were tested using a stepwise regression, both for sand and clay separately and together. When the soils were assessed together, the best fit for predicting the HC_{2pool} was obtained by 7 parameters resulting in a R^2-adj. of 92.0 (Total N, DOC, N_{org}, COD/BOD, Alanine, F1 and soil type). A limited number of analyses resulted in a relatively good fit as well: using only total N, Alanine and F3 resulted in a R^2-adj. of 90.9. When soil types were assessed separately, the results slightly improved (Figure 3-4 and Table 3-3). The prediction of the HC with regression had better results for sandy soil than for clay soil. The deviation from the HC_{2pool} result is for sandy soil the largest for champost (14.) and codigestate (16.), and for clay for organic waste compost (3), monodigested cattle slurry(9) and WWTP sludge (12). The deviation for sand is between 0 and 7 percentage point, and for clay between 2 and 12. The fit for clay could be slightly improved when adding two MicroResp. parameters (data not shown).

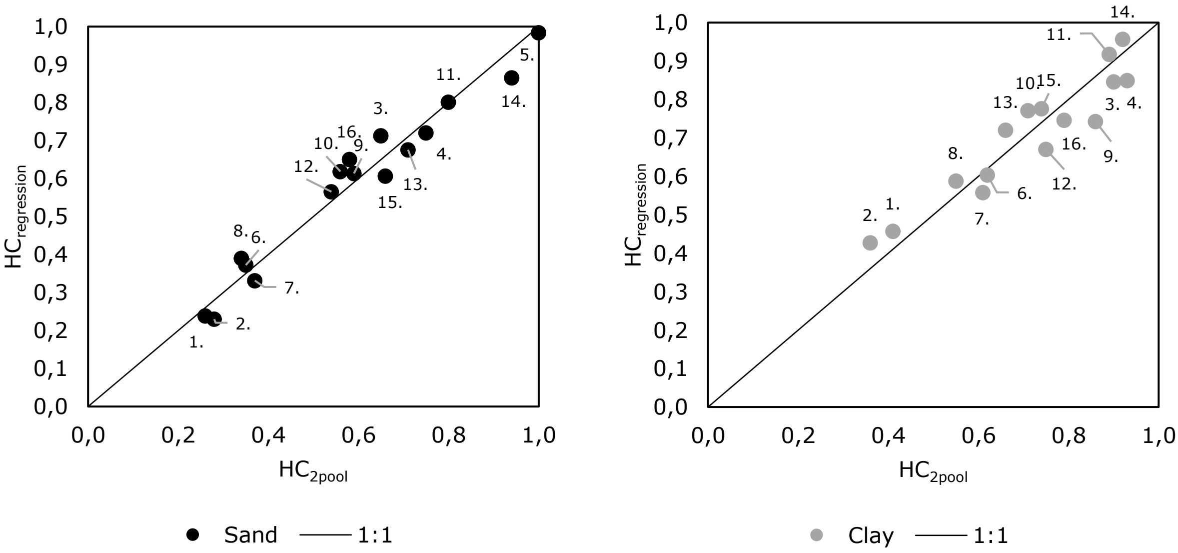


__Figure 3-4__ Correlation between the HC_{2pool} and $HC_{regression}$, for sand (left) and clay (right).

Table 3-3 *Estimates for the $HC_{regression}$ of the organic fertilisers for the sand and clay soil.*

	Sand	Clay
Constant	7.02E-01	8.47E-01
Total N	-6.34E-04	-7.50E-04
Alanine (MicroResp.)	-2.53E-03	-1.87E-03
F1 (Pyrolysis)	1.72E-02	1.32E-02
R^2adj.	94.8	86.0

3.2.3 RothC

3.2.3.1 Decomposable and resistant fractions in RothC

In fact, with the RothC approach the same two-pool model is assumed as described in section 2.4.1 and presented in 3.2.2, but in this case with Roth-C fixed values for k_1 (10) related to DPM and k_2 (0.3 for sand and 0.08 for clay) related to RPM. So, only DPM values of the organic materials can be fitted, since RPM fraction is set as 1-f_{DPM}. The RothC fractions (DPM and RPM) obtained on the basis of the incubation experiment are presented in Table 3-4. $DPM_{calibration}$ is found to be high for fresh material such as grass, straw, chicken manure, cattle- and pig slurry. Processed materials, such as bokashi and monodigested cattle slurry, had a high $RPM_{calibration}$ fraction. Garden peat and champost decomposed slowly and therefore all carbon was allocated to the $RPM_{calibration}$ fraction.

For most agricultural crops and improved grassland a standard value of 1.44 for the ratio of DPM and RPM is used (Coleman and Jenkinson, 1996). We found a range between 0.00 and 1.94 for our data, underlining the need for a differentiated DPM/RPM ratio when using RothC for a wide range of organic materials.

Another approach is to calculate the DPM/RPM ratios on the basis of the HC (Bodemkundige Dienst van België and Universiteit Gent, 2006). We did not find a good agreement between the DPM/RPM ratios from Table 3-4 and the DPM/RPM ratios obtained by using the equation presented by Bodemkundige Dienst van België and Universiteit Gent (2006) using HCs collected from literature (see Figure 3-5). This is for a great part due to the differences in the HC values used, and partly because of the difference in approach (using the formula vs fitting with RothC). When using the HC_{2pool} values for sand and clay, the fit is better (Figure 3-6). It is thus very important that the HC value represents the product well, in case a formula is used to predict DPM/RPM-ratios based on HC values.

These finding suggest that the equation of Bodemkundige Dienst van België and Universiteit Gent (2006) provides a refinement compared to the standard value (1.44), but requires accurate input for the HC value, and is also soil-type dependent.

As discussed at section 3.2.2, the values of the SSE do not represent a relative error and therefore cannot be compared between organic fertilising products.

Table 3-4 *RothC fractions ($DPM_{calibration}$ and $RPM_{calibration}$) and the sum of squared errors that resulted from the calibration of the model output with incubation experiment data.*

	DPM (-)	RPM (-)	DPM/RPM ratio (-)	SSE for sandy soil	SSE for clay soil
1. Cattle slurry	0.60	0.40	1.50	156891	343083
2. Pig slurry	0.66	0.34	1.94	553923	650465
3. Organic waste compost	0.20	0.80	0.25	1905124	804782
4. Farmyard manure (cattle)	0.10	0.90	0.11	40374	23232
5. Garden peat	0.00	1.00	0.00	566918	32139
6. Straw	0.46	0.54	0.85	186034	157681
7. Grass	0.53	0.47	1.13	365256	233156
8. Chicken manure	0.52	0.48	1.08	82899	61324
9. Monodigested cattle slurry	0.16	0.84	0.19	119545	64547
10. Deep litter stable manure	0.30	0.70	0.43	34862	67220

	DPM (-)	RPM (-)	DPM/RPM ratio (-)	SSE for sandy soil	SSE for clay soil
11. Bokashi	0.05	0.95	0.05	10799	5768
12. WWTP sludge	0.30	0.70	0.43	255148	236788
13. Struvite with organic matter	0.19	0.81	0.23	73593	113708
14. Champost	0.00	1.00	0.00	277083	67354
15. Soil improver from GZV	0.18	0.82	0.22	69858	105205
16. Codigestate from GZV	0.17	0.83	0.20	88723	35694

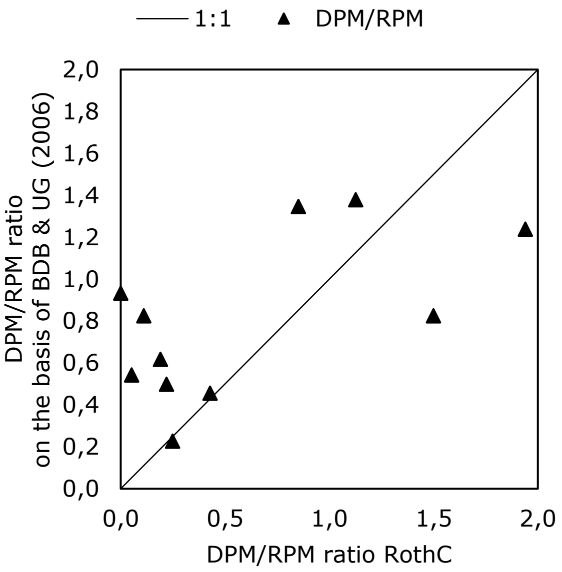


Figure 3-5 *Comparison between DPM/RPM ratios fitted in RothC vs based on literature using the equation introduced by Bodemkundige Dienst van België and Universiteit Gent (2006).*

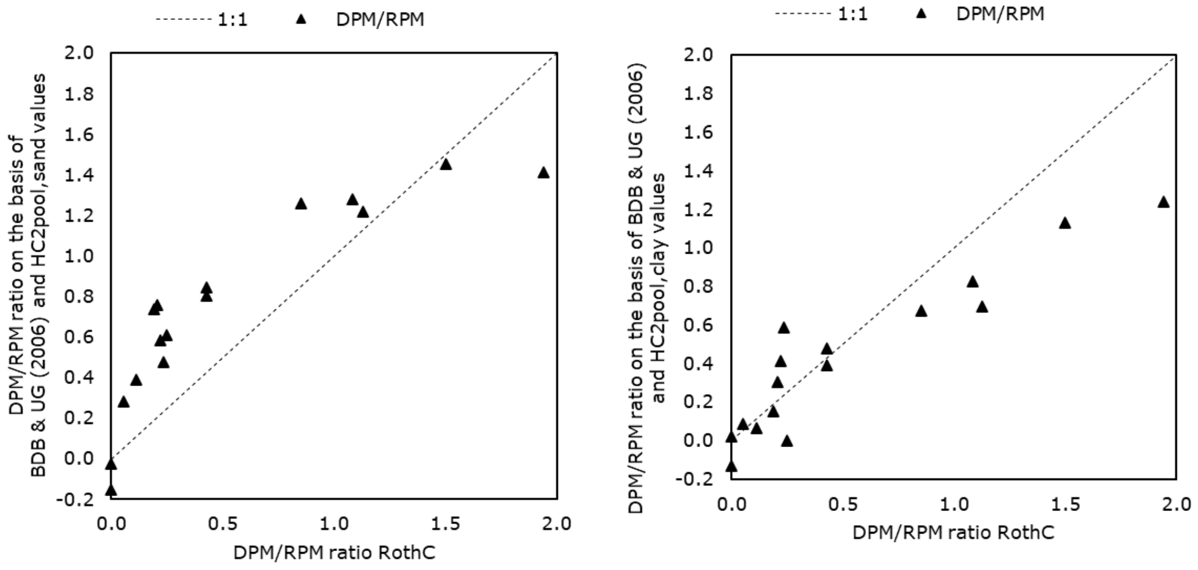


Figure 3-6 *Comparison between DPM/RPM ratios fitted in RothC vs based on* HC_{2pool} *for sand (left) and clay (right) using the equation introduced by Bodemkundige Dienst van België and Universiteit Gent (2006).*

3.2.3.2 Correlations

Single parameter

Since the RPM fraction was fitted as 1-DPM, correlations with measured characteristics were equal for both fractions, with opposite directions. The proportion of variation associated with the correlations is shown in Table 3-5. Strong correlations (R^2>0,5) were mainly found for some Microresp. parameters. Contrary to the expectations, the Rock Eval fractions did not show very strong correlations with the $DPM_{calibration}$ and $RPM_{calibration}$ fractions. It is remarkable that, even though the major part of the correlations are weak, most parameters show a positive relation with $DPM_{calibration}$ (data not shown). These findings suggest that most parameters are an indicator of the labile part of organic carbon, rather than the resistant fraction.

Table 3-5 *Correlations between the characteristics of the organic fertilisers and the $DPM_{calibration}$ fraction.*

Parameter category	Parameter	Unit	R^2
	Total N	[g/kg C_{org}]	0.04
	NH4	[g/kg C_{org}]	0.13
	H	[g/kg C_{org}]	0.04
	C/H	[-]	0.03
	DOC	[g/kg C_{org}]	0.47
	N_{org}	[g/kg C_{org}]	0.00
	C_{org}/N	[-]	0.01
	C_{org}/N_{org}	[-]	0.00
	EC	[mS/cm]	0.18
	BOD(5)	[g/kg C_{org}]	0.22
	BOD(7)	[g/kg C_{org}]	0.24
	COD	[g/kg C_{org}]	0.44
	COD/BOD	[-]	0.23
	HWC(1)	[g/kg C_{org}]	0.08
	HWC(2)	[g/kg C_{org}]	0.08
	HWN	[g/kg C_{org}]	0.02
	N in pepsin	[g/kg C_{org}]	0.03
	N in pepsin/TN	[-]	0.11
	PMN	[g/kg C_{org}]	0.17
Microresp.	Lignin	[ug/g C_{org}/h]	0.70
	Alanine	[ug/g C_{org}/h]	0.81
	Aminobutyric acid	[ug/g C_{org}/h]	0.61
	N-acetyl glucosamine	[ug/g C_{org}/h]	0.67
	D(+) glucose	[ug/g C_{org}/h]	0.65
	Alpha ketoglutarate	[ug/g C_{org}/h]	0.08
	Malic acid	[ug/g C_{org}/h]	0.26
	Total respiration	[ug/g C_{org}/h]	0.61
Rock Eval	F1	[%]	0.32
	F2	[%]	0.22
	F3	[%]	0.36
	F4	[%]	0.16
	I-index	[-]	0.25
	R-index	[-]	0.26
	OI	[-]	0.06
	HI	[-]	0.08
Van Soest	NDF	[g/kg C_{org}]	0.05
	ADF	[g/kg C_{org}]	0.16
	ADL	[g/kg C_{org}]	0.47

Combination of parameters

For the combination of parameters, the same approach was used as for the HC. The best fit was found for the combination of six parameters (DOC, HWC(2), Lignin, Alanine, N-acetyl, F1), with a R^2adj. of 97.65.

Reducing the number of parameters resulted in a good fit as well. A maximum of three parameters (**Total N, Alanine, F1**) resulted in a R^{2}adj. of 96.51. Regression parameters were 0.0004631, 0.002935 and 0.004543 resp. for Total N, Alanine and F1, and -0.3656 for the constant (see Equation 14). A comparison between the pool size obtained by using RothC in combination with incubation data (DPM$_{\text{calibration}}$) and fitted on the basis of laboratory analyses (DPM$_{\text{regression}}$) is shown in Figure 3-7. Various materials are plotted close to the 1:1 line, such as cattle- and pig slurry (1. and 2.). Materials with a DPM between 0.1 and 0.2 show some deviation. The DPM$_{\text{regression}}$ fraction of compost and struvite with organic matter (3. and 13.) are somewhat underestimated, and the DPM$_{\text{regression}}$ fraction of monodigested cattle slurry, soil improver and codigestate (9. 15. and 16.) are somewhat overestimated. The deviation is still very small, and varies between 2 and 8 percentage point.

$$DPM = -0.3656 + 0.0004631 * Total\ N + 0.002935 * Microresp\ Alanine + 0.004543 * Pyrolyse\ F1 \quad (24)$$

with total N in g/kg TOC, Microresp Alanine in µg/kg TOC/h, and F1 in %.

In a follow-up study, this method is being researched. Unfortunately, the results indicate, that the MicroResp method does not give robust results. Therefore, correlations with other parameters are being investigated. The findings will be reported in 2024.

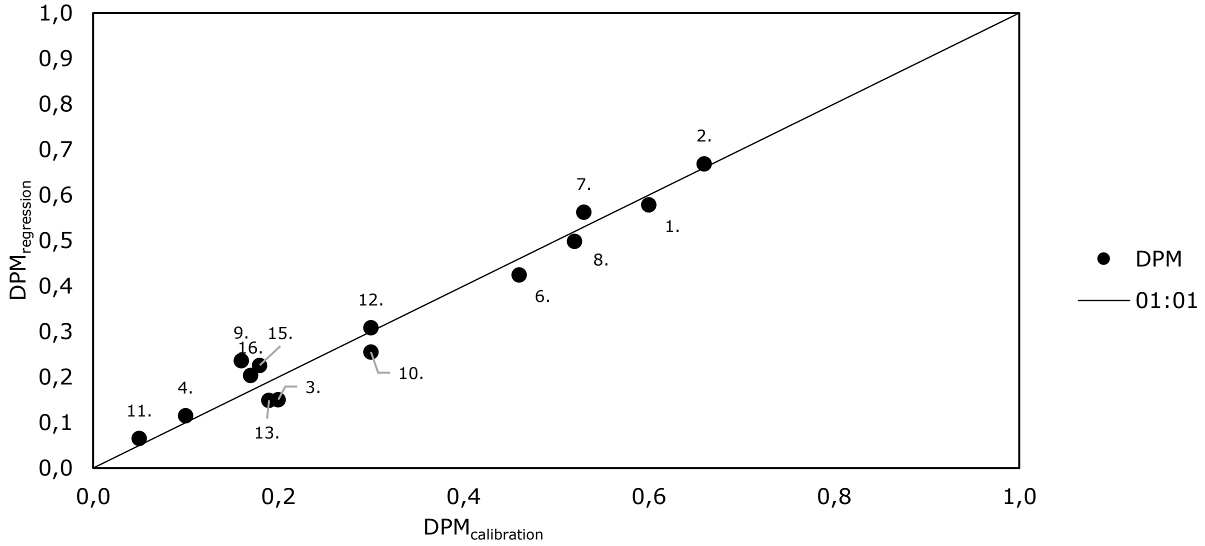


Figure 3-7 *Correlation between DPM pool size estimated by using the RothC model (DPM$_{\text{calibration}}$) and the DPM pool size as predicted with the regression model based on simple laboratory analyses (DPM$_{\text{regression}}$).*

3.2.3.3 Carbon dynamics in RothC

The HCs obtained by applying RothC are shown in Table 3-6 and the comparison between HC obtained from RothC and the HC$_{\text{2pool}}$ in Figure 3-8. For sand, materials with a relatively low HC are overestimated by RothC compared to the two-pool model. Materials with a relatively high HC are somewhat underestimated by RothC compared to the two-pool model. As expected at high HC-values (14. champost and 5. garden peat) the values are under estimated, because no HUM pool has been fitted for materials with a high HC (above 74%; see section 2.4.2.2). For clay soils the differences are limited.

The HC values obtained with RothC range from 0.34 to 0.79 for sand and from 0.44 to 0.95 for clay. Organic materials tend to decompose more slowly when applied to clay soils compared to sandy soils. The results obtained with RothC – as well as the results found with the two pool model; based on our incubation experiments – are generally in line with the HCs known from literature, with a few exceptions. Organic waste compost (3.) had a slightlylower HC in sandy soil than generally assumed, which is a result of the fast decomposition during the first days of the incubation in sand. Other materials had a higher HC than is generally assumed. This was the case for farmyard manure (4.), straw (6.), grass (7.), bokashi (11.) and struvite with organic matter (13.). For straw (6.) when applied to sand this might be due to an overestimation of RothC, for the other organic materials this is a result of the incubation experiments (see section 3.2.4).

Table 3-6 *HC's obtained using RothC on the basis of $DPM_{regression}$ (HC_{RothC}).*

	HC_{RothC}		
	Sand	**Clay**	**HC literature**
1. Cattle slurry	0.40	0.51	0.4-0.7
2. Pig slurry	0.34	0.44	0.3-0.42
3. Organic waste compost	0.68	0.83	0.75-0.9
4. Farmyard manure (cattle)	0.70	0.85	0.5-0.6
5. Garden peat	0.79	0.95	*>0.7*
6. Straw	0.50	0.62	0.31
7. Grass	0.41	0.52	0.26-0.3
8. Chicken manure	0.46	0.57	*<0.35*
9. Monodigested cattle slurry	0.62	0.76	0.57-0.72
10. Deep litter stable manure	0.61	0.75	0.72
11. Bokashi	0.74	0.89	0.68
12. WWTP sludge	0.58	0.71	*0.35-0.7*
13. Struvite with organic matter	0.68	0.83	*<0.35*
14. Champost	0.78	0.95	0.42-0.9
15. Soil improver from GZV	0.63	0.77	0.7
16. Codigestate from GZV	0.65	0.79	*>0.7*

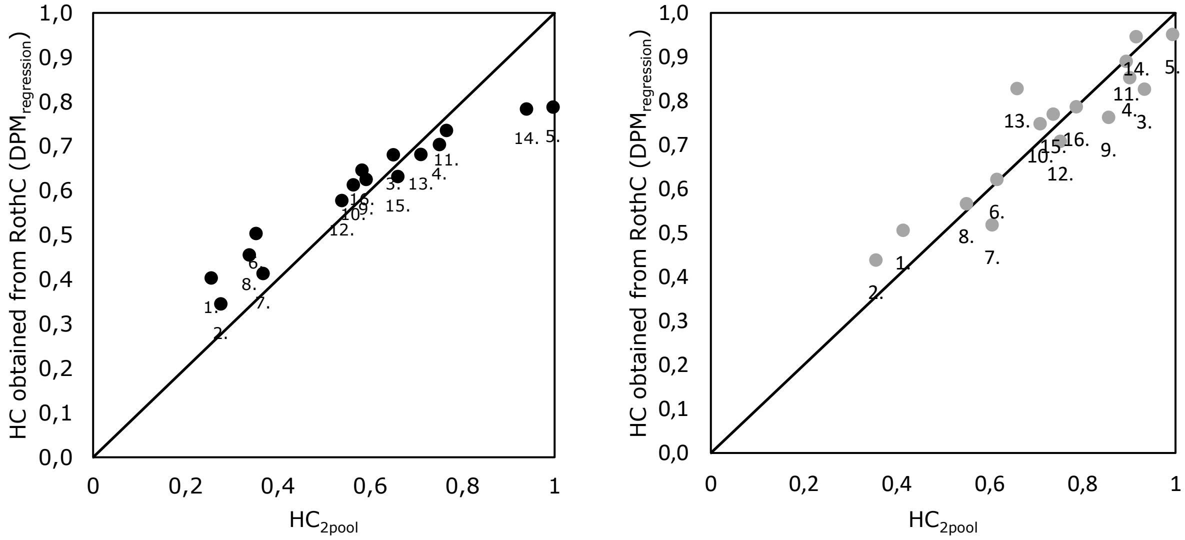


Figure 3-8 *Comparison between HC_{2pool} and HC from RothC (HC_{RothC}) for sand (left) and clay (right).*

3.2.4 Model output versus incubation data

A comparison between the measured C decomposition and modelling approaches is made in Figure 3-9. The results show that the modelling approaches are able to predict the C decomposition to a large extent. Especially applying the two pool model results in C decomposition values close to the measured values (see section 3.2.2), underlining that the two-pool model structure is well suited to describe C decomposition. Although the deviations are somewhat larger, the RothC model structure is also able to describe C decomposition to a large extent. Organic materials that decompose relatively slow are completely assigned to the $RPM_{calibration}$ pool. Although the decomposition parameter belonging to the RPM pool is low, it appeared to be too high for materials associated with a very low decomposition rate, and therefore overestimated the decomposition. This is caused by the fact that for very stable organic materials (poorly decomposable) the contribution of the HUM pool in the organic material was not included (see section 2.4.2.2)

Against the expectations, the modelled C decomposition with RothC using DPM fractions as assessed by the regression of laboratory analysis ($\text{DPM}_{\text{regression}}$) performs in some cases better than RothC using DPM derived from the incubation experiments ($\text{DPM}_{\text{calibration}}$). As shown in Figure 3-9, $\text{DPM}_{\text{regression}}$ did not lead to extremely different results compared to $\text{DPM}_{\text{calibration}}$. This indicates that the approach estimation DPM based on three relatively simple laboratory analyses, is suited to estimate the C-decomposition with RothC.

In fact in all approaches (being i) the freely-fitted two pool model, ii) the regression based on lab analysis and iii) RothC) the calculated values of the past pool/DPM and the slow pool/RPM based on incubation measurements were able to predict the measured emissions (model calibration). Model validation with an independent dataset should be done to indicate (1) the accuracy of the regression model approach to determine DPM and (2) to determine if indeed for materials with a high HC value the HUM fraction should be taken into account in the RothC approach.

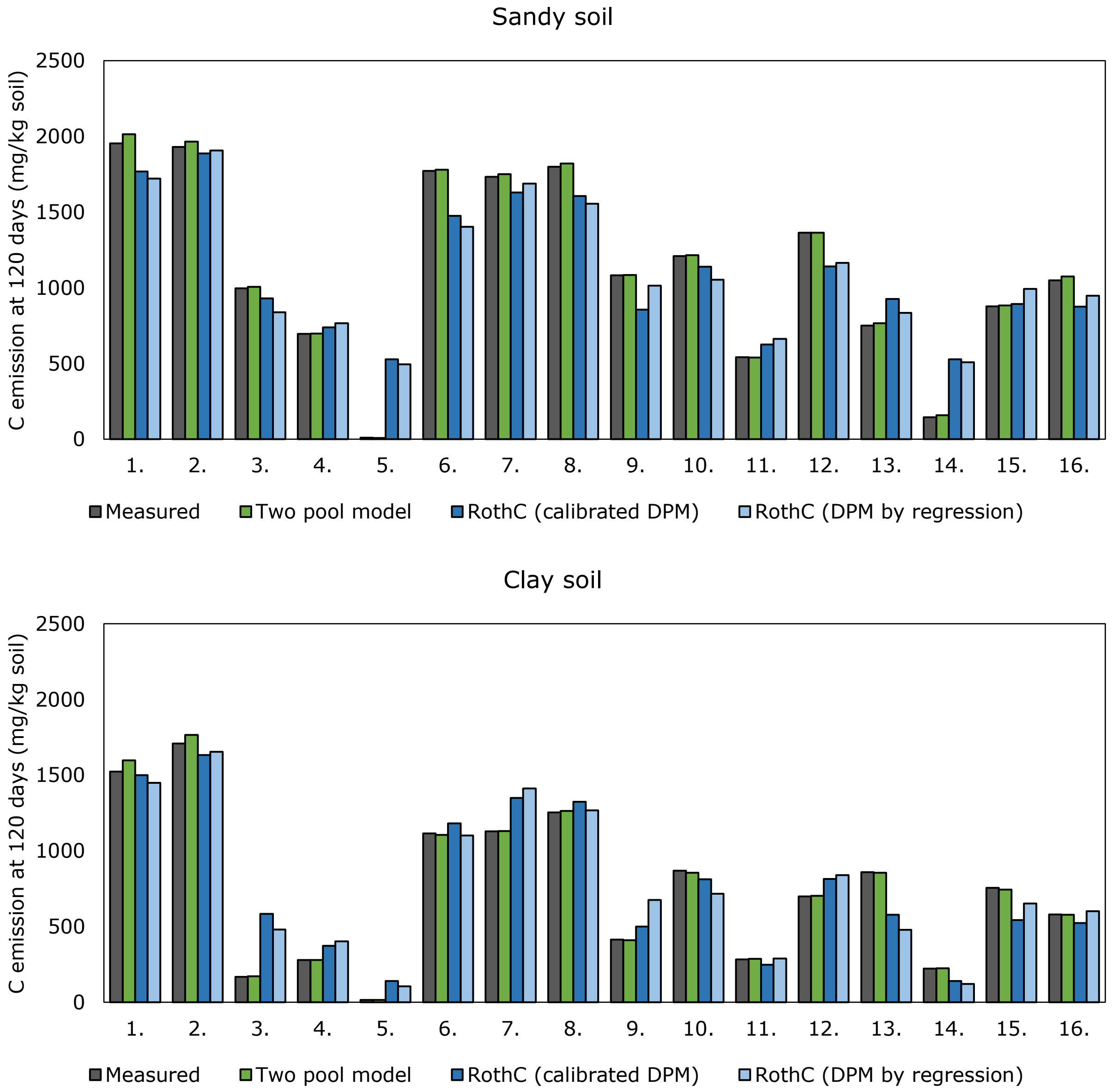


Figure 3-9 *Comparison between C emission (net mineralisation) at 120 days at 20 °C (~ 280 days at 9 °C) between measured data from the C incubation experiment, the two pool model applied on measured data, RothC using calibrated DPM/RPM ratio's and RothC using DPM/RPM ratio's obtained by regression.*

3.3 Nitrogen

3.3.1 Incubation experiment results

Mineralisation of N between day 0 and 120 is presented in 0. The $N_{min,net}$ (%) incubation (the total amount of N mineralised at the end of the experiment relative to the amount of organic N added, see section 2.4.3 for details) for both sand and clay are presented in Table 3-7 and in Figure 3-10. The N mineralisation fluctuated much over time (see 0) and did not show a clear trend over time. Therefore, we focus here on the mineralisation results at the end of the experiment.

Table 3-7 *$N_{min,net}$ (%) incubation of the organic materials, presented separately for sand and clay soils.*

	$N_{min,net}$ (%)		
Organic material	**Sand**	**Clay**	**Handboek bodem en bemesting**
1. Cattle slurry	16.5	-32.1	5-20
2. Pig slurry	66.1	-33.7	25-60
3. Organic waste compost	8.4	-3.4	
4. Farmyard manure (cattle)	24.4	-11.2	5-25
5. Garden peat	-5.1	-4.6	
6. Straw	-111.9	-100.9	
7. Grass	22.4	0.2	
8. Chicken manure	43.1	20.1	30-65
9. Monodigested cattle slurry	34.0	-8.2	
10. Deep litter stable manure	-7.8	-8.2	
11. Bokashi	-14.0	-16.6	
12. WWTP sludge	43.6	40.3	
13. Struvite with organic matter	100.2	36.8	
14. Champost	12.0	2.4	10-40
15. Soil improver from GZV	-45.3	-67.6	
16. Codigestate from GZV	31.3	19.3	

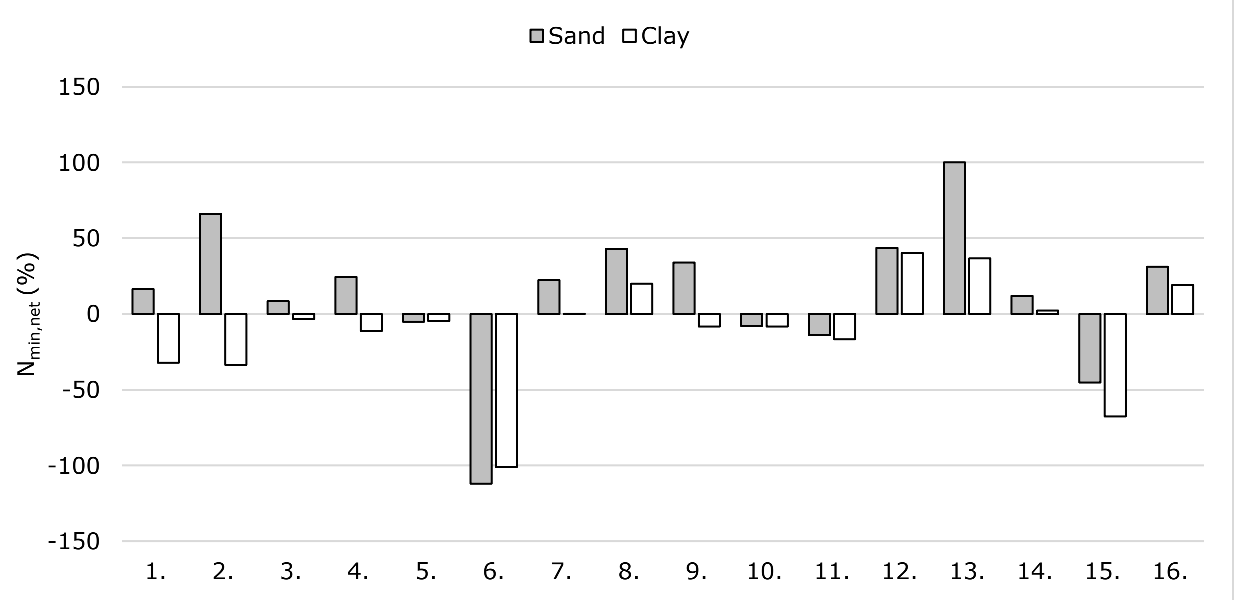


Figure 3-10 *$N_{min,net}$ (%) incubation of the 16 organic materials, based on N that is mineralised during the incubation experiments averaged over 80-120 days.*

The highest $N_{min,net}$ (%) incubation was found for struvite containing some organic matter, which mineralised completely in a sandy soil. Relatively seen, straw immobilised the greatest amount of mineral N: almost no mineral N was measured in the soils with added straw, which corresponds with an immobilisation of as much as its own organic N content compared to the blank. Immobilisation of N occurred more often in clay than in sandy soils. For some materials, net mineralisation occurred in sandy soils, while net immobilisation occurred in clay soils. This was the case for compost, slurry and cattle manure (without straw). The difference between soils was especially remarkable for the slurries, and in particular the pig slurry (66.1 versus -33.7%, see Table 3-7). Some materials were associated with N immobilisation, independent of the soil type. This was the case for garden peat, straw, deep litter stable manure and soil improver. It is generally accepted that organic products with a C/N (= C_{org}/N_{tot}) <15 cause rapid mineralisation, and with a C/N >35 cause immobilisation (Reuland *et al.*, 2022). In the current study, the three products with a C/N ratio >35 all caused immobilisation. Not all products, however, with C/N <15 caused net mineralisation of organic N: deep litter stable manure immobilised nitrogen in both soil types, and application of cattle- and pig slurry, farmyard manure and monodigested cattle slurry led to mineralisation in a sandy but not in a clay soil. It is unclear why immobilisation occurred in the clay soil for products with C/N <15. Possibly, more gaseous emissions occurred in the clay soil, therefore causing an artefact in the mineral N measurements.

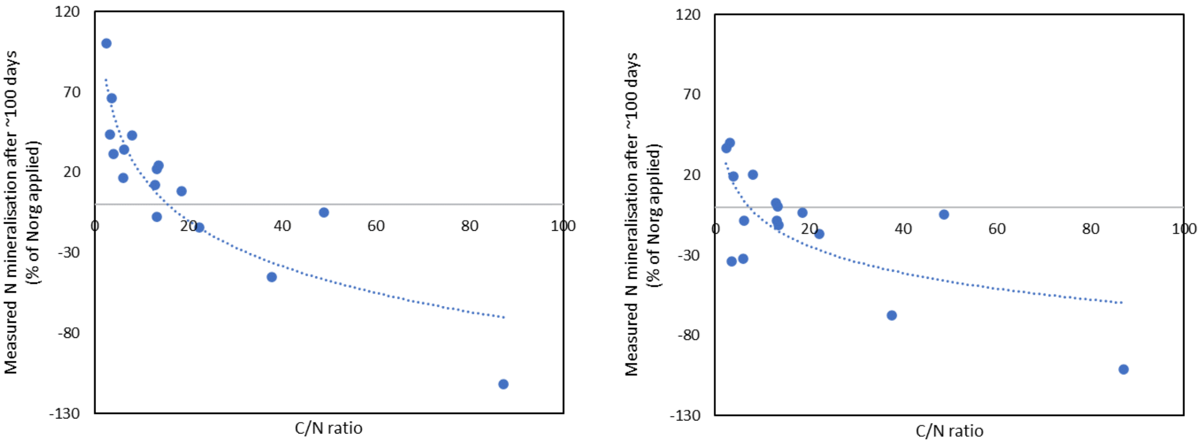


Figure 3-11 *Measured N mineralisation versus C/N ratio. Calculated by subtracting measured mineral N at t=t with mineral N at day 1 of the incubation experiment, and corrected for the blank. Averaged values for mineralisation at 80 and 120 days of incubation. Expressed per amount of* N_{org} *applied. Left: sandy soil, right: clay soil. The values for measured N mineralisation are reported per product in Table 3-7.*

The $N_{min,net}$ of some common organic materials are studied before. Van Groenigen and Zwart (2007) assessed several kinds of compost and straw after applying to a sandy soil (Droevendaalsesteeg, Wageningen). In their experiment, straw barely led to immobilization, both with and without additional N application. The origin of the composts are too different from the one in the current study, and therefore not compared. Reuland *et al.* (2022) assessed several digestates and reference products, and applied these products to a loamy sand. The $N_{min,net}$ was 20-52% for digestate, 16% for the solid fraction of digestate and 4% for compost. The $N_{min,net}$ found for digestates in the current study fit in the range found by Reuland *et al.* (2022), the $N_{min,net}$ found in the current study was somewhat higher. The latter is surprising, as the C/N ratio in the current study was 18.6 vs 11.6 in the study of Reuland *et al.* (2022).

In the Handboek Bodem en Bemesting (N.B.) standard values are available for the expected mineralisation of N_{org} for cattle slurry, pig slurry, cattle manure, chicken manure and champost. These values are based on field experiments with a duration of one year. These conditions differ from the controlled setting during incubation experiments (shorter duration, higher temperature, constant moisture content). These values are presented in Table 3-7. Ranges are indicated, dependent on the moment of application. The standard values for cattle slurry, pig slurry, cattle manure and champost are in line with our results of the sandy soils. The values found for clay soils were very different than what is commonly assumed.

3.3.2 Correlations

Single parameter

The proportion of variation associated with the correlations is shown in Table 3-8. The $N_{min,net}$ of sand showed good relations with total and mineral N, HWC, HWN and N in pepsin. The $N_{min,net}$ of clay showed a good relation with organic N and the Rock Eval parameters. Both the $N_{min,net}$ of sand and clay showed strong correlations (R^2>0,5) with C/N related parameters and the van Soest parameters.

Table 3-8 *Correlations between the characteristics of the organic fertilisers and the* $N_{min,net}$ *(%) incubation.*

Parameter		**R^2**	
		Sand	**Clay**
	Total N	0.61	0.32
	NH4	0.42	0.05
	H	0.39	0.19
	C/H	0.31	0.18
	DOC	0.27	0.00
	N_{org}	0.38	0.52
	C_{org}/N	0.76	0.55
	C_{org}/N_{org}	0.74	0.67
	EC	0.24	0.24
	BOD(5)	0.12	0.08
	BOD(7)	0.07	0.05
	COD	0.17	0.01
	COD/BOD	0.02	0.00
	HWC(1)	0.45	0.19
	HWC(2)	0.43	0.17
	HWN	0.45	0.18
	N in pepsin	0.44	0.26
	N in pepsin/TN	0.02	0.02
	PMN	0.13	0.14
Microresp.	Lignin	0.01	0.03
	Alanine	0.01	0.09
	Aminobutyric acid	0.03	0.09
	N-acetyl glucosamine	0.06	0.15
	D(+) glucose	0.09	0.18
	Alpha ketoglutarate	0.14	0.16
	Malic acid	0.09	0.19
	Total respiration	0.07	0.17
Rock Eval	F1	0.01	0.15
	F2	0.16	0.02
	F3	0.11	0.34
	F4	0.27	0.49
	I-index	0.02	0.13
	R-index	0.19	0.43
	OI	0.13	0.24
	HI	0.11	0.01
Van Soest analysis	NDF	0.59	0.53
	ADF	0.43	0.24
	ADL	0.07	0.01
	ADF-ADL	0.63	0.56

Combination of parameters

Correlations were tested both for sand and clay together, using the soil type as a factor, and for sand and clay separately. Soil type appeared to be a very important determinant. For sand and clay together, the best fit was found for six parameters (C_{org}/N, COD, HWN, F2, F4, soil type), with a R^2adj. of 80.64. Reducing the parameters to C_{org}/N_{org}, HWN, F2, F4 and soil type resulted in a R^2adj. of 79.97. For sand, the $N_{min,net}$ can be estimated better with even less parameters. Only taking C_{org}/N_{org}, HWN and F2 into account results in a R^2adj. of 89.76. For clay, quite a few parameters are needed to find a good fit. Using DOC, C_{org}/N_{org}, HWN, F2 and F4 results in a R^2adj. of 81.35. We assessed the various combinations of parameters on the outcome (see 0). On the basis of these results, we decided to select the combination of the following parameters, together for sand and clay: C_{org}/N_{org}, HWN, F2, F4 and soil type. The estimates are provided in Table 3-9. Adding DOC would improve the fit (R^2adj.) for sand and clay to 90.8 and 81.3 respectively, but the figures show that the improvement is only marginal (figures not shown).see 0).

Table 3-9 *Estimates for $N_{min,net}$ (%) of organic products by means of multiple linear regression.*

Constant	-1.6
C_{org}/N_{org}	-0.722
HWN	0.1759
F2	-1.379
F4	2.448
Soil type	24.08
R2adj.	79.97

3.3.3 Net nitrogen mineralisation by using fixed C/N ratios for the RothC pools

De afgeleide C/N verhoudingen voor DPM moeten we nog opnemen in een tabel.
Vervolgens ook de N release aangeven als gevolg van een afbraak van het product na 1 jaar bij 9°C:

$$\frac{N_{release,i}}{N_{tot}} = \left(\frac{f_{DPM,i}}{C/N_{DPM}} * (1 - e^{-10*0.75*t}) + \frac{(1-f_{DPM,i})}{C/N_{DPM}} * (1 - e^{-0.3*0.75*t})\right) \qquad (25)$$

Ook een tabel van de bodeminitialisatie over de pools (zand en klei).

The net N mineralisation obtained by RothC is presented in Figure Figure 3-12. The results hardly show any difference in $N_{min,net}$ between sand and clay soils. With a few exceptions, the range of $N_{min,net}$ is very small, between 50 and 70% for 7 of the 16 materials. Straw (6.) immobilised large amounts of nitrogen, even more than its own content. Straw therefore subtracts N from the soil. Immobilising large amounts of N is possible in RothC, since the soil N status is not limiting. For the other organic materials, immobilisation did not occur. This is contrary to the results of the incubation experiment, which is further elaborated in section 3.3.4.

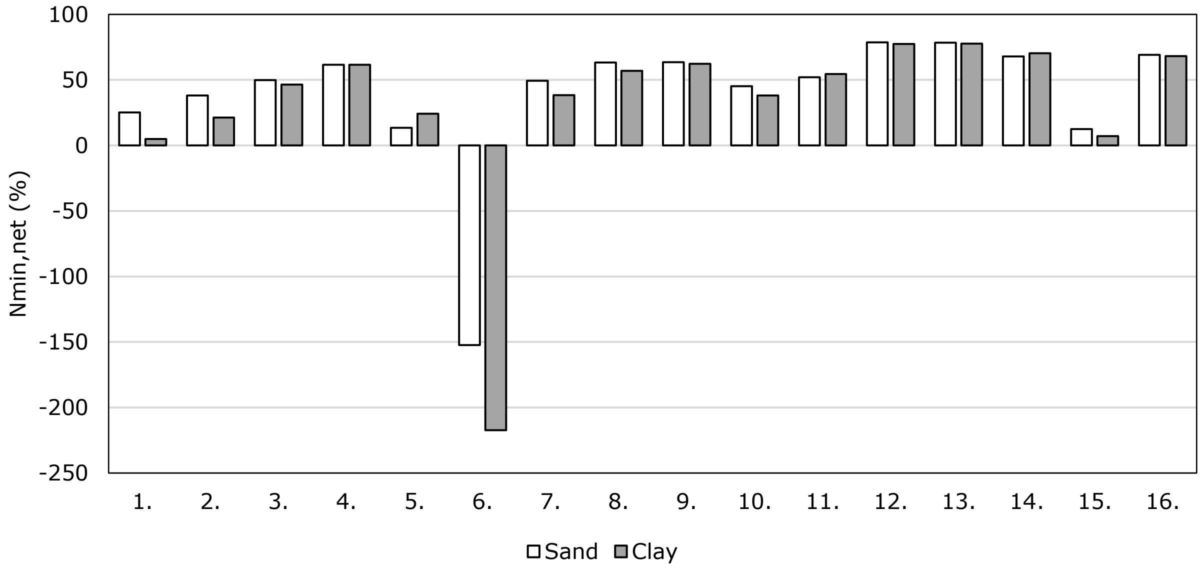


Figure 3-12 *$N_{min,net}$ (%) after 365 days of the 16 organic materials, based on RothC.*

3.3.4 Model output versus incubation data

Model results of N mineralised at 100 days were compared to $N_{min,net}$ (%) incubation (see section 2.4.3 for the description of $N_{min,net}$ (%) incubation). A comparison between the N mineralisation resulting from RothC and the incubation experiments both at ~100 days and 20℃ is shown in Figure 3-13. The results show that the N mineralisation is overestimated by RothC for 13 out of 16 materials in sandy soils and for 15 out of 16 materials in clay soils. In RothC only one organic material led to N immobilisation, while the incubation experiments indicate that N immobilisation did occur for more organic materials. The question is, however, whether RothC overestimates the N mineralisation or the mineralisation during the incubation experiments was low due to incubation settings.

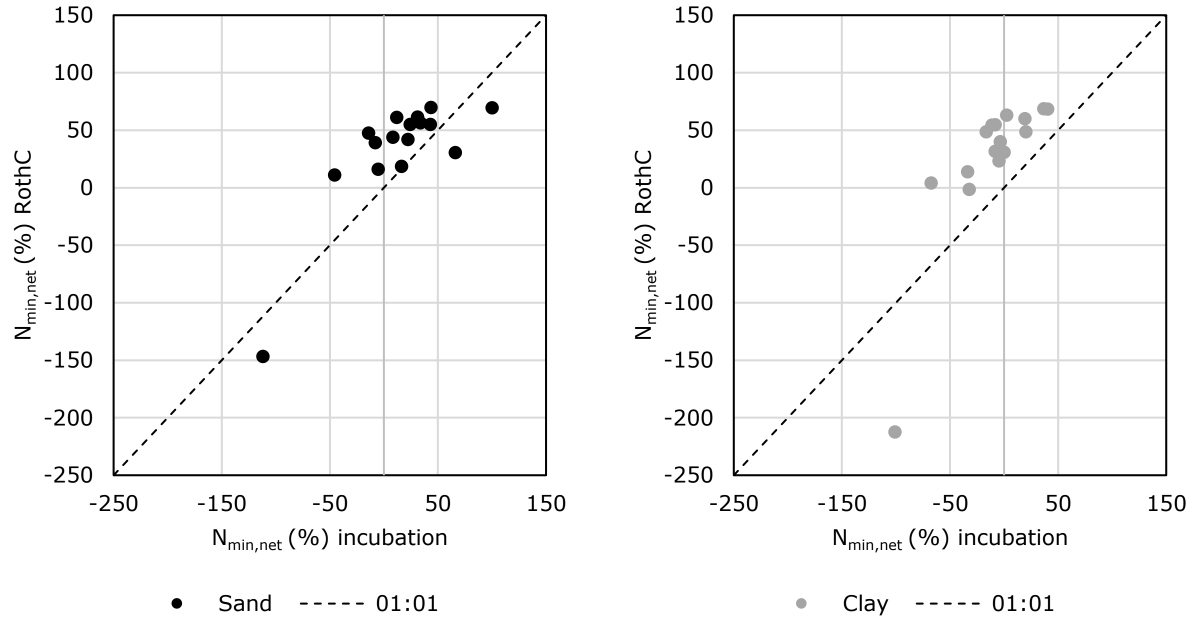


Figure 3-13 *Comparison between $N_{min,net}$ (%) on the basis of incubation experiments and the $N_{min,net}$ (%) obtained from RothC, for sand (left) and clay (right).*

3.4 Organic product characterisation

Table 3-10 shows the results for C and N obtained with the RothC model in terms of HC and the N availability. It becomes apparent that none of the materials had a low HC. Compared to the values known from literature (see Table 3-11), RothC found higher HC's. As described in section 3.2.3.3, the results generally fit in the range found in literature, but the results (averaged over sand and clay) are somewhat at the upper part of the range. For example, in literature a range of 0.3-0.42 was found for pig slurry, and the HC obtained by RothC was 0.39. For monodigested cattle slurry the HC in literature was 0.57-0.72 while RothC found a HC of 0.69. Other materials that were in the range found in literature include cattle slurry, compost, deep litter stable manure, soil improver GZV and champost. Some other materials showed a larger deviation (farm yard manure, grass and straw). For some other materials, no ranges were available in literature. Also for N mineralisation a comparison was made. It must be noted however, that $N_{min,net}$ and long-term N availability coefficient are not the exact same. The latter refers to the percentage of N_{org} that mineralises under field conditions and is taken up by the crop, while $N_{min,net}$ refers to the percentage of N_{org} that mineralises, both refer to one year. As described in section 3.3.4, RothC overestimated the N mineralisation compared to the results of the incubation experiments. However, when the N mineralisation (averaged over sand and clay) obtained by RothC is compared to literature, mineralisation in RothC was only higher for 3 out of 10 materials of which data is available in literature. These include organic waste compost, farmyard manure, WWTP sludge and champost. For 3 out of 10 materials the N mineralisation in RothC was low compared to literature, these include cattle- and pig slurry and straw. Values found for chicken manure, monodigested cattle slurry and codigestate fit in the range. It is therefore not likely that RothC consequently overestimated N mineralisation. It is still possible that the N mineralisation during the incubation experiments was relatively low, but it cannot be confirmed nor disproved on the basis of these results. Low N mineralisation measurements could occur for example if part of the mineralised N escaped as gas (NH_3, N_2O or N_2), as the audiothene plastic bags used are permeable for gases.

Table 3-10 *Matrix for the humification coefficient and N availability coefficient (during one year or growing season) of the chosen organic fertilisers, based on RothC. Deviations from literature are indicated in blue.*

		Humification coefficient (HC_{RothC})		
		Low **< 0.35**	**Moderate** **0.35 - 0.7**	**High** **≥ 0.7**
$N_{min,net}$ (%) RothC	**Low** **<0.35**		Cattle slurry, pig slurry, straw	Garden peat, soil improver GZV
	Moderate **0.35 - 0.7**		Grass, chicken manure, monodigested cattle slurry, deep litter stable manure	Organic waste compost, farmyard manure, bokashi, codigestate GZV
	High **≥ 0.7**		WWTP sludge	Struvite with organic matter, champost

Table 3-11 *Matrix for the humification coefficient and long-term N availability coefficient of the chosen organic fertilisers, based on literature study (copy of Table 2-2).*

		Humification coefficient		
		Low **< 0.35**	**Moderate** **0.35 - 0.7**	**High** **≥ 0.7**
N availability coefficient	**Low** **<0.35**	Straw	Champost Farmyard manure	Bokashi Deep litter stable manure Garden peat Soil improver from GZV Organic waste compost
	Moderate **0.35 – 0.7**	Grass Pig slurry Chicken manure	Cattle slurry WWTP dairy sludge	Codigestate from GZV Monodigested cattle slurry
	High **≥ 0.7**	Struvite with organic matter		

3.5 Applicability and recommendations

The model was applied to two common crop rotations and fertilisation schemes in the Netherlands, one for sandy soils (South-East) and one for clay soils (South-West) (0). In these scenarios, the contribution of a certain fertilising product to the carbon and nitrogen provision is based on the nitrogen and carbon content and C/N ratio of a certain product, the amount applied (both limited by legal limits and crop nitrogen requirements) and the pace at which carbon and organic nitrogen mineralises. Using RothC in a context of crop-rotation and fertilisation scheme provides more detailed information about the contribution of a certain product to the nitrogen provision, and the carbon build-up in the soil. Therefore, the results are valuable to be able to benchmark products on their potential contribution to the nitrogen provision in an agricultural context.

3.5.1 South-East of the Netherlands

In a context of crop rotation and fertilisation, the amount of organic products that can be applied varies. In a common crop rotation and fertilisation scheme in the South-East of the Netherlands, an average amount of 16 ton ha^{-1} yr^{-1} of pig slurry is applied, 4 ton ha^{-1} yr^{-1} of cattle slurry and 3 ton ha^{-1} yr^{-1} of compost is applied. Including other types of organic products results in various scenarios; the associated amounts are presented in Table 3-12. The phosphorus application standards are often the limiting factor for application of fertilisers, therefore, the P_2O_5-content determined the amount applied. The limit for the South-East of the Netherlands was set at 50 kg P_2O_5 ha^{-1} jr^{-1}. Several organic products studied in this research are associated with a high P_2O_5-content, and the amount that is allowed to apply is therefore limited. This is the case for chicken manure, WWTP sludge, struvite with organic matter and champost. Other materials contain relatively low amounts of P, thus larger amounts can be applied. This is the case for compost, garden peat, monodigested cattle slurry and bokashi.

Table 3-12 *The fertilisation strategies and the associated amount of C and N applied in the South-East of the Netherlands.*

Scenario	Product	Amount		Product	Amount		Product	Amount	C application with organic materials	N application with organic materials	N application with artificial fertiliser
	-	ton ha^{-1}		-	ton ha^{-1}		-	ton ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Control	Pig slurry	16.3	+	Cattle slurry	4.3	+	Compost	2.5	795	142	0
A	Cattle slurry	18.9	+	Compost	2.5				941	127	16
B	Cattle slurry	5.9	+	Compost	2.5	+	Farm yard manure	10.0	1642	138	4
C	Pig slurry	16.3	+	Cattle slurry	5.9	+	Garden peat	5.6	1261	142	0
D	Cattle slurry	5.9	+	Compost	2.5	+	Chicken manure	1.5	902	104	39
E	Compost	2.5	+	Monodigested cattle slurry	26.5				1054	142	0
F	Pig slurry	5.9	+	Cattle slurry	2.5	+	Deep litter stable manure	11.3	1345	122	20
G	Pig slurry	16.3	+	Cattle slurry	4.3	+	Bokashi	2.0	690	134	8
H	Pig slurry	16.3	+	Cattle slurry	4.3	+	WWTP sludge	0.1	528	127	15
I	Compost	2.5	+	Struvite	0.26				291	24	118
J	Pig slurry	16.3	+	Cattle slurry	4.3	+	Champost	0.3	558	130	13
K	Pig slurry	16.3	+	Cattle slurry	4.3	+	Soil improver GZV	0.5	615	129	13
L	Compost	2.5	+	Codigestate of pig slurry	13.0				682	119	23

3.5.1.1 Carbon

The carbon application rates used in the model to simulate various fertilising strategies are presented in Table 3-12. The control was associated with a supply of 795 kg C ha^{-1} jr^{-1}, coming from pig slurry, cattle slurry and compost. In this study, soil improvers contribute relatively little to the C provision. Soil improvers are only applied prior to the cover crops, and therefore in relatively low quantities. But more importantly, soil improvers in this study replace organic waste compost. Due to regulation, compost has an exemption for 50% of the P_2O_5 content. Therefore, it is difficult to increase the carbon supply by exchanging compost for another soil improving organic material. Relative to slurries, most of the organic materials increased the carbon supply, except for co-digestate of pig slurry. Scenario B, in which farmyard manure is included, resulted in the largest supply of carbon: 1642 kg C ha^{-1} jr^{-1}. This is due to the favourable C/P_2O_5 ratio. The build-up of organic soil organic carbon is, however, not just a result of the supply, but also of the decomposition.

The modelled contribution of organic materials to the build-up of carbon in the soil is presented in Figure **3-14**. The distribution over the RothC pools is presented in 0. As can be derived from the graphs, scenario B, in which farm yard manure was included, resulted in the largest contribution to the build-up of soil carbon (+ ca. 6 ton C/ha in total, or ca. 3.5 ton C/ha compared to the control, over 15 years). Compared to the control, seven scenarios resulted in a higher build-up of soil carbon. These are scenarios A-F and L, in which pig slurry was exchanged for other (processed) animal manures, or compost was exchanged for garden peat. These products contributed the most due to the application possibilities in an arable system. Besides, it becomes visible that some of the scenarios are associated with a large input of C that decomposes quickly. For example, scenario F is associated with a higher carbon input than scenario C, but due to the relative easy decomposable material included in scenario F, scenario C resulted in a higher build-up of soil carbon. The same applies to scenario L and G. To put the results in context, the organic products applied in the scenarios resulted in 1.2-5.9 ton C ha^{-1} over 15 years. The initial soil carbon stock in the soil was 28 ton C ha^{-1}. A part of this initial carbon stock is expected to decompose, and C needs to be applied to compensate for this decomposition. In case of 2% decomposition of organic matter per year, this amounts to 7.3 ton C/ha over 15 years. As the organic materials tested in this study contributed 1.2-5.9 ton C ha^{-1} over 15 years, the scenarios are not expected to increase the soil carbon stock without other input such as carbon from roots and other crop residues left in the soil.

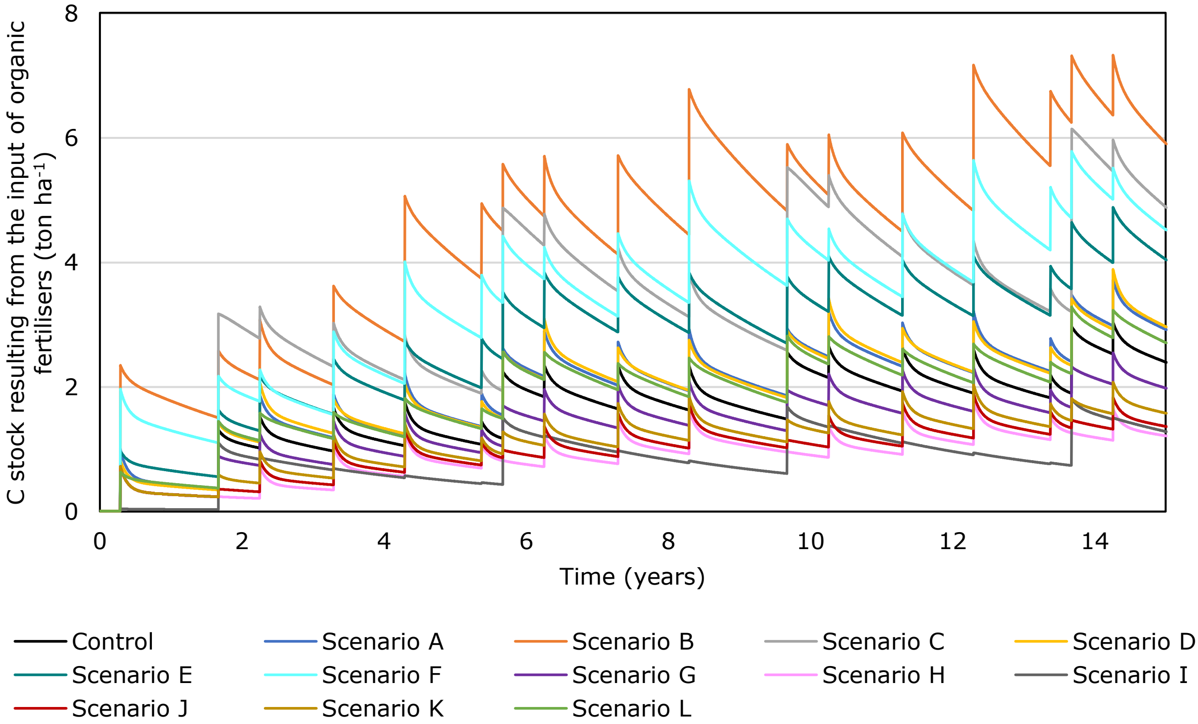


Figure 3-14 *Contribution of the organic materials to the C build-up in the soil associated with the various fertilisation strategies in the South-East of the Netherlands. The C stock (Y-axis) refers to the accumulation of the organic materials only, soil C is not included in the figure.*

3.5.1.2 Nitrogen

Some of the organic products contribute largely to the crop N requirements, such as pig- and cattle slurry. In scenarios with organic materials with relatively low N-contents or application rates (e.g. because of a high phosphate content), additional N fertilisation (with artificial fertiliser) is needed to meet the crop needs. Including chicken manure or struvite in the fertilisation strategy, for example, results in large additional requirements of artificial N application. The N provision, however, depends for a large part on the mineralisation of organic N in the products. The cumulative N mineralisation of the products and associated mineral N application in a crop rotation are shown in 0, together with the cumulative crop N requirement. The difference between the N originating from applying organic materials (both mineral N and organic N that mineralises over time) and the crop N requirements indicates the required amount that should be provided by applying synthetic N and N that mineralises from the soil.

As can be derived from the graphs, the control provides an amount of mineral N that is relatively close to the crop N requirements, which was 149 kg N ha^{-1} yr^{-1} averaged over all crops grown in the crop rotation. Only scenario C, in which compost is exchanged for compost, provides an amount of mineral N that is even closer to the crop N requirement. It must be mentioned, however, that the mineral N provision of several scenarios is relative close to the control, including scenarios G, H, J and K. As could be expected from Table 3-12, some scenarios provide relatively little N and require additional artificial N fertiliser (e.g. scenario D and I). For some other scenarios, Table 3-12 indicates that sufficient N is provided, but the graphs show that a substantial part of the organic N does not become available. This was the case for scenario E. In this scenario, pig- and cattle slurry was exchanged for monodigested cattle slurry while keeping the N application constant, however, less N was modelled to become available for crop growth due to a lower mineralisation rate.

3.5.1.3 Applicability

Including C and N in RothC provides insights in the contribution of mineral N to crop growth and the build-up of soil carbon in an agricultural context. Scenario C showed to be both helpful in the nitrogen provision and the build-up of soil carbon. For some other scenarios, a trade-off became visible, for example for scenario F (relative high contribution to C build-up but not to the N provision) and scenario G (relative high N provision but a relative low contribution to C build-up).

3.5.2 South-West of the Netherlands

Phosphate levels in the South-West of the Netherlands are in general lower than on the sandy soils of the South-East. Therefore larger amounts of organic products are allowed to be used on these clay soils. The limit for the South-West of the Netherlands was set at 70 kg P_2O_5 ha^{-1} yr^{-1}. Organic products are used in only a few crops in the crop rotation. The rates of application are on average 16 ton ha^{-1} yr^{-1} of pig slurry, 10 ton ha^{-1} yr^{-1} of cattle slurry and 7 ton ha^{-1} yr^{-1} of compost. Again, these products are replaced by other types of organic products, resulting in various scenarios as presented in Table 3-13. In this case, products which are used in larger amounts are garden peat, farmyard manure, monodigested cattle slurry and deep litter stable manure. Due to high P_2O_5-content smaller amounts were used of WWTP sludge, struvite, chicken manure and soil improver GZV.

Table 3-13 The fertilisation strategies and the associated amount of C and N applied in the South-West of the Netherlands.

Scenario	Product	Amount		Product	Amount		Product	Amount	C appl. with org. products	N appl. with org. products	N appl. with artificial fertiliser
	-	ton ha^{-1}		-	ton ha^{-1}		-	ton ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Control	Pig slurry	16.0	+	Cattle slurry	10.0	+	Compost	7.0	1509	205	0
A	Pig slurry	13.2	+	Cattle slurry	12.1	+	Compost	7.0	1536	203	3
B	Compost	7.0	+	Farm yard manure	18.3				2819	193	13
C	Pig slurry	16.0	+	Cattle slurry	10.0	+	Garden peat	17.5	3043	212	0
D	Compost	7.0	+	Chicken manure	2.8				1468	130	77
E	Compost	7.0	+	Monodigested cattle slurry	34.0				1761	204	2
F	Compost	7.0	+	Deep litter stable manure	20.7				2485	172	34
G	Pig slurry	14.0	+	Cattle slurry	10.0	+	Bokashi	10.9	1602	193	13
H	Pig slurry	14.0	+	Cattle slurry	10.0	+	WWTP sludge	0.3	687	146	61
I	Compost	7.0	+	Struvite	0.3				782	53	153
J	Pig slurry	14.0	+	Cattle slurry	10.0	+	Champost	1.3	877	166	41
K	Pig slurry	14.0	+	Cattle slurry	10.0	+	Soil improver GZV	2.6	1183	165	41
L	Compost	7.0	+	Codigestate of pig slurry	17.4				1303	181	26

3.5.2.1 Carbon

The amounts of carbon applied for the various fertilising strategies are presented in Table 3-13. The control is associated with a supply of 1509 kg C ha^{-1} jr^{-1}. Lowest amounts of C applied are found in scenario H, where compost (relatively high C content) is replaced by WWTP sludge, containing a fairly higher amount of P2O5, leading to a lower dosage. The highest amount of C application can be found in scenario C, where compost is replaced by a product with an even higher C content: garden peat. Similar to the South-East case, compost is a relatively favourable way of applying large C amounts on the field, due to the exemption for 50% of the P_2O_5 content.

The contribution of organic materials to the build-up of carbon in the soil is presented in Figure 3-15. The distribution over the RothC pools is presented in 0. As can be derived from the graphs, scenario B, in which farm yard manure was included, resulted in the largest build-up of soil carbon. Scenarios B-G, J and L contributed to a higher C stock than the reference situation. These were first of all the situations where compost was applied, in combination with a replacement of the pig and cattle slurry, except where struvite was the replacement product (I). Besides, higher C stocks were found in the scenarios where compost was replaced by garden peat, bokashi and champost. Scenario I showed almost no increase in C stock on the moments where the struvite was applied. Similar to the South-East scenarios, some products add larger amounts of C, but due to the presence of relatively easy decomposable material, the C stock build-up is similar to that from products that are applied in smaller amounts. An example of this phenomenon is the high C application in scenario L (codigestated pig slurry) compared to J (champost), but similar curve for the change in C stock. The graph shows the trend of a soil starting with a soil organic carbon content of around 50 t ha^{-1}. At a decomposition rate of 2% of organic matter per year, the soil carbon content is expected to decrease with 13.1 t ha^{-1} over 15 years when no organic matter is supplied with either addition of organic matter via organic products or via roots and other crop residues. The build-up arising from addition of organic products is estimated to be 8-22 ton C/ha. It is therefore likely that some scenarios are able to increase the soil organic carbon content considerably.

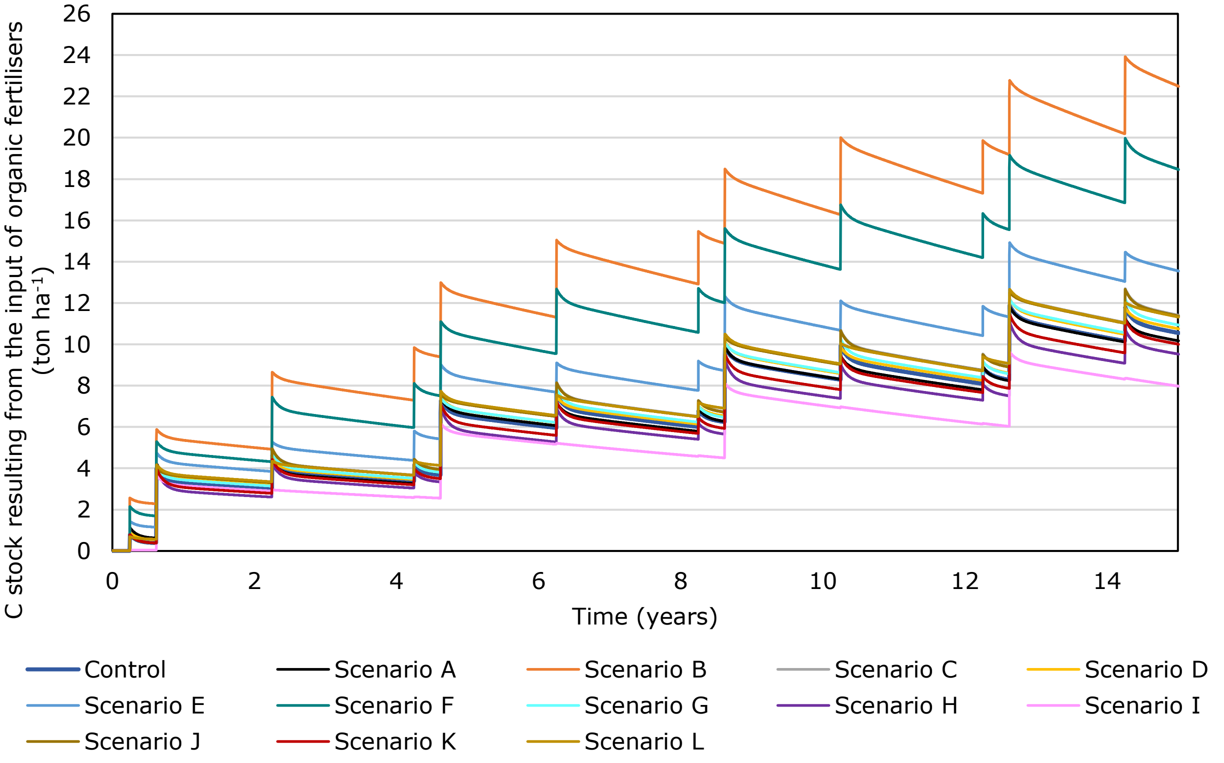


Figure 3-15 *Contribution of the organic materials to the C build-up in the soil associated with the various fertilisation strategies in the South-East of the Netherlands. The C stock (Y-axis) refers to the accumulation of the organic materials only, soil C is not included in the figure.*

3.5.2.2 Nitrogen

The cumulative N mineralisation of the products and associated mineral N application in a crop rotation are shown in 0, together with the cumulative crop N requirement.

As can be derived from the graphs, the control provides an amount of mineral N that fulfils most of the crop N requirements, around 80% (the crop N requirement was 169 kg N ha^{-1} yr^{-1} when averaged over all the crops in the rotation). Scenario A, C, G, H, J and K provide comparable values of mineral N to the crop. Comparing Table 3-13 with the graphs from 0, it is visible that (similar to carbon content) a high application of N from an organic product directly means that it fulfils the crop N requirement. As explained in the South-East description, this holds for monodigested cattle slurry (scenario E). The opposite happens in scenario H, where the N application from the organic products was only 70% of the control, but available N values comparable to the control are found.

3.5.2.3 Applicability

For the case of South-West of the Netherlands, scenarios C (garden peat) and J (champost) showed the most potential in agricultural context. Both scenarios led to similar mineral N values as the control, but contributed to a slightly higher C build-up over the years. In three scenarios (B, E and F) a trade-off was visible with a remarkably higher C build-up, but also lower mineral N values compared to the control.

3.6 Discussion on methodology

For both the experimental work and the modelling some aspects should be taken into account.

The data of the experimental work is dependent on the pre-treatment of the materials. We had to make decisions on pre-treatment, such as drying and cutting or grinding material. Using the same material that has undergone a different pre-treatment will most likely lead to different mineralisation results: e.g. using straw or grass that is *not* (freeze-)dried and ground, as was done in our experiments, will likely have a lower decomposition rate, due to the material having less reactive surface.

Furthermore, based on literature, more correlations between lab analyses and carbon mineralisation were expected. A difference with some other experiments is that we had organic materials varying in origin, and not for example many organic materials of the same category (e.g. only manures). It is to be expected that other lab analyses can explain differences within a fertiliser category than between categories.

During the nitrogen incubation experiment, mineral N was measured in the soil-fertiliser mixtures and compared to the mineral N content at the start of the experiment to indicate how much organic N was mineralised over time. However, part of the N mineralised may have been converted to gas (N_2O, N_2, NH_3) and therefore was not measured. The actual nitrogen mineralisation might therefore be higher than was measured in this experiment.

When the nitrogen experiment had already started, with additions of fertilisers based on their N content, it was found that the analytical results of the nitrogen content were not trustworthy. It was therefore decided to redo the analyses of total N and mineral N with a different method which could be used in fresh material instead of in dried material. This gave different results for total N and mineral N. Therefore, we concluded that per fertiliser a different amount of N was added to the soil in the incubation experiment, and thus that the ratio to the amount of N in the soil is different as well. The data has been expressed as % of N_{org} applied, which enables comparing N mineralisation from the different fertilisers. However, there might be an effect due to the different dosage in relation to the soil that we cannot correct for.

One of the model assumptions was that soil N is not a limiting factor for C decomposition. The assumption was made since the focus is on agricultural soils which are often rich in N, and including a full N balance would require a lot more effort (our model should therefore be coupled with a crop growth model for example). In practice, however, N limitation can occur. Furthermore, great differences exist between N mineralisation in field and in incubation studies, largely dependent on factors such as rainfall, temperature and soil life. Since the focus of the project is on benchmarking products, the limitations are of less importance.

RothC is suitable for three organic input pools: DPM, RPM and HUM. In our study the HUM fraction was excluded from our approach (f_{HUM}=0). As a result, some materials with a low decomposition rate (champost and garden peat) were assigned completely to RPM. However, it turned out that the decomposition rate of RPM was still too high for the actual decomposition of these materials. As a consequence of excluding HUM, the model is less suitable for recalcitrant materials. It is recommended to include the HUM pool for products with a low decomposition rate. The opposite could also occur: that materials decompose more C during incubation tests than what the model predicts after t days with all C being assigned to the DPM pool. Probably, the fixed decomposition rate for each pool (in this case DPM) is an over-simplification. In this study, no soil type dependent decomposition rate value of DPM was used, but a fixed value ($k_{DPM}=10\ y^{-1}$). Only k_{RPM} became soil type dependent, with $k_{RPM,\ sand}$=0.3 and $k_{RPM,\ clay}$ =0.08. In fact, in RothC normally all decomposition rates are influenced by the clay content (via the calculation of the topsoil moisture deficit). So, in principle the decomposition rate of all pools could have been soil type specific. However, in our study we only (accidently) corrected the k_{RPM} value for soil type. It is expected that the impact on the assessment of the fraction of DPM and RPM is limited. Assigning all C in a product to DPM will result in a HC of 0.13 (sand) or 0.19 (clay), assigning all C to RPM will result in a HC of 0.78 (sand) or 0.94 (clay). Therefore, the model is only suitable for products with an expected 0.13 < HC < 0.78 for sandy soils or 0.19 < HC < 0.94 for clay soils. In the future, it should be studied in more detail for which material(characteristics) an extra pool with either a higher or lower decomposition rate is needed.

Using fixed C/N values for each of the RothC pools often leads to a calculated net N mineralisation, because the N release by decomposition of the product is higher than the accumulation of N in the organic pools (BIO and HUM) in the soil. Probably the initialisation of the soil organic carbon content of the soil (SOC) over the five pools, as described by RothC, is an oversimplification to fit the results of small scale laboratory N incubation tests. On the other hand the set up of N-incubation tests to determine net N mineralisation are very difficult to carry out in the laboratory and errors made can result in a substantial error in the results of the experiment. It is recommended to focus more on both the modelling and measuring of the net N mineralisation.

3.7 Economic analyses

3.7.1 Value of organic matter

In Table 3-14 an example is given for a top soil (20 cm) with a organic matter content of 4% and an annual decomposition rate ($DC_{rate,soil}$) of 2.5% per year resulting in an organic matter decomposition ($OM_{DC,\ soil}$) of 2800 kg OM per ha. Since maximum 50 kg P_2O_5 may be applied, 56 kg of organic matter enrichment – thus EOM - is needed for each kg of phosphate applied.

Table 3-14 *Organic matter decomposition of the soil*

Parameter	Name	Unit	Value
Soil characteristics	SOM	%	4
	d	m	0.2
	ρ	kg m^{-3}	1400
	$DC_{rate,soil}$	%	2.5
OM maintenance	$OM_{DC,\ soil}$	kg OM ha^{-1}	2800
P-norm (max P_2O_5 application)	PN	kg P_2O_5 ha^{-1}	50
P norm based maintenance of OM	$M_{OM,PN}$	kg OM (kg $P_2O_5)^{-1}$	56

In Table 3-15 the characterisation of organic products are shown, including the calculated percentage of the amount of OM maintenance of the soil that can be reached by applying an amount of the organic product corresponding with 50 kg P_2O_5 per ha. Furthermore, the pricing settings are shown. The price of the organic fertiliser 'dairy slurry' has been used as reference for benchmarking purposes and set on €5/ton. The prices of the other organic products were proportional to the organic matter content of the product and the organic matter content of dairy slurry (see section 2.5.1). The table shows clear differences in capability of the products to compensate the organic matter decrease of the soil with the amount of applied effective organic matter. For this example, it is the goal to show the value of organic matter from the products. Therefore, the value of nitrogen in the products, which can help replace nitrogen from artificial fertiliser, is not taken into account.

Table 3-15 *Characteristics of organic fertilisers used to calculate economic aspects.*

#	manure type	OM[1] kg/ton	HC[2] fraction	EOM kg/ton	P_2O_5[1] kg/ton	EOM / P_2O_5 kg/kg	fr P norm[3] (-)	%$OM_{compensated}$[3] %	price (reference dairy slurry) [4] €/ton	P-based price index €/P_2O_5	Price field PN=50 €/ha
	Slurries										
1	Cattle slurry	71	0.70	49.70	1.5	33.13	1.0	59.17	5.00	3.33	166.67
2	Fattening pigs	79	0.33	26.07	3.9	6.68	1.0	11.94	5.55	1.42	71.11
3	Sows	25	0.34	8.50	3.5	2.43	1.0	4.34	1.67	0.48	23.81
4	Mineral concentrates	14	0.70	9.80	0.4	24.50	1.0	43.75	1.14	2.84	142.16
5	Rose calves	71	0.70	49.70	2.6	19.12	1.0	34.13	5.10	1.96	98.04
6	White meat calves	17	0.70	11.90	1.1	10.82	1.0	19.32	1.19	1.08	54.11
	Liquid manure										
7	Cattle	10	0.70	7.00	0.2	35.00	1.0	62.50	0.81	4.06	203.08
8	Fattening pigs	5	0.70	3.50	0.9	3.89	1.0	6.94	0.41	0.45	22.56
9	Sows	10	0.70	7.00	0.9	7.78	1.0	13.89	0.81	0.90	45.13
	Solid manure										
10	Cattle corrugated barn	155	0.70	108.50	4.3	25.23	1.0	45.06	11.09	2.58	128.98
11	Pigs (straw)	153	0.33	50.49	7.9	6.39	1.0	11.41	10.39	1.32	65.77
12	Poultry	416	0.33	137.28	23	5.97	1.0	10.66	28.80	1.25	62.60
13	Poultry + drying	393	0.33	129.69	25.6	5.07	1.0	9.05	28.33	1.11	55.34
14	chicken, litter bedding	359	0.34	122.06	25.6	4.77	1.0	8.51	24.80	0.97	48.45
15	Broilers and guinea fowl	419	0.36	150.84	16.6	9.09	1.0	16.23	28.68	1.73	86.40
16	Fattening turkeys	427	0.36	153.72	19.7	7.80	1.0	13.93	29.08	1.48	73.80
17	Sheep	195	0.70	136.50	4.5	30.33	1.0	54.17	13.33	2.96	148.15
18	Goats	174	0.70	121.80	5.3	22.98	1.0	41.04	12.61	2.38	118.92
19	Mink	293	0.70	205.10	26.9	7.62	1.0	13.62	23.80	0.88	44.24
20	Ducks	237	0.70	165.90	7.3	22.73	1.0	40.58	19.25	2.64	131.86
21	Rabbits	332	0.70	232.40	6.7	34.69	1.0	61.94	26.97	4.03	201.26
22	Horses	160	0.70	112.00	2.7	41.48	1.0	74.07	13.00	4.81	240.69
	Compost										
23	Champost	211	0.50	105.50	4.5	23.44	1.0	41.87	15.13	3.36	168.07
24	VFG compost	242	0.90	217.80	4.4	49.50	0.25	353.57	14.75	3.35	167.59
25	Green compost	179.00	0.90	161.10	2.2	73.23	0.25	523.05	11.34	5.16	257.83

1) Composition of various types of manure (Adviesbasis Bemesting Grasland en Voedergewassen, 2023).

2) Handboek bodem en bemesting.

3) % of SOM compensated by EOM of an organic fertiliser application up to 50 kg P_2O_5 per ha and by taking into account the fraction of phosphate of the organic product that has to be taken into account according to legislation (see section 2.5.1).

4) price settings based on organic matter content of the product relative to organic matter content of dairy slurry (see section 2.5.1).

Figure 3-15 shows the relationship between the percentage OM maintenance and the associated costs (excluding the composting products which will compensate for more than 100% since only 25% of the amount phosphate is taken into account, resulting in large amounts of effective organic matter (also large HC) that can be applied. Especially, at low maintenance values (25%; Figure 3-15) the difference in pricing effects is relatively large. New organic fertilisers coming to the market can be easily compared with this concept. However, as long as manure products have a negative value (arable farmers will get money for applying such products), instead of a value based on their organic matter content as done in this example, this leads to artifacts in the organic matter pricing system.

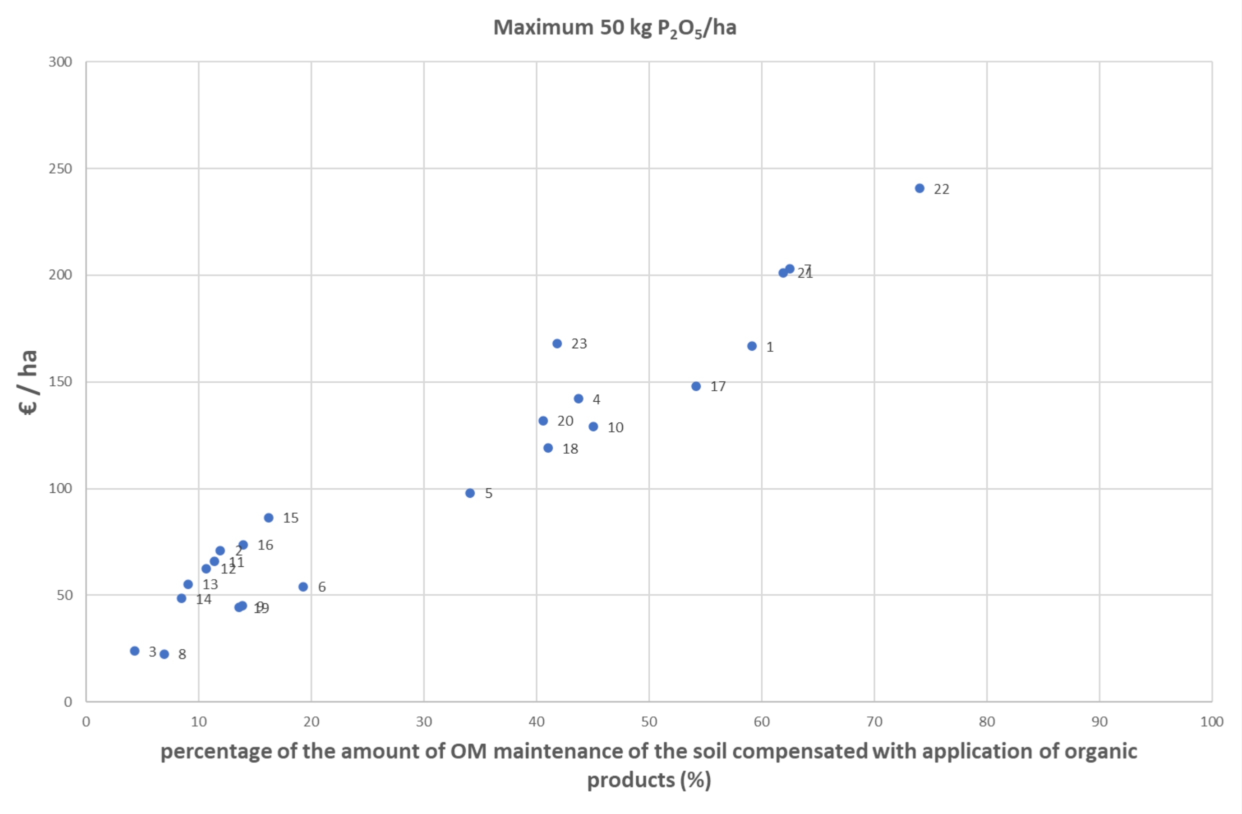


Figure 3-16 *The cost of applying organic fertilisers (numbers correspond with the listing in Table 3-15) and the percentage of the amount of annual soil decomposition that can be compensated with the application of 50 kg phosphate as the organic fertiliser.*

This exercise is based on general assumptions, like organic matter content and decomposition rate of SOM, manure cost and composition and humification coefficients (EOM-contents) of organic fertilisers manure and compost. In reality these are different for every region and product. However the methodology remains the same for different values and can be used for benchmarking purposes of organic fertilisers. The exercise shows that there are clear differences in capacity of organic fertilisers to maintain the organic matter content of the soil and the associated costs.

Additional to organic fertilisers, other sources contribute to the OM-supply for regionally specific cropping plans, like crop residues and cover crops. Figure 3-17 shows this contribution, based on {van Dijk, 2012 #98@@author-year}, presented as 'no manure', next to the contribution of slurries combined with the effects of crop residues and cover crops.

The maximum OM-input via slurry is based on the P-application regulations for each region specifically. Figure 3-17 shows that 100% application of cattle slurry leads to the highest amounts of OM of 3,300 – 3,600 kg/year. These result from both cattle slurry and 'no manure', thus, the OM supply coming from crop residues remaining in the soil.

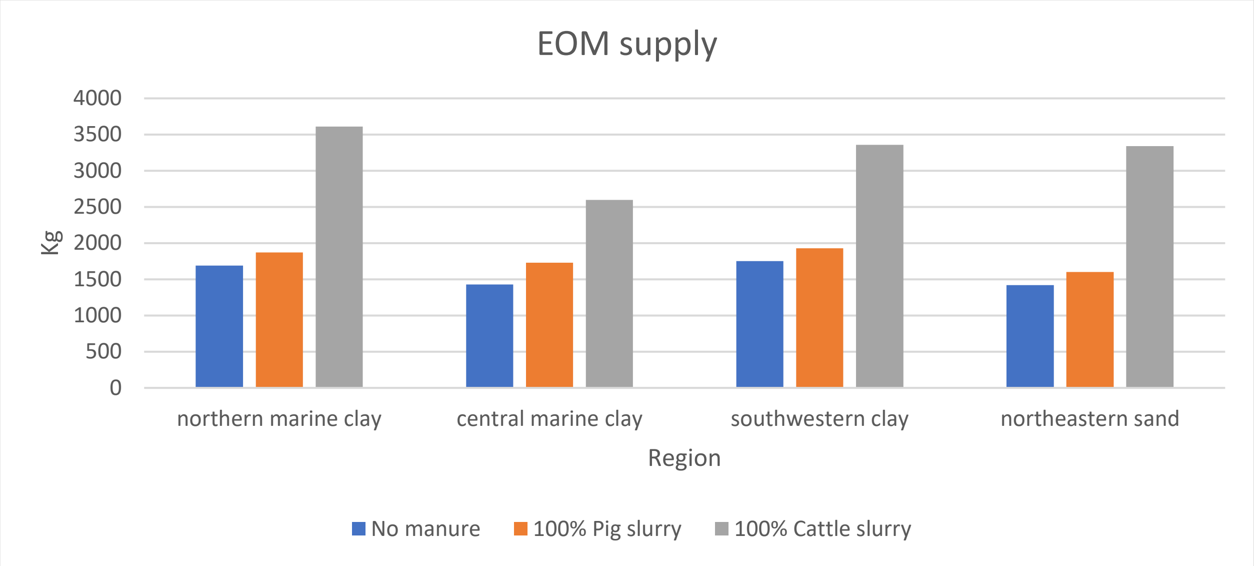


Figure 3-17 *EOM-supply (kg/ton) from no manure, pig and cattle slurry. For both manure scenarios the EOM supply of the category 'no-manure', being EOM from crop residues remaining in the soil, is included as well. (Source: Handboek Bodem en Bemesting (N.B.)).*

In this study the focus lies on cattle slurry because more EOM can be applied compared to pig slurry. Figure 3-18 shows the amount of EOM supplied by different levels of cattle slurry application in this region.

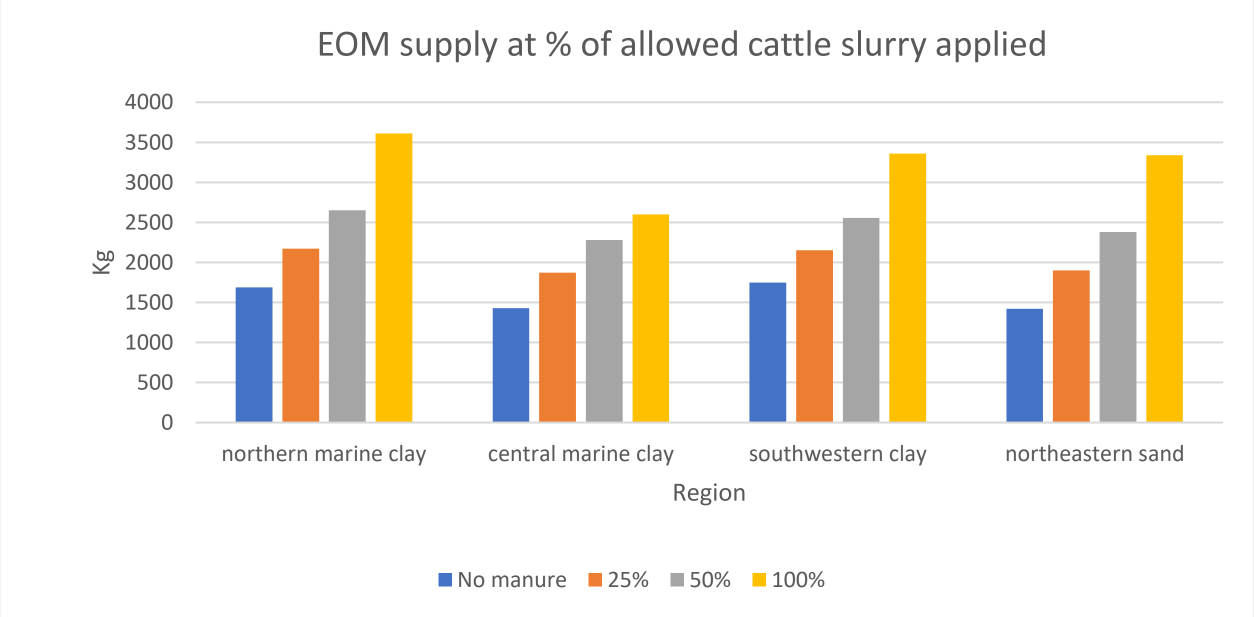


Figure 3-18 *Total EOM supply at fractions of legally allowed application limits (region with central marine clay).*

Besides the economic value of organic matter present in organic fertilisers, required to maintain the SOM content, the use of organic fertilisers could be beneficial in other ways, for example by decreasing the use of artificial fertilisers.

3.7.2 Carbon credits

The carbon credits increase OM supply per ha in both cases. On both the clay cereals and clay potato clusters the effect seems to have a diminishing effect, while in the Sandy soil cluster the effect is relatively larger for the €200 compared to the €30 scenario (see Figure 3-19).

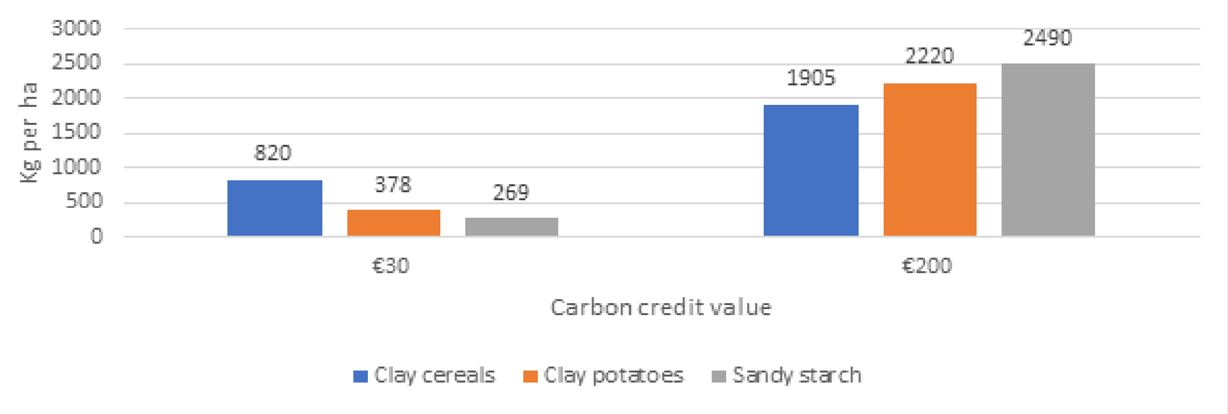


Figure 3-19 *Effect on organic matter supply per arable farm type with the introduction of a carbon credit (kg/ ha).*

The carbon credits increase income per hectare in all three scenarios and clusters (see Figure 3-20). The effects are relatively higher for the €200 carbon credit. While the reward per ton CO2 is 200/30 times higher, the effect on income per hectare is larger than that. This is due to the decisions the famer makes to maximize farm income.

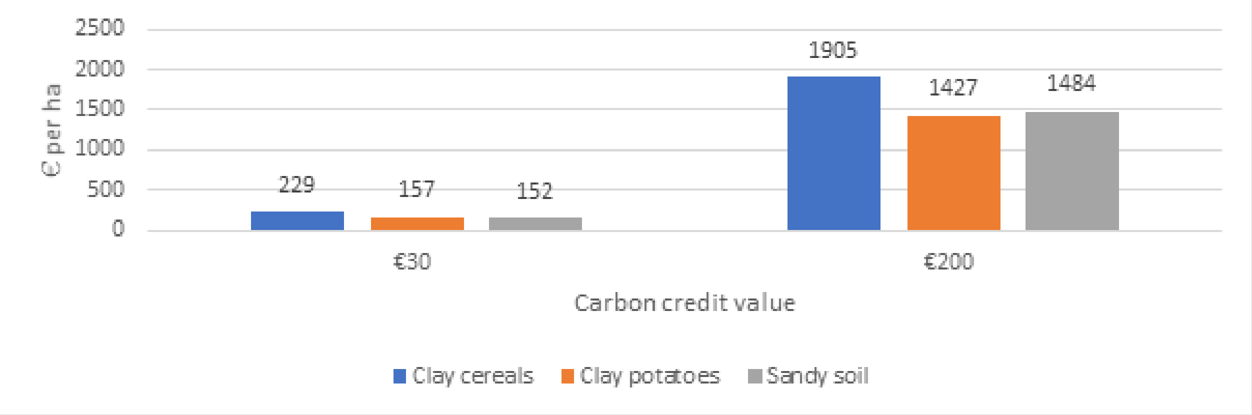


Figure 3-20 *Effect on income per arable farm type with the introduction of a carbon credit (€/ha).*

With a carbon credit of 30 euros, there is an effect on leaving crop-residue (straw). There is no effect on the choice of crops or fertilisers (see Table 3-16). When the carbon credit is raised to €200 the choice in crops (green manure) and fertiliser are also affected (see Table 3-17). Green manure and green compost both contribute to increasing SOM.

Table 3-16 *Effect on acreage of green manure (ha), use of animal manure (m^3 per ha), use of green compost (m^3 per ha), and supply of crop-residue(straw) (kg per ha) in the Netherlands and per type of farm upon introduction of a carbon credit worth 30 euros.*

	Green manure	Cattle slurry	Green compost	Crop-residue
Clay cereals	0	0	0	+1,4
Clay potatoes	0	0	0	+0,6
Sandy starch	0	0	0	+0,5

Table 3-17 *Effect on acreage of green manure (ha), use of animal manure (m^3 per ha), use of green compost (m^3 per ha) and application of crop-residue (straw) (kg per ha) in the Netherlands and per type of farm with the introduction of a carbon credit of 200 euros.*

	Green manure	Cattle slurry	Green compost	Crop-residue
Clay cereals	0	-26	+15	+1,4
Clay potatoes	+9	-23	+16	+0,9
Sandy starch	+18	-24	+18	+0,8

The introduction of a €30 carbon credit does not change the cropping plan of a farm, in the scenario with €200 carbon credits the cropping plan does change: in the clusters of clay soil with potatoes and sandy with starch production, sugar beets get replaced by cereals and green manure (see Figure 3-21).

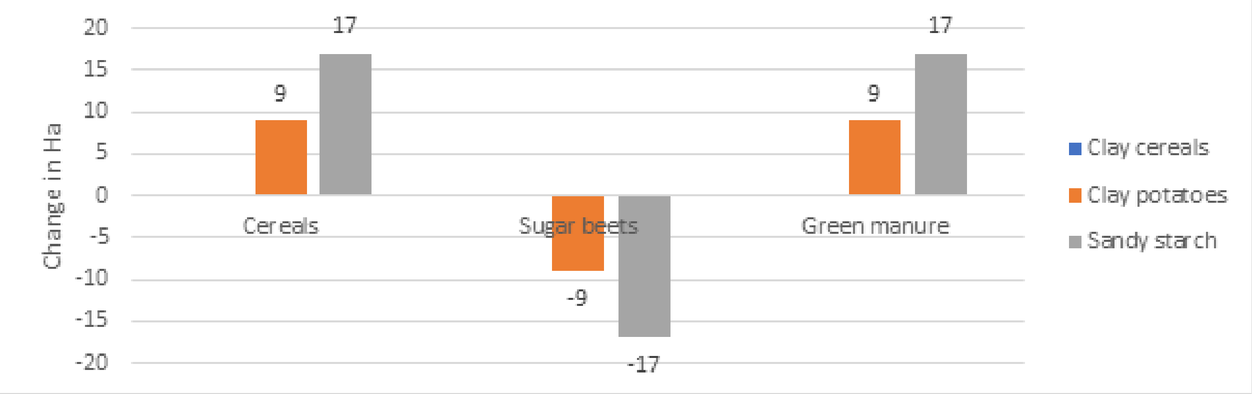


Figure 3-21 *Change in cropping plan with a €200 carbon credit (ha).*

The cropping plan shifts towards a less intensive cropping system. This shift is a result of the valuation of EOM, which is higher for cereals that for potatoes or sugar beets. There is no effect on the cropping plan in the clay cereal cluster, the cropping plan is already dominated by cereals as can be seen in Table 3-18.

Table 3-18 *The optimised cropping plan per individual representative farm in the scenario with 200 euros carbon credit (ha per farm).*

	Cereals	Sugar Beets	Ware potatoes	Starch potatoes	Onions	Green manure	Total acreage
Clay cereals	38	8	0	0	0	38	46
Clay potatoes	32	0	19	0	10	32	61
Sandy starch	39	1	0	40	0	39	80

As second approach the contribution of an organic fertiliser on the long-term carbon storage (after 50 years) is determined. Based on the HC values of the organic fertiliser, the size of each of the Roth-C pools can be determined and used to estimate the long term storage of carbon in the soil. For this, the described RothC parametrisation for sandy and clay soils (2.4.2) has been applied for different combinations of DPR, RPM and

HUM (3-pool approach). Figure 3-22 shows the HC-values after one year (sum of the remaining amount of carbon in all soil pools DPM, RPM, HUM, BIOM divided by the amount of applied carbon; x-axis) and the associated combination of pool fractions (y-axis) for sandy (left) and clay soils (right). For example, if the DPM fraction is 1 (and consequently RPM and HUM are zero), the HC of that product in sandy soils will be 0.13. If only RPM is available the HC value will be 0.78 and if only HUM is available as pool in the organic product the HC value will be approx. 0.98. At the same HC value, the clay soil requires less RPM or HUM than the sandy soil. In other words: a product with a specific amount of RPM will have a higher HC value in a clay soil than a sandy soil. This is caused both by the assimilation factor and the k_{RPM} value that is lower for clay than for sandy soil in our model adaptation.

If, the HC value of an organic product in a sandy soil is known, e.g. 0.6, the fraction of DPM, RPM and HUM will be resp. 0.27, 0.73 and 0. By using the specific distribution of the RothC pools in organic fertilisers, the long term amount of organic matter that remains in the soil can be calculated for each organic fertiliser. Figure 3-23 shows the fraction of OM that remains in the soil over time for different vales of HC. At the long term only a part of the organic matter of a fertilising product will become part of 'stable' organic matter fraction of the soil if the HC value of an organic fertiliser is sufficient high (>0.8 on sand and >0.9 on clay, i.e. no DPM present in the organic fertiliser). However, if the organic fertiliser is applied every year, the HC value itself gives a good prediction of the annual amount of organic carbon that will become part of the SOC pool (fresh material and stable) and a new SOC equilibrium will be reached.

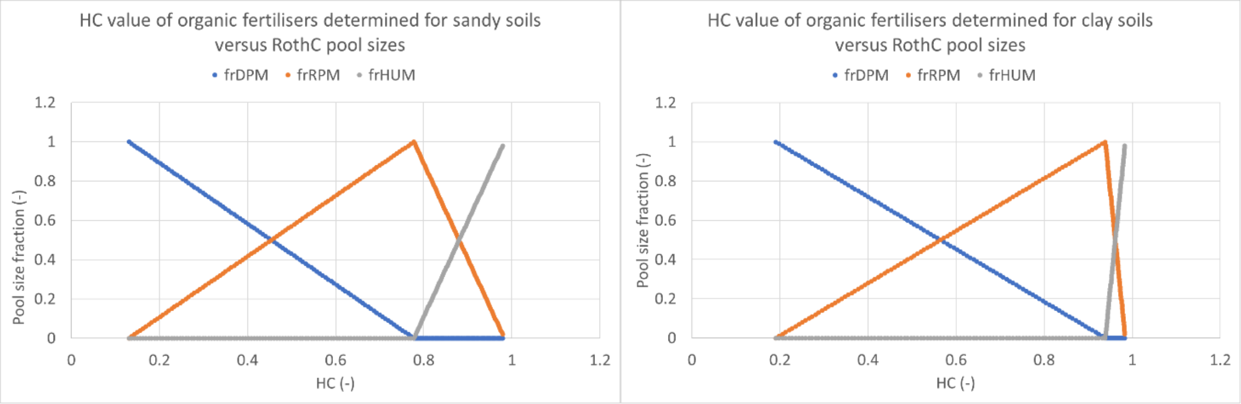


Figure 3-22 *The distribution of the RothC pools (DPM, RPM and HUM) versus the HC-value of an organic fertilisers as determined in a sandy soil (left) and clay soil (right), based on the settings as described in section 2.4.2.*

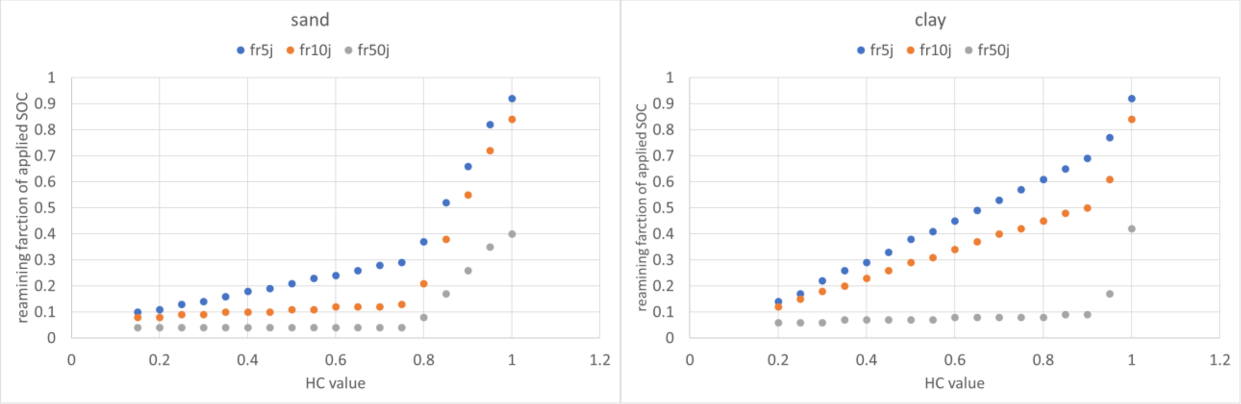


Figure 3-23 *The fraction of the amount of organic carbon that remains in the soil over time (resp. 5, 10 and 50 years) for different vales of the humification coefficient (HC) of an organic fertiliser in a sandy (left) and clay (right) soil.*

It is concluded that carbon credits will have an effect on farm management and the value of soil organic matter. When the OM in organic fertilisers with contribute to soil sequestration the value of those products will most likely rise. Furthermore, carbon credits could also have an effect on the value of agricultural land. The income per hectare increases by using organic matter as well as the value of the land. These impacts are not taken into account.

Another discussion point is the availability of products. The demand for compost is not yet at a level that creates a shortage, however, when the demand increases there will most likely be a shortage.

4 Conclusions and recommendations

In this study, the conceptual framework for the evaluation of organic fertilisers has been evaluated in terms of agronomic and economic aspects. The following conclusions were drawn:

- With incubation experiments, distinctive differences between the C and N mineralisation of organic fertilisers in sandy and clay soils were found.
- Each organic fertiliser can be characterised by means of the size of the DPM and RPM pool. With the new approach presented in this study, it is shown that DPM and RPM can be estimated by using a regression equation based on more simple laboratory analyses: total N, a Microresp. parameter (Alanine) and a pyrolysis parameter (F1). However, a follow-up study indicates that the MicroResp method does not give robust results. Therefore, correlations with other parameters are currently being investigated.
- The differences in C and N mineralisation of organic products can be predicted with the model approach of RothC when values of the organic pool fractions of DPM and RPM are known as well as the C/N ratio of the product.
- For organic products with a very low decomposability, the RothC approach leads to too high modelled C mineralisation, because the decomposition rate of the RPM pool is too high for these fertilisers. For products with a low decomposability (a high HC), it is recommended to fit the RPM and HUM pool. In a follow-up study, the relationship between the size of these two slowly decomposable pools and simple laboratory analyses will be investigated.
- Using the regression equation and RothC, modelled C mineralisation mimics the differences of measured C mineralisation of the organic fertilisers. However, by using just the measured C/N ratio of the DPM pool and fixed C/N values for the other pools, the modelled net N mineralisation was higher than the measured net N-mineralisation with the incubation experiments. It remains unclear whether the model predicted too high net mineralisation or artefacts occurred during the measurements, such as loss of nitrogen gas, that lead to too low values for N mineralisation. In future studies attention will be paid to the origin of the differences.
- Simple laboratory analyses can determine distinctive differences in the decomposability of organic fertilisers. We required three analyses to predict the right order of decomposability, based on the measured decomposability in the carbon incubation experiment. In literature, several analyses have been indicated as single predictors for similar C fractions (e.g. the lignin-fraction of the van Soest method and the Oxitop method are both used to indicate stable organic matter), whereas they do not lead to the same order for decomposability and also do not describe the order of the measured decomposability in our study. We have not been able to find one parameter that can benchmark the decomposability found in the incubation studies.
- Calculations with common fertilisation schemes showed that the developed approach presented in this report can give insight in the impact of an organic fertiliser on C sequestration and N mineralisation for different crop rotations.
- Because a broad range of organic fertilisers was used to calibrate the model, this approach should be suitable to give a first indication of C and N mineralisation of various other organic fertilisers. Furthermore, it can be used for benchmarking purposes of new organic products coming to the market. In a follow-up study the model will be validated with an additional set of organic materials.
- With FarmDyn the behaviour of farmers can be simulated for different prices of carbon credits, showing for example at what price per credit farmers would keep plant residuals on their land because it was more profitable thanks to the carbon credits.
- The economic break even point of supplementing SOM can be calculated. It is dependent on the cost of high EOM materials like compost and the price of the grown crops. Because of the unnatural state of the Dutch manure market, the real cost is likely higher.

References

Albrecht, R., Sebag, D., Verrecchia, E., 2015. Organic matter decomposition: bridging the gap between Rock–Eval pyrolysis and chemical characterization (CPMAS 13 C NMR). Biogeochemistry 122, 101-111.

Amery, F., Vandaele, E., Körner, I., Loades, K., Viaene, J., Vandecasteele, B., Willekens, K., 2020. Compost quality indicators. SoilCom. Aarslev, Denmark.

Antil, R., Bar-Tal, A., Fine, P., Hadas, A., 2011. Predicting nitrogen and carbon mineralization of composted manure and sewage sludge in soil. Compost Science & Utilization 19, 33-43.

Baars, J., Hendrix, E., Hendrickx, P., 2021. Project Biopulping: Selectieve Lignocellulose Ontsluiting met Witrotschimmels': Rapportage over uitvoering van werkpakketten 1 en 3 (door WUR) en werkpakket 5 (door CNC). Stichting Wageningen Research, Wageningen Plant Research.

Bodemkundige Dienst van België, Universiteit Gent, 2006. Ontwikkelen van een expertsysteem voor het adviseren van het koolstofbeheer in de landbouwbodems. Departement Leefmilieu, Natuur en Energie, ALBON, BDB,

UGBB, Brussel.

Bonten, L.T., Reinds, G.J., Posch, M., 2016. A model to calculate effects of atmospheric deposition on soil acidification, eutrophication and carbon sequestration. Environmental Modelling & Software 79, 75-84.

Brust, G.E., 2019. Management strategies for organic vegetable fertility. Safety and practice for organic food. Elsevier, pp. 193-212.

Castellanos, J., Pratt, P., 1981. Mineralization of manure nitrogen—correlation with laboratory indexes. Soil Science Society of America Journal 45, 354-357.

CDM, 2017. Criteria voor organische-stofrijke meststoffen.

Chescheir Iii, G., Westerman, P., Safley Jr, L., 1986. Laboratory methods for estimating available nitrogen in manures and sludges. Agricultural Wastes 18, 175-195.

Clemens, J., Huschka, A., 2001. The effect of biological oxygen demand of cattle slurry and soil moisture on nitrous oxide emissions. Nutrient Cycling in Agroecosystems 59, 193-198.

Coleman, K., Jenkinson, D., 1996. RothC-26.3-A Model for the turnover of carbon in soil. Evaluation of soil organic matter models: using existing long-term datasets. Springer, pp. 237-246.

Coleman, K., Jenkinson, D., 2014. RothC-A Model for the Turnover of Carbon in Soil-Model description and users guide. Rothamsted Research, Harpenden, UK.

Coleman, K., Muhammed, S.E., Milne, A.E., Todman, L.C., Dailey, A.G., Glendining, M.J., Whitmore, A.P., 2017. The landscape model: a model for exploring trade-offs between agricultural production and the environment. Science of the Total Environment 609, 1483-1499.

Conijn, J., Lesschen, J., 2015. Soil organic matter in the Netherlands: Quantification of stocks and flows in the top soil. Plant Research International, Business Unit Agrosystems Research.

Corwin, D.L., Lesch, S.M., 2005. Apparent soil electrical conductivity measurements in agriculture. Computers and electronics in agriculture 46, 11-43.

Curtin, D., Wright, C., Beare, M., 2006. McCallum FJSSSOAJ. 2006. Hot water-extractable nitrogen as an indicator of soil nitrogen availability. Soil Science Society of America Journal, pp. 1512-1521.

De Neve, S., Van de Steene, J., Hartmann, R., Hofman, G., 2000. Using time domain reflectometry for monitoring mineralization of nitrogen from soil organic matter. European Journal of Soil Science 51, 295-304.

De Willigen, P., Janssen, B., Heesmans, H., Conijn, J., Velthof, G., Chardon, W., 2008. Decomposition and accumulation of organic matter in soil; comparison of some models. Alterra.

Delin, S., Stenberg, B., Nyberg, A., Brohede, L., 2012. Potential methods for estimating nitrogen fertilizer value of organic residues. Soil Use and Management 28, 283-291.

Doran, J., Sarrantonio, M., Liebig, M., 1996. Soil health and sustainability In: Advances in Agronomy (Ed.), DL Sparks, Vol. 56. Academic Press, San Diego.

Douglas, B.F., Magdoff, F., 1991. An evaluation of nitrogen mineralization indices for organic residues. Wiley Online Library.

Eigenberg, R., Doran, J.W., Nienaber, J.A., Ferguson, R.B., Woodbury, B., 2002. Electrical conductivity monitoring of soil condition and available N with animal manure and a cover crop. Agriculture, ecosystems & environment 88, 183-193.

Ghani, A., Dexter, M., Perrott, K., 2003. Hot water extractable carbon in soils: a sensitive measurement determining impacts of fertilization, grazing and cultivation. Soil Biology and Biochemistry, pp. 1231-1243.

Groenendijk, P., Boogaard, H., Heinen, M., Kroes, J., Supit, I., de Wit, A., 2016. Simulation nitrogen-limited crop growth with swap/wofost: process descriptions and user manual. Wageningen Environmental Research.

Gutser, R., Ebertseder, T., Weber, A., Schraml, M., Schmidhalter, U., 2005. Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. Journal of Plant Nutrition and Soil Science 168, 439-446.

Handboek Bodem en Bemesting, N.B. Kengetallen organische stof. Accessible. https://www.handboekbodemenbemesting.nl/nl/handboekbodemenbemesting/Handeling/Organische-stofbeheer/Organische-stofbalans/Kengetallen-organische-stof.htm.

Heinen, M., de Willigen, P., 2005. Vergelijking van de organische stofmodellen MOTOR en MINIP. Alterra.

Hendriks, C., 2011. Quick Scan organische stof: kwaliteit, afbraak en trends. Alterra.

Hendriks, C., Lesschen, J.P., Timmermans, B., Hanegraaf, M., Dijkman, W., Rougoor, C., Cruijsen, J., Schepens, J., 2021. Beschrijving en ontwikkeling Praktijktool BodemCoolstof.

Hijbeek, R., Ten Berge, H., Whitmore, A., Barkusky, D., Schröder, J., Van Ittersum, M., 2018. Nitrogen fertiliser replacement values for organic amendments appear to increase with N application rates. Nutrient cycling in agroecosystems 110, 105-115.

Inagro, 2011. Code van goede praktijk bodembescherming. Advies organische koolstofgehalte en zuurtegraad., https://docplayer.nl/14180201-Inagro-code-van-goede-praktijk-bodembescherming-advies-organische-koolstofgehalte-en-zuurtegraad-onderzoek-advies-in-land-tuinbouw.htm.

IRS, 2011. Teelthandleiding – Stikstofbemesting. https://www.irs.nl/interessegebieden/alle-interessegebieden/teelthandleiding/4-3-stikstofbemesting/.

Janssen, B.H.J., B.H., 2002. Organic Matter and Soil Fertility. Collegedictaat. In: Wageningen, L. (Ed.).

Jenkinson, D., Harkness, D., Vance, E., Adams, D., Harrison, A., 1992. Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. Soil Biology and Biochemistry 24, 295-308.

Jenkinson, D., Hart, P., Rayner, J., Parry, L., 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted.

Jensen, L.S., 2013. Animal manure fertiliser value, crop utilisation and soil quality impacts. Animal manure recycling: treatment and management, 295-328.

Kalamdhad, A.S., Kazmi, A.A., 2009. Effects of turning frequency on compost stability and some chemical characteristics in a rotary drum composter. Chemosphere 74, 1327-1334.

Lashermes, G., Nicolardot, B., Parnaudeau, V., Thuriès, L., Chaussod, R., Guillotin, M.-L., Lineres, M., Mary, B., Metzger, L., Morvan, T., 2009. Indicator of potential residual carbon in soils after exogenous organic matter application. European Journal of Soil Science 60, 297-310.

Lashermes, G., Nicolardot, B., Parnaudeau, V., Thuriès, L., Chaussod, R., Guillotin, M.-L., Lineres, M., Mary, B., Metzger, L., Morvan, T., 2010. Typology of exogenous organic matters based on chemical and biochemical composition to predict potential nitrogen mineralization. Bioresource technology 101, 157-164.

Lee, J., Viscarra Rossel, R.A., Zhang, M., Luo, Z., Wang, Y.-P., 2021. Assessing the response of soil carbon in Australia to changing inputs and climate using a consistent modelling framework. Biogeosciences 18, 5185-5202.

Leifeld, J., Klein, K., Wüst-Galley, C., 2020. Soil organic matter stoichiometry as indicator for peatland degradation. Scientific reports 10, 7634.

Lesschen, J.P., Hendriks, C., van de Linden, A., Timmermans, B., Keuskamp, J., Keuper, D., Hanegraaf, M., Conijn, S., Slier, T., 2020. Ontwikkeling praktijktool voor bodem C. Wageningen Environmental Research.

Major, A.G., Hessel, R., van den Elsen, E., Ritsema, C., 2017. Identification of critical changes preceding catastrophic shifts: ecosystems affected by increasing wildfire recurrence. Cascade Project.

Mewes, P., 2017. Persistence of exogenous organic carbon in soil as a cultivation property. Humboldt Universitaet zu Berlin (Germany).

Moolenaar, S.W., Veeken, A. and Postma, R., 2002. Toetsen en normeren stabiliteit van bodemverbeteraars. Nutriënten Management Instituut.

Muhammed, S.E., Coleman, K., Wu, L., Bell, V.A., Davies, J.A., Quinton, J.N., Carnell, E.J., Tomlinson, S.J., Dore, A.J., Dragosits, U., 2018. Impact of two centuries of intensive agriculture on soil carbon, nitrogen and phosphorus cycling in the UK. Science of the Total Environment 634, 1486-1504.

Peltre, C., Christensen, B.T., Dragon, S., Icard, C., Kätterer, T., Houot, S., 2012. RothC simulation of carbon accumulation in soil after repeated application of widely different organic amendments. Soil Biology and Biochemistry 52, 49-60.

Poeplau, C., Don, A., Six, J., Kaiser, M., Benbi, D., Chenu, C., Cotrufo, M.F., Derrien, D., Gioacchini, P., Grand, S., 2018. Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils–A comprehensive method comparison. Soil Biology and Biochemistry 125, 10-26.

Qian, P., Schoenau, J., 2002. Availability of nitrogen in solid manure amendments with different C: N ratios. Canadian Journal of Soil Science 82, 219-225.

Regelink, I., Ehlert, P., Smit, G., Everlo, S., Prinsen, A., Schoumans, O., 2019. Phosphorus recovery from co-digested pig slurry: development of the RePeat process. Wageningen Environmental Research.

Reuland, G., Sigurnjak, I., Dekker, H., Sleutel, S., Meers, E., 2022. Assessment of the carbon and nitrogen mineralisation of digestates elaborated from distinct feedstock profiles. Agronomy 12, 456.

Rietra, R., van't Hull, J., Velthof, G., in press. Afbraak van organische meststoffen. Wageningen, Wageningen Environmental Research.

Rietra, R.P.J.M., B.J.A. Berendsen, Y. Mi- Gegotek, P.F.A.M. Römkens, and A. Pustjens. 2023. Prediction of the mobility and persistence of eight antibiotics based on soil characteristics. Prediction of the mobility and persistence of eight antibiotics based on soil characteristics.

Ros, G.H., 2011. Predicting soil nitrogen supply: relevance of extractable soil organic matter fractions. Wageningen University and Research.

RVO, 2018. Mestbeleid 2019-2021 Tabel 3: Werkingscoëfficiënt.

Saenger, A., Cécillon, L., Sebag, D., Brun, J.-J., 2013. Soil organic carbon quantity, chemistry and thermal stability in a mountainous landscape: A Rock–Eval pyrolysis survey. Organic Geochemistry 54, 101-114.

Schipper, L., Sparling, G., 2000. Performance of soil condition indicators across taxonomic groups and land uses. Soil Science Society of America Journal 64, 300-311.

Schoumans, O., Ehlert, P., Hanegraaf, M., Römkens, P., Pustjens, A., De Koeijer, T., De Boer, H., Nienhuis, C., Kortstee, H., Smit, A., 2019. Development of a conceptual framework to evaluate organic fertilisers: assessment on soil quality and agronomic, environmental and economics aspects. Wageningen Environmental Research.

Schoumans, O., Sigurnjak, I., Veenemans, L., van Dijk, K., Lesschen, J.P., Römkens, P., Brienza, C., Giordano, A., Zilio, M., 2021. Full report on environmental impact assessment of recovered products. Wageningen Environmental Research (WENR), Wageningen, Netherlands.

Schouten, S., van Groenigen, J.W., Oenema, O., Cayuela, M.L., 2012. Bioenergy from cattle manure? Implications of anaerobic digestion and subsequent pyrolysis for carbon and nitrogen dynamics in soil. Gcb Bioenergy 4, 751-760.

Sebag, D., Disnar, J.-R., Guillet, B., Di Giovanni, C., Verrecchia, E.P., Durand, A., 2006. Monitoring organic matter dynamics in soil profiles by 'Rock-Eval pyrolysis': bulk characterization and quantification of degradation. European journal of soil science 57, 344-355.

Sebag, D., Verrecchia, E., Cécillon, L., Adatte, T., Albrecht, R., Aubert, M., Bureau, F., Cailleau, G., Copard, Y., Decaens, T., 2016. Dynamics of soil organic matter based on new Rock-Eval indices. Geoderma 284, 185-203.

Senapati, N., Smith, P., Wilson, B., Yeluripati, J., Daniel, H., Lockwood, P., Ghosh, S., 2013. Projections of changes in grassland soil organic carbon under climate change are relatively insensitive to methods of model initialization. European Journal of Soil Science 64, 229-238.

Serna, M., Pomares, F., 1992. Indexes of assessing N availability in sewage sludges. Plant and soil 139, 15-21.

Skjemstad, J., Spouncer, L., Cowie, B., Swift, R., 2004. Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. Soil Research 42, 79-88.

Sleutel, S., De Neve, S., Hofman, G., 2007. Assessing causes of recent organic carbon losses from cropland soils by means of regional-scaled input balances for the case of Flanders (Belgium). Nutrient Cycling in Agroecosystems 78, 265-278.

Smit, A., Radersma, S., van't Riet, S., Hack-ten Broeke, M., Conijn, J., 2004. Zoeken naar een indicator voor mobiel N in de bodem. Alterra.

Smith, J.L., Doran, J.W., 1997. Measurement and use of pH and electrical conductivity for soil quality analysis. Methods for assessing soil quality 49, 169-185.

Soucémarianadin, L., Cécillon, L., Chenu, C., Baudin, F., Nicolas, M., Girardin, C., Barré, P., 2018. Is Rock-Eval 6 thermal analysis a good indicator of soil organic carbon lability?–A method-comparison study in forest soils. Soil Biology and Biochemistry 117, 108-116.

Spijker, J., Korthals, G., Rietra, R., Römkens, P., Timmermans, L., Visser, J., 2022. Kennisprogramma Circulair Terreinbeheer Jaarrapportage 2021: Bokashi, lokale organische bodemverbeteraars en compost: chemische kwaliteit en effecten op micro-organismen in landbouwbodems.

Stowa, 2002. Optimalisatie van de BZV5-analyse.

Straathof, A.L., Comans, R.N., 2015. Input materials and processing conditions control compost dissolved organic carbon quality. Bioresource Technology 179, 619-623.

Straatsma, G., 2014. Spent mushroom substrate, SMS;'livestock manure'according to the Nitrate Directive or compost? Applied Plant Research, Research Unit Mushrooms.

Sullivan, D.M., 2008. Estimating plant-available nitrogen from manure.

Sultana, S., 2011. Effects of organic amendment on soil quality as assessed by biological indicators.

Tas, D.O., Karahan, Ö., I˙nsel, G., Övez, S., Orhon, D., Spanjers, H., 2009. Biodegradability and denitrification potential of settleable chemical oxygen demand in domestic wastewater. Water Environment Research 81, 715-727.

Ten Berge, H., Schroder, J., Olesen, J.E., Cervera, J.V.G., 2019. Soil quality: a confusing beacon for sustainability. Proceedings International Fertiliser Society.

Thuriès, L., Pansu, M., Larré-Larrouy, M.-C., Feller, C., 2002. Biochemical composition and mineralization kinetics of organic inputs in a sandy soil. Soil Biology and Biochemistry 34, 239-250.

van den Elsen, E., Knotters, M., Heinen, M., Römkens, P., Bloem, J., Korthals, G., 2019. Noodzakelijke indicatoren voor de beoordeling van de gezondheid van Nederlandse landbouwbodems: Selectie van fysische, chemische en biologische indicatoren voor het meten van de bodemgezondheid. Wageningen Environmental Research.

van der Burgt, G., Dekker, P., van Geel, W., Bokhorst, J., van den Berg, W., 2011. Duurzaamheid organische stof in mest: analysemethoden om de stabiliteit van organische stof van verschillende organische meststoffen inclusief digestaat te beoordelen: eindrapportage 2010. PPO-agv/WUR/LBI.

van Dijk, W., Spruijt, J., Runia, W., van Geel, W., 2012. Verruiming vruchtwisseling in relatie tot mineralenbenutting, bodemkwaliteit en bedrijfseconomie op akkerbouwbedrijven. Praktijkonderzoek Plant & Omgeving, Business Unit AGV.

Van Dijk, W.v., Van Dam, A., de Ruijter, F., van Middelkoop, J., Zwart, K., 2005. Onderbouwing N werkingscoëfficiënt overige organische meststoffen. Studie ten behoeve van onderbouwing gebruiksnormen. PPO publicatie.

Van Faassen, H., Lebbink, G., 1994. Organic matter and nitrogen dynamics in conventional versus integrated arable farming. Agriculture, ecosystems & environment 51, 209-226.

Van Groenigen, J., Zwart, K., 2007. Koolstof en stikstof mineralisatie van verschillende soorten compost: een laboratorium studie. Alterra.

van Soest, P., 1963. Use of detergents in the analysis of fibrous feeds. II. A rapid method for the determination of fiber and lignin. Journal of the Association of official Agricultural Chemists 46, 829-835.

van Soest, P., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. Journal of dairy science 74, 3583-3597.

van Soest, P., Wine, R., 1967. Use of detergents in the analysis of fibrous feeds. IV. Determination of plant cell-wall constituents. Journal of the Association of Official Analytical Chemists 50, 50-55.

Velthof, G.L., 2003. Relaties tussen mineralisatie, denitrificatie en indicatoren voor bodemkwaliteit in landbouwgronden. Alterra.

Velthof, G.L., 2004. Achtergronddocument bij enkele vragen van de evaluatie Meststoffenwet 2004. Alterra.

Watson, C.A., Atkinson, D., Gosling, P., Jackson, L.R., Rayns, F., 2002. Managing soil fertility in organic farming systems. Soil use and management 18, 239-247.

Woodard, Curran, I., 2006. 7-Methods for Treating Wastewaters from Industry. Butterworth-Heinemann, pp. 149-334.

Zimmermann, M., Leifeld, J., Schmidt, M., Smith, P., Fuhrer, J., 2007. Measured soil organic matter fractions can be related to pools in the RothC model. European Journal of Soil Science 58, 658-667.

Zmora-Nahum, S., Markovitch, O., Tarchitzky, J., Chen, Y., 2005. Dissolved organic carbon (DOC) as a parameter of compost maturity. Soil Biology and Biochemistry 37, 2109-2116.

Zwart, K., 2007. Mineralisatie van mest en organische stof in de bodem: een indicator op basis van (bio) chemische parameters. Alterra.

Annex 1 Description of the regions

South-East of the Netherlands

The South-East of the Netherlands is located on dry sandy soils, and dominated by animal husbandry and grasslands. Arable farming in the region is dominated by the cultivation of consumption potatoes and maize. The crop rotation consists of the following 4-year crop rotation: potato, spring barley/green bean followed by a cover crop, sugar beet, and maize followed by a catch crop. Due to the long history of animal husbandry and associated use of manure, most soils have a high phosphorus status. A Pw-value of >46 is common in the region, with an associated maximum permitted fertiliser use of 50 kg P2O5 ha-1 jr-1. Manure is applied in spring, pig slurry is applied for the potatoes, sugar beet and green beans, cattle slurry is applied for maize, and compost is applied for the cover crop.

South-West of the Netherlands

The South-West of the Netherlands, in contradiction to South-East, is located on moist (heavy) clay soils. The crop rotation consists of five crops in the following order: winter wheat, followed by a green manure, either onions or chicory roots, potatoes, sugar beets. Pw values around 50 are common in the region. The permitted fertiliser use is often neutral 60 kg P_2O_5 ha^{-1} yr^{-1}. Cattle slurry prior to potato planting is commonly used, even as pig slurry on the winter wheat and a combination of pig slurry and compost on the cover crop after winter wheat.

Annex 2 Laboratory analyses results

	General				Forms of N					C/N		Forms of C and related parameters								Van Soest		
	DM	OM	pH	EC	Total N	Nmin totaal	HWN	N in pepsin	PMN	C_{org}/N	C_{org}/N_{org}	Total C_{org}	HWC	DOC	Total C	Total H	BOD(7)	COD	Oxitop	NDF	ADF	ADL
Parameter	% of FM	% of DM	-	mS/cm, DM	g/kg DM	mg/kg DM	g/kg DM	g/kg DM	g/kg DM	-	-	g/kg DM	g/kg DM	mg/kg DM	g/kg DM	g/kg DM		g/kg DM	mmol O2/kg OS/hour	g/ kg	g/ kg	g/ kg
Cattle slurry	11.5	82	7.9	181.5	59.7	45.6	9.0	20.1	5.6	6.0	25.4	358	41.6	96.7	410	62	44.4	1389	39.6	432	239	80
Pig slurry	6.8	73	7.9	350.9	88.7	71.9	26.9	19.8	7.7	3.6	19.0	319	54.9	142.7	394	63	33.2	1393	83.5	355	191	55
Organic waste compost	60.3	47	6.4	3.4	9.6	1.7	0.6	0.2	0.8	18.6	22.7	178	3.1	3.3	191	27	10.2	489	0.1	277	250	140
Farmyard manure	30.8	64	9.0	117.4	27.0	5.7	2.5	6.5	-0.3	13.5	17.1	366	17.8	32.3	364	51	8.9	932	0.5	439	375	167
Garden peat	26.2	98	3.0	2.1	10.2	2.1	0.4	4.0	0.1	48.9	61.3	499	2.2	0.5	500	60	1.5	1296	0.1	644	718	467
Straw	90.8	98	6.0	3.8	4.9	1.2	3.6	2.7	0.2	87.2	114.7	430	30.6	15.0	446	65	132.0	1370	1.0	786	479	54
Grass	92.6	91	6.0	46.1	30.0	5.2	7.9	25.2	1.4	13.3	16.1	398	43.1	95.8	423	62	356.0	1273	4.3	513	252	15
Chicken manure	84.6	76	7.3	40.7	38.2	6.9	7.6	23.9	24.8	8.0	9.8	306	31.3	38.2	350	52	238.0	874	1.4	369	196	41
Monodigested cattle slurry	8.9	72	8.2	265.9	54.2	31.0	7.3	10.7	10.1	6.2	14.4	334	34.1	75.5	362	53	11.6	1003	9.8	377	235	85
Deep litter stable manure	22.6	82	8.8	132.4	28.1	11.8	3.6	9.1	4.3	13.2	22.8	371	24.6	21.8	378	58	19.8	1073	1.2	564	353	67
Bokashi	37.4	45	7.8	5.2	9.8	1.5	0.7	-0.4	0.1	22.2	26.1	218	3.7	1.9	177	25	5.6	603	0.2	273	302	185
WWTP dairy sludge	15.2	28	7.6	22.0	37.8	4.3	7.4	12.8	4.8	3.2	3.6	121	20.4	4.5	134	27	5.7	501	1.0	83	13	0
Struvite with organic matter	82.1	35	8.0	19.4	44.9	23.6	21.8	34.2	0.0	2.4	5.0	107	37.5	16.8	113	43	74.9	384	0.4	52	12	5
Champost	54.6	41	7.2	33.4	17.7	2.2	2.0	1.1	0.6	12.9	14.7	229	14.6	3.9	207	28	5.1	595	0.1	151	207	139
Soil improver from GZV	32.6	93	5.4	14.0	14.4	3.0	4.5	2.6	0.3	37.7	47.8	543	32.9	4.2	429	61	10.9	1460	0.4	780	553	243
Codigestate from GZV	8.9	73	8.3	326.4	90.8	56.6	16.6	16.1	8.5	3.9	10.5	358	57.0	54.2	356	53	13.9	1092	5.2	355	231	116

	Microresp.								Rock-Eval								
	Lignin	Alanine	Aminobutyric acid	N-acetyl glucosamine	D(+) glucose	Alpha ketoglutarate	Malic acid	Total respiration	C_{org}	F1	F2	F3	F4	I-index	R-index	OI	HI
Parameter	CO2-C (ug/g DM/h)	CO2-C (ug/g DM/h)	CO2-C (ug/g DM/h)	CO2-C (ug/g DM/h)	CO2-C (ug/g DM/h)	CO2-C (ug/g DM/h)	CO2-C (ug/g DM/h)	CO2-C (ug/g DM/h)	[g.kg .ds]	[%]	[%]	[%]	[%]	[-]	[-]	[-]	[-]
Cattle slurry	34	51	22	43	68	116	134	466	267	99	0	0	1	3.1	0.0	144	309
Pig slurry	55	72	40	54	88	108	132	549	331	54	15	16	15	0.6	0.3	116	598
Organic waste compost	14	20	10	17	27	66	69	223	175	37	29	19	15	0.5	0.3	129	357
Farmyard manure	17	22	10	14	30	60	95	246	331	60	16	12	11	0.8	0.2	160	413
Garden peat	27	30	16	18	35	167	180	473	481	37	23	26	15	0.4	0.4	95	299
Straw	37	79	62	84	143	117	155	678	377	53	32	8	6	1.0	0.1	140	518
Grass	48	87	61	90	141	146	168	741	373	55	20	13	11	0.8	0.2	167	520
Chicken manure	36	57	32	50	80	93	115	462	283	57	17	14	12	0.7	0.3	168	463
Monodigested cattle slurry	21	31	15	29	48	106	127	377	313	56	16	15	14	0.7	0.3	162	473
Deep litter stable manure	19	42	15	27	59	104	123	391	293	55	17	15	13	0.7	0.3	164	393
Bokashi	14	18	7	15	25	70	74	223	197	36	29	20	16	0.5	0.4	123	435
WWTP dairy sludge	10	19	12	15	26	30	38	149	104	17	28	26	29	0.2	0.6	171	515
Struvite with organic matter	3	7	4	3	6	11	23	56	78	27	27	24	23	0.3	0.5	158	697
Champost	2	14	7	10	18	59	69	178	200	32	27	21	20	0.4	0.4	143	329
Soil improver from GZV	28	72	38	65	114	194	208	719	372	42	34	15	10	0.7	0.2	101	517
Codigestate from GZV	24	28	23	24	47	69	97	311	326	48	18	18	16	0.6	0.3	150	539

Table 4-1 *Correlation matrix (part I), R^2 is presented in %, values >50% are indicated in bold. Units are only provided in the rows.*

		C	C_{org}	N	Mineral N	H	C/H	DOC	C_{org}/ N	C_{org}/ N_{org}	BOD (5)
C_{org}	[g.kg. ds]	88									
N	[g.kg. ds]	1	1								
Mineral N	[g.kg. ds]	3	0	89							
H	[g.kg. ds]	**80**	**64**	8	13						
C/H	[mol.mol]	36	40	9	4	4					
DOC	[g.kg. ds]	15	3	**56**	**61**	29	0				
TON	[g.kg. ds]	4	8	36	8	0	14	7			
C_{org}/N	[-]	19	28	38	20	9	14	15			
C_{org}/N_{org}	[-]	27	32	23	8	18	14	6	96		
EC	[mS.cm]	8	2	**79**	**83**	14	0	**58**	20	9	
BOD(5)	[g.kg. ds]	5	1	0	2	10	1	12	0	0	
BOD(7)	[g.kg. ds]	6	2	0	2	12	0	10	0	0	99
COD	[g.kg. ds]	**89**	**80**	4	10	**82**	22	25	16	26	3
COD/BOD	[-]	12	15	8	4	1	19	9	11	9	9
HWC	[g.kg. ds]	9	3	**66**	**59**	34	11	**56**	9	3	11
HWN	[g.kg. ds]	1	5	**69**	**66**	7	37	40	20	12	2
N in pepsin	[g.kg. ds]	0	6	37	23	9	43	30	27	21	33
N in pepsin/TN	[-]	4	1	0	1	21	19	4	1	1	**61**
PMN	[g.kg. ds]	1	0	22	10	3	0	12	14	11	12
MR Lignin	[ug.g.h]	**54**	32	10	16	**56**	9	**52**	4	9	27
MR Alanine	[ug.g.ds product.h]	**50**	41	0	2	**56**	7	25	14	20	34
MR Aminobutyric acid	[ug.g.ds product.h]	40	32	0	0	45	4	18	23	27	40
MR N-acetyl glucosamine	[ug.g.ds product.h]	41	34	0	0	45	5	19	19	24	41
MR D(+) glucose	[ug.g.ds product.h]	46	41	0	0	**50**	6	15	23	28	35
MR Alpha ketoglutarate	[ug.g.ds product.h]	**71**	**81**	3	0	48	38	4	23	27	4
MR Malic acid	[ug.g.ds product.h]	**85**	**90**	1	0	**63**	36	7	26	31	6
MR Total respiration	[ug.g.ds product.h]	**70**	**67**	0	0	**63**	20	16	24	30	22
Oxitop	[mmol O2.kg OM.h]	6	0	43	**64**	13	0	**66**	7	1	0
TOC Rock-Eval	[g.kg.ds]	**91**	**89**	0	0	**60**	49	7	25	30	3
F1	[%]	37	20	10	17	40	9	39	0	1	5
F2	[%]	13	2	39	38	17	1	**51**	25	13	2
F3	[%]	28	18	2	7	33	6	25	2	7	7
F4	[%]	**54**	47	0	1	45	25	11	15	24	5
I-index	[-]	13	6	4	10	16	2	19	0	2	1
R-index	[-]	42	33	0	4	41	15	19	7	15	6
OI	[-]	9	18	5	0	1	18	2	21	22	16
HI	[-]	5	5	17	11	2	**53**	6	2	2	7
NDF	[g.kg.ds]	**76**	**87**	9	3	**56**	32	0	**51**	**57**	1
ADF	[g.kg.ds]	**51**	**70**	24	10	22	**51**	7	**54**	**52**	3
ADL	[g.kg.ds]	13	26	15	7	0	38	15	16	12	17
ADF-ADL	[g.kg.ds]	**63**	**71**	15	6	48	26	0	**60**	**65**	3
Lignin/nitrogen	[-]	7	16	33	18	0	28	24	34	27	10

Table 4-2 *Correlation matrix (part II), R^2 is presented in %, values >50% are indicated in bold. Units are only provided in the rows.*

		BOD (7)	**COD**	**COD/ BOD**	**HWC**	**HWN**	**N in pepsin**	**N in pepsin /TN**	**PMN**	**MR Lignin**	**MR Alanine**
COD	[g.kg. ds]	4									
COD/BOD	[-]	9	4								
HWC	[g.kg. ds]	11	22	22							
HWN	[g.kg. ds]	1	1	10	**63**						
N in pepsin	[g.kg. ds]	28	0	11	46	**56**					
N in pepsin/TN	[-]	**61**	3	1	14	9	**53**				
PMN	[g.kg. ds]	10	0	6	14	7	18	3			
MR Lignin	[ug.g.h]	28	**64**	0	30	10	7	11	10		
MR Alanine	[ug.g.ds product.h]	38	**64**	4	25	2	3	17	3	**79**	
MR Aminobutyric acid	[ug.g.ds product.h]	47	50	4	25	2	3	24	1	**69**	**90**
MR N-acetyl glucosamine	[ug.g.ds product.h]	47	**52**	6	22	1	2	20	2	**69**	**96**
MR D(+) glucose	[ug.g.ds product.h]	40	**57**	5	21	0	1	18	1	**66**	**96**
MR Alpha ketoglutarate	[ug.g.ds product.h]	5	**72**	16	1	6	5	1	0	40	**52**
MR Malic acid	[ug.g.ds product.h]	7	**83**	11	4	3	3	2	0	49	**60**
MR Total respiration	[ug.g.ds product.h]	26	**78**	0	14	0	0	10	1	**72**	**91**
Oxitop	[mmol O2.kg OM.h]	0	18	2	29	43	10	1	4	37	13
TOC Rock-Eval	[g.kg.ds]	4	**74**	23	2	3	4	1	0	42	37
F1	[%]	5	38	5	18	0	5	1	8	31	22
F2	[%]	1	12	1	19	9	20	1	19	13	1
F3	[%]	8	35	19	17	0	1	1	4	28	33
F4	[%]	6	**53**	0	5	4	1	1	0	32	37
I-index	[-]	1	20	4	8	0	3	0	1	11	9
R-index	[-]	8	46	7	10	1	0	1	2	32	37
OI	[-]	16	13	34	7	1	23	17	14	3	1
HI	[-]	7	0	20	37	55	33	18	1	2	4
NDF	[g.kg.ds]	3	**70**	8	0	11	11	1	1	31	49
ADF	[g.kg.ds]	2	37	44	11	28	34	2	9	6	10
ADL	[g.kg.ds]	18	6	**78**	28	22	33	14	11	1	3
ADF-ADL	[g.kg.ds]	6	**56**	3	0	14	12	3	2	26	48
Lignin/nitrogen	[-]	9	2	**77**	42	27	34	6	16	1	1

Table 4-3 *Correlation matrix (part III), R^2 is presented in %, values >50% are indicated in bold. Units are only provided in the rows.*

		MR Aminobutyric acid	MR N-acetyl glucosamine	MR D(+) glucose	MR Alpha keto glutarate	MR Malic acid	MR Total resp.	Oxitop	TOC Rock eval
MR N-acetyl glucosamine	[ug.g.ds product.h]	**95**							
MR D(+) glucose	[ug.g.ds product.h]	**95**	**99**						
MR Alpha ketoglutarate	[ug.g.ds product.h]	36	44	48					
MR Malic acid	[ug.g.ds product.h]	46	**53**	57	96				
MR Total respiration	[ug.g.ds product.h]	**80**	**86**	89	78	86			
Oxitop	[mmol O2.kg OM.h]	5	6	4	2	3	6		
TOC	[g.kg.ds]	33	31	36	70	81	61	2	
F1	[%]	11	17	17	13	20	21	19	17
F2	[%]	0	0	0	0	1	1	29	3
F3	[%]	23	33	33	12	19	28	11	11
F4	[%]	25	35	36	39	47	45	4	37
I-index	[-]	3	8	7	6	7	8	14	2
R-index	[-]	25	36	36	25	33	38	7	23
OI	[-]	0	0	0	29	21	8	5	16
HI	[-]	8	5	4	6	3	0	3	5
NDF	[g.kg.ds]	41	45	**53**	**75**	**83**	**70**	0	**73**
ADF	[g.kg.ds]	7	8	11	**59**	**59**	30	3	**66**
ADL	[g.kg.ds]	5	5	3	24	18	1	4	28
ADF-ADL	[g.kg.ds]	44	47	**55**	**56**	**66**	**63**	1	**60**
Lignin/nitrogen	[-]	1	2	1	20	14	2	7	19

Table 4-4 *Correlation matrix (part IV), R^2 is presented in %, values >50% are indicated in bold. Units are only provided in the rows.*

		F1	F2	F3	F4	I-index	R-index	OI	HI	NDF	ADF	ADL	ADF-ADL
F2	[%]	**66**											
F3	[%]	**86**	32										
F4	[%]	**74**	18	**79**									
I-index	[-]	**76**	47	**72**	**56**								
R-index	[-]	**85**	26	**95**	**94**	**67**							
OI	[-]	1	9	2	4	0	0						
HI	[-]	8	6	3	11	12	7	4					
NDF	[g.kg.ds]	16	0	22	**53**	6	38	16	4				
ADF	[g.kg.ds]	2	3	2	27	0	11	43	20	73			
ADL	[g.kg.ds]	2	3	7	2	2	1	**58**	29	17	**65**		
ADF-ADL	[g.kg.ds]	14	1	25	**50**	4	38	7	3	93	**62**	8	
Lignin/nitrogen	[-]	7	13	12	1	4	2	**59**	23	16	**63**	**87**	10

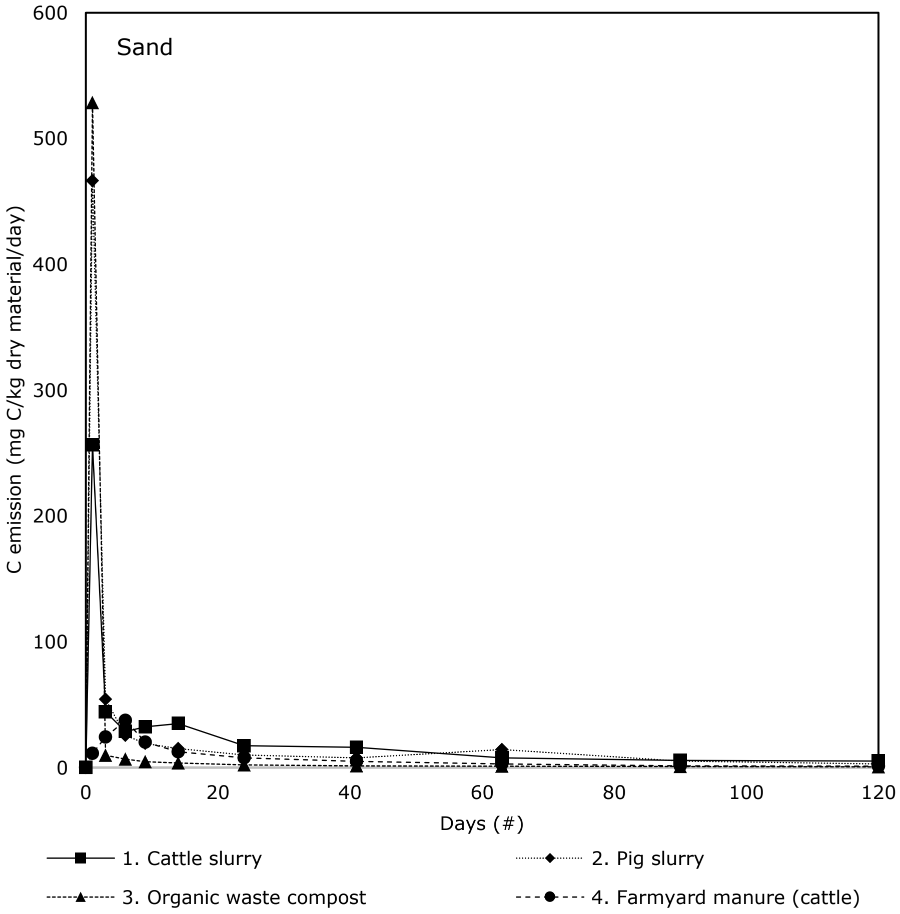
Annex 3 Incubation experiment results

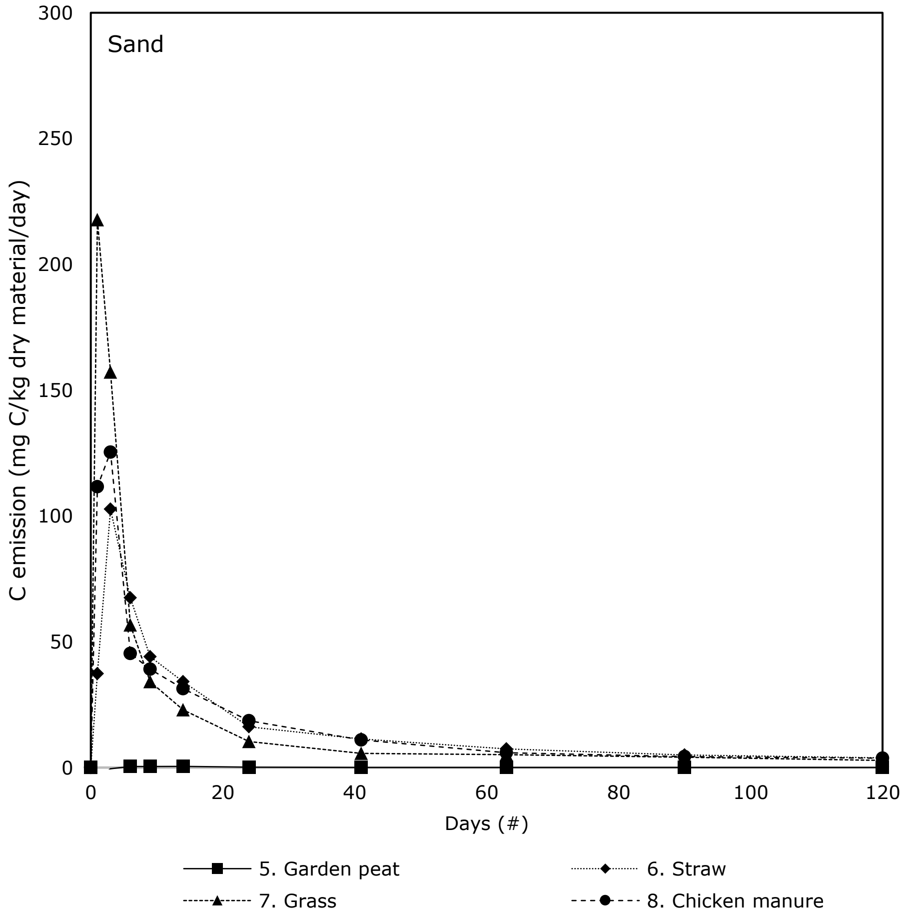
Annex 3a Results of the carbon incubation experiment

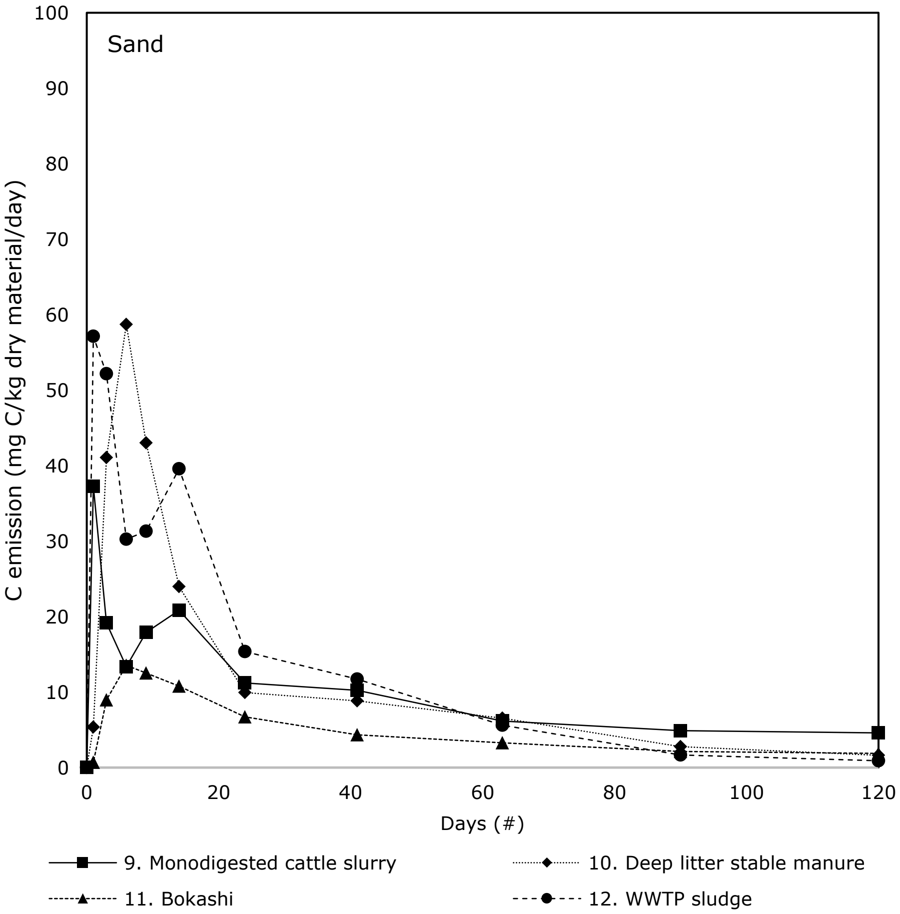
Table 4-5 *C emission (mg C kg-1 dry material day-1), averaged for the duplicate and corrected for the blank.*

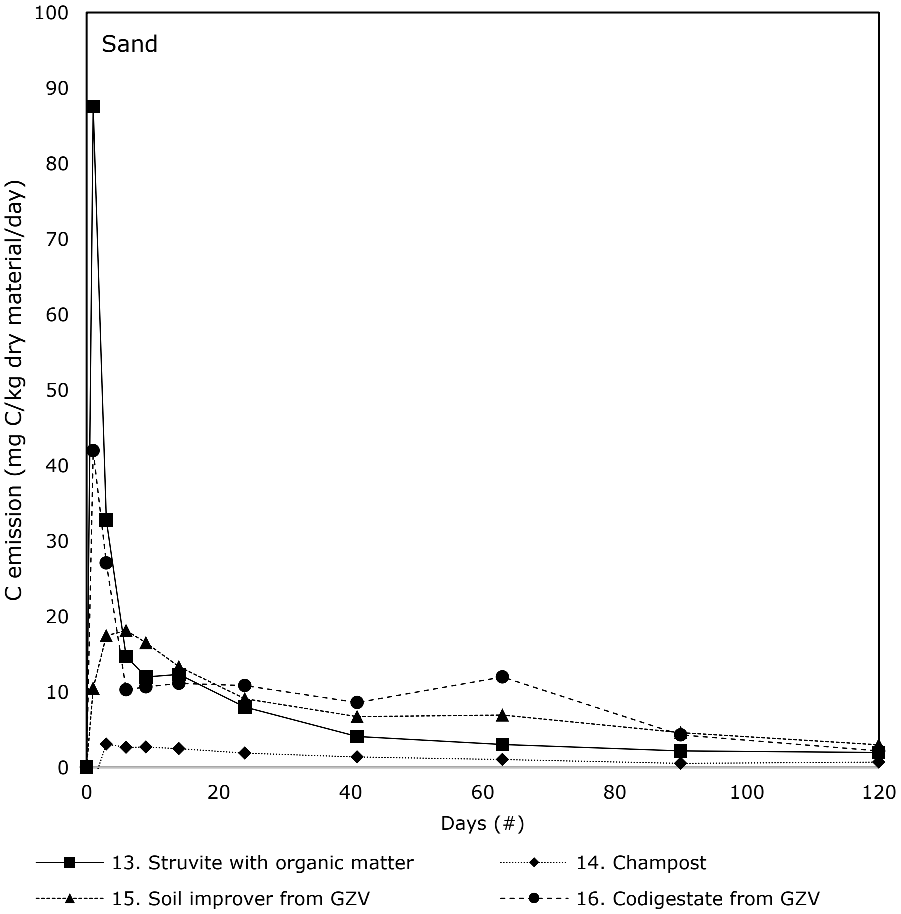
Days	1	3	6	9	14	24	41	63	90	120
Sand										
1. Cattle slurry	257	44	29	32	35	17	16	8	6	5
2. Pig slurry	467	54	26	19	15	10	8	14	5	3
3. Organic waste compost	529	10	7	5	4	2	1	1	1	1
4. Farmyard manure (cattle)	11	24	38	20	13	8	5	3	1	1
5. Garden peat	-4	0	0	0	0	0	0	0	0	0
6. Straw	37	103	67	44	34	16	11	7	5	4
7. Grass	218	157	57	34	23	10	6	5	4	3
8. Chicken manure	112	125	45	39	31	19	11	6	4	4
9. Monodigested cattle slurry	37	19	13	18	21	11	10	6	5	5
10. Deep litter stable manure	5	41	59	43	24	10	9	7	3	2
11. Bokashi	1	9	14	13	11	7	4	3	2	2
12. WWTP sludge	57	52	30	31	40	15	12	6	2	1
13. Struvite with organic matter	87	33	15	12	12	8	4	3	2	2
14. Champost	-2	3	3	3	2	2	1	1	1	1
15. Soil improver from GZV	11	17	18	17	13	9	7	7	5	3
16. Codigestate from GZV	42	27	10	11	11	11	9	12	4	2
Clay										
1. Cattle slurry	428	31	26	23	18	13	7	3	3	2
2. Pig slurry	528	39	26	19	14	11	8	5	3	3
3. Organic waste compost	14	9	3	2	2	1	1	1	1	1
4. Farmyard manure (cattle)	7	10	17	10	5	3	2	1	1	0
5. Garden peat	0	1	0	-1	0	0	0	0	0	0
6. Straw	15	41	50	47	27	11	6	3	2	2
7. Grass	94	121	61	36	17	5	3	2	1	1
8. Chicken manure	65	109	47	34	24	11	6	3	2	2

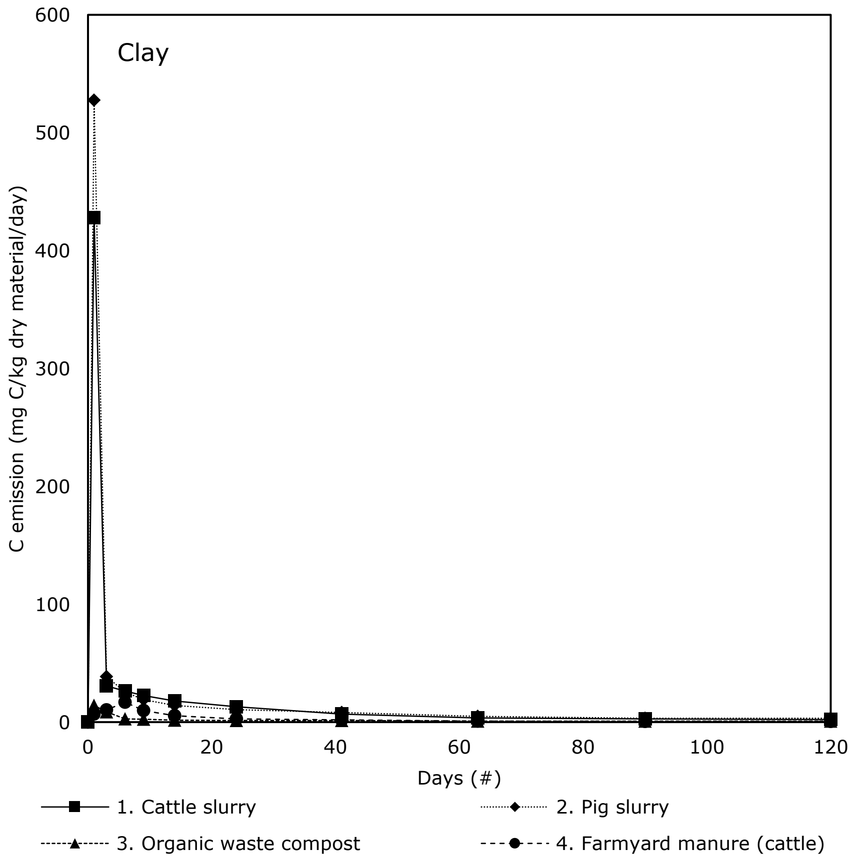
Days	1	3	6	9	14	24	41	63	90	120
9. Monodigested cattle slurry	10	10	10	12	10	6	3	1	1	1
10. Deep litter stable manure	2	8	41	35	22	11	6	3	2	2
11. Bokashi	4	3	3	5	5	4	3	2	1	1
12. WWTP sludge	27	19	18	16	11	9	7	3	2	1
13. Struvite with organic matter	41	42	14	11	8	6	4	6	5	4
14. Champost	16	14	4	5	3	2	1	1	1	0
15. Soil improver from GZV	6	7	23	25	17	11	5	3	2	4
16. Codigestate from GZV	12	11	10	14	12	6	4	3	3	2

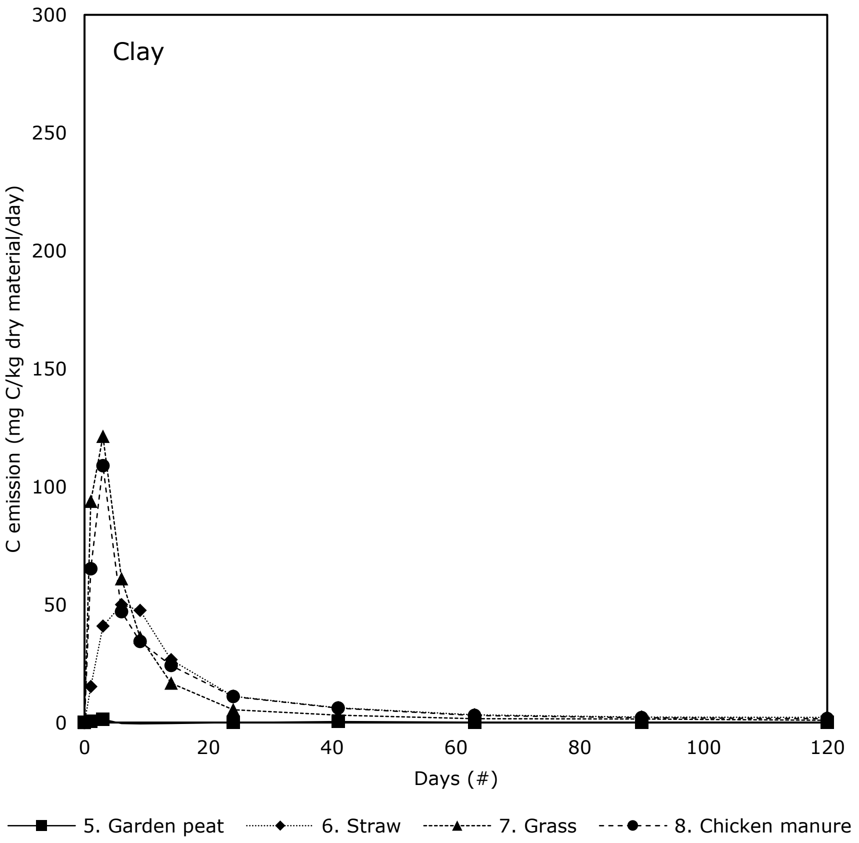

Sand
C emission (mg C/kg dry material/day)
600
500
400
300
200
100
0
0
20
40
60
80
100
120
Days (#)
1. Cattle slurry
2. Pig slurry
3. Organic waste compost
4. Farmyard manure (cattle)


Sand
C emission (mg C/kg dry material/day)
300
250
200
150
100
50
0
0
20
40
60
80
100
120
Days (#)
5. Garden peat
6. Straw
7. Grass
8. Chicken manure


Sand
C emission (mg C/kg dry material/day)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
Days (#)
9. Monodigested cattle slurry
10. Deep litter stable manure
11. Bokashi
12. WWTP sludge


Sand
C emission (mg C/kg dry material/day)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
Days (#)
13. Struvite with organic matter
14. Champost
15. Soil improver from GZV
16. Codigestate from GZV


Clay
C emission (mg C/kg dry material/day)
600
500
400
300
200
100
0
0
20
40
60
80
100
120
Days (#)
1. Cattle slurry
2. Pig slurry
3. Organic waste compost
4. Farmyard manure (cattle)


Clay
C emission (mg C/kg dry material/day)
300
250
200
150
100
50
0
0
20
40
60
80
100
120
Days (#)
5. Garden peat
6. Straw
7. Grass
8. Chicken manure

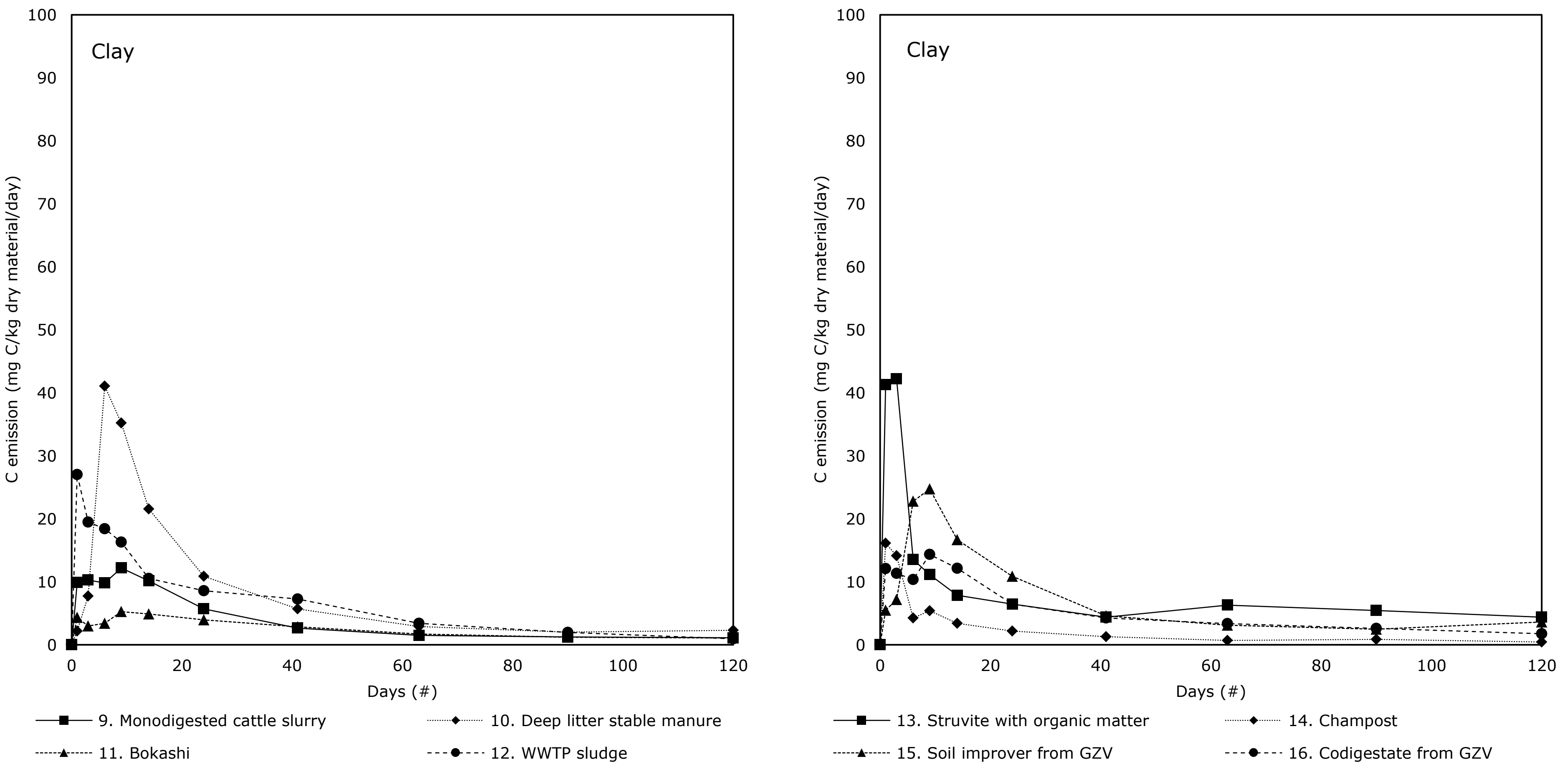


Figure 4-1 *C emission during the incubation experiment (average for duplicate), note the different scale on the Y-axis.*

Annex 3b Results of the nitrogen incubation experiment

Table 4-6 *Measured mineral N(mg kg-1) in the soil-material mixture.*

Days	1	3	10	25	50	80	120
Sand							
1. Cattle slurry	103	103	107	103	110	134	148
2. Pig slurry	135	159	151	177	149	185	205
3. Organic waste compost	31	36	43	49	54	64	76
4. Farmyard manure (cattle)	33	46	43	50	61	81	85
5. Garden peat	30	33	40	44	51	56	63
6. Straw	20	3	0	1	1	1	0
7. Grass	27	24	33	42	60	64	82
8. Chicken manure	50	60	59	80	78	109	110
9. Monodigested cattle slurry	109	119	123	128	142	160	169
10. Deep litter stable manure	79	89	71	73	91	101	111
11. Bokashi	32	34	37	39	41	47	58
12. WWTP sludge	42	48	61	79	107	116	134
13. Struvite with organic matter	76	75	98	113	126	147	153
14. Champost	34	38	44	51	61	70	78
15. Soil improver from GZV	30	32	29	16	22	31	37
16. Codigestate from GZV	147	158	162	173	187	199	207
Blank + N	105	109	116	114	125	130	149
Blank	30	37	39	45	50	57	67
Clay							
1. Cattle slurry	77	71	76	103	75	100	97
2. Pig slurry	124	111	116	115	130	137	151
3. Organic waste compost	21	26	33	36	45	51	55
4. Farmyard manure (cattle)	25	31	30	38	40	50	51
5. Garden peat	19	25	31	37	41	49	54
6. Straw	12	1	2	0	0	0	0
7. Grass	20	15	21	28	33	50	59
8. Chicken manure	32	39	46	63	73	80	80
9. Monodigested cattle slurry	84	88	90	99	104	110	116
10. Deep litter stable manure	49	56	56	54	64	74	81
11. Bokashi	19	25	29	30	31	38	42
12. WWTP sludge	27	34	53	64	90	104	113

Days	1	3	10	25	50	80	120
13. Struvite with organic matter	64	69	89	104	101	109	119
14. Champost	23	29	37	43	49	56	61
15. Soil improver from GZV	22	28	18	8	6	11	20
16. Codigestate from GZV	102	119	127	138	137	148	154
Blank + N	80	93	101	110	111	113	122
Blank	20	26	35	37	42	48	60

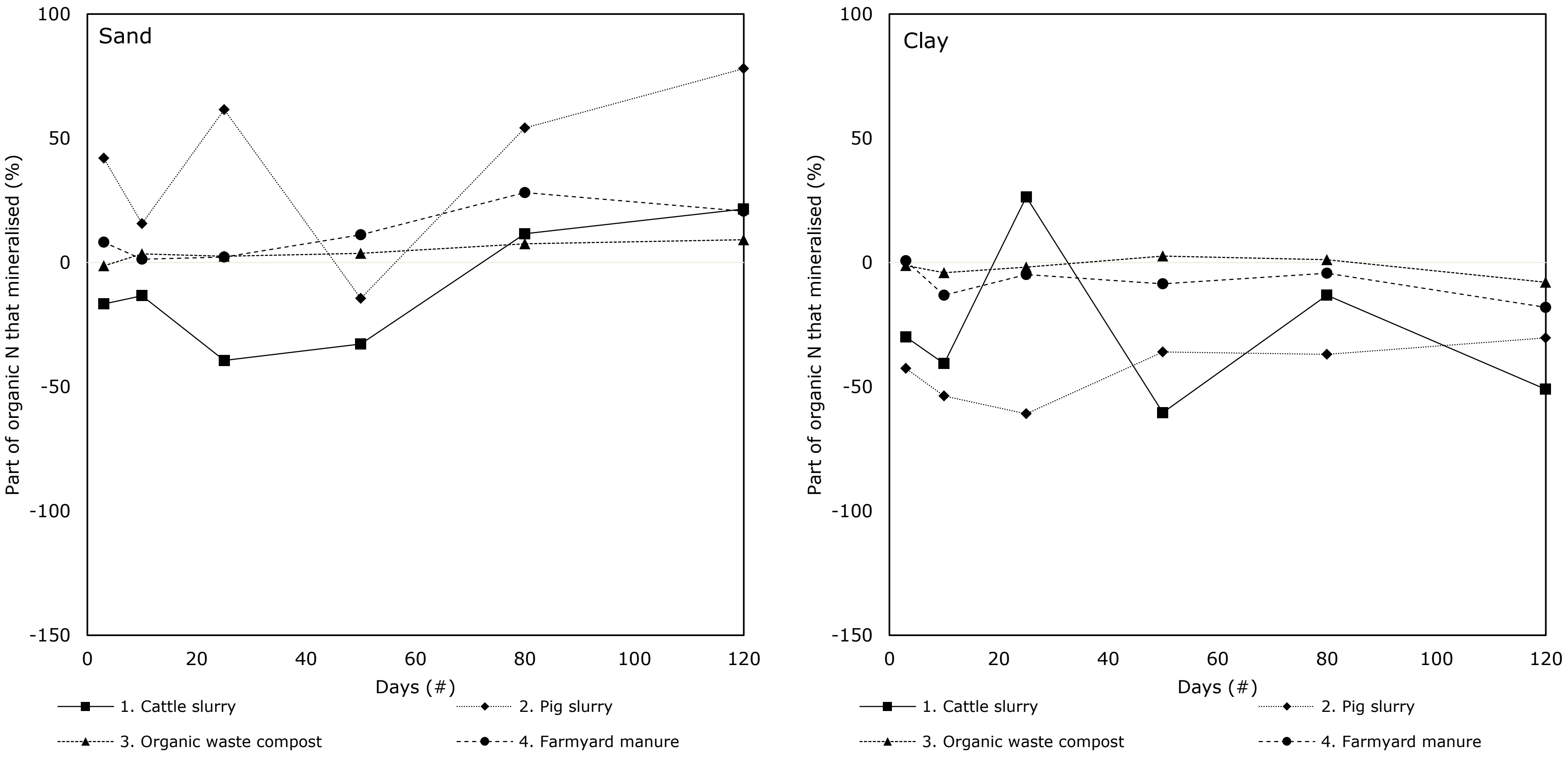


Figure 4-2a *Net nitrogen mineralisation of the organic materials, expressed as a percentage of total organic nitrogen, between day 0 and day 120 (material 1-4).*

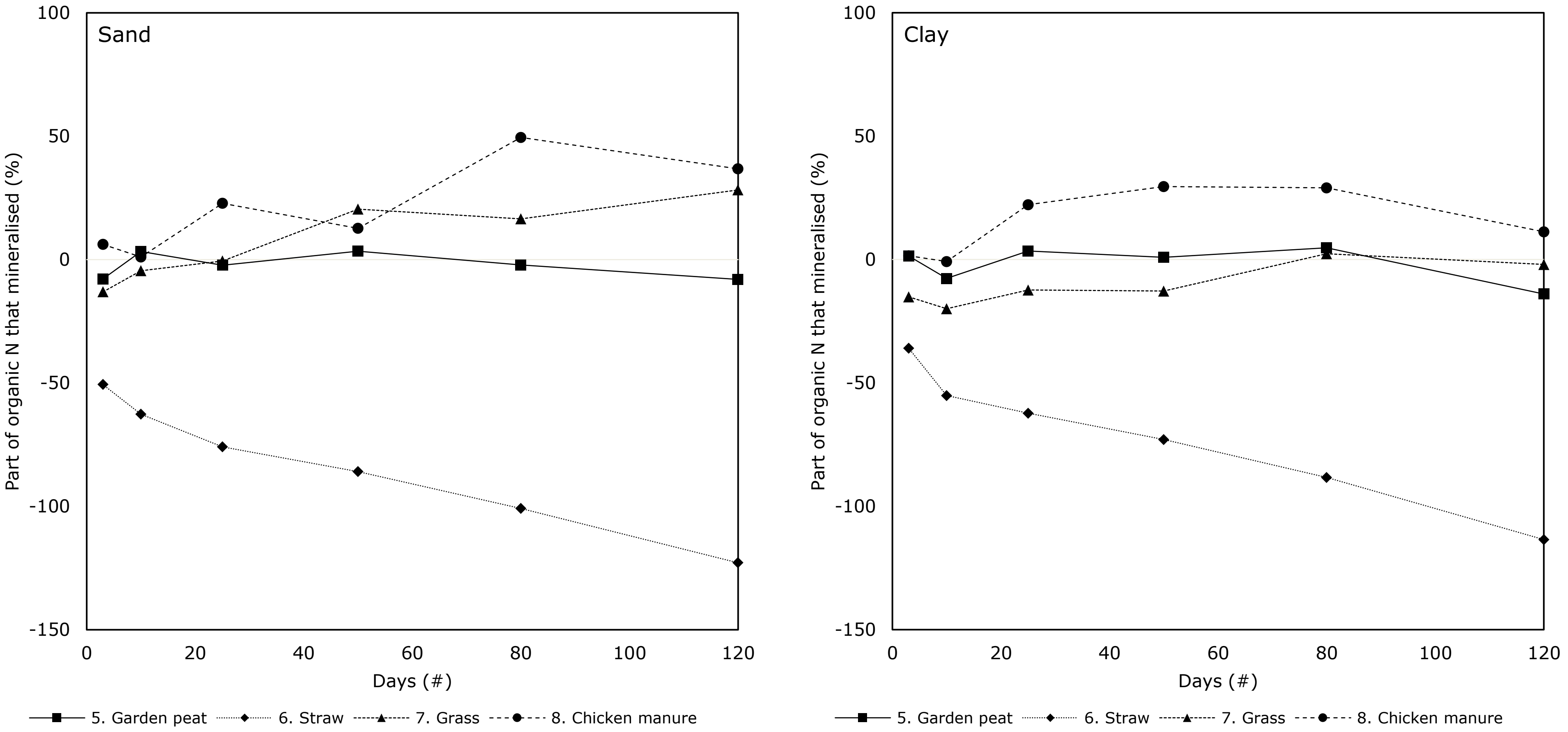


Figure 4-2b *Net nitrogen mineralisation of the organic materials, expressed as a percentage of total organic nitrogen, between day 0 and day 120 (material 5-8).*

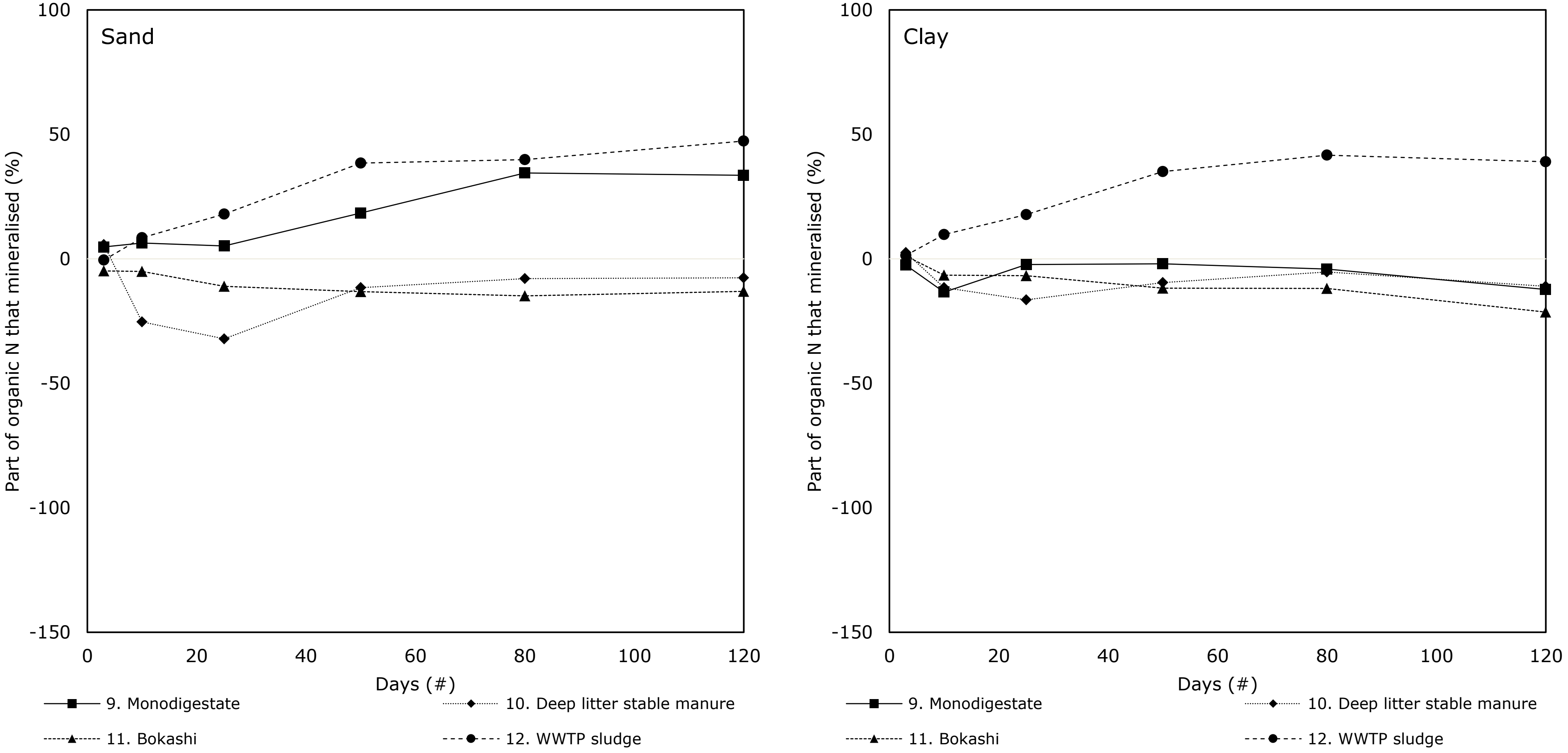


Figure 4-2c *Net nitrogen mineralisation of the organic materials, expressed as a percentage of total organic nitrogen, between day 0 and day 120 (material 9-12).*

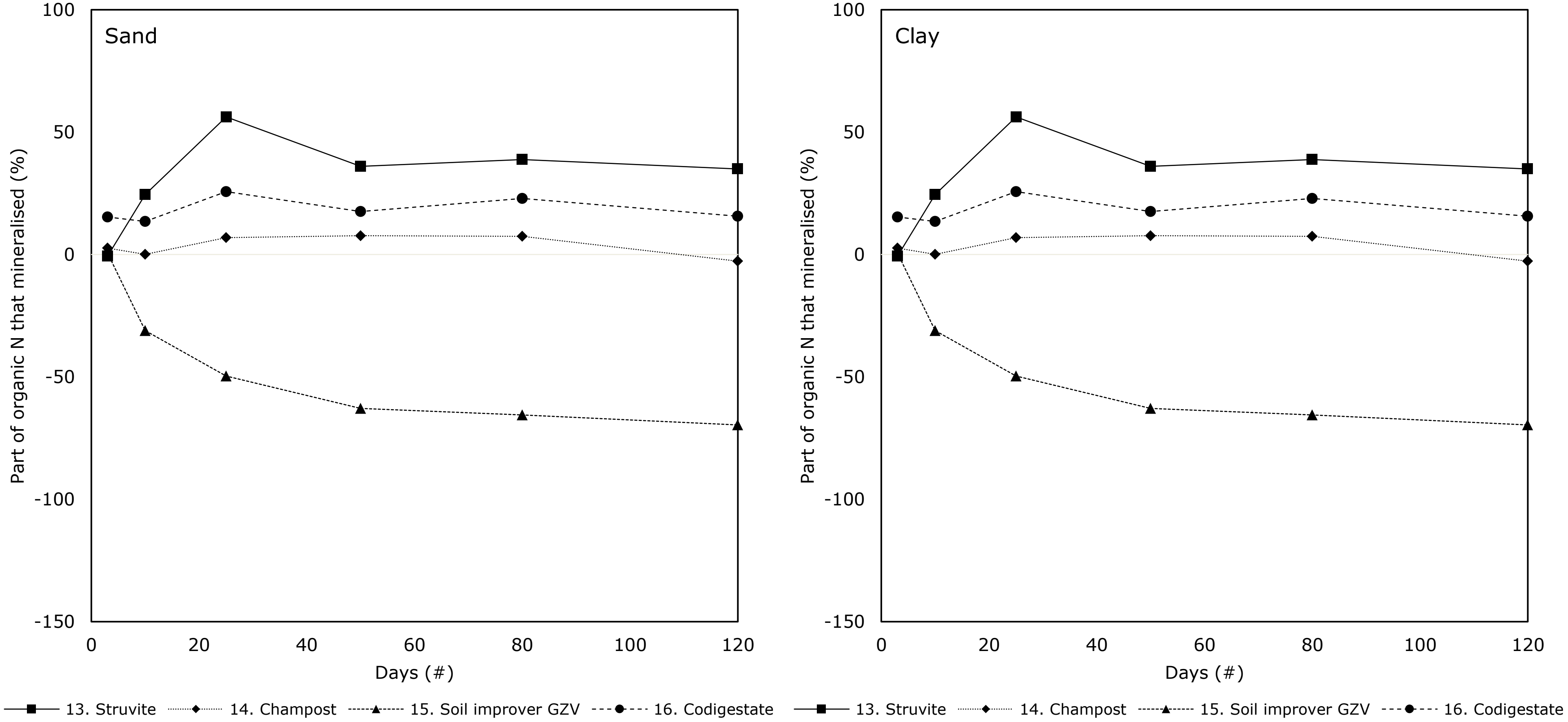


Figure 4-2d *Net nitrogen mineralisation of the organic materials, expressed as a percentage of total organic nitrogen, between day 0 and day 120 (material 13-16).*

Annex 4 Fitting nitrogen mineralisation parameters

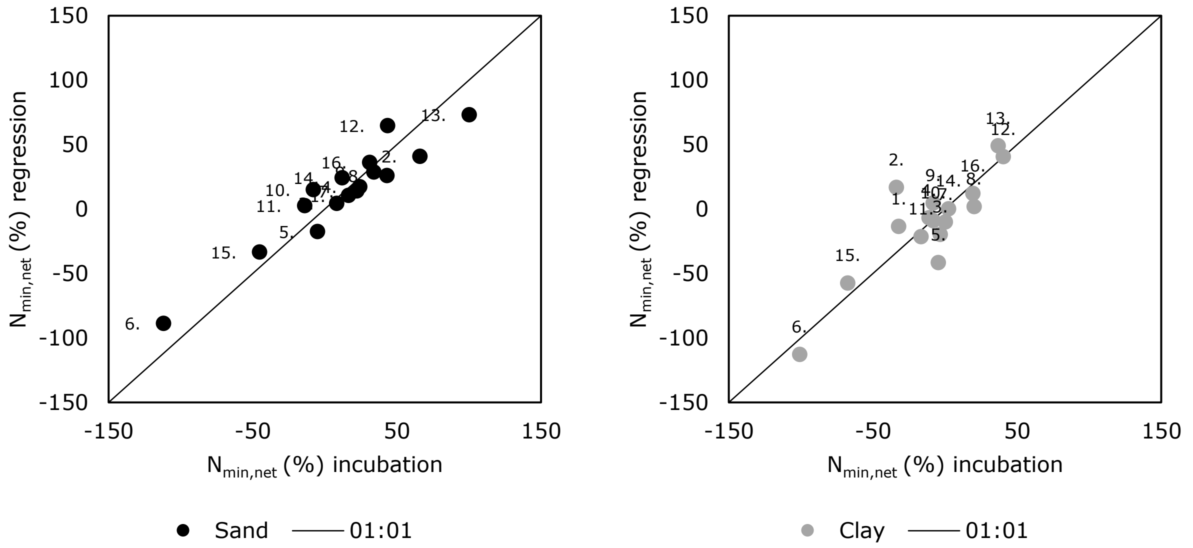


Figure 4-3 *Correlation between $N_{min,net}$ (%) on the basis of incubation data and $N_{min,net}$ (%) on the basis of regression (using Corg/N_{org}, HWN, F2 and F4), for sand (left) and clay (right).*

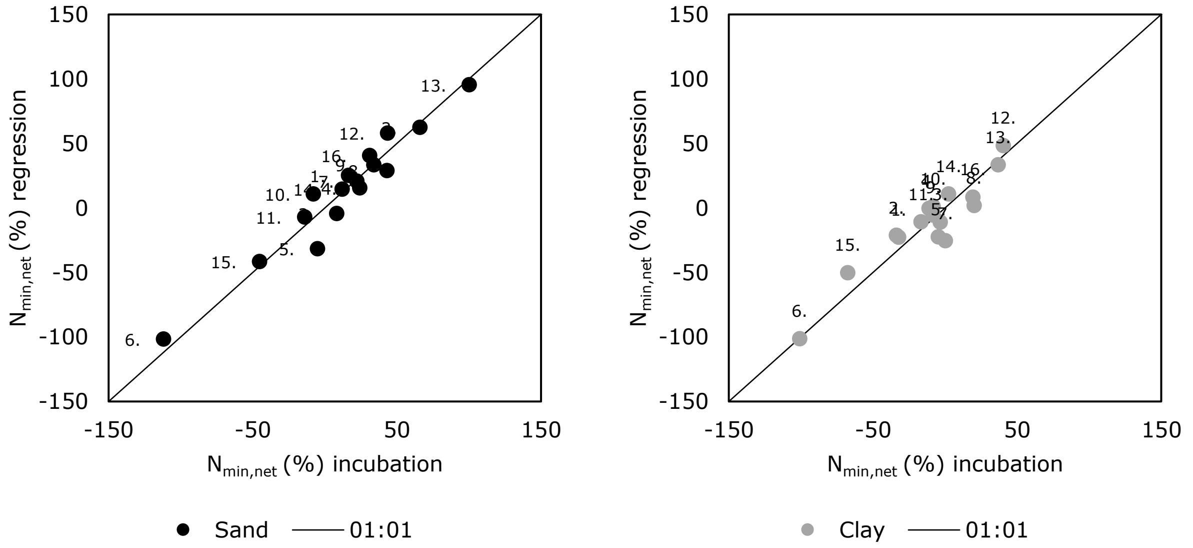
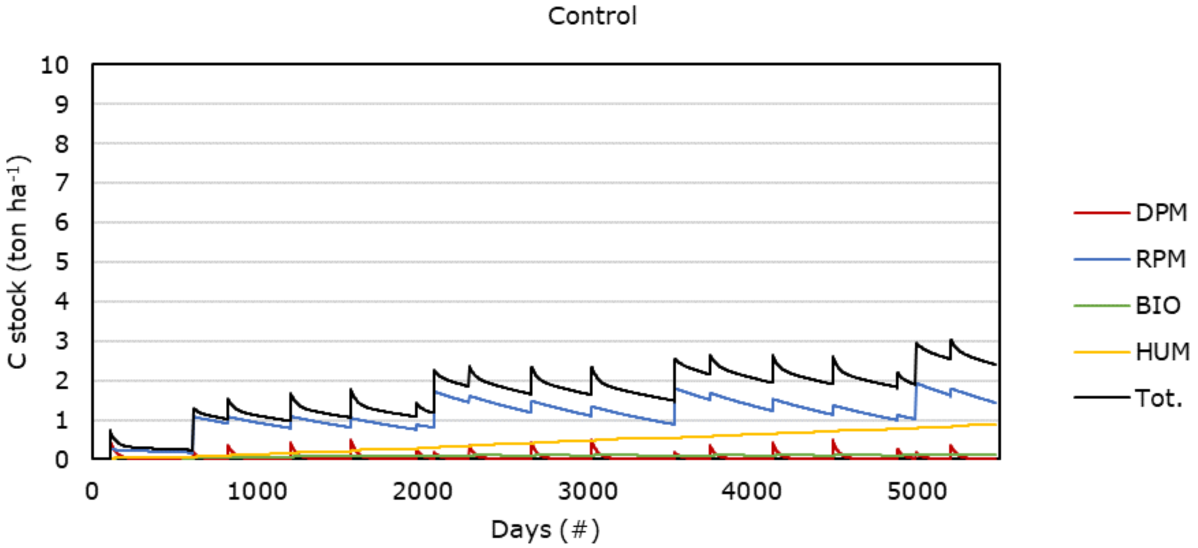


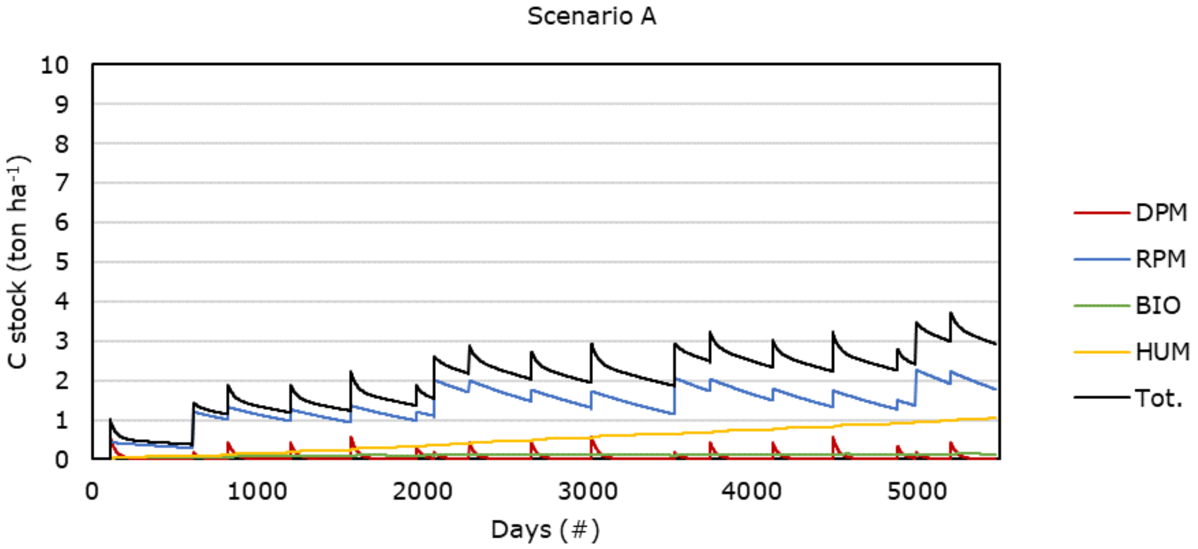
Figure 4-4 *Correlation between $N_{min,net}$ (%) on the basis of incubation data and $N_{min,net}$ (%) on the basis of regression (using Corg/N_{org}, HWN, F2, F4 and DOC), for sand (left) and clay (right).*

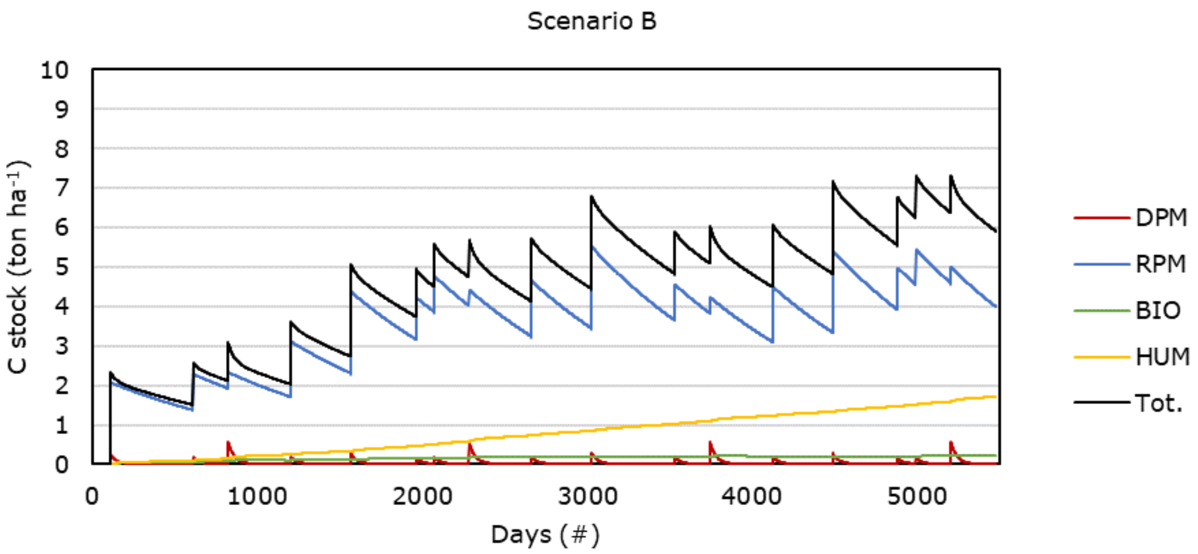
Annex 5 C and N dynamics for various scenario

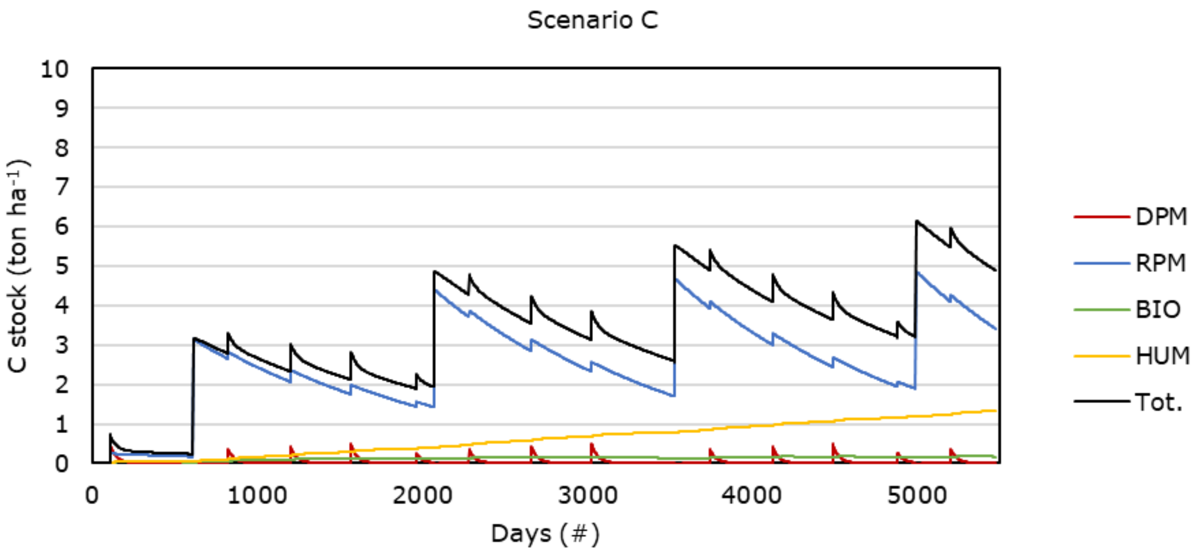
South-East of the Netherlands

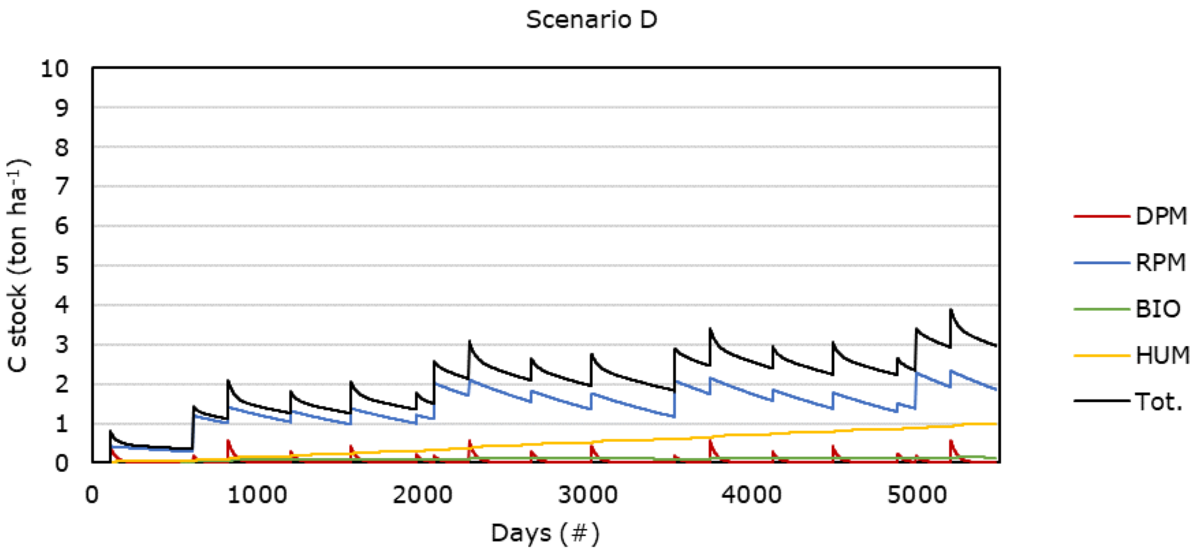
Carbon

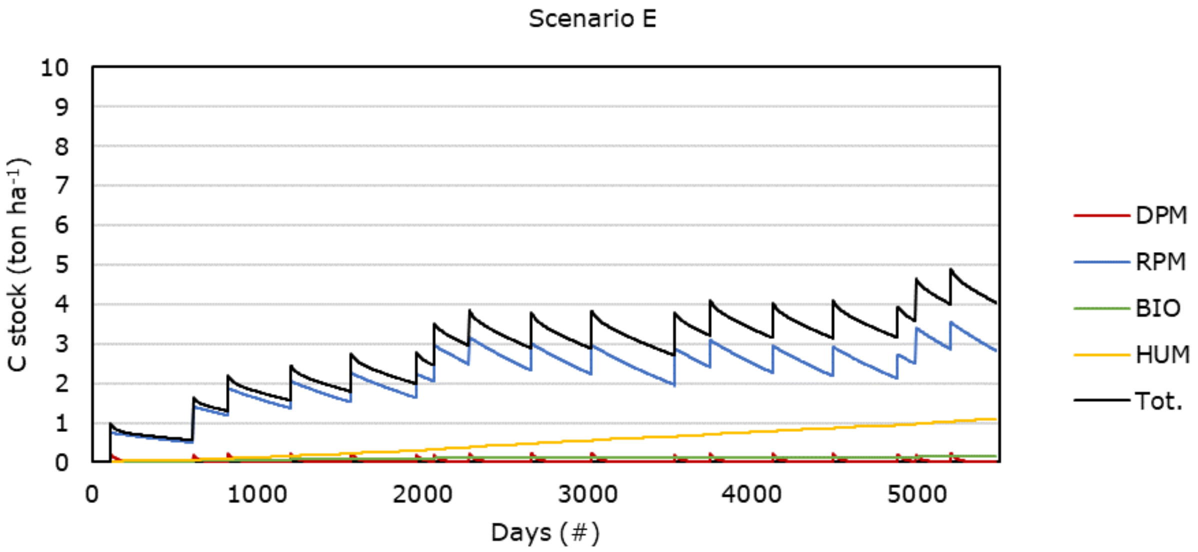


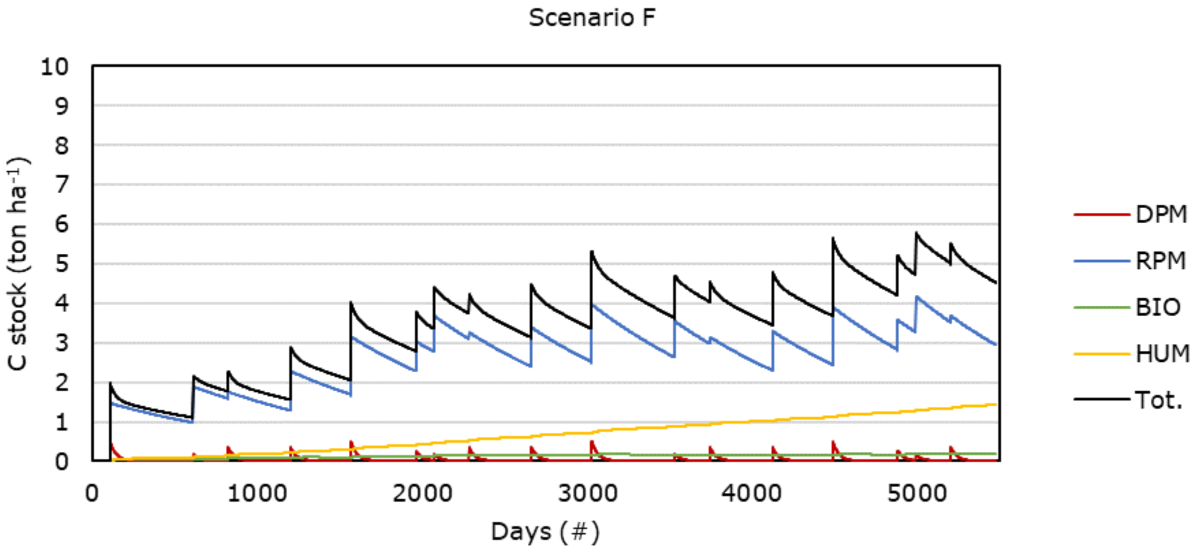


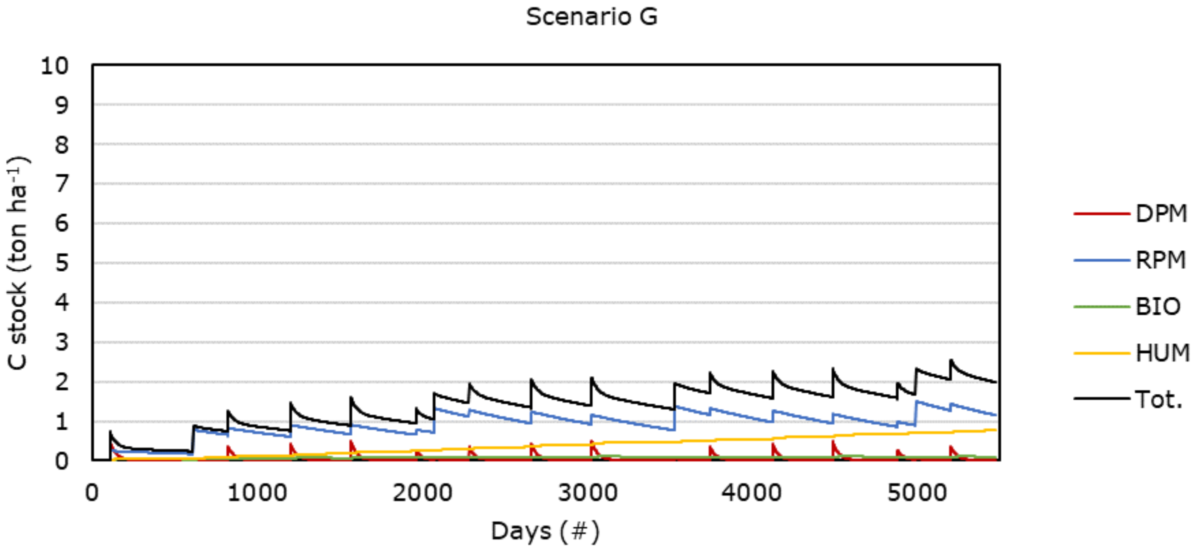

Scenario B
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.

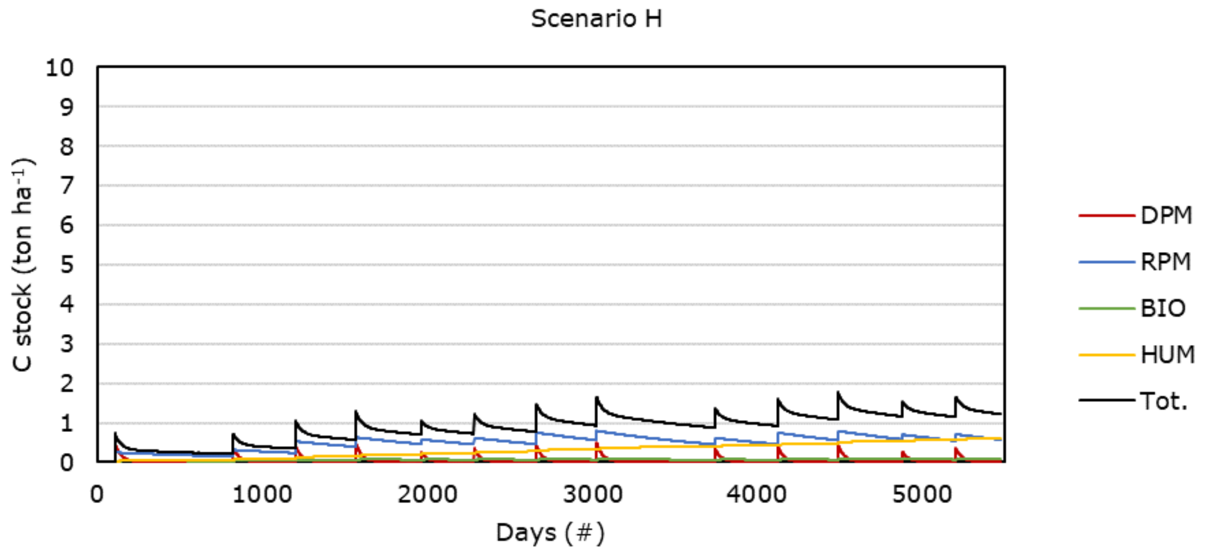

Scenario C
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.

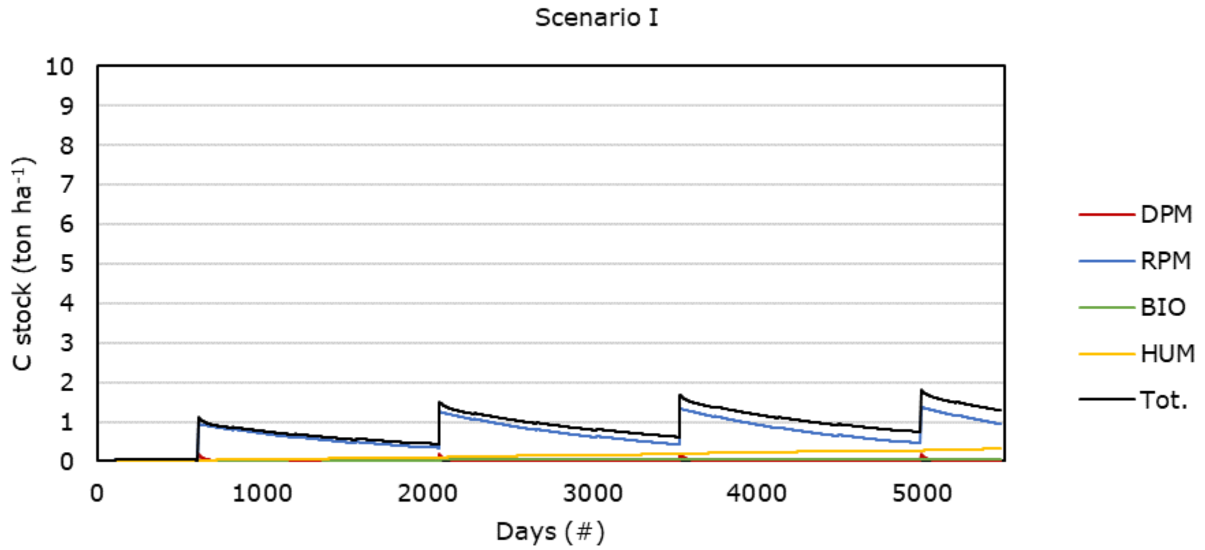

Scenario D
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.

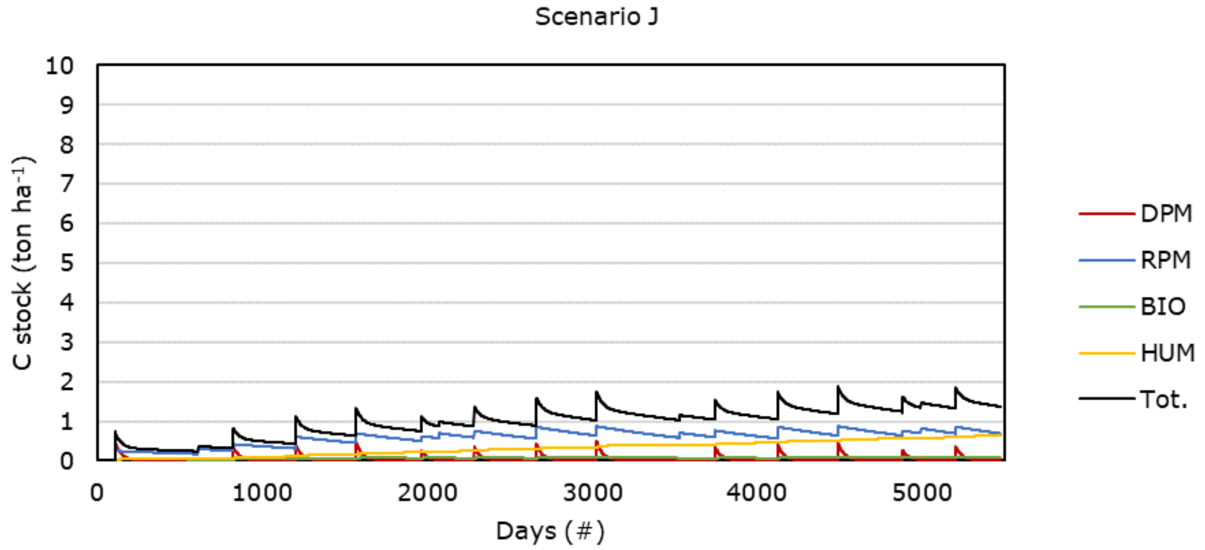

Scenario E
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.

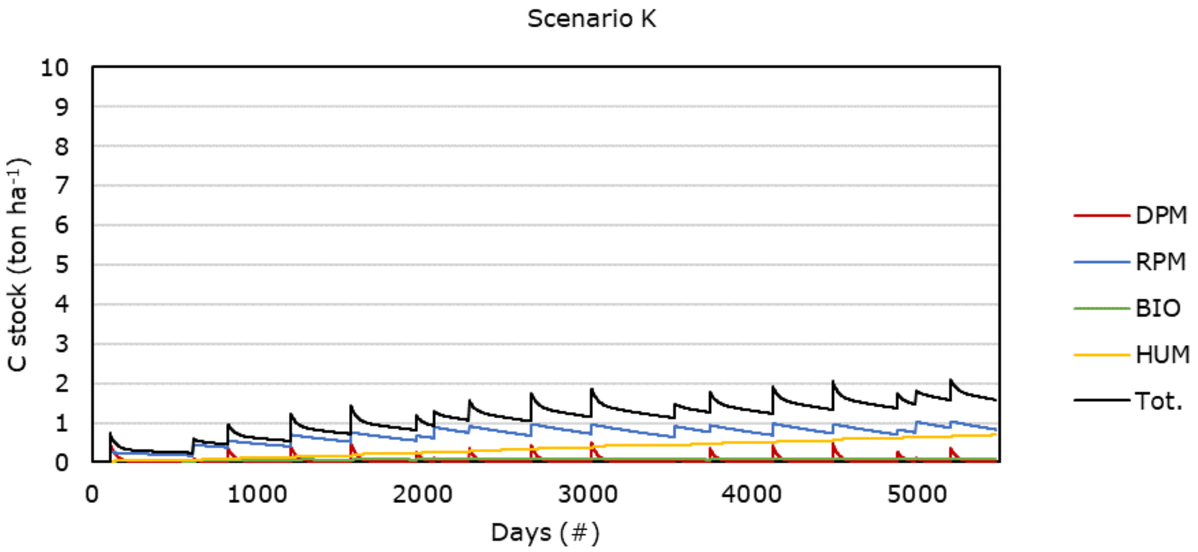

Scenario F
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario G
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario H
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario I
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario J
C stock (ton ha^{-1})
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.



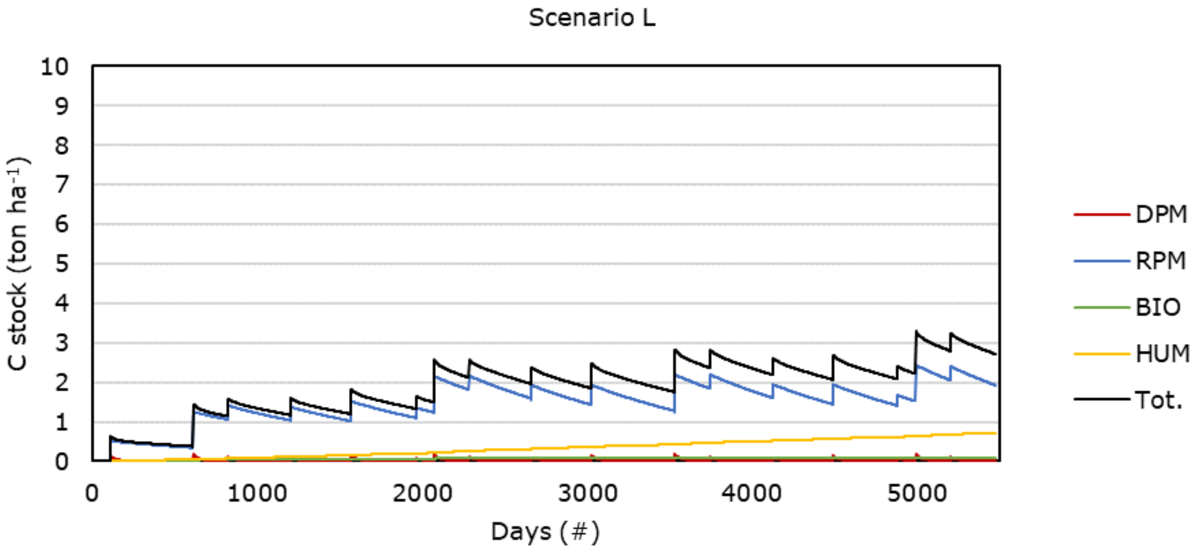
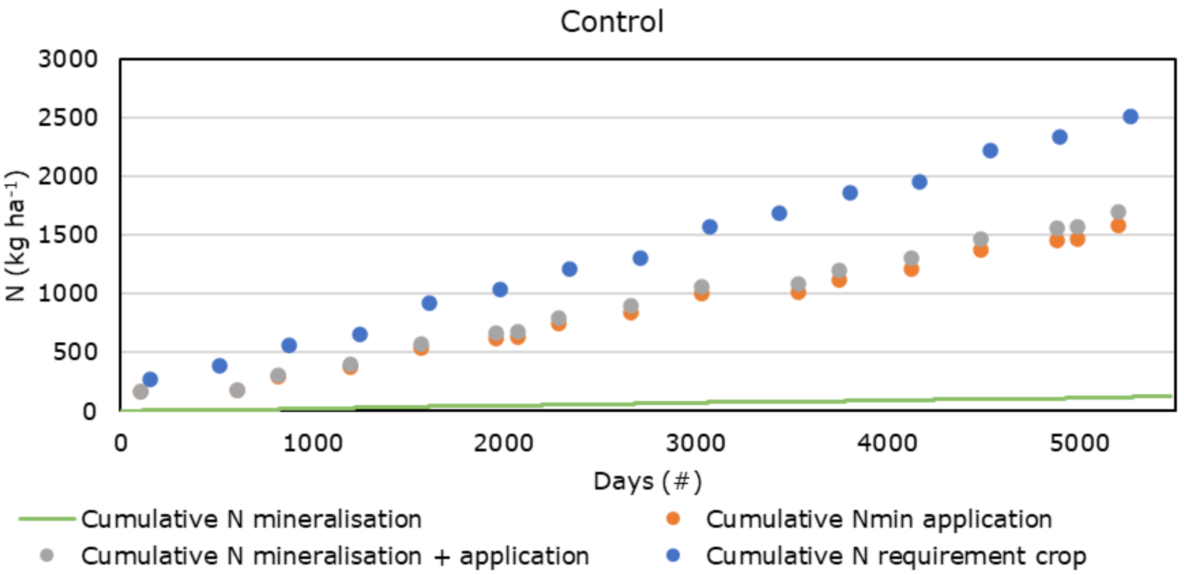
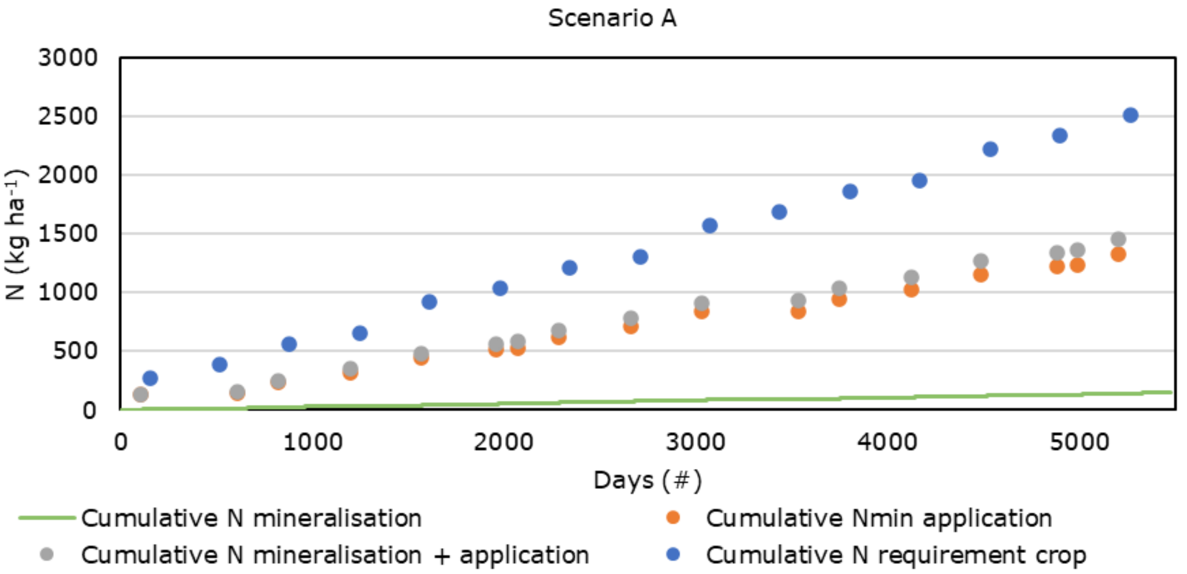
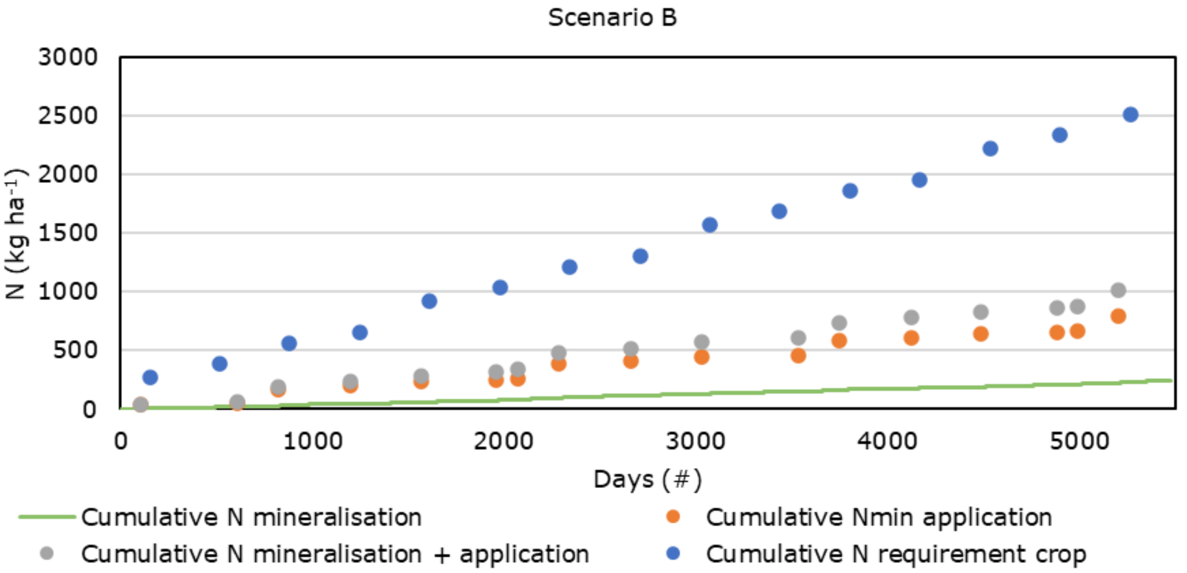


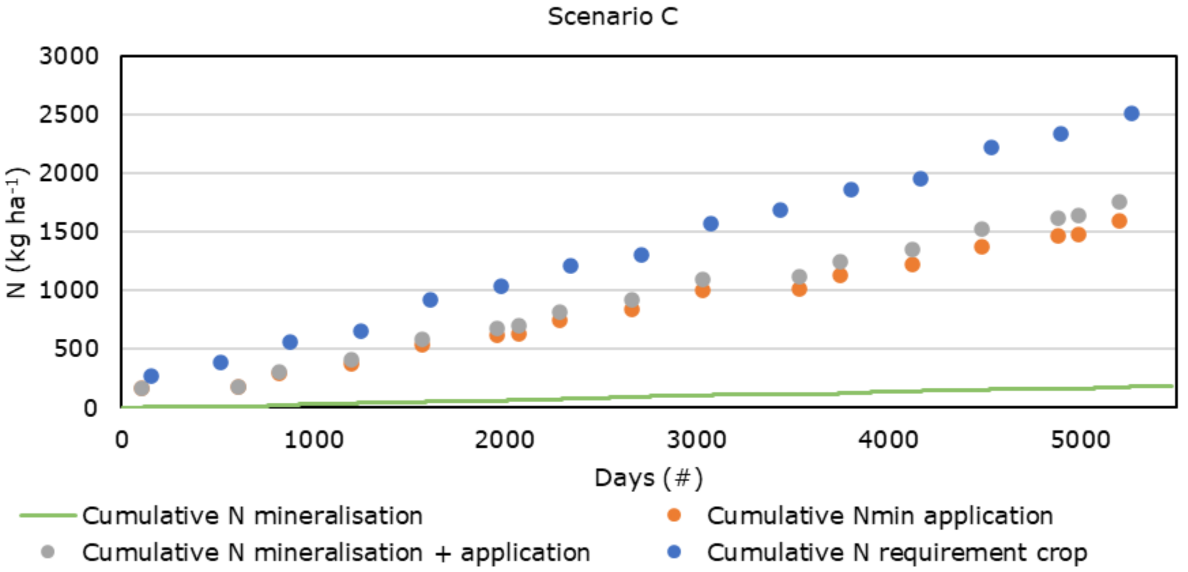
Figure 4-5 *Contribution of the organic materials to the C build-up in the soil associated with the various fertilisation strategies in the South-East of the Netherlands, distributed over the RothC pools: decomposable plant material (DPM), resistant plant material (RPM), soil biology (BIO), soil humus (HUM) and total (Tot.). The C stock (Y-axis) only refers to the addition by organic fertilisers, and is therefore excl. the soil C stock.*

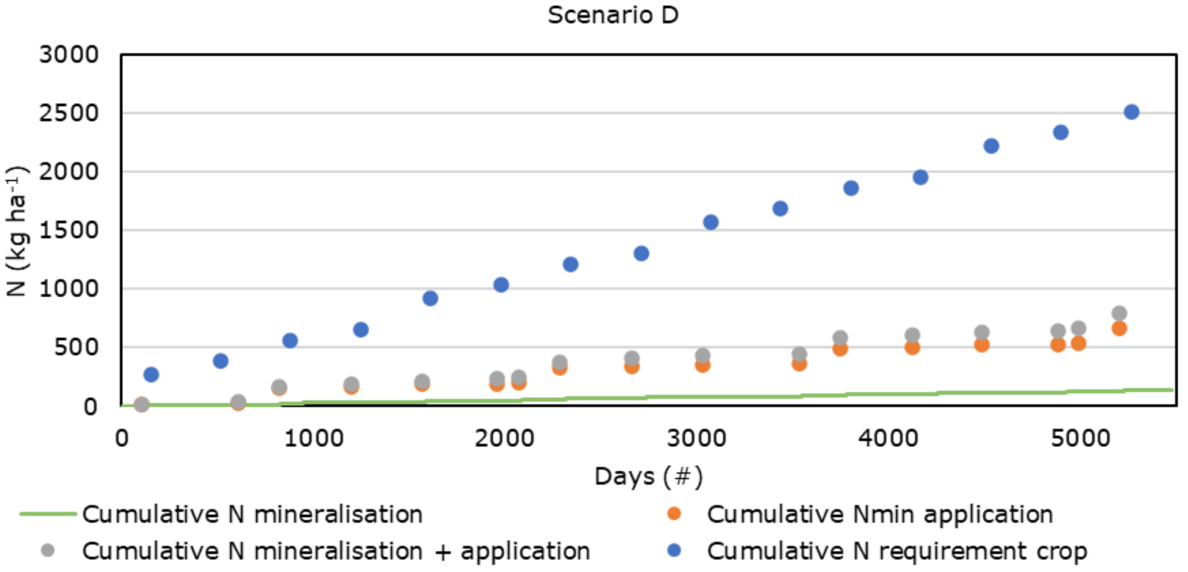
Nitrogen

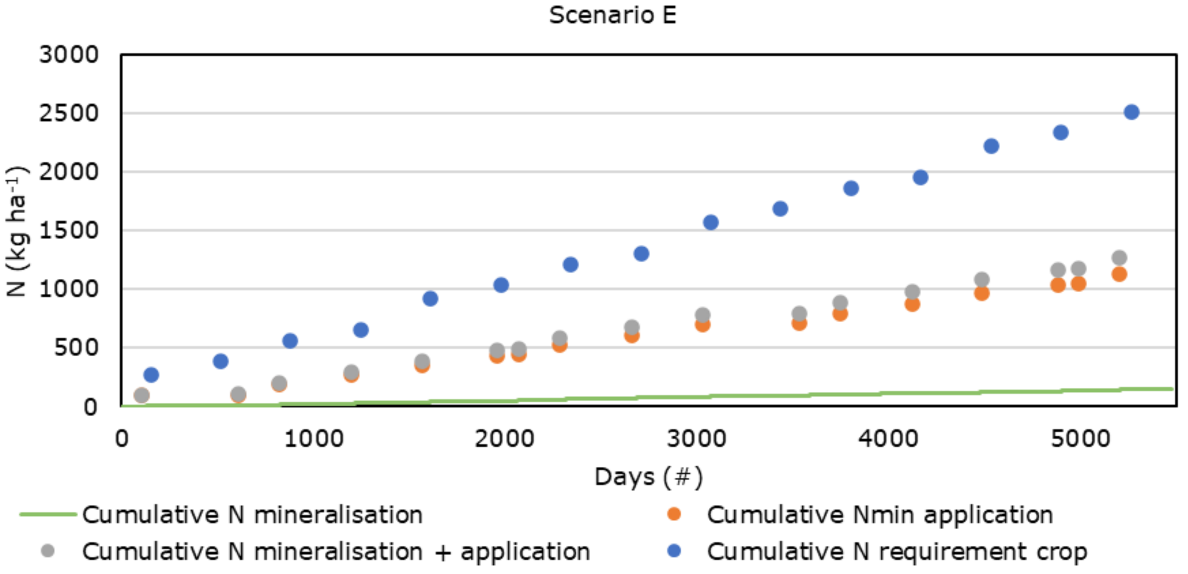

Control
3000
2500
2000
1500
1000
500
0
N (kg ha-1)
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application
Cumulative N requirement crop

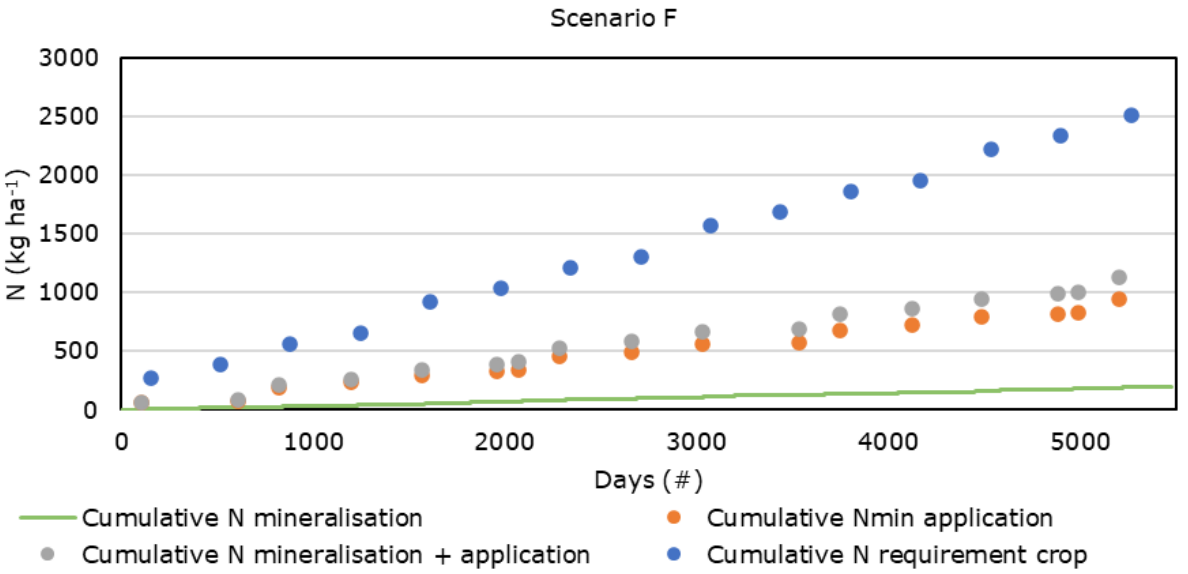

Scenario A
3000
2500
2000
1500
1000
500
0
N (kg ha-1)
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application
Cumulative N requirement crop

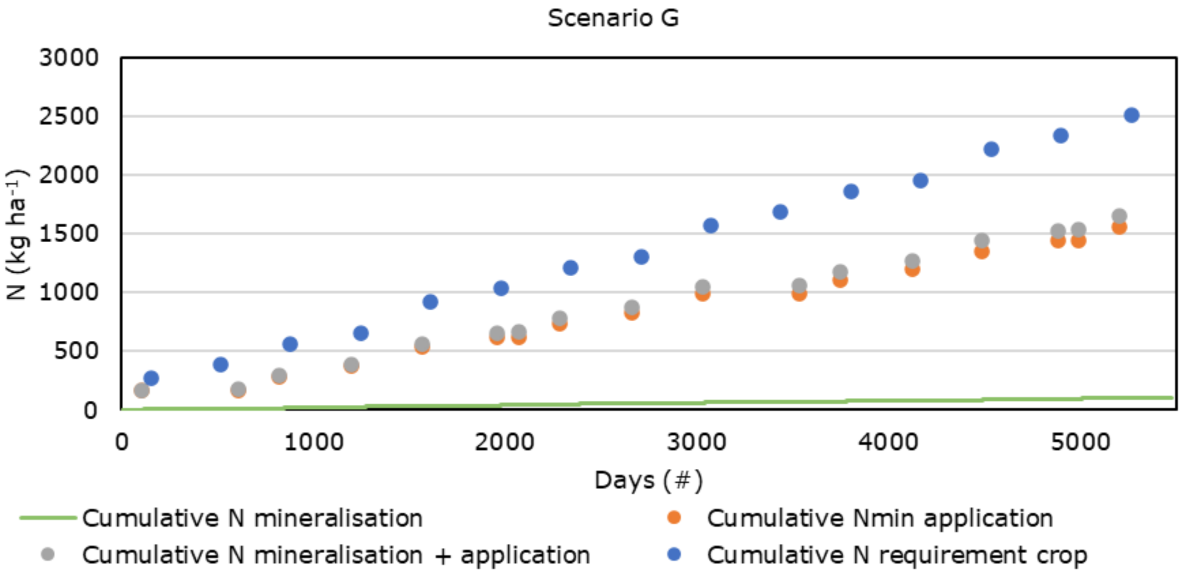

Scenario B
3000
2500
2000
1500
1000
500
0
N (kg ha-1)
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application
Cumulative N requirement crop

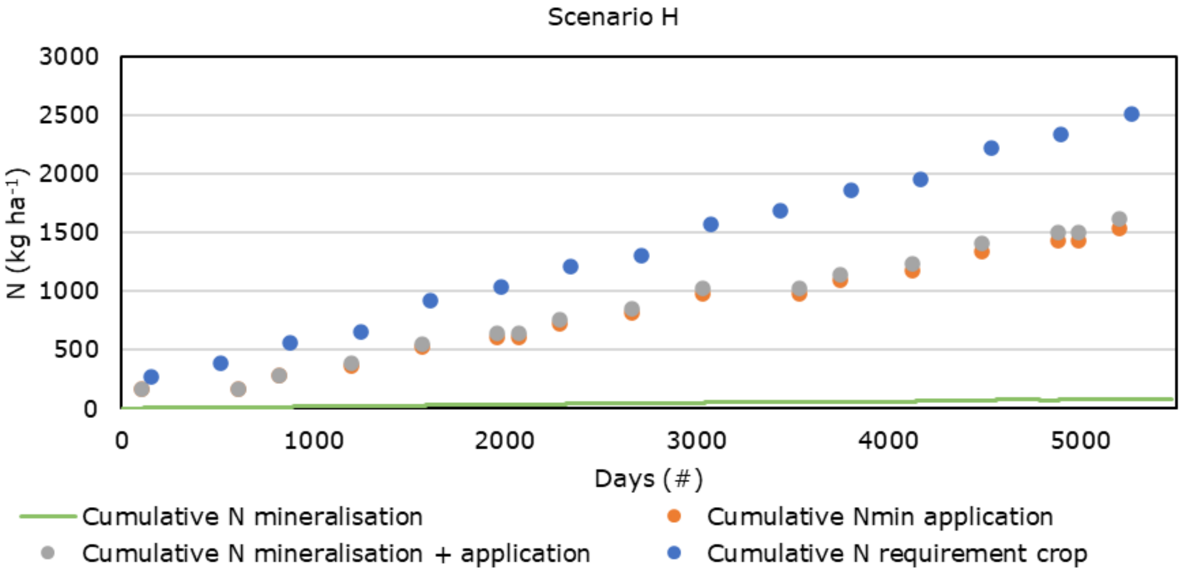

Scenario C


Scenario D


Scenario E


Scenario F
3000
2500
2000
1500
1000
500
0
N (kg ha-1)
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application
Cumulative N requirement crop


Scenario G
3000
2500
2000
1500
1000
500
0
N (kg ha-1)
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application
Cumulative N requirement crop


Scenario H
3000
2500
2000
1500
1000
500
0
N (kg ha-1)
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application
Cumulative N requirement crop

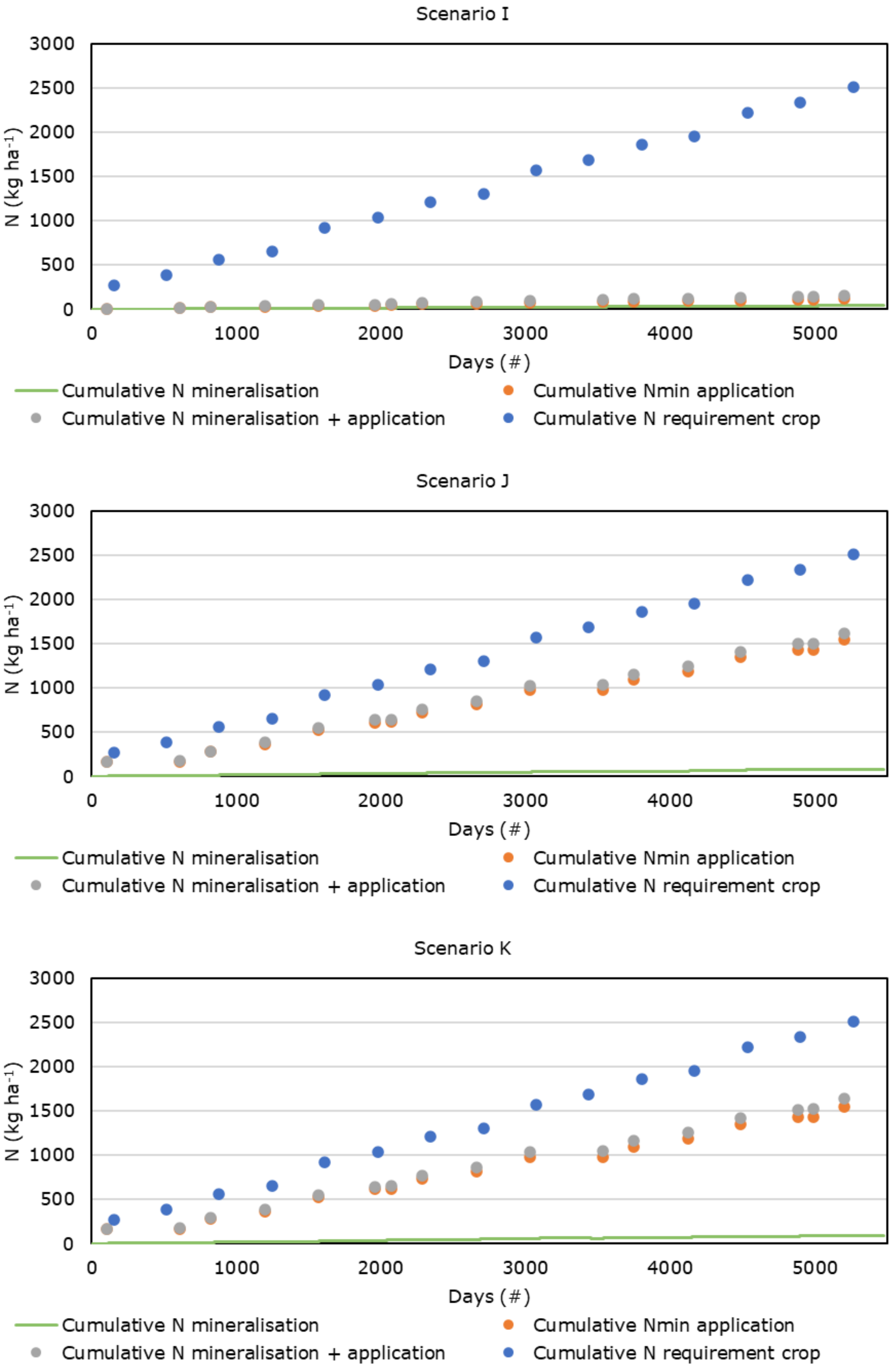
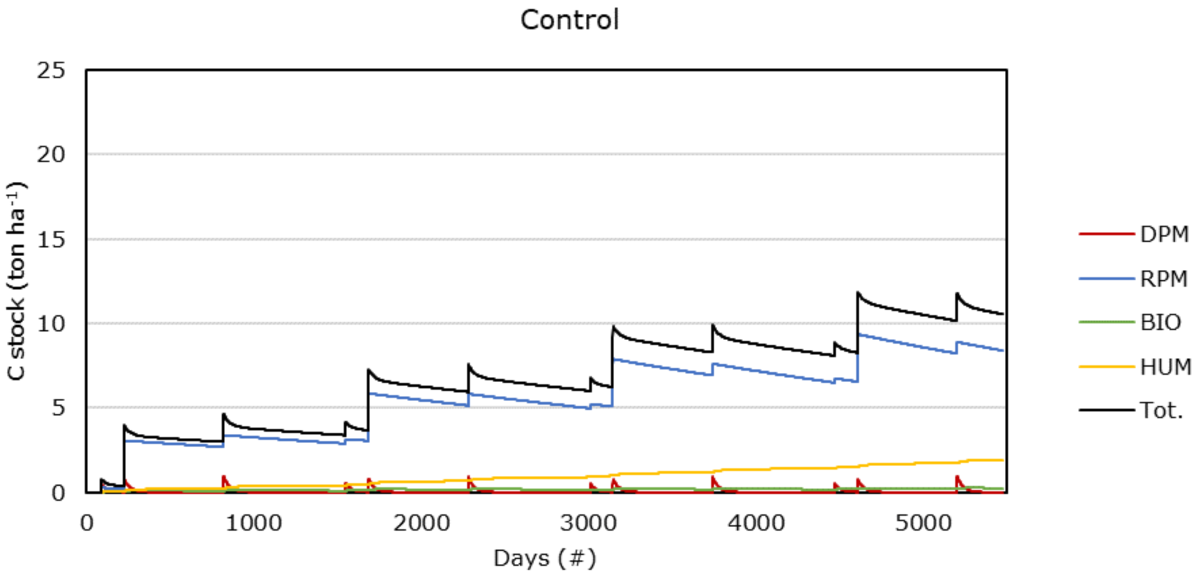
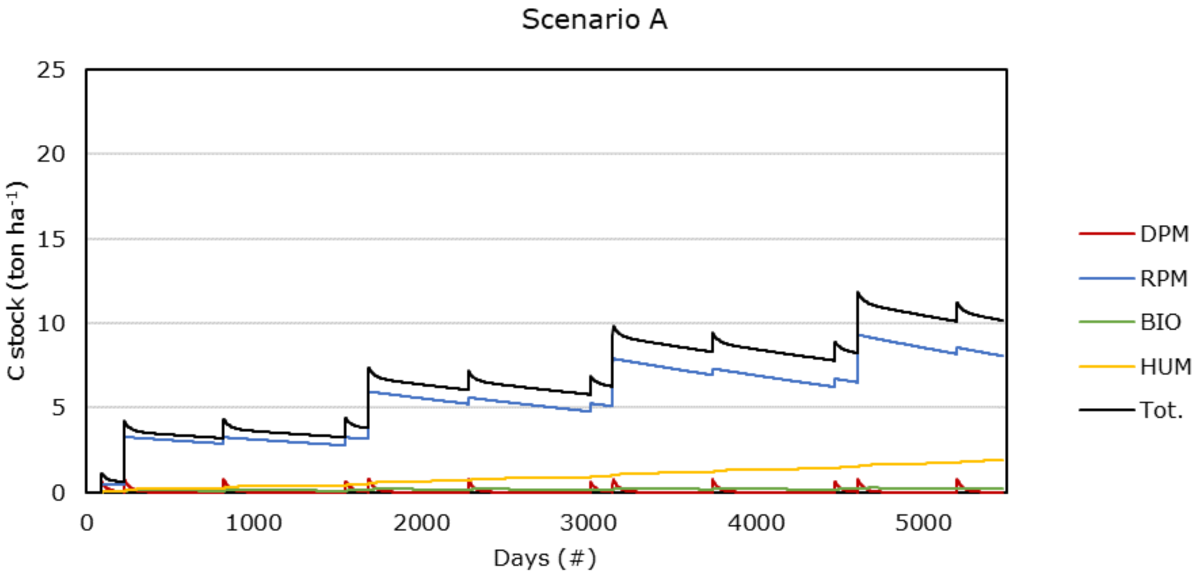


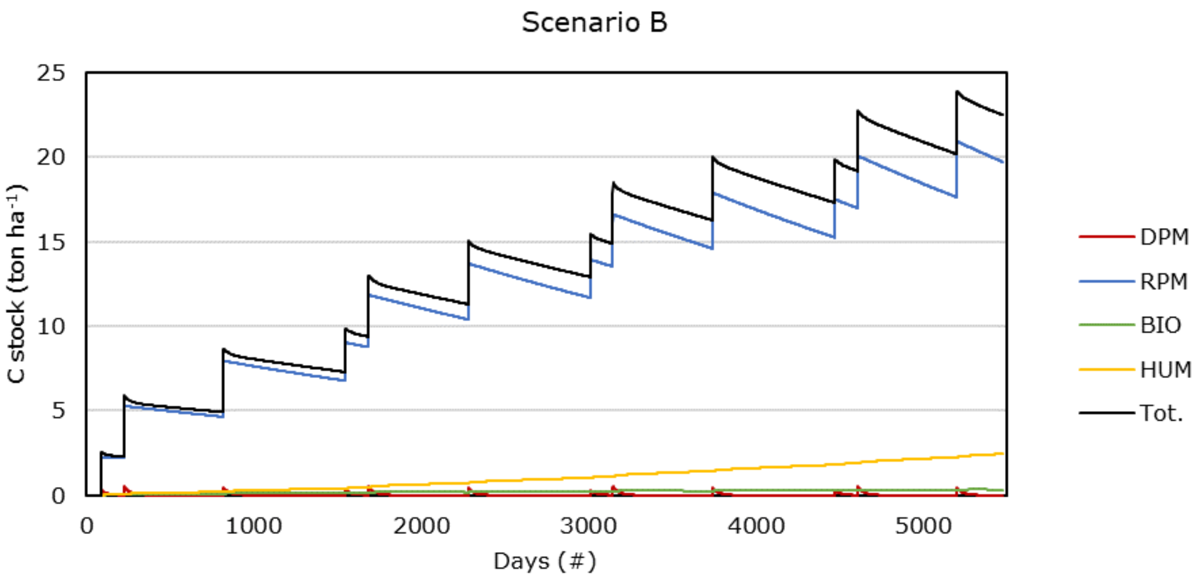
Figure 4-6 *The cumulative mineral N contribution to the soil as a result of the application of organic materials, and the crop N requirements (South-East of the Netherlands). N deriving from the soil or applied with synthetic fertilisers are not presented here.*

South-West of the Netherlands

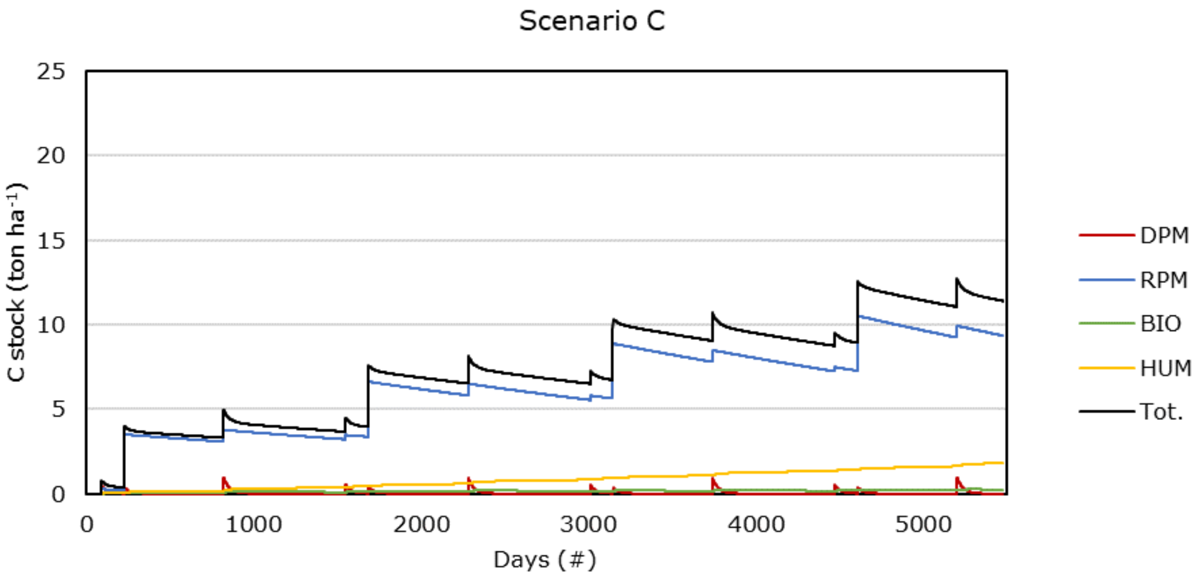
Carbon



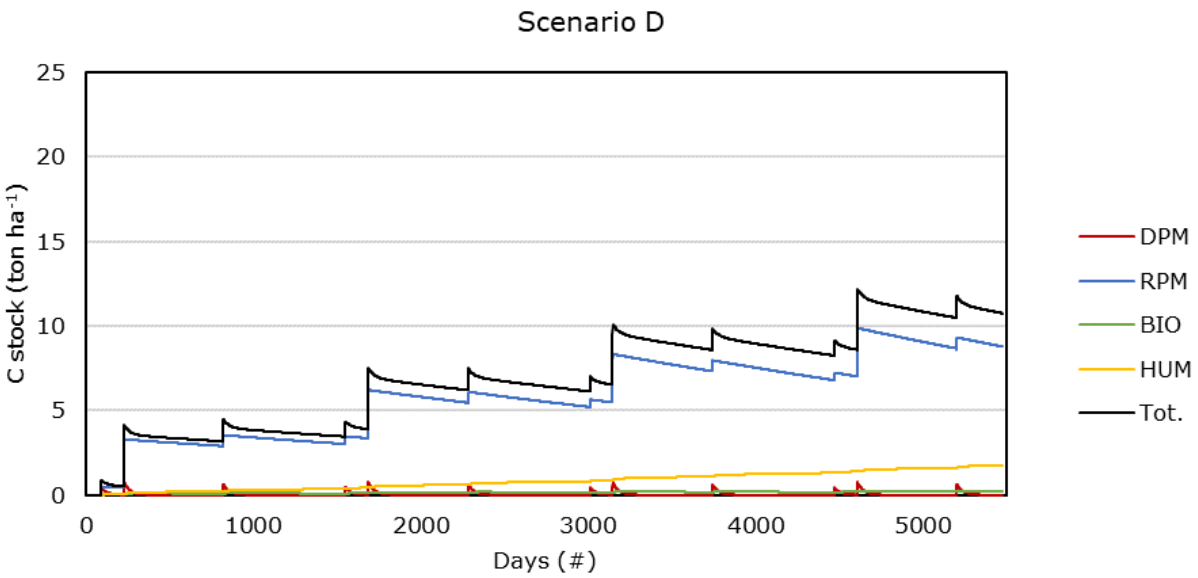




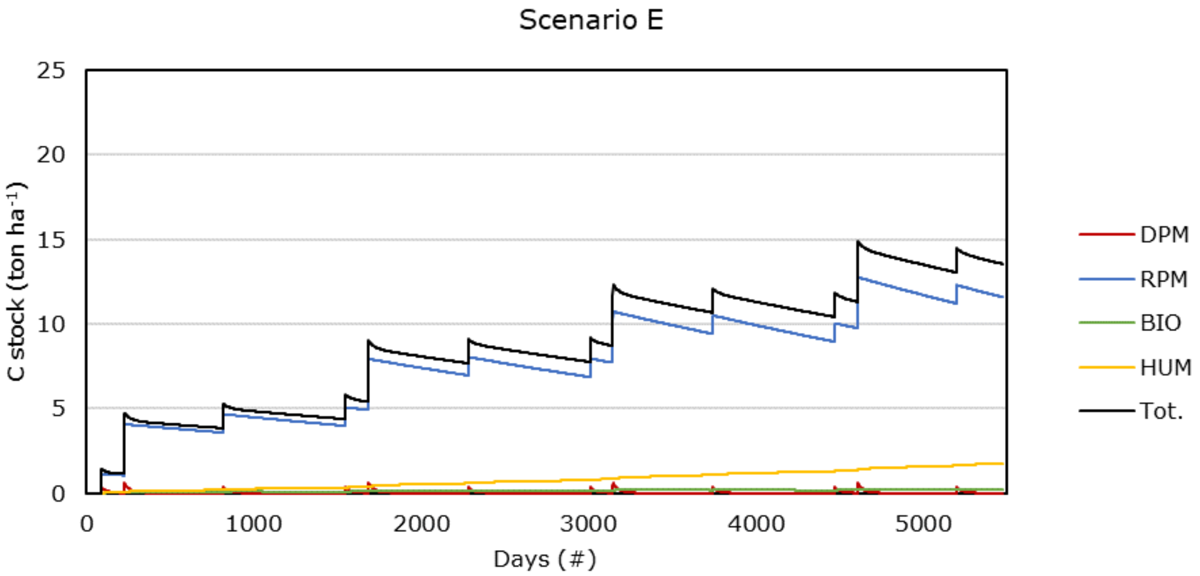
Scenario B

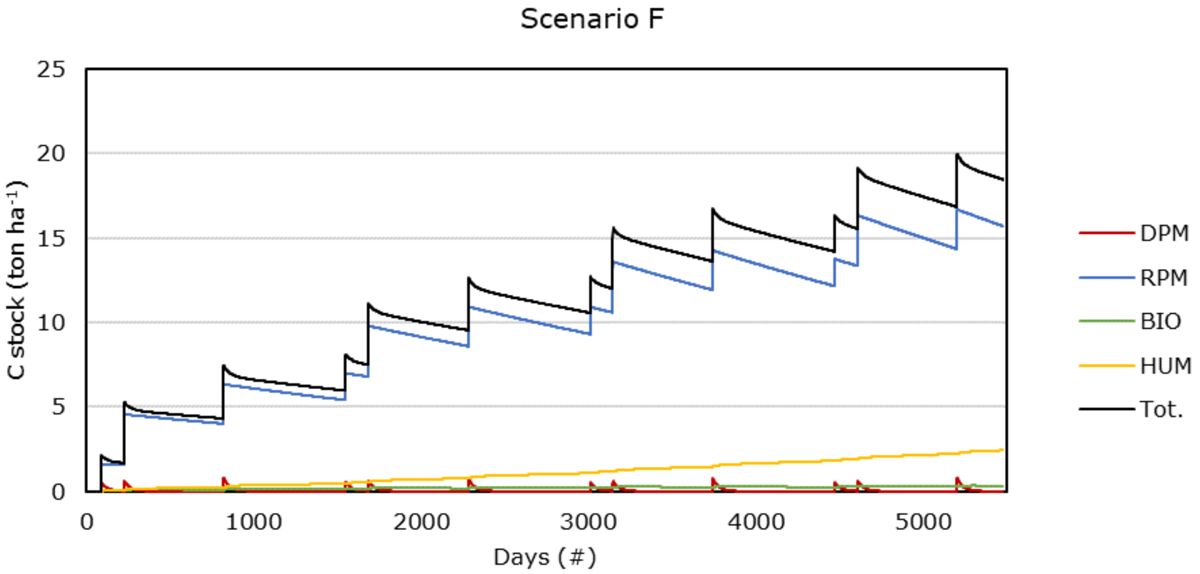


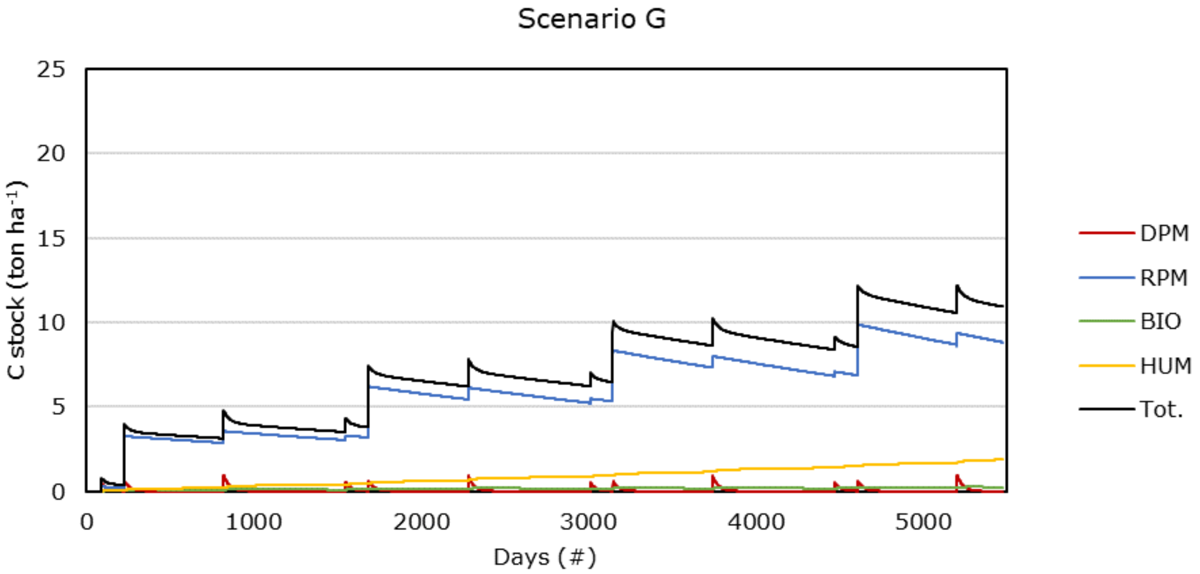
Scenario C

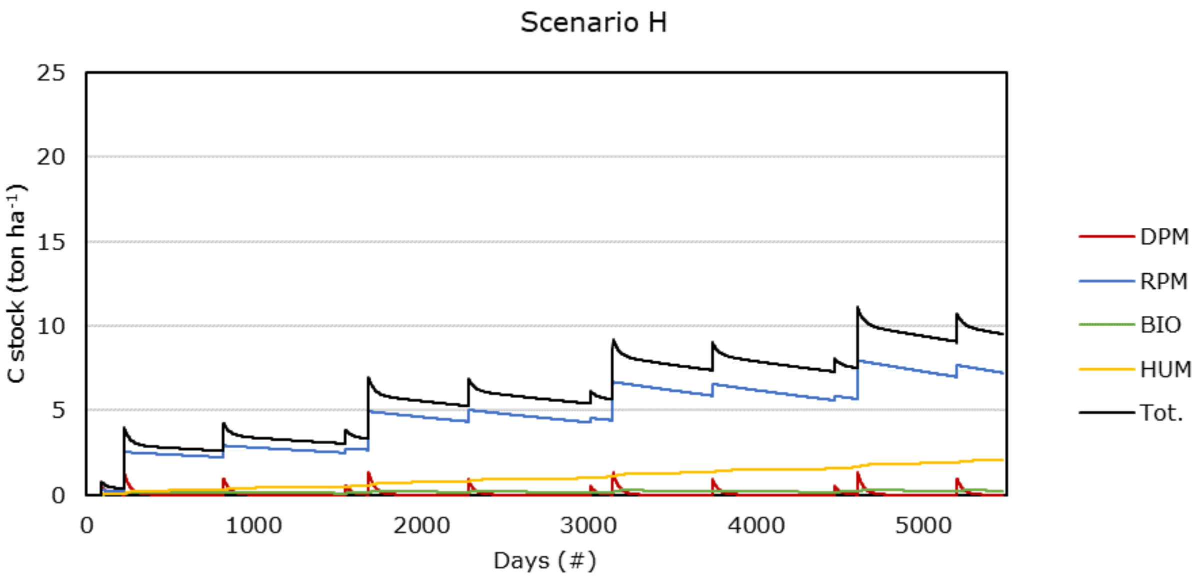


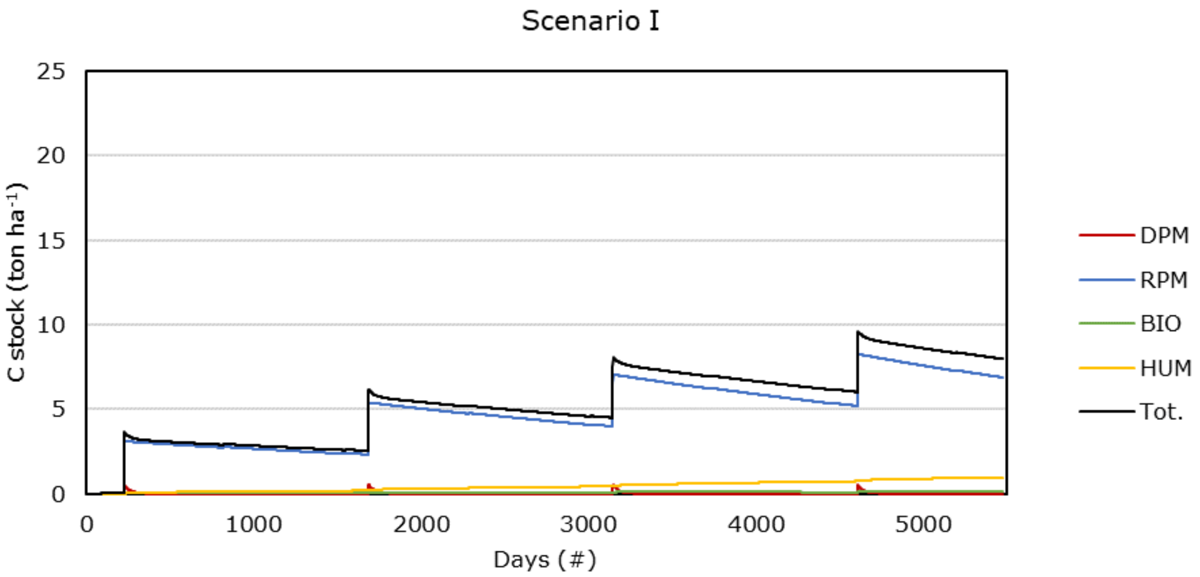
Scenario D

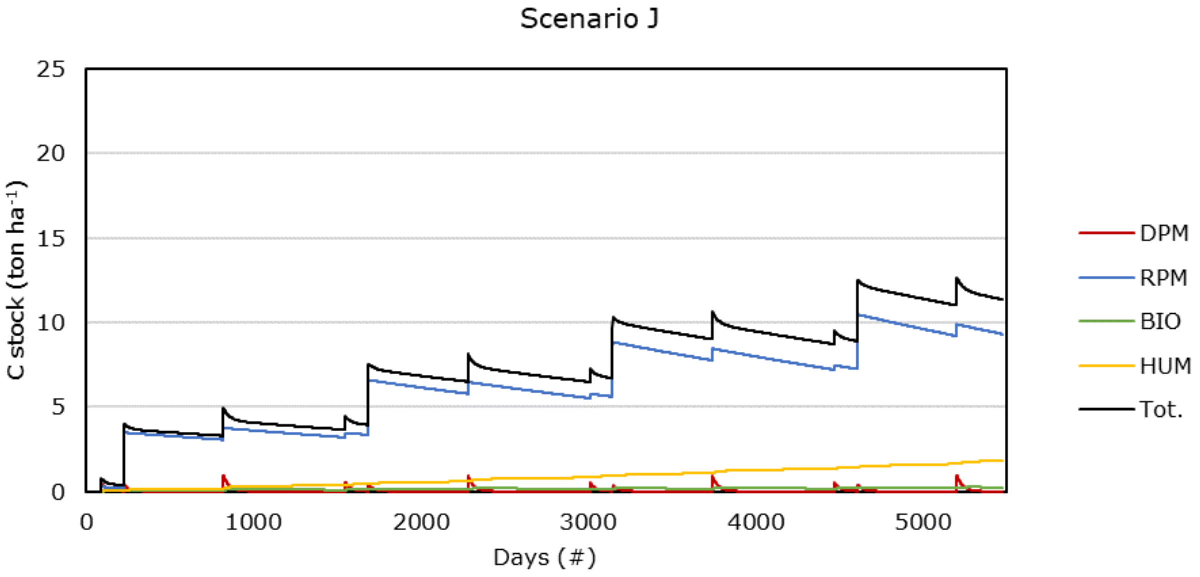

Scenario E
C stock (ton ha^{-1})
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.

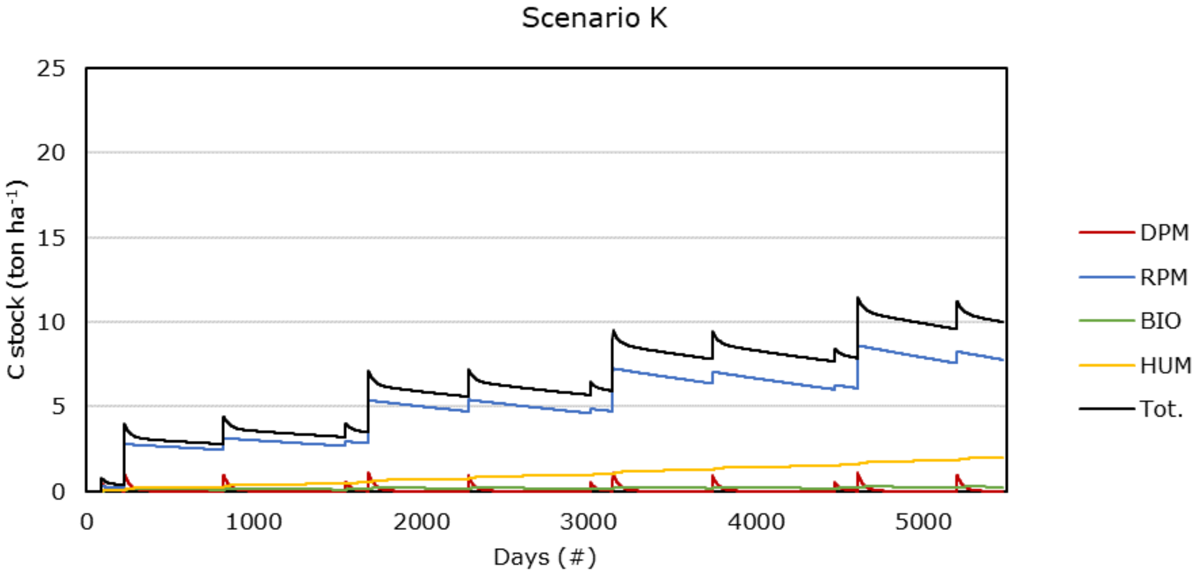

Scenario F
C stock (ton ha^{-1})
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario G
C stock (ton ha^{-1})
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario H
C stock (ton ha-1)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario I
C stock (ton ha-1)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.


Scenario J
C stock (ton ha-1)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Days (#)
DPM
RPM
BIO
HUM
Tot.



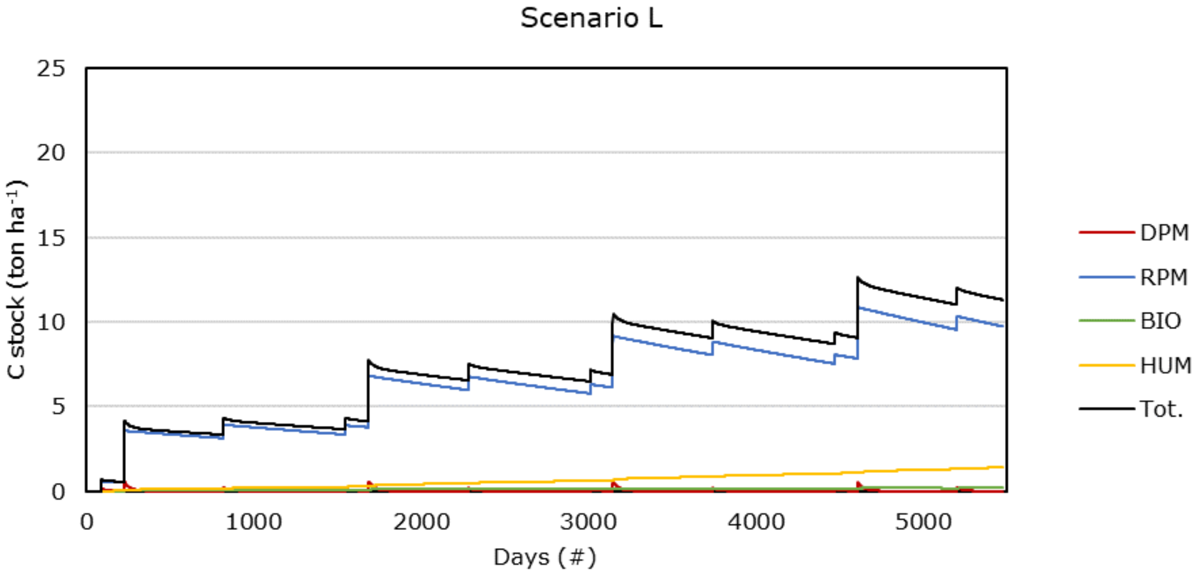
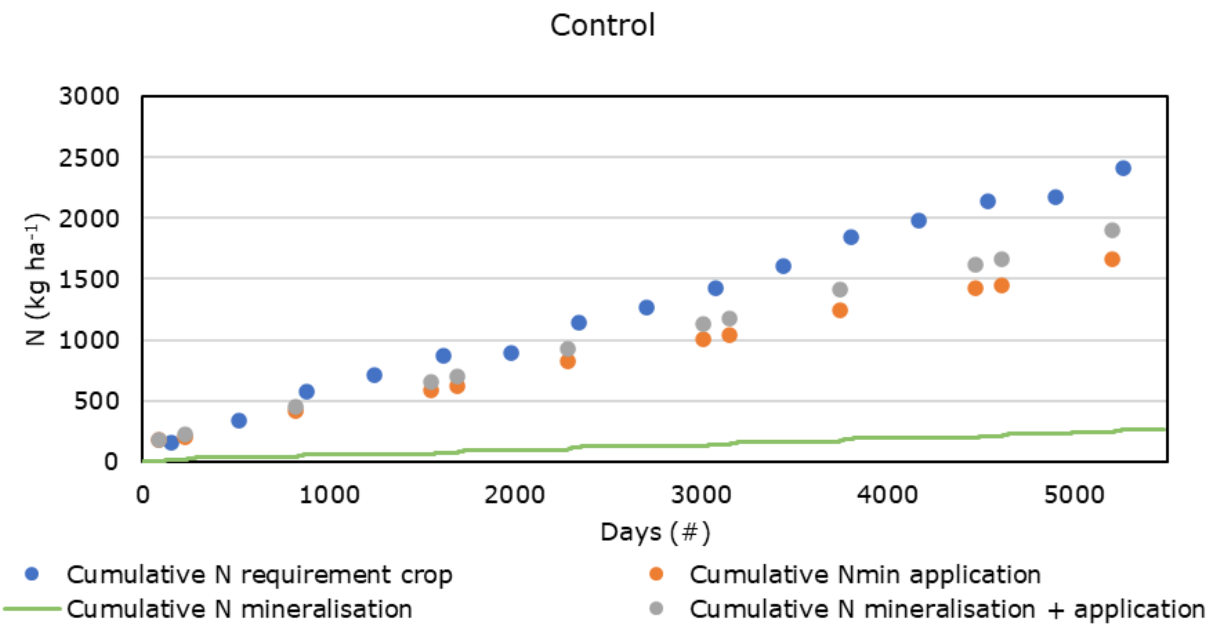
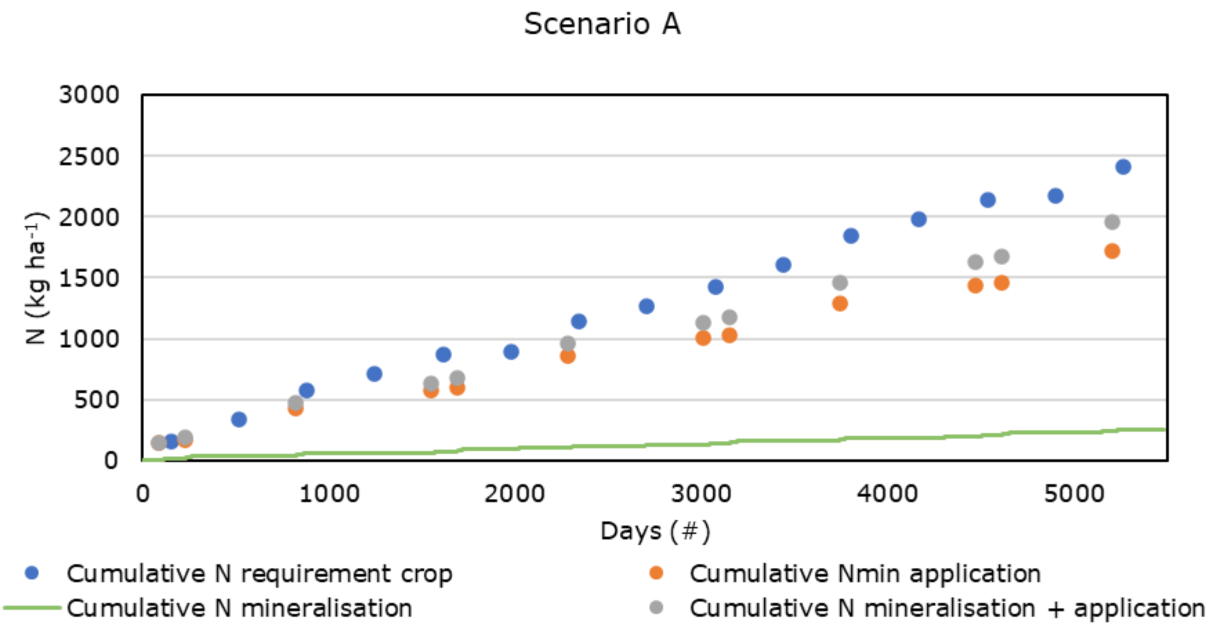
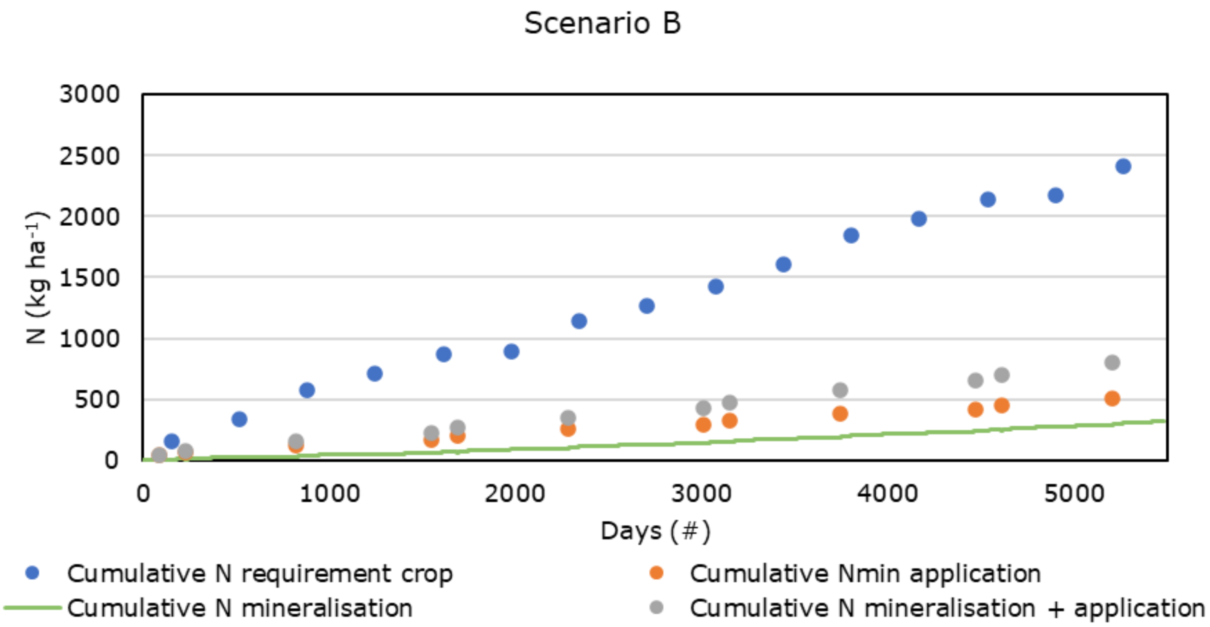
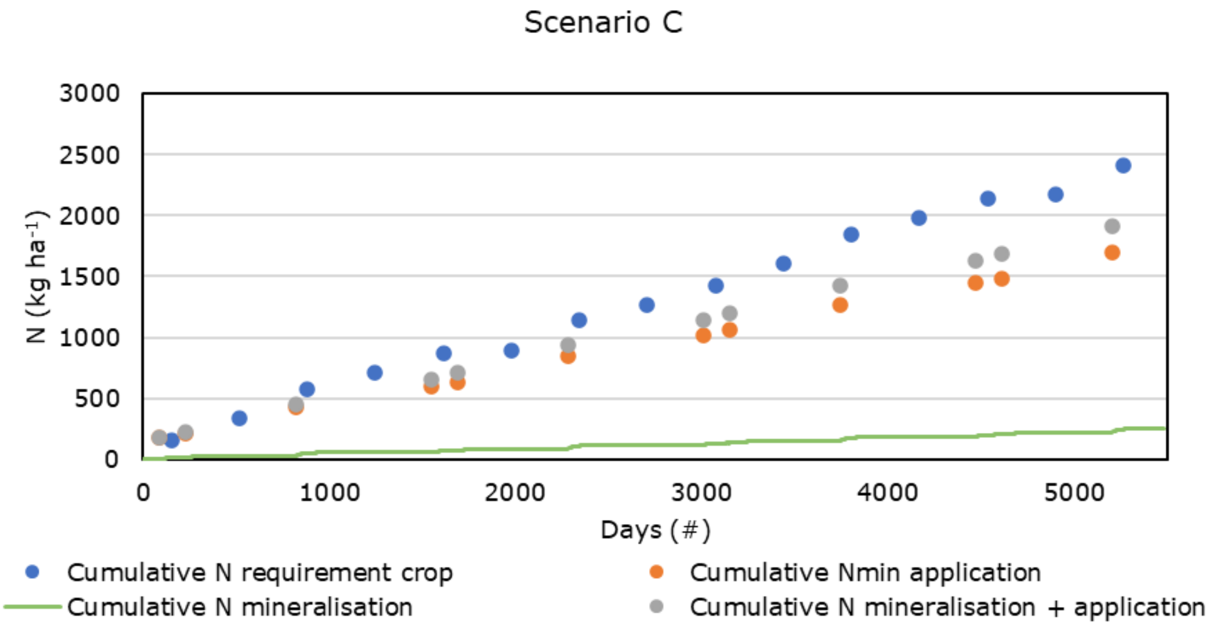


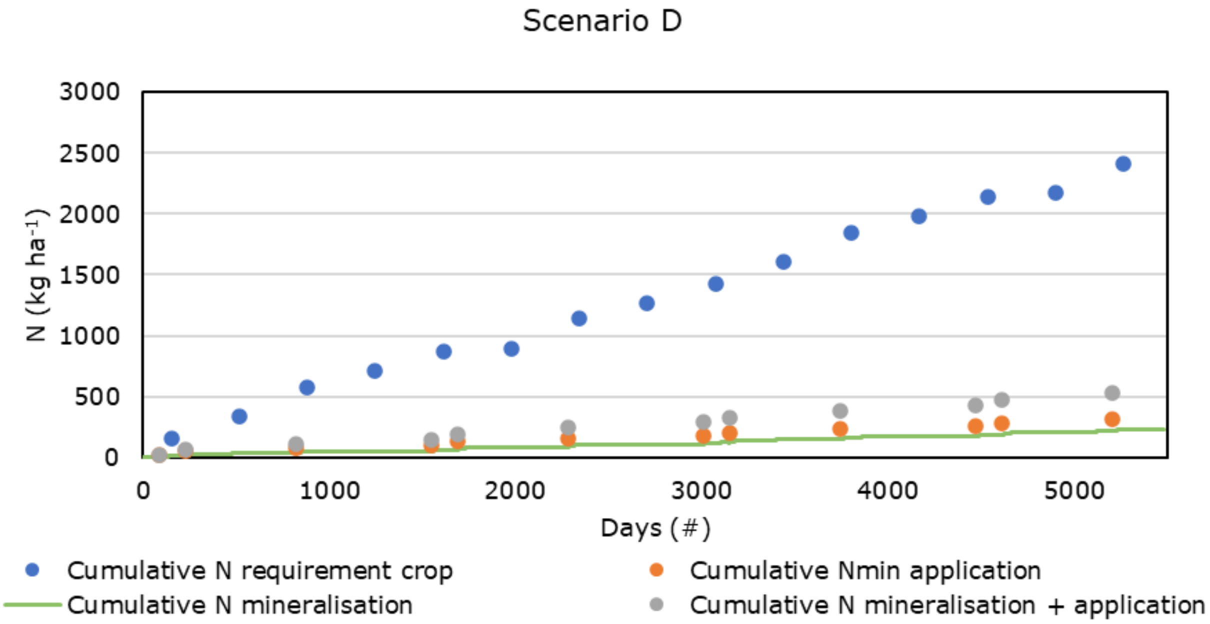
Figure 4-7 *Contribution of the organic materials to the C build-up in the soil associated with the various fertilisation strategies in the South-West of the Netherlands, distributed over the RothC pools: decomposable plant material (DPM), resistant plant material (RPM), biodiversity (BIO), humus (HUM) and total (Tot.). The C stock (Y-axis) only refers to the addition by organic fertilisers, and is therefore excl. the soil C stock.*

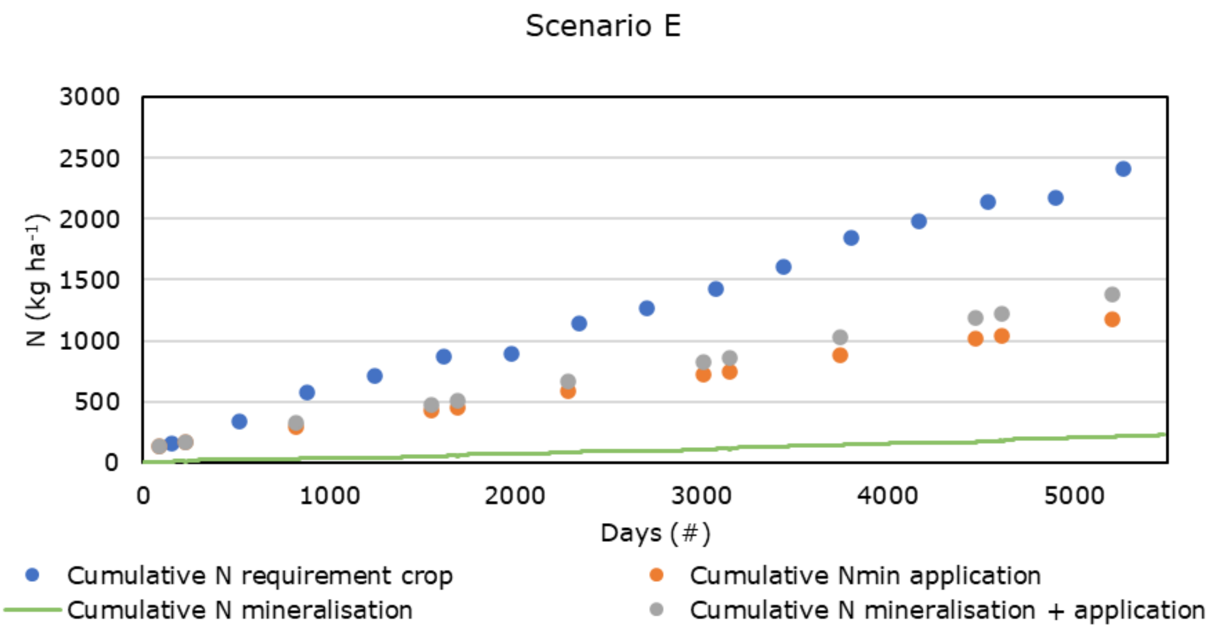

Control
N (kg ha-1)
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application

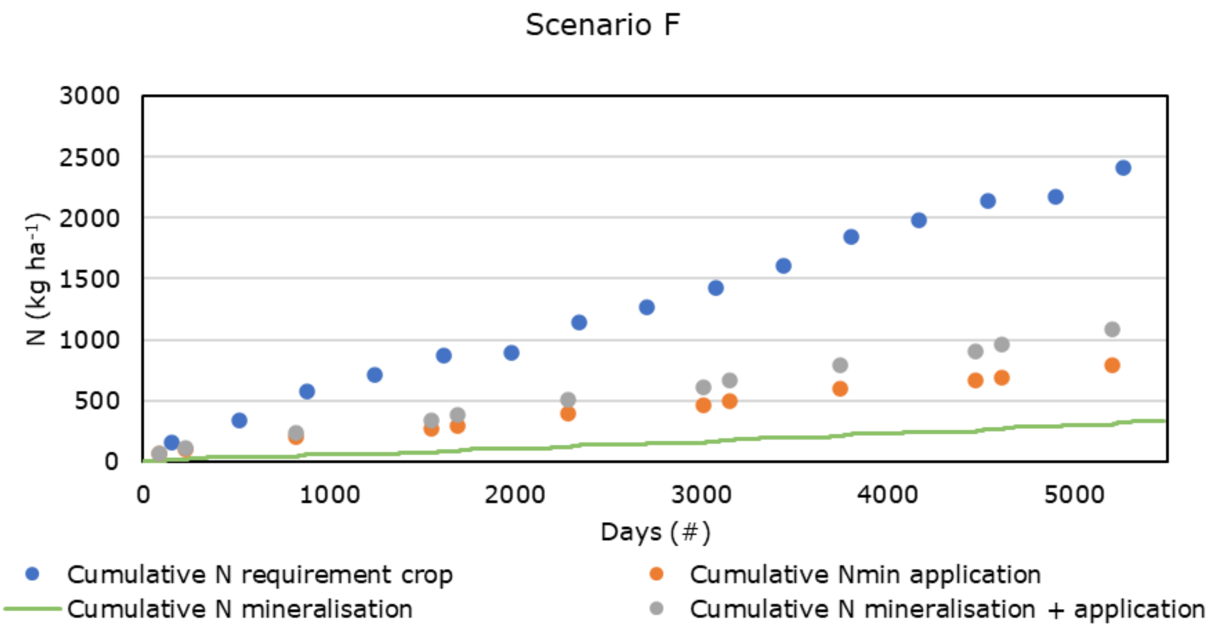

Scenario A
N (kg ha-1)
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative N mineralisation
Cumulative Nmin application
Cumulative N mineralisation + application

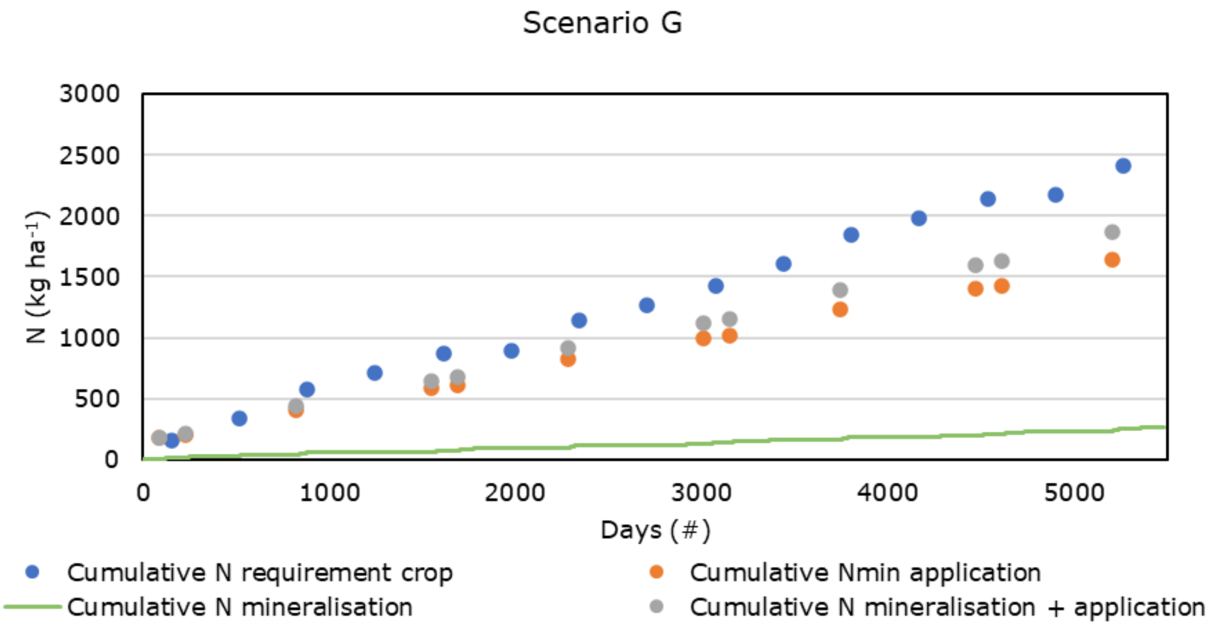

Scenario B
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
● Cumulative N requirement crop
● Cumulative Nmin application
Cumulative N mineralisation
● Cumulative N mineralisation + application

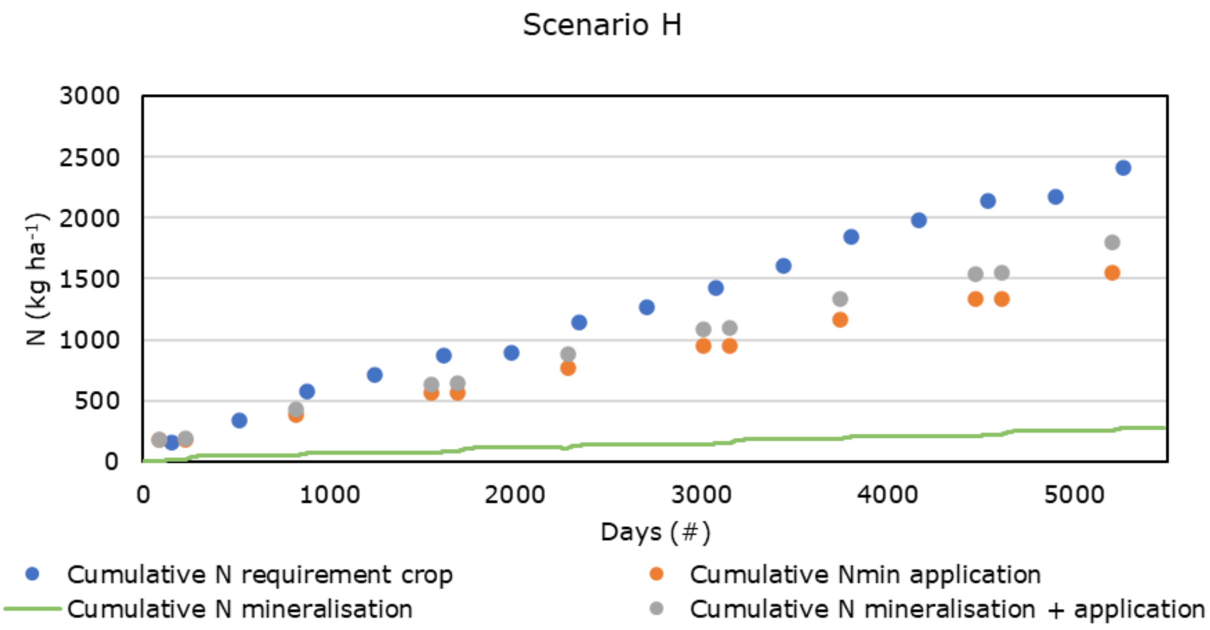

Scenario C
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
● Cumulative N requirement crop
● Cumulative Nmin application
Cumulative N mineralisation
● Cumulative N mineralisation + application

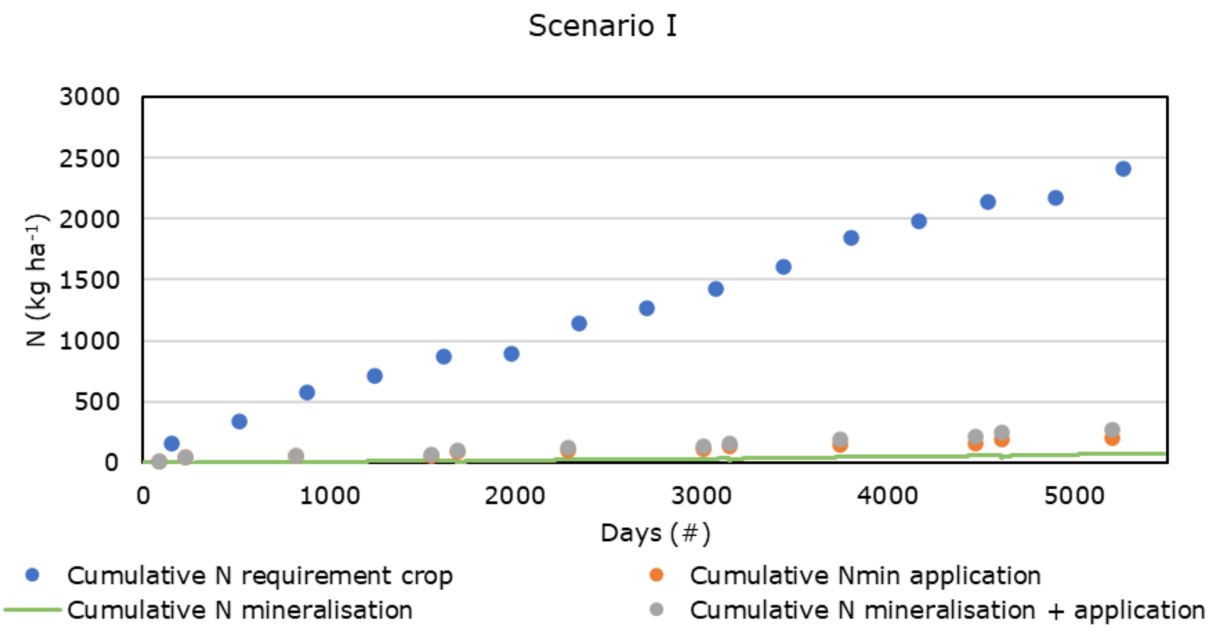

Scenario D
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
● Cumulative N requirement crop
● Cumulative Nmin application
Cumulative N mineralisation
● Cumulative N mineralisation + application

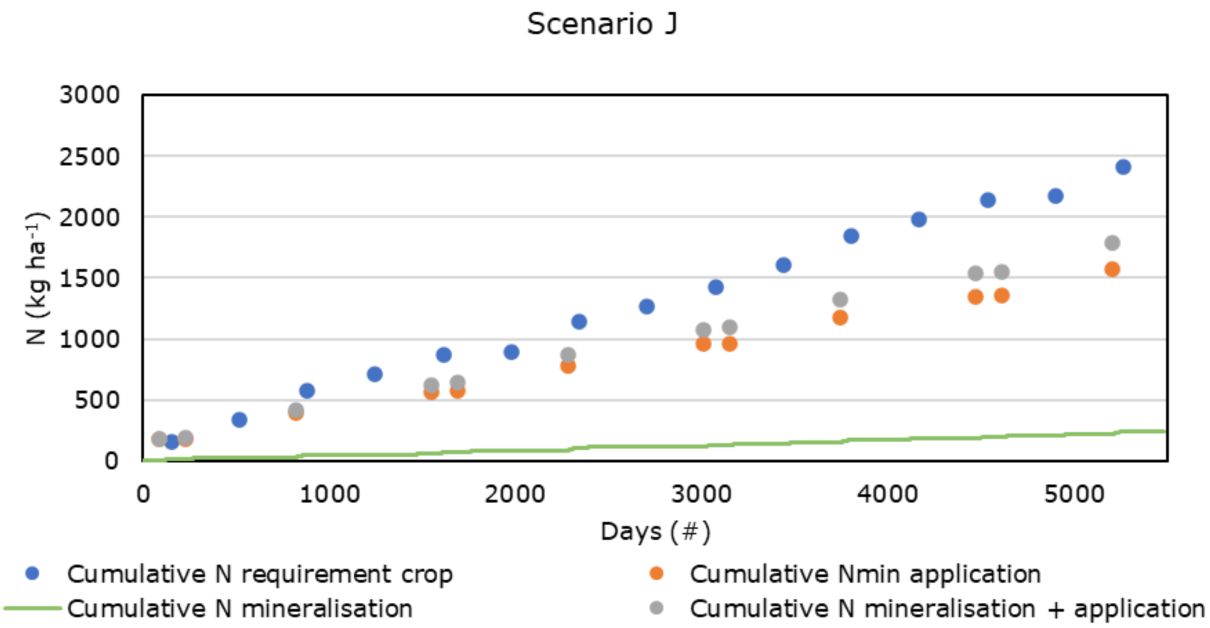

Scenario E
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative Nmin application
Cumulative N mineralisation
Cumulative N mineralisation + application

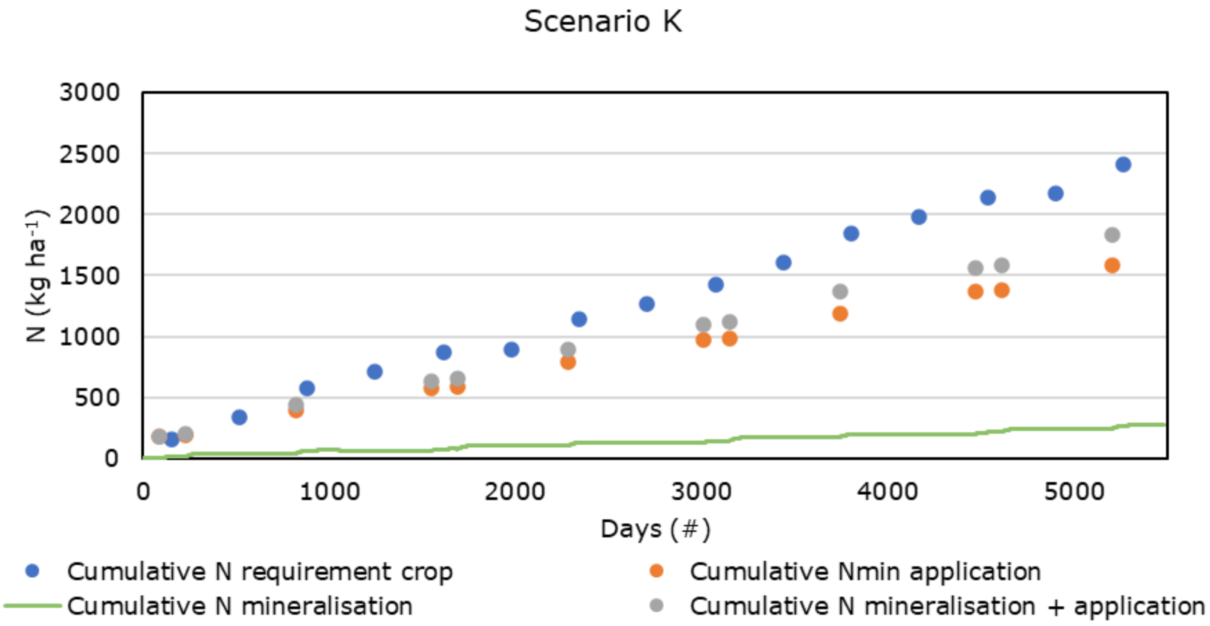

Scenario F
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative Nmin application
Cumulative N mineralisation
Cumulative N mineralisation + application


Scenario G
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative Nmin application
Cumulative N mineralisation
Cumulative N mineralisation + application


Scenario H
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative Nmin application
Cumulative N mineralisation
Cumulative N mineralisation + application


Scenario I
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative Nmin application
Cumulative N mineralisation
Cumulative N mineralisation + application


Scenario J
3000
2500
2000
1500
1000
500
0
N (kg ha^{-1})
0
1000
2000
3000
4000
5000
Days (#)
Cumulative N requirement crop
Cumulative Nmin application
Cumulative N mineralisation
Cumulative N mineralisation + application



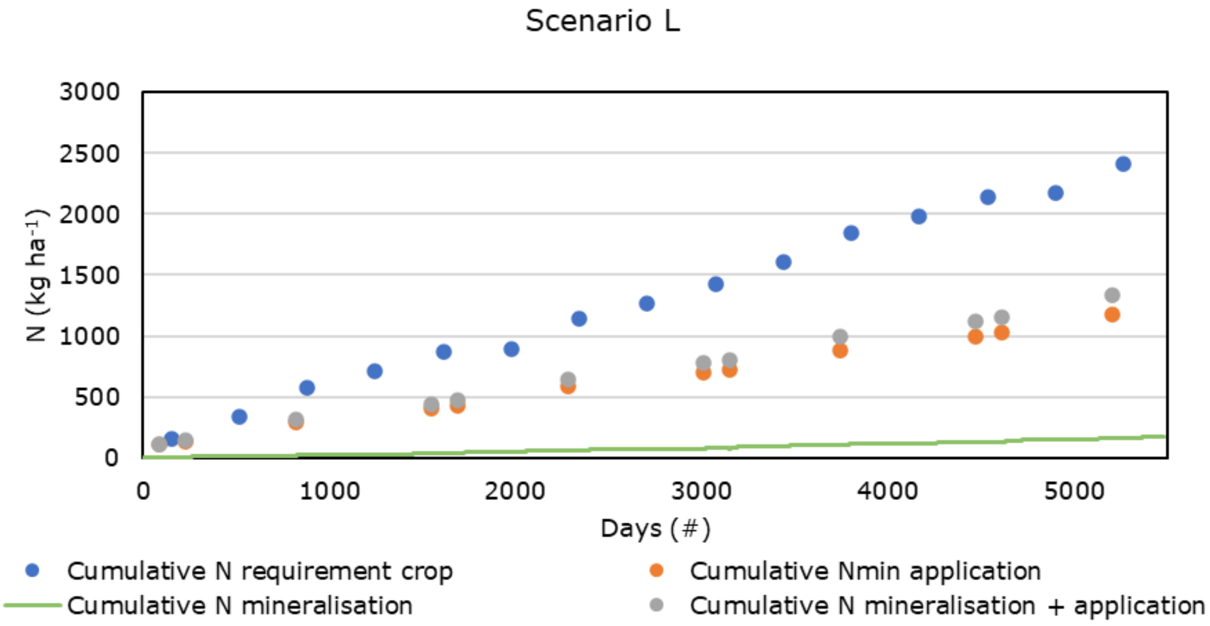


Figure 4-8 *The cumulative mineral N contribution to the soil as a result of the application of organic materials, and the crop N requirements (South-West of the Netherlands). N deriving from the soil or applied with synthetic fertilisers are not presented here.*

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