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Quantification of stocks and flows in the top soil

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WAGENINGEN UR
For quality of life

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J.G. Conijn[1] and J.P. Lesschen[2]

1 Plant Research International, part of Wageningen UR
2 Alterra Wageningen UR

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Research Institute Plant Research International, P.O. Box 16, 6700 AA Wageningen, The Netherlands; T +31 (0)317 48 07 00; www.wageningenur.nl/en/pri.
Alterra (an institute under the auspices of the Stichting Dienst Landbouwkundig Onderzoek), P.O. Box 47, 6700 AA Wageningen, The Netherlands, T +31 (0)317 48 07 00, E info.alterra@wur.nl, www.wageningenUR.nl/en/alterra. Alterra is part of Wageningen UR (University & Research centre).

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Foreword

This report is based on a study and three PowerPoint presentations held for the working group "*Koolstofstromen*" of the "*Technische Commissie Bodem*" (TCB) at 25-11-2013, 26-02-2014 and 25-06-2014. The TCB initiated and funded this work. Based on this and other studies the working group "*Koolstofstromen*" of the TCB will produce the book "Organische stof in de bodem van betekenis voor voedsel, water, klimaatregulatie, energie en gezondheid" to provide national, regional and local policy makers with background information on soil organic matter issues. The current report serves as a background publication of the book for reference purposes.

In the last two to three decades soil carbon was studied intensively, both nationally and internationally. This has led to many publications. In this report we present an overview on stocks, flows and risks of soil organic carbon in the Netherlands based on available knowledge and new model calculations. We would like to acknowledge the contributions of Ben Rutgers (GIS analysis of global datasets) and Leo Renaud (for calculations with STONE 2.4) and the financial support from the FP7 HYSOL project (EC-grant agreement 308912) and the FP7 SmartSoil project (EC-grant agreement 289694).

Sjaak Conijn
Jan Peter Lesschen

Summary

Introduction

Soil organic matter (SOM) and especially decreasing SOM are since many decades on the agenda of different stakeholders due to the importance of SOM for various issues ranging from local crop profitability to global climate change. Globally large amounts of organic carbon are stored in the soil and changes in the amount of SOM may sequester or release CO_2 from/into the atmosphere. The global stock of soil organic carbon (SOC) in the upper 100 cm equals roughly two times the amount of carbon in the atmosphere and soil respiration equals circa ten times the release of carbon by burning fossil fuels. Other functions of SOM with a (more) local dimension relate to e.g. soil fertility, soil structure, soil erosion, regulation of soil water flows, plant productivity and maintenance of soil biodiversity. Declining SOM is considered as one of the most serious processes of soil degradation and has been identified as one of the main soil threats. Next to positive effects, decomposition of SOM may also have adverse effects by enhancing N_2O and CH_4 emissions, and releasing nutrients of which part is leached to surface and ground waters.

In the Netherlands, the "*Technische Commissie Bodem*" (TCB) gives advice to the government on soil related issues and has recently developed an advice for the Dutch government on the effects of future trends (such as the biobased economy, climate change, safeguarding food productivity, water management) on soil functioning. As part of the information gathering underlying this advice, the TCB asked Plant Research International and Alterra to conduct a literature research of (a) SOM stocks, flows and recent trends, (b) variation and uncertainty in the data and (c) determination of areas of having/reaching low SOM levels in the Netherlands. In this study we have focussed on the top soil of 0-30 cm and mainly on soils under agricultural use. SOM in deeper soil layers may be important (e.g. globally the layer 30-100 cm contains approximately an equal amount of SOC as compared to the 0-30 cm layer), but due to lack of data this fell outside the scope of this study. The findings of this study have been presented to the working group "*Koolstofstromen*" of the TCB in three separate sessions in 2013-2014.

Soil carbon stocks

Generally, high spatial variation in SOC exists with soil texture, historic land use/management, moisture conditions, prevailing temperature and soil pH as main driving factors. Based on the available data, maps of SOC in the Netherlands were constructed by linking a map of major soil types with a map of current main land use (i.e. grassland, arable land and nature). Two different sources were used: Dutch SOM matter data from the LSK data set combined with Dutch maps of soils and land use and data from the Harmonised Soil World Database (HWSD, which uses data from the European Soil Database) combining major soil types with average SOM per soil type (this dataset does not contain land use data).

In the Dutch LSK dataset average SOC stock density per soil type varies from 52 ton C ha^{-1} ("*Kalkhoudende zandgrond*") to 191 ton C ha^{-1} ("*Veengrond*") in the upper 30 cm. The overall mean for the Netherlands, i.e. based on arable land, grassland and nature, equals 108 ton C ha^{-1}. Dutch grasslands contain more SOM (123 ton C ha^{-1}) compared to cropland (94 ton C ha^{-1}) and nature (98 ton C ha^{-1}), mainly caused by a higher frequency of peat soils under grassland. The difference in stock density between cropland and nature is negligible which is probably due to high inputs of manure and compost on arable land in the Netherlands. In many situations the average SOC contents (%) of land use and soil type were not significantly different among each other (e.g. on 10 out of 11 soil types we did not find a statistically significant difference between arable land and grassland use), which suggests that soil type and (current) land use can only partly explain spatial differences of SOM in the Netherlands and other factors, e.g. historic land use and groundwater level, may be (more) important. Overall uncertainty has not be assessed due to the many sources and types of uncertainty, such as ongoing loss of peat(y) soils, soil bulk density and C content, which are both not measured and the LSK measurement period which is on average already 20 years ago.

In the international HWSD average SOC stocks of soil types comparable with the LSK data are both lower (Fluvisols with circa 30 ton ha^{-1} and "zeekleigrond" with circa 100 ton ha^{-1}) and higher (Histosols with >300 ton ha^{-1} and "veengrond" with <200 t ha^{-1}). Differences between soils in the HWSD are thus larger, whereas those from the Dutch

database are more similar. This can be partly explained by the high (manure) inputs on Dutch agricultural soils compared to the same soil types outside the Netherlands. According to the HWSD the Netherlands is dominated by soils with <3% organic matter, whereas following the LSK data only a small part of the Netherlands has SOM contents lower than 3%. Despite these differences the average carbon stock density of the Netherlands from the HWSD is with 93 ton C ha^{-1} more or less similar to that derived from the LSK dataset (108 ton C ha^{-1}).
Another more recent international dataset of measured SOM values (LUCAS) shows that the average SOM contents of grassland, cropland and nature in the Netherlands are roughly 20% lower compared to the data from the LSK dataset and that the average stock density for the Netherlands would equal 84 ton C ha^{-1}. Reasons for the lower values are not known. The Joint Research Centre (JRC) of the European Commission has also constructed a European map with calculated SOM values by using pedo-transfer functions (OCTOP). This product suggests that Dutch soils contain 800 Mton organic C in the upper 30 cm, which is more than two times the estimates from the LSK (360 Mton C) and the HWSD (320 Mton C). International databases that estimate the SOC amount of the Netherlands result both in lower (LUCAS, HWSD) and much higher (OCTOP) values compared to the value derived from the LSK dataset and should therefore be used with caution.

Carbon input flows

In this study we have distinguished three main input flows of carbon to agricultural soils: 1) crop and grass residues (incl. roots), 2) animal manure and 3) compost. Roughly 84% of total produced manure is applied to agricultural soils, because the remaining part is exported or incinerated in the Moerdijk energy plant (mostly poultry manure). During the first year after application the more easily degradable part of the input is decomposed and carbon is emitted to the atmosphere as CO_2. The part that remains in the soil after one year is called the "*effective organic matter*" (EOM) input which contributes most to maintaining the organic matter in the soil. The fraction that remains after the first year ("*humification coefficient*": hc) is different for different inputs and depends on the degradability of the input. Hc values reported for organic matter inputs in the Netherlands range roughly from 0.2-0.4 for plant residues, 0.33-0.7 for animal manure types and 0.75-0.95 for compost which illustrates that 5% to 80% of the original input can be lost during the first year.

The annual average total EOM input in the Netherlands has been estimated at 2.1 ton ha^{-1} on cropland and 3.6 ton ha^{-1} on grassland, based on various sources of e.g. crop residue productivity, animal numbers, animal excretion and hc values. Annual EOM inputs vary among provinces between 1.9 ton ha^{-1} in Zeeland and 2.5 ton ha^{-1} in Utrecht on cropland and between 3.1 ton ha^{-1} in Zeeland and 3.8 ton ha^{-1} in Utrecht on grassland. For both land use types circa half of the EOM input consists of plant residues while the other half comes from manure/compost inputs. Compost input is negligible in Groningen, Friesland, Drenthe and Overijssel and has only a very modest contribution in the other provinces. EOM inputs expressed as percentage of the soil organic carbon stock in the upper 30 cm (assuming a C:OM ratio of 0.5) range for grassland between 1.2% and 1.8% (average value: 1.5%) and for cropland between 0.7% and 1.3% (average value: 1.1%).

Considerable uncertainty exists in the estimate of annual grass residue production. According to MITERRA-NL 1.95 Mton EOM from grass residues is annually produced which is part of the above 3.6 ton EOM ha^{-1}, whereas STONE v2.4 estimates a grass residue production of 4.43 Mton EOM per year (based on QUADMOD). We decided to adjust the value of grass residue production from 1.95 (MITERRA-NL) to 3.6 Mton EOM per year. This "new" value was used further in the analysis of this study, but should be analysed in more detail to find the right value. Due to this adjustment the average total EOM input at grassland increases from 3.60 to 5.25 ton ha^{-1} y^{-1}, which equals circa 2.1% of the SOM stock in the upper 30 cm of grassland soils. Another uncertainty is found in the values of the humification coefficients which seem to originate from the same publication(s) of about 40 years ago and due to uncertainty in the validity of these values for current situations, a more thorough investigation, including a comparison with data from other countries, and an update of the values is needed.

Carbon output flows

The following main losses of SOM apply to the Netherlands: (1) respiration of existing SOM, (2) SOM leaching and (3) SOM loss with erosion. For both SOM leaching and erosion we did not find enough (national) data for a reliable estimate and we assumed these losses to be negligible in the Netherlands. By doing this, the net availability of EOM in the upper soil layer is overestimated. The loss of organic carbon during the first year after application of organic matter to the soil of circa 5-80% (i.e. the difference between the original and the effective OM inputs) has already been taken into account by expressing the input flows as effective organic matter inputs using the humification coefficients.

Reported variability and uncertainty of relative loss rates of the existing SOM by decomposition are high due to different conditions in the field of e.g. soil texture, initial organic matter content, manure history and pH. Estimates for Dutch conditions range from 0.5% (sandy soils with >2% SOM) to 10% (dune sand) per year. Some estimates are more directly linked to experimental data, whereas others are based on (dynamic) model calculations. Uncertainty of estimated/calculated loss rates for the same conditions is also high up to a factor of almost 4 as illustrated in this report and in other studies. Methodologies to determine SOM loss differ in time period, measurement, soil layer, relevant covariates and resulting equations, which all add to the uncertainty. Various tools are available for the farmer to calculate the amount of organic matter input, required for an equilibrium of current SOM level. To maintain this equilibrium the loss of existing SOM should be compensated by fresh inputs and for this balance method the required amount of input is estimated by calculating the annual loss of existing SOM. Probably a significant difference exists between the first year decomposition or loss of existing SOM and the long term average value (e.g. 3.3% or 4.5% versus 1.7%; example of a loam soil left uncropped for 22 years), because the decomposition of easily degradable components during the early years increases the share of more resistant components in later years.

With relative loss rates and the amount of SOM in the top layer (0-25 cm), SOM losses have been calculated for arable land and grassland per province (only for mineral soils, peat(y) soils excluded). In these calculations we used average relative loss rates from three different sources: (a) an existing tool for calculating the organic matter balance of a field (to be used by (arable) farmers), (b) an adjusted version of this organic matter balance tool and (c) an average 2% for all situations. Results from these three sources indicate that averaged for the Netherlands the annual SOM loss on arable land is between 2200 and 3000 kg ha^{-1} and on grassland between 2400 and 4000 kg ha^{-1}. The lower values result from the calculations with the farmer's tool and the higher value was calculated by applying the 2% relative loss rate, with the results from the adjusted tool more similar to that of 2% loss rate. The farmer's tool probably underestimates the loss rate of SOM from the 0-25 cm soil layer in the Netherlands.

Recent trends

Two sources were used to estimate the development of SOM in the Netherlands during recent years, one based on measurements during the period of 1984-2004 (Reijneveld *et al.*, 2009) and the other one on calculations with a dynamic crop-soil model for the period 1981-2010 (STONE v2.4). The measurements refer to the soil layers 0-25 cm (arable and maize land) and 0-5 cm (grassland) and the calculations are performed for 0-25 cm (all land use types). According to both sources SOM in grassland soils (0-5 cm and 0-25 cm, respectively) has increased with on average 0.2-0.4% per year during the 80s and the 90s, overall for the Netherlands. For soils with arable crops a difference in the estimated trend was found: a positive change according to the measurements and a negative trend in the calculations. Trends on maize land were either positive (measurements) or zero (calculations). Difference in maize land trends can be explained by the situation that maize is often cultivated in rotation with grassland (not modelled, but part of the measurements because only land use at the moment of sampling is determined). Especially the calculated negative trend for arable land compared to the measured positive trend in the data requires further study. For 13 combinations of land use and region measurements indicate either no significant change or a positive change and in only one situation a significant negative change was measured. However, the situation may be different for specific fields or farms as was published in literature. With changing future climate (increasing temperature and more irregular precipitation) and increasing regulation on manure application the situation for the coming decades can become different compared to the results based on current available data.

Risk areas

To assess the areas that are under potential risk of too low soil carbon stocks we used two different approaches. The first approach was based on simple balance equations of effective OM inputs (crop residues, manure and compost) minus output (OM decomposition, i.e. loss by respiration). A negative value for this balance indicates a declining SOM level (SOM loss > EOM input), whereas a positive value points to the opposite (EOM input > SOM loss). This approach of calculating the SOM balance of one year resembles the available (simple) tools for practical farmer advice. For the second approach we used the dynamic soil model RothC to calculate the soil carbon balance. For both approaches the same sources were used for current SOM level (in the top layer of mineral soils; 0-25 cm) and carbon input and calculations were done at the same spatial units.

Balance equation

We used three different equations to calculate the SOM decomposition (see above: carbon output flows) and compared the results of the balance with the results of the RothC model. Total EOM inputs are on average 2 ton ha^{-1} y^{-1} on arable soils and 5 ton ha^{-1} y^{-1} on grassland soils. Combined with the estimated SOM losses, all balances for grassland are positive at the province level (ranging between 0.7 ton ha^{-1} in Zeeland assuming 2% loss rate and 3.2 ton ha^{-1} in Utrecht calculated with the farmer's tool). Consistently higher values are found for the farmer's tool due to the calculation of the lowest loss rates. The aggregated total increase of SOM in the top soil of grassland in the Netherlands ranges from 1.3 (2% loss rate) to 2.9 (farmer's tool) ton ha^{-1} y^{-1}, which equals approximately 0.7% and 1.5% of the current SOM amount. For arable soils the balances per province are mostly negative, except for some results calculated with the farmer's tool and the RothC model in combination with compost application. Again the farmer's tool has the least negative values, due to the calculated low relative loss rates. The aggregated total change of SOM in the top soil of arable soils in the Netherlands ranges from -0.9 (2% loss rate) to -0.08 (farmer's tool) ton ha^{-1} y^{-1}.

Detailed mapping

Results of the RothC model have been used for mapping the SOC balance in the Netherlands at higher resolution (postcode level). As was concluded above, almost all grassland areas show positive balances throughout the Netherlands, especially on the clayey soils. For arable land the SOC balance is mostly close to zero or moderately negative. Only in the north-east (Veenkoloniën) and in some dune sand areas in Noord and Zuid Holland more negative SOC balances are found (> -0.5 ton SOC ha^{-1} y^{-1}). A combined SOC balance for agricultural land (arable and grassland) gives a more realistic picture in those areas where crops are grown in rotation with temporary grassland and only in a few areas (again the Veenkoloniën and some dune sand areas in Noord and Zuid Holland) clear negative balances were simulated.

Based on the first year SOC balance and the SOC stock, risks were assessed and mapped to illustrate which areas in the Netherlands are most vulnerable for declining SOC up to critical low SOC levels. In this study a SOC level of 1.5% (~ 3% SOM) was chosen as critical low value. High risks were estimated for some dune sand areas in Noord and Zuid Holland and medium risks for the Veenkoloniën (both in combination with arable land use), whereas all other situations were characterised with a low risk. Another methodology to estimate the risk yielded similar results in the distribution of low, medium or high risk over agricultural land use types of the Netherlands.

Many drivers affect the decomposition rate and their effects on the SOC balance are often difficult to quantify (such as the temperature effect and characterisation of current SOM in relation to decomposition and input history; the effect of regular grassland renovation). E.g. a temperature rise of 2 °C may require an extra 0.6 ton EOM input per ha to compensate for the higher decomposition (only based on temperature effects on decomposition rate). This example also illustrates the sensitivity of the results to the assumed effect of temperature which appears to be very different according to different sources. Besides the decomposition rate, also the soil depth which is chosen in the calculation adds to the uncertainty of the balance. In practice it is not well-known which part of the soil should be selected in combination with the fresh OM inputs, especially at grassland where currently only the top 10 cm of the soil is sampled for a SOM analysis. Specific situations in the Netherlands exist which differ considerably from the mainstream situation and these situations have not been adequately described by the various models in this study because they represent more extreme conditions that fall outside the average range for which the models were developed. It adds to the general uncertainty of our results but specifically points to careful further use and in-depth examination of what we have presented in this report, especially for local situations.

1. Introduction

1.1 Background

1.1.1 Global carbon balance

Both soil and plant organic carbon play an important role in the global carbon balance. In Figure 1 soils contain 1500 Gton of C, which is twice the amount in the atmosphere, whereas C in plants amounts circa 75% of the amount in the atmosphere. Global flows of carbon are mainly influenced by ocean uptake and loss (both roughly 90 Gton C y^{1}) and by processes in plant and soil through litter fall (60 Gton C y^{1} or 11% of total C in plants) and soil respiration (also 60 Gton C y^{1} or 4% of total C in soils). The emission from burning fossil fuels is “only” 10% of the annual flow by biological activities. It is clear that major disturbances in plant and litter production or in soil respiration can have dramatic effects in the long run on the atmospheric C concentration and thus on global warming.

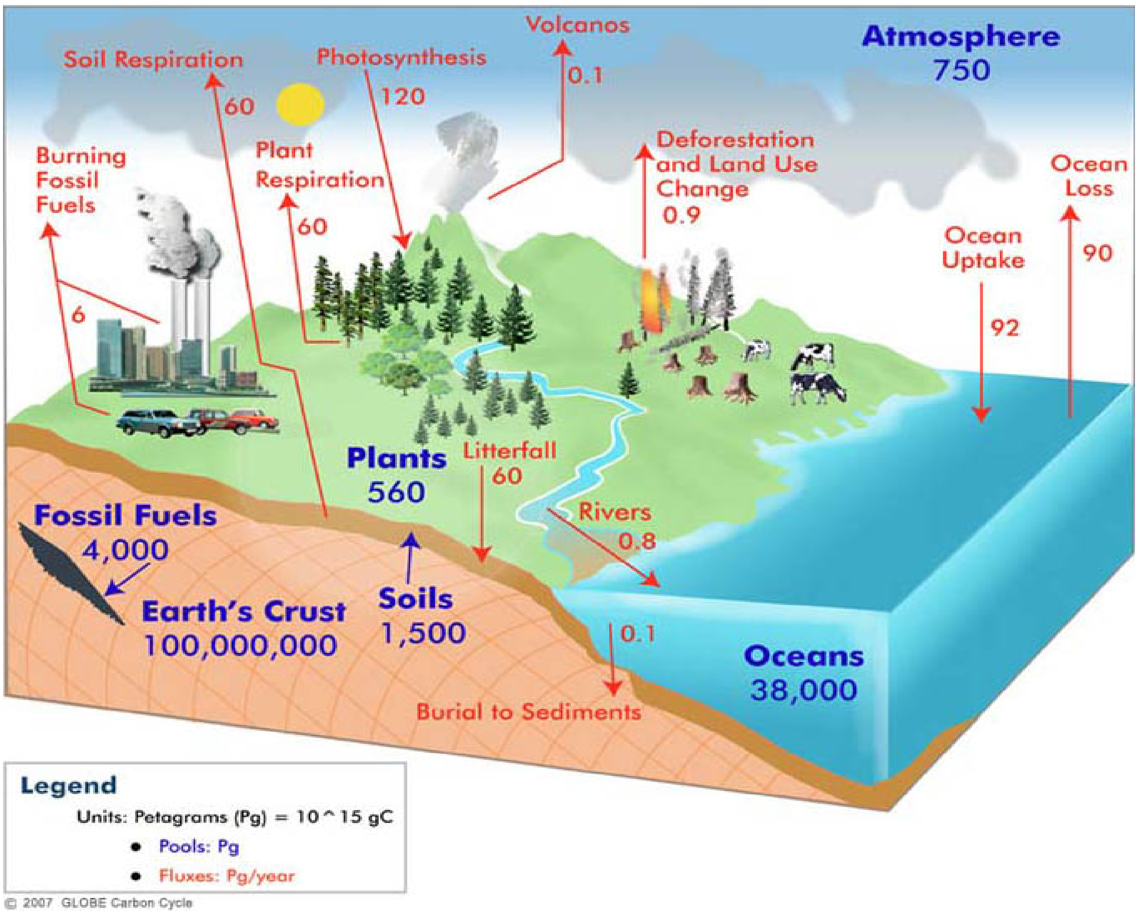

Figure 1. The global carbon cycle showing carbon stocks in blue (in Pg C = Gton C) and carbon fluxes in red (in Gton C yr^{1}). Source: GLOBE carbon cycle project, http://globecarboncycle.unh.edu/diagram.shtml (accessed December 2014).

The magnitude of the soil carbon in Figure 1 is similar to estimates from four other sources (Table 1). These data reveal that on average 50% of the total soil carbon is found in the upper 30 cm (i.e. the top soil), and the other 50% in the soil layer from 30 to 100 cm (sub soil). In agricultural areas top soils contain most biological activity and are most prone to disturbances (such as ploughing or erosion). Due to practical issues, most knowledge of stocks and flows is based on this upper soil layer and this report will therefore focus on that part. Due to this lack of knowledge we have treated in our study the sub soil as a black box without C input nor output which is a simplification of reality.

Table 1. Summary of estimates of global total amount of organic carbon (Gton C) in top and sub soil (based on soil organic matter estimates; Hiederer & Köchy, 2011).

Source	**HWSDa**	**NRCS**	**FAO**	**WISE_5x5**	**DSMW**
Topsoil (0-30 cm)	699	-	710	504	574
Subsoil (30-100 cm)	718	-	746	487	632
Total (0-100 cm)	1417	1399	1459	991	1206

HWSDa : amended Harmonized World Soil Database;
NRCS : Natural Resources Conservation Service of the Unites States Department of Agriculture;
FAO : FAO-UNESCO Soil Map of the World;
WISE_5x5 : ISRIC-WISE data set of derived soil properties (ver. 1.1) combined with the FAO-UNESCO Soil Map of the World;
DSMW : Digital Soil Map of the World (Ver. 3.6).

Contribution of the C stock of the top soils in the Netherlands to the global carbon cycle is rather small: Dutch soil carbon contributes only 0.05% to the total global top soil stock of 750 Gton C (= 50% of 1500) based on the estimate of circa 350 Mt C in Dutch top soils according to Lesschen *et al.* (2012). The interest in soil carbon in the Netherlands should therefore be more focused on the role that soil organic carbon (matter) plays in local ecosystem functioning than in global warming issues.

1.1.2 Role of soil organic matter

Soil organic matter (SOM) plays an important role with various functions/effects in a number of environmental themes. Globally SOM stores large amounts of organic carbon and changes in the amount of SOM may sequester or release CO_2 from/into the atmosphere (theme: climate change, discussed above). In general, SOM has a positive effect on soil fertility and plant productivity through the release of nutrients when SOM is decomposed and through the adsorption of nutrients which prevents leaching into surface and ground waters (themes: food security & eutrophication). SOM also improves the soil structure and reduces soil loss by erosion. Better infiltration of water in the soil and higher water-holding capacity influences water logging, deep percolation and local storage and availability of water in the soil (themes: soil erosion/degradation & water management). The decomposition of SOM is the primary source of food for many soil biota in the soil food web, ultimately affecting biodiversity of the soil (theme: biodiversity). From the list above it seems that more SOM is always positive (more carbon stored, more nutrients available, more infiltration of water, etc.). However, (more) SOM can also have adverse effects. The emission of N_2O from soils is positively related with SOM decomposition and contributes to climate change. Soil carbon can under water logged conditions also be emitted to the atmosphere as CH_4, which has a larger global warmer potential compared to CO_2. Mineralisation of organically-bound nutrients in combination with a precipitation surplus may also enhance nutrient leaching if plant requirement and uptake are insufficient to accommodate the released amounts. In these situations (high) SOM levels and related decomposition can have negative effects next to the positive effects mentioned above. Defining an optimum SOM level is therefore not an easy and straightforward task and requires a thorough understanding of processes and trade-offs of goals.

1.1.3 Concerns about soil organic matter?

SOM and especially decrease of SOM are on the agenda of different stakeholders since many decades due to the importance of SOM for various issues ranging from local crop profitability to global climate change. Notably the (possible) loss of SOM has received much attention, and declining SOM is considered as one of the most serious processes of soil degradation and has been identified as a main threat to soils, especially in Southern Europe (Van-Camp *et al.*, 2004). According to Jones *et al.* (2012) around 45% of mineral soils in Europe have low or very low soil organic matter contents (<3.5% SOM), which particularly occur in Southern countries of Europe but are also found elsewhere.

In the Netherlands declining SOM levels is not wide-spread. According to research of Hanegraaf *et al.* (2009) on sandy soils only continuous maize may be denoted as high-risk area, and possibly grassland fields but not grassland areas may be at risk. Based on recent research of SOM trends in the Netherlands BLGG concluded that for most soils the SOM level is adequate for agriculture.

It is difficult to pinpoint a critical or even an optimal SOM level as general threshold. Jones *et al.* (2012) report that 3.4% SOM (= 2% SOC) is widely used as threshold for a soil to function optimally, but also acknowledge that there is much debate on the quantitative evidence for this level. On the other hand in Zwart *et al.* (2013a) a much lower value of 1.5% OM is mentioned as possible critical level in the Netherlands. Van Camp *et al.* (2004) concluded that it is not possible to define one single threshold and that depending on climate, soil type and soil use probably hundreds of target SOC values in Europe may be identified.

1.2 Objectives and outline

The "*Technische Commissie Bodem*" (TCB) gives advice to the government on soil related matters in the Netherlands. The TCB has decided to gather information on the effects of a number of future trends (such as the biobased economy, climate change, safeguarding food productivity, water management) on soil functioning (and vice versa). Part of this work focusses on soil carbon and the TCB asked Wageningen UR to conduct a literature research on this subject, to look for relevant data and to estimate soil carbon changes in order to assess risk areas in the Netherlands.

This project aims to deliver quantitative information on the following questions:

- What are the stocks, inputs and outputs and recent trends of soil organic carbon in the Netherlands?
- How much is the variation and uncertainty of the data?
- Which soils are at risk of declining and reaching low SOM levels?

This report describes the findings and data sources which have also been presented to the working group "*Koolstofstromen*" of the TCB in three separate sessions on (A) stocks, trends and flows (25-11-2013), (B) variation and uncertainty (26-02-2014) and (C) assessment of risk areas (25-06-2014). Data on stocks appeared to be available for various types of land use (including forest and nature), but the other data required appeared to be only available for agricultural soils (viz., separately for grassland and arable land). Chapter two deals first with soil carbon stocks comparing maps and data from two sources. Secondly, the input and output flows of soil organic matter/carbon in agricultural soils are presented and finally the recent trends in SOM dynamics are described. In chapter three various methods are described to assess risk areas of reaching (too) low SOM levels in the future and data and maps are presented visualizing these areas in the Netherlands.

2. Soil organic carbon in the Netherlands

2.1 Introduction

As described above this report focuses on soil carbon in the top soil (0-30 cm), thereby neglecting stocks and flows that occur in deeper soil layers. The top soil is the most important layer for agriculture because most biological activity occurs in this layer, including mineralization, it is important for the water balance, e.g. through infiltration of precipitation and this layer is directly subject to agricultural management like ploughing. Any carbon released from deeper layers and/or transferred from the top soil to the sub soil is not taken into account in this study. Assuming zero carbon dynamics of the sub soil might affect some conclusions of this study, but effects have not been quantified, because of the limitations of this study and relative lack of knowledge of soil carbon in deeper layers.

One of the first questions of the TCB concerned the method how to quantify and illustrate soil carbon stocks in the Netherlands in relation to possible management options. Soil organic carbon is known to be spatially highly variable with soil texture, historic land use/management, moisture conditions, prevailing temperature and soil pH as main parameters. However, based on available data it was decided to develop a soil carbon map only with major soil type, current main land use and province as map layers. The first two layers are explanatory for soil carbon (following the chosen methodology a combination of soil and land use has an unique soil carbon content), whereas the latter was added to allow for the option of exploring regional policy measures at province level without explaining the distribution of current soil carbon stocks in the Netherlands.

Next to Dutch databases we also used international (i.e. global/European) databases. We only did this for mapping of soil carbon stocks. Because large differences became clear between both sources we decided to continue only with the Dutch databases in the assessments of soil carbon flows and risks. Nevertheless, the found differences between both sources is interesting because in international studies (and proposed measures?) the Netherlands is often represented by data from these international databases (such as the European soil database) and due to large deviations this can be misleading (see e.g. Panagos *et al.*, 2013).

2.2 Soil carbon stocks and content

2.2.1 Sources

The Netherlands has detailed soil information of its entire land area (except for soils under buildings and infrastructure), which is derived from the soil map of The Netherlands at a scale of 1:50,000 (de Vries *et al.*, 2009). The soil map is based on soil surveys from the period 1965-1995. Currently the soil map is being updated for the areas with peat and peaty ("*moerig*") soils, since these areas have been declining due to drainage, ploughing, etc. (de Vries *et al.*, 2009). However, the soil map does not directly provide information on the chemical or physical soil properties, which need to be derived from other sources. The Landelijke Steekproef Kartering (LSK) was a national sample survey of soil map units (Finke *et al.*, 2001), which quantified a limited number of soil chemical parameters in the laboratory, including soil organic matter content. In total about 1400 locations were sampled at five different depths during the period 1990-2000. The LSK was a stratified survey based on soil type and groundwater class. De Groot *et al.* (2005) used these data to quantify the soil carbon stocks for the Netherlands. Later Lesschen *et al.* (2012) used the same data but related the soil carbon stocks to soil type and land use (land use was included in the LSK survey), to make it useful for the assessment of soil carbon stock changes for the National GHG inventory for UNFCCC and Kyoto reporting for which a link with land use is needed.

Soil carbon stocks and contents were determined for the combination of land use (arable land, grassland and nature, which are shown in Figure 2) and the main soil types (11 classes). Soil organic carbon stocks are calculated by the following equation: SOC = SOM% * C_content * BulkDensity * 100 * SoilDepth. Lesschen *et al.* (2012) determined the carbon stocks for the upper 30 cm, which is the default soil depth for the IPCC guidelines. For this study we calculated in addition also soil carbon stocks and contents for the upper 20 and 25 cm for comparison with other sources. For the conversion of organic matter to organic carbon we used a factor of 0.5 (Kuikman *et al.*, 2003; Pribyl, 2010). Bulk density was not determined in the LSK survey and derived through pedo-transfer functions for sand, clay and peat soils (de Groot *et al.*, 2005).

Land use data are based on the land use maps that are used for the Dutch LULUCF (land use, land use change and forestry) GHG inventory, which are based on the topographical map, see Kramer *et al.* (2009). The data as presented in Lesschen *et al.* (2012) were based on the land use map of 2004, for this study we additionally used the land use map from 2012 (Figure 2).

Figure 2. Land use map of the Netherlands for 2012, based on Basiskaart natuur.

Soils of the Netherlands are also represented in other soil databases, such as the Harmonized World Soil Database (HWSD). The HWSD version 1.2 is a compilation of the following four source databases: the Soil Map of the World, various regional SOTER databases, the European Soil Database (ESDB) and the Soil Map of China (FAO *et al.*, 2012). Soil properties have been derived from analyzed profile data obtained from a wide range of countries and sources (such as those from version 2.0 of the WISE database, comprising 9607 profiles). This means that the properties of a specific soil type in the Netherlands as presented with the HWSD, can be influenced by the properties of that soil type outside the Netherlands. The HWSD with amendments (HWSDa) has been based on the HWSD version 1.1 and a number of improvements related to the parameters used to calculate soil organic carbon density (viz., organic carbon content, dry bulk density and volume of stones). If possible, the total amount of soil organic carbon (t ha^{-1}) is computed for two soil layers: 0-30 cm and 30-100 cm. The combination of the soil map of HWSD v1.2 and the soil carbon data from HWSDa was used to represent an alternative map of soil types and SOM contents/SOC stocks of the Netherlands which is compared with the results from the Dutch soil map in combination with the LSK data.

2.2.2 Results

Distribution of the major soil types in the Netherlands is illustrated in Figure 3. Most dominant soil types are “zeekleigrond”, “podzol grond”, “kalkloze zandgrond”, “veengrond” en “rivierklei grond” based on the Dutch soil map and Fluvisiols, Histosols and Podzols based on the data from HWSD. Mainly due to different definitions, soils from both sources do not match exactly but in general a large resemblance in both maps is clearly visible with fluvisols equal to “zeekleigrond”, Histosols equal to “veengrond” and “moerige grond” and Podzols equal to “podzol grond” and “kalkloze zandgrond”.

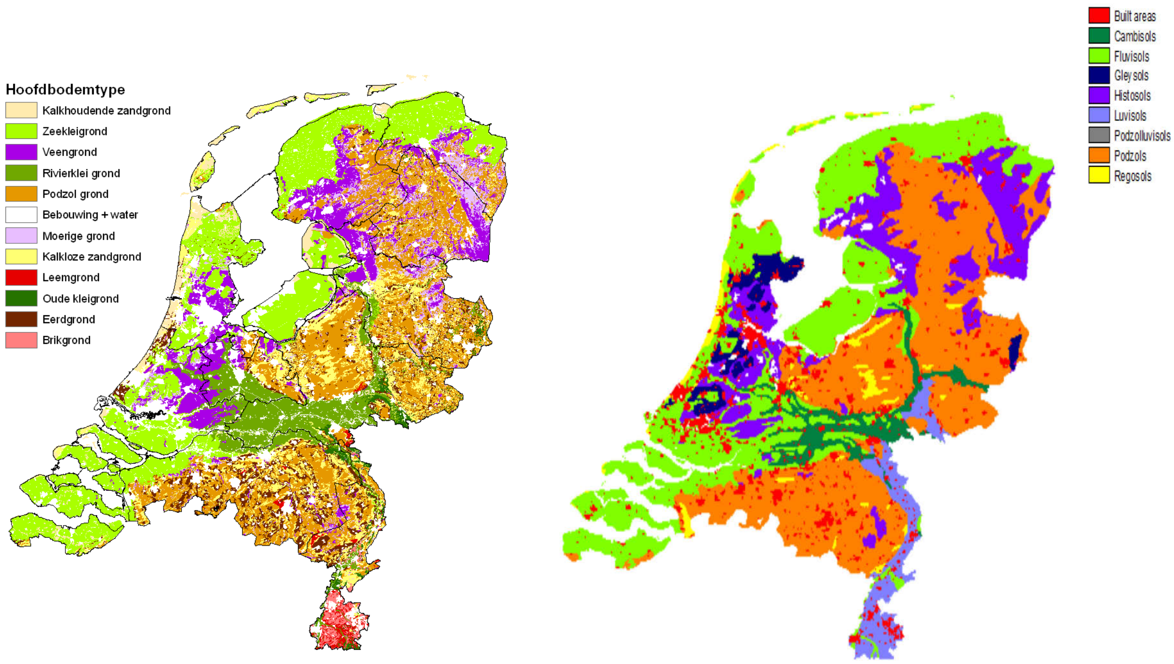

Figure 3. *Distribution of major soil types in the Netherlands according to two different sources (left: Dutch 1:50000 soil map, reclassified into 11 main soil types (Lesschen et al., 2012) ; right: Harmonized World Soil Database (HWSD) (FAO et al., 2012).*

Figure 4a illustrates the distribution of estimated soil organic matter contents in the upper 30 cm of the soil in the Netherlands according to Dutch databases and the amended HWSD (note: illustrated areas from the Dutch databases only refer to grassland, arable land and nature). Following the LSK data only a small part of this area in the Netherlands has soil organic matter contents lower than 3%, whereas the area from the HWSDa is clearly dominated by soils with <3% organic matter. Soil organic carbon stocks (0 -30 cm) are illustrated in Figure 4b. Again low stock values of <60 ton ha^{-1} are not widespread in the Dutch databases, but dominate in the HWSDa. In both maps soils with peat (Histosols, “veengrond” and “moerige grond”) are visible by the high values of >20% and >140 ton ha^{-1}. The underlying data of Figure 4b are presented in Table 2 for each soil type. Comparing these data clearly reveals that both lower and higher values of the HWSDa are not represented in the Dutch database (e.g. Histosols with >300 ton ha^{-1} and “veengrond” with <200 t ha^{-1} ; Fluvisols with circa 30 ton ha^{-1} and “zeekleigrond” with circa 100 ton ha^{-1}. Differences between soils in the HWSDa are larger, whereas those from the Dutch database are more similar. Agricultural management in the Netherlands may partly explain this. The high input of animal manure (typical for most Dutch mineral soils) has increased the soil organic carbon stocks compared to the same soils in areas outside the Netherlands with lower manure inputs. Because both the low and the high values are uncommon in the Dutch databases, compared to the HWSDa, the average carbon stock density of both data sources for the Netherlands is rather similar: 10.8 and 9.3 kg m^{-2}, respectively (Table 2).

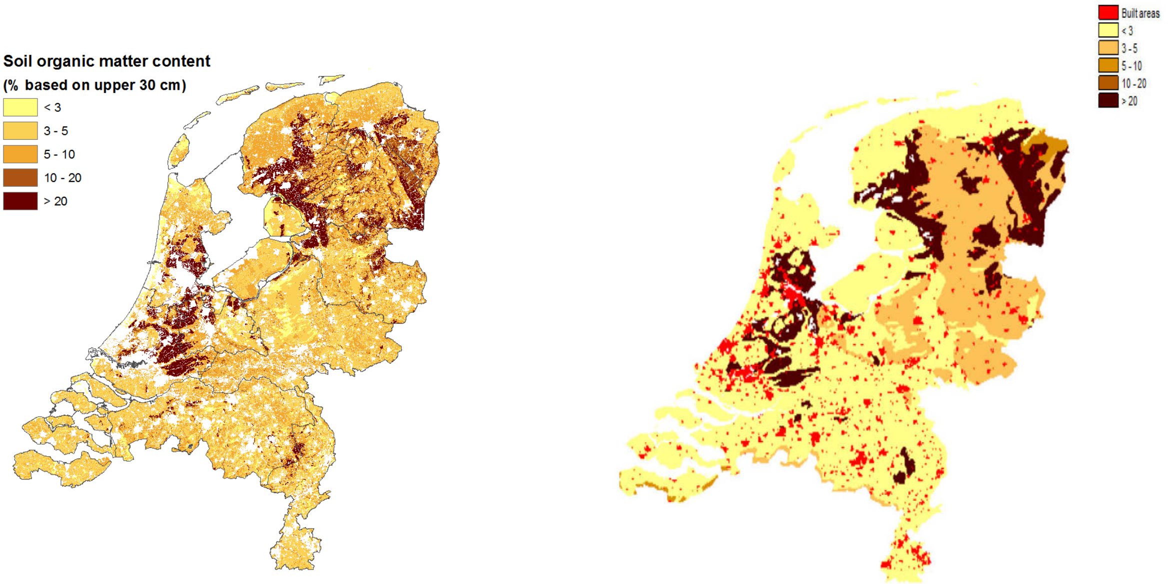

Figure 4a. Estimated soil organic matter content (%) in the upper 30 cm in the Netherlands according to two different sources (left: Dutch soil map, land use map and LSK data (Lesschen et al., 2012) ; right: amended Harmonized World Soil Database (HWSDa) from Hiederer & Köchy (2011).

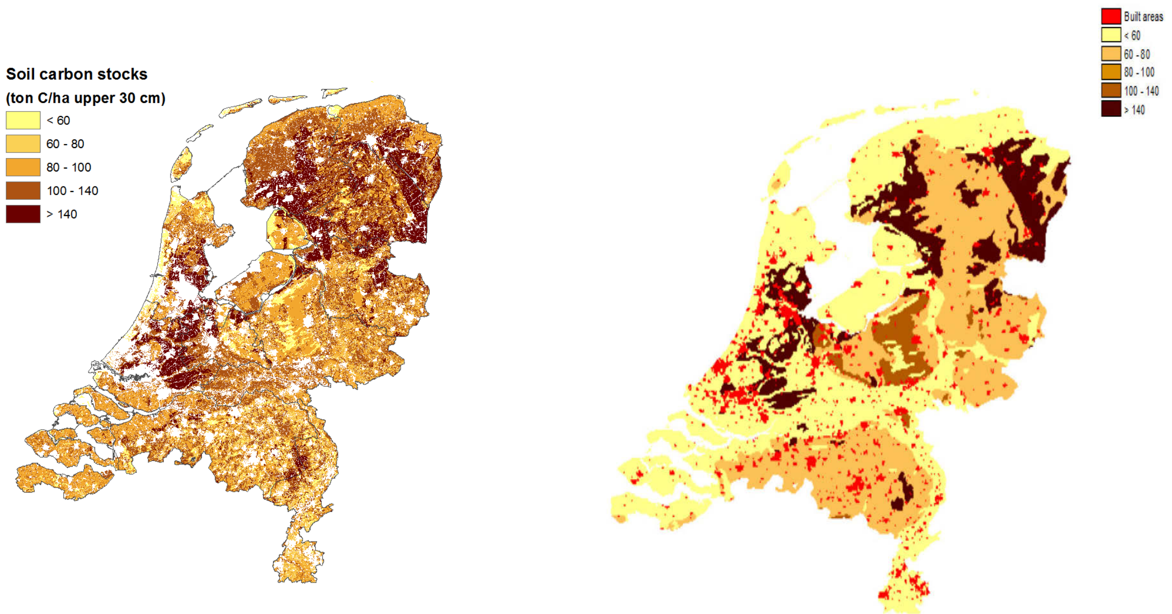

Figure 4b. Calculated soil organic carbon stocks (ton OC ha^{1}) in the upper 30 cm in the Netherlands according to two different sources (left: Dutch soil map, land use map and LSK data (Lesschen et al., 2012); right: Amended Harmonized World Soil Database (HWSDa) from Hiederer & Köchy (2011).

Table 2. Soil organic carbon content (ton C ha^{-1}) and total amount (Mton C) in the top 30 cm per soil type for the Netherlands. Based on Figure 4b and for the LSK data only for land use types grassland, arable land and nature according to Lesschen et al. (2012), in combination with the land use map of 2012.

Source		**LSK + Dutch soil map**		**Source**			**HWSDa**
Soil type	Area (km^2)	ton C/ha	Mton C	Soil type	Area (km^2)	ton C/ha	Mton C
Rivierklei grond	2131	106	23	Cambisols	1670	32	5
Zeekleigrond	6700	95	64	Fluvisols	10737	29	32
				Gleysols	1100	56	6
Veengrond	2903	191	55	Histosols	4923	327	161
Moerige grond	1683	155	26				
Leemgrond	224	93	2	Luvisols	1741	46	8
Brikgrond	221	77	2				
Oude kleigrond	324	79	3				
Podzol grond	6467	105	68	Podzols	13343	77	103
Eerdgrond	1539	82	13	Podzoluvisols	4	51	0
Kalkloze zandgrond	3241	75	24	Regosols	823	34	3
Kalkhoudende zandgrond	592	52	3				
The Netherlands	26026	108	282	The Netherlands	34341	93	318

Note: area of the Netherlands in the LSK column excludes wetlands, sands dunes and built-up (ca. 20% of total country area).

Dutch grasslands contain more soil organic matter compared to cropland and nature, both in total stock amount and stock density (Table 3). The higher stock density (ton C ha^{-1}) is mainly caused by a higher frequency of peat soils under grassland as will be shown below (Table 5 in section 2.2.3). The difference in stock density between cropland and nature is negligible which is remarkable. Due to frequent ploughing and removal of harvested biomass from croplands a lower soil organic carbon density would be expected compared to nature. Probably, the higher input of organic carbon with manure and compost compensates the higher decay (due to ploughing) and lower crop biomass input (due to harvesting). Based on the input flows at croplands, shown below in section 2.3.2, it is estimated that without these inputs the carbon density of croplands would be halved which results in a much clearer difference with the value for nature.

Soil organic matter contents per land use type vary among provinces of the Netherlands from 6% (Limburg) to 14% (Zuid-Holland) for grasslands, from 4% (Noord-Holland) to 10% (Drenthe) for croplands and from 5% (Gelderland and Zeeland) to 15% (Friesland) for nature (Figure 5).

Table 3. Soil organic carbon content (ton C ha^{-1}) and total amount (Mton C) in the top 30 cm per major land use type and for the Netherlands. Based on Figure 2 and Dutch soil, LSK and land use of 2012 data.

Land use	**Area (km^2)**	**ton C/ha**	**Mton C**
Grassland	12229	123	150
Cropland	9379	94	88
Nature	4417	98	43
The Netherlands	26026	108	282

Note: land use type grassland includes also grasslands not used for agriculture.

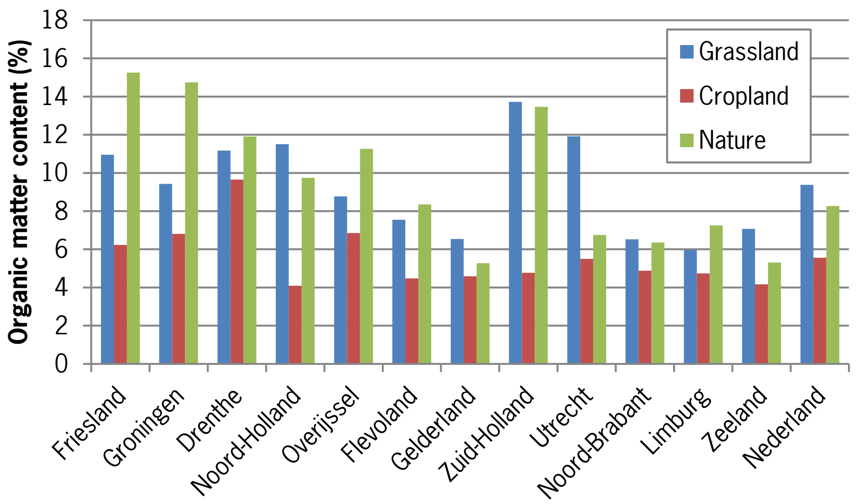

Figure 5. Soil organic matter content (%) per province and land use type based on Dutch soil, LSK and land use of 2012 data (0-30 cm).

2.2.3 Uncertainty

Various studies in the past and the results of this study have estimated the soil organic carbon stock and density of the Netherlands (Table 4). Because different studies have used different areas, the total Dutch stocks of these studies differ considerably. However, comparison of the organic carbon density shows that except for the lowest and highest value in Table 4 all remaining values are quite similar, (ranging from 93 to 109 ton C ha^{-1}; all (re)calculated for 0-30 cm). The large resemblance of the data from Dutch sources cannot be taken as proof of a high certainty but is probably the result of using the same data base, i.c. LSK data. The lowest value is reported by a relatively new European monitoring program LUCAS (Appendix I). The reason why this value is lower than values based on e.g. the LSK data is not clear. The highest value comes from the European Soil Portal of the joint research Centre (JRC). This value is not directly based on measurements but calculated with pedo-transfer functions and the area for which the stock accounts is not reported. However, it is clearly an extremely high value if compared to the others (this became already evident in Panagos *et al.*, 2013).

Table 4. Total amount of soil organic carbon and soil organic carbon density in the Netherlands, according to different sources, based on different areas.

Area (Mha)	Total stock (Mton C)	Density (ton C ha^{-1})	Source (soil layer: 0-30 cm)
2.6	223	84[1]	LUCAS (NL, Appendix I)
3.4	318	93	HWSDa (Table 1, this report)
2.8	264	94	Kuikman *et al.* (2003)
3.4	336	99	De Groot *et al.* (2005)
3.4	357	106	Lesschen *et al.* (2012)
2.6	282	108	Dutch soil and LSK data (Table 1, this report)
2.8	306[2]	109[2]	Results from STONE 2.4 (recalculated to 0-30 cm)
3.4(?)[3]	800	230(?)[3]	OCTOP from JRC (Jones *et al.*, 2005)

1 *See Appendix I for more background information on LUCAS.*

2 *Values of STONE were reported for 0-25 cm (276 and 98) but were recalculated assuming that 0-25 cm contains 90% of the stock of 0-30 cm.*

3 *The OCTOP map reports 800 Mt C for the Netherlands (Appendix II), but the area nor the density are mentioned explicitly. Here we have assumed an area of 3.4 Mha.*

Analysis of Variance (ANOVA) was used to identify significant differences in soil organic matter content between soil types and land uses based on the LSK data. Figure 6 and Table 5 show that only the 'moerige gronden' and 'veengronden' differ significantly from the other soil types and that 'rivierkleigrond' differs significantly from 'kalkhoudende zandgrond', whereas the other mineral soils are not significantly different in their soil organic matter content. Likewise most land use types are not significantly different per soil type. For the comparison of grassland with cropland, only at 'zeekleigrond' a significant difference exists and for the comparison of grassland with nature, significant differences exist at three soil types ('kalkloze zandgrond', 'rivierkleigrond' and 'veengrond'). This is in line with the conclusion from Schulp & Verburg (2009) that current land use only has limited value in explaining the variation of soil organic matter in the Dutch sand area.

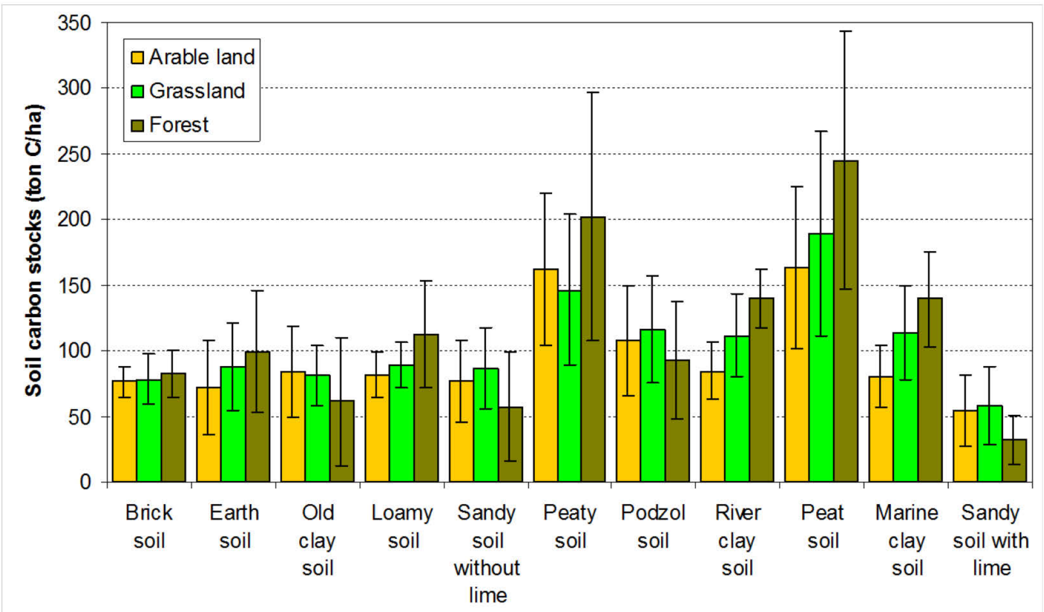

Figure 6. *Soil organic carbon stocks (ton C/ha) based on LSK data for 0-30 cm layer and based on original land use at time of soil sampling (source: Lesschen et al., 2012). Forest (see above) and nature (see e.g. Table 5) refer to almost identical areas.*

Table 5. *Average soil organic matter content (%) for the Netherlands based on LSK data and land use of 2012. The letters indicate whether there are significant differences, for the column "All land uses" it refers to differences between soil types, while for the other three columns with land use it refers to significant differences within a certain soil type for the land uses.*

Soil type	**All land uses**	**Grassland**	**Cropland**	**Nature**
Kalkhoudende zandgrond	2.4^{a}	2.8^{a}	2.3^{a}	2.2^{a}
Brikgrond	3.7^{ab}	3.7^{a}	3.7^{a}	4.0^{a}
Kalkloze zandgrond	3.7^{ab}	4.4^{b}	3.7^{b}	2.7^{a}
Oude kleigrond	4.0^{ab}	4.1^{a}	4.2^{a}	3.1^{a}
Eerdgrond	4.3^{ab}	4.3^{a}	4.2^{a}	4.9^{a}
Leemgrond	4.6^{ab}	4.3^{ab}	3.6^{a}	5.9^{b}
Zeekleigrond	5.4^{ab}	7.1^{b}	4.2^{a}	7.0^{b}
Podzol grond	5.6^{ab}	6.2^{a}	5.4^{a}	5.0^{a}
Rivierklei grond	6.7^{b}	7.1^{a}	4.4^{a}	11.7^{b}
Moerige grond	15.5^{c}	13.8^{a}	15.8^{a}	23.6^{a}
Veengrond	26.1^{d}	24.9^{a}	21.4^{a}	42.5^{b}

Soil organic carbon stocks are calculated by SOC = SOM% * C_content * BulkDensity * 100 * SoilDepth (effect of stones excluded). Except for soil depth each of the factors has an uncertainty that contributes to the overall uncertainty of SOC. In De Groot *et al.* (2005) the uncertainty of the carbon stocks based on LSK data was discussed. The lab analyses of organic matter content have a maximum standard error of 0.179% at an organic matter content of 5%. Above this value the standard error is 3.6% of the determined organic matter content. For the conversion of organic matter content to carbon stocks the bulk density is needed. This parameter is not measured in the LSK data, but derived via pedo-transfer functions for sand, clay and peat. The correlation coefficient for the measured and estimated values is respectively 72% and 77% for sand and clay soils, while it has not been determined for peat soils, and uncertainty for these soils is much higher. Besides there is uncertainty in the C content of organic matter. We have used a value of 50% as proposed by the review of Pribyl (2010), which agrees with measurements by BLGG, but the range is quite large (40-60%). In addition there is uncertainty related to the upscaling to the Netherlands through the Dutch soil map. Concluding, it is not feasible to estimate precisely the total uncertainty due to the many sources of uncertainty and lack of data herein. A full uncertainty analysis, based on MonteCarlo simulations and uncertainty distributions for the uncertain parameters, was beyond the scope of this study.

Another source of uncertainty relates to the area of peat(y) soils ('veengronden' en 'moerige gronden'). Due to degradation peat soils are converted into peaty soils with lower soil carbon levels in the 0-30 cm as a result. The total peat area in the Netherlands, after the 'veencheck' in 2001-2004, is estimated at 289000 ha (Table 6, sum of non-deformed and other peat soils). From this area about 223000 ha is under agricultural land. For this area GHG emissions are reported to the UNFCCC. The average CO_2 emissions from these peat soils under agriculture is estimated at 19 ton CO_2 ha^{-1} y^{-1}, according to the approach described in Kuikman *et al.* (2005). This is a carbon loss of about 5.2 ton C ha^{-1} y^{-1}, but ranges from 1.8 ton C ha^{-1} y^{-1} on the poorer drained soils to 11 ton C ha^{-1} y^{-1} on the well-drained peat soils. This CO_2 emission is calculated as a function of ground surface lowering (Figure 7), carbon content and bulk density.

Table 6. Overview of areas under peat and peaty soils in the Netherlands (de Vries et al., in press).

Main soil type	**Area (ha)**
Peaty soils (Moerige gronden, incl. some other soil types with a thin peat layer)	191 417
Deformed peat soils (according to veencheck 2001-2004)	46 640
Non-deformed peat soils (according to veencheck 2001-2004)	54 199
Other peat soils (mainly with thick peat layer)	234 803

De Vries *et al.* (2009) showed that also peaty soils ('moerige gronden'), defined as soils with a peat layer between 5 and 40 cm thick, are losing peat, especially on soils with deep groundwater and under arable land (e.g. in the Veenkoloniën). An analysis of recently sampled locations showed that in 50% of the sample sites on peaty soils under agriculture the peat layer has disappeared (see Figure 8). The average loss of the peat layer from these soils was estimated at 3.3 mm per year, which is about 2.6 ton C ha^{-1} y^{-1} (de Vries *et al.*, in press). The total annual loss of carbon from peat layer due to drainage and ploughing is estimated at 1160 kton C from peat soils (223000 ha under agriculture) and 385 kton C from the peaty soils (about 146000 ha under agriculture).

If 50% of peat soils are lost and changed into peaty soils and 50% of peaty soils are lost and changed into Podzols, total loss of soil organic carbon in the top soil would amount circa 9 Mt C, which equals 3% of the estimated total stock of 282 Mt (based on values of Table 2). This is a theoretical example to illustrate the possible significance for the total soil carbon stock, because the actual loss of peat(y) soils relative the situation as shown in Figure 2 and the carbon density of the deformed peat(y) soil types are not yet known. An update of the soil map which is foreseen in 2015, would give more information on the current distribution of soil types in the Netherlands.

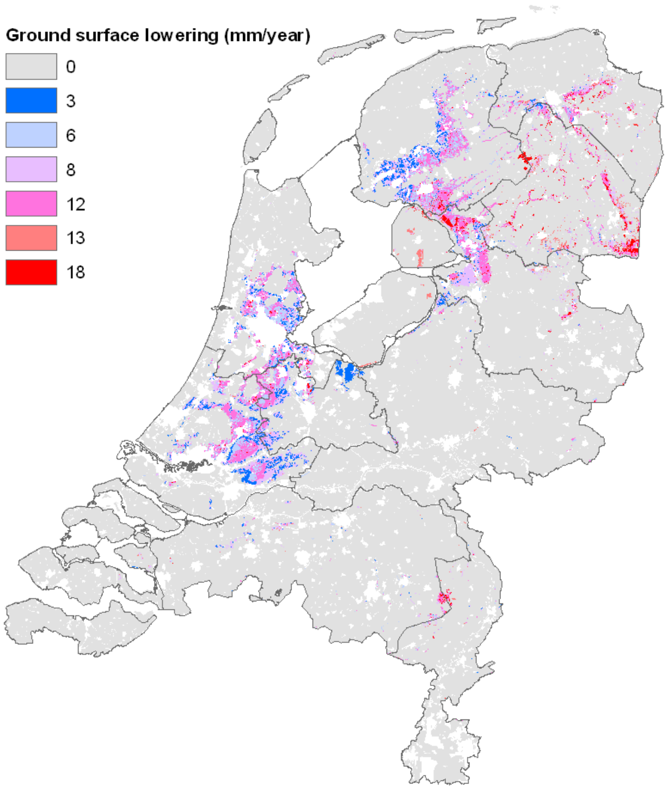

Figure 7. *Ground surface lowering under peat soils (based on Kuikman et al., 2005).*

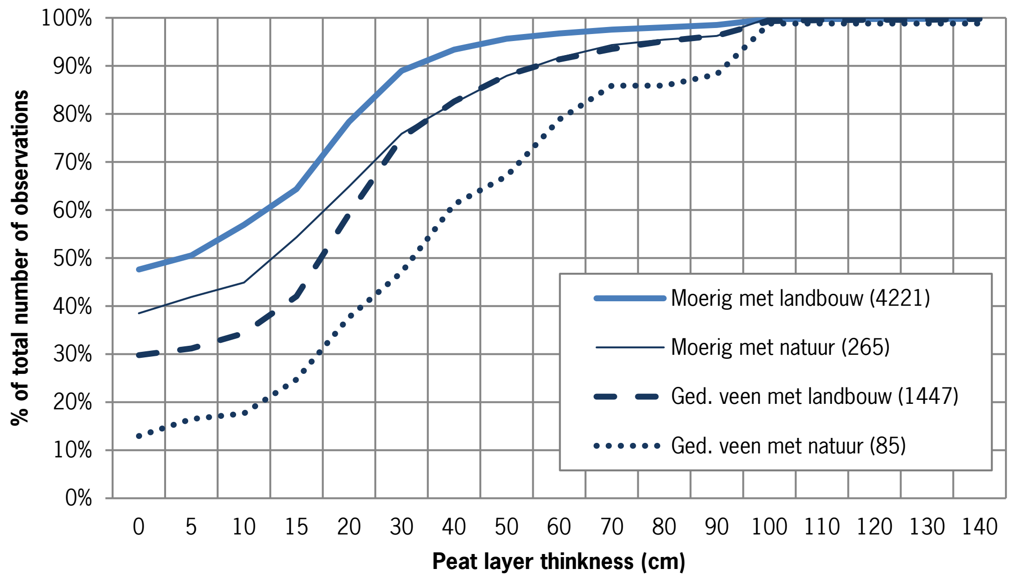

Figure 8. *Cumulative frequency of peat thickness per soil group in combination with land use (in between brackets the number of observations is indicated), (de Vries et al., in press).*

2.2.4 Conclusions

In Dutch soils the organic carbon density amounts circa 108 ton C ha-1 (based on LSK data, 0-30 cm) and the total stock is estimated at 360 Mton C (whole Dutch land area, based on Lesschen *et al.*, 2012) and 210 Mton C (only agricultural land). Most part of grassland, arable land and nature has a soil organic matter content of more than 3%. These values are based on LSK measurements of on average 20 years ago and a Dutch soil map with data from surveys of on average 30 years old. Due to loss of carbon from peat(y) areas under agricultural management and conversion of peat –> peaty –> mineral soils the values are probably overestimated but not much (likely less than 5%). Remaining uncertainty could not be assessed due to the many sources and types of uncertainty, which is especially large for peat(y) soils.

Most SOM contents of the major soil types and land uses do not statistically differ, which indicates that there is a large variation within these groups driven by other factors, e.g. soil management and groundwater level. Soil type and (current) land use alone can only partly explain spatial differences of SOM in the Netherlands. Especially, ground water levels seem better correlated with SOM levels for explaining variation in SOM contents in the Netherlands (De Groot *et al.*, 2005).

International databases present SOM values in the Netherlands with a much larger difference between low and high values (HWSDa) and the estimation of the total SOC stock of the Netherlands in 0-30 cm by the OCTOP data of JRC exceeds the LSK-based value by more than 2 times. A new EU monitoring program (LUCAS) has recently published some results for the Netherlands, but unexpectedly (and still unexplained) these are 20% lower than the values based on LSK data.

2.3 Carbon input flows

2.3.1 Sources

We have distinguished three main input flows of carbon to the soil: 1) crop and grass residues (incl. roots), 2) animal manure and 3) compost. When organic matter is applied to soils, decomposition by soil microbes starts and organic carbon is used for the growth of the microbes whereas another apart is emitted as CO_2 through respiration. After some time the more stable, less easily degradable part of the original applied organic matter remains and contributes to the existing soil organic matter. The part of the input that remains one year after addition is called "*effective soil organic matter"* (EOM) input and the "*humification coefficient*" (hc) is defined as the fraction that is still in the soil after one year. The other part (1-hc) is the fraction of the organic matter/carbon input that is lost during the first year.

For the calculation of carbon input flows in this study we used the environmental impact assessment model MITERRA-NL. This model calculates among others the manure and fertilizer distribution according to the current Dutch manure policy and soil carbon stock changes. MITERRA-NL is parameterised with recent emission factors and data sets of the Netherlands, which are also used for NEC and UNFCCC reporting. The main input data of the model are crop areas and livestock numbers, which were derived from the Geographical Information system Agrarian Businesses database (GIAB) and Basis Registratie Percelen (BRP) on 4 digit postal code level with a total number of about 4400 in the Netherlands. For this study data are based on animal numbers of 2009 (GIAB data at postal code level) and 2007 crop areas (BRP data at postal code level). The distribution of manure is described in Lesschen *et al.* (2011) and is based on the manure policy, application standards and derogation area of 2009.

Various manure types are applied in the Netherlands and their specific EOM and carbon contents are based on the C:N ratio and humification coefficient from BLGG manure sample measurements[1]. Effective organic carbon input from crop residues is based on the HLB organic carbon balance tool (Zwart *et al.*, 2013; see Appendix IV). For grass the amount of effective OM input is taken from Velthof (2004), which was also used in the 2012 evaluation of the manure policy. Carbon inputs with compost applications have been estimated for the year 2005, based on Milieu Ltd *et al.* (2009), however, based on other Dutch data that we found later this might be an overestimation.

[1] http://www.nutrinorm.nl/nl-nl/Paginas/De-samenstelling-van-organische-meststoffen.aspx

2.3.2 Results

Crop residues

Crop residues consist of all organic material produced by crops or grass that remains in the field and is added to the soil. Amount of crop residues depends on total biomass production and the fraction harvested and differs among crops. Moreover, different residues have different humification coefficients (based on their degradability) and therefore each crop/grass is characterised by a specific amount of EOM input. Although a relation may exist with the yield (e.g. higher yield may be caused by a higher production which also results in more residues) and crop varieties may differ (e.g. by their harvest index which affects the amount of residues), one value was used in this study for each crop and for grass in the Netherlands (see Appendix IV). In case of cereals and rapeseed a crop specific straw removal fraction is assumed.

Manure

From the manure produced, part is excreted in the field during grazing and part is collected in manure storages. Due to the manure excess in the Netherlands part of the stored manure is exported or treated and not used within the Dutch agriculture (especially poultry manure, which is incinerated in the Moerdijk energy installation). About 374 kton C in manure is not used in agriculture (about 16% of total manure produced), this amount is mainly poultry manure (65%; Figure 9). Given the more strict manure policies and the requirement to treat surplus manure from 2014 onwards, the amount of manure (and thus carbon) that is not applied to Dutch agricultural soils will probably increase.

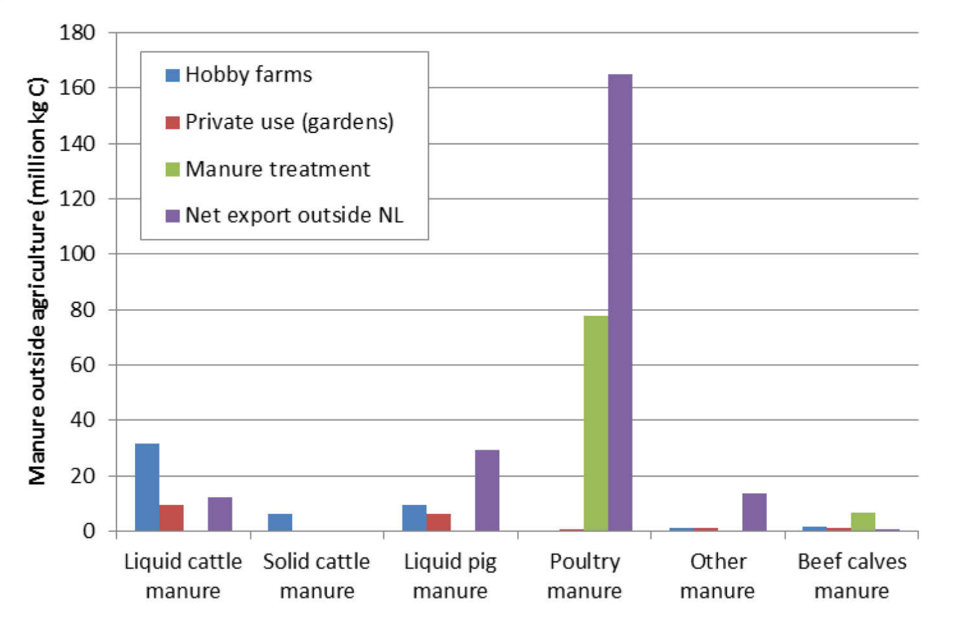

Figure 9. Amount of manure C used outside Dutch agriculture (based on data from CBS/NEMA for 2009).

Compost

Total compost use in Dutch agriculture was estimated at about 900 kton, however, based on more recent data from the BVOR[2], this value might be overestimated and should be around 700 kton, but this lower value was not yet included in the calculations. We assumed that half is green compost and half is biowaste (GFT) compost. The average EOM content was set at 185 kg EOM/kg compost for each compost type.

2 http://www.bvor.nl/

Total EOM input

Average EOM inputs in grassland and arable land of the Netherlands amount circa 3.6 ton ha^{-1} and 2.1 ton ha^{-1}, respectively (Table 7a). EOM inputs expressed as percentage of the soil organic carbon stock in the top soil (0-30 cm and assuming a C:OM ratio of 0.5) range for grassland between 1.2% and 1.8% (average value: 1.5%) and for arable land between 0.7% and 1.3% (average value: 1.1%).

For grassland and arable land the differences in per ha EOM input are relatively small among the provinces in the Netherlands (Figure 10). For both land use types EOM input with plant residues is approximately equal to EOM input with manure and compost. This illustrates the large influence of manure inputs which are partly produced from feed imports from outside the Netherlands. Part of current soil organic carbon stocks in the Netherlands thus originate from crop biomass produced in other countries. Compost input is negligible in Groningen, Friesland, Drenthe and Overijssel and has only a very modest contribution in the other provinces.

Table 7a. Total annual EOM input, SOC stock in 0-30 cm and input of EOC, expressed as percentage of SOC stock per province and agricultural land use in the Netherlands. Agricultural land use of EOM input data is based on 2007 crop areas from BRP at postal code level), data of SOC_30 are based on the LSK data and the land use map.

	input EOM (ton $ha^{-1}y^{-1}$)		SOC_30 (ton ha^{-1})		Input EOC_30 (% y^{-1})	
Province	**Grassland**	**Cropland**	**Grassland**	**Cropland**	**Grassland**	**Cropland**
Groningen	3.40	2.00	125	106	1.4%	0.9%
Friesland	3.76	2.31	133	100	1.4%	1.2%
Drenthe	3.44	1.98	136	132	1.3%	0.7%
Overijssel	3.67	2.27	120	109	1.5%	1.0%
Flevoland	3.38	1.91	110	81	1.5%	1.2%
Gelderland	3.65	2.30	105	87	1.7%	1.3%
Utrecht	3.78	2.45	136	92	1.4%	1.3%
Noord-Holland	3.47	2.02	134	77	1.3%	1.3%
Zuid-Holland	3.56	2.11	147	84	1.2%	1.3%
Zeeland	3.11	1.90	108	80	1.4%	1.2%
Noord-Brabant	3.47	2.10	107	90	1.6%	1.2%
Limburg	3.54	2.24	99	88	1.8%	1.3%
Nederland	3.60	2.09	123	94	1.5%	1.1%

Table 7b. Total EOM inputs and SOC stocks of agricultural area in the Netherlands according to MITERRA-NL.

Inputs	**Mton EOM y^{-1}**	**Land use**	**Million ha**	**Mton SOC (0–30 cm)**
Grazing manure	0.65	Grassland	0.99	122[1]
Applied manure	1.82	Cropland	0.91	85
Grass residues	1.95			
Crop residues	0.96			
Compost	0.17			
Total	5.55	Total	1.90	207
		Ratio input/stock[2]		1.3%

1 SOC stock values are slightly lower than in Table 3 due to lower estimates of agricultural land use (e.g. data refer only to agricultural grassland, whereas the land use map refers to all grassland).

2 EOC input calculated by taking 50% of EOM.

Annual total input of effective organic matter in Dutch agriculture is estimated by MITERRA-NL at 5.55 Mton EOM with highest contributions from Friesland, Overijssel, Gelderland and Noord-Brabant (together >50%; Figure 11). This input equals approximately 1.3% of total stock in the top soil of agricultural land in the Netherlands (Table 7b). Annual input per ha agricultural land is circa 2900 kg, which compares well with a study for EMW 2012 (Schils *et al.*, 2012; see Figure 12 below) that gives approximately 2700 kg ha^{-1} y^{-1} at the end of the period. This consistency is largely due to using the same data sources.

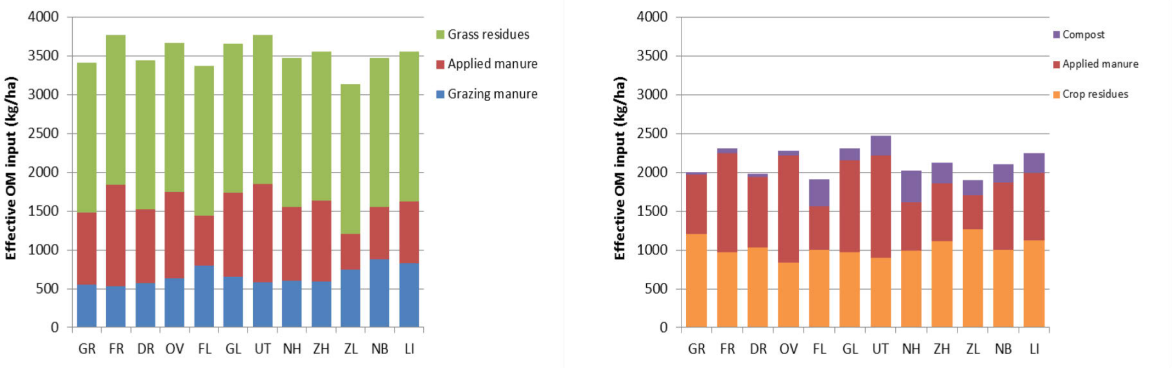

Figure 10. *Input of effective organic matter per ha agricultural land of the provinces in the Netherlands (left: grassland, right: arable land).*

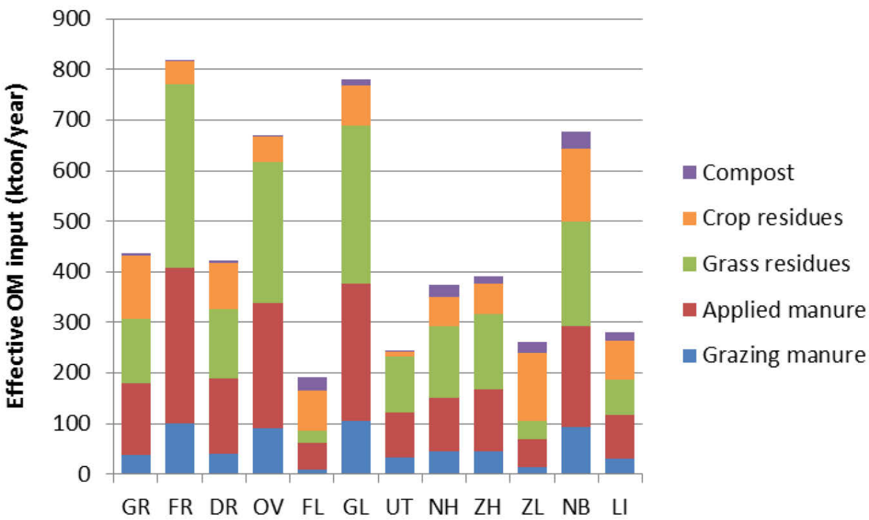

Figure 11. *Total input of effective organic matter per province.*

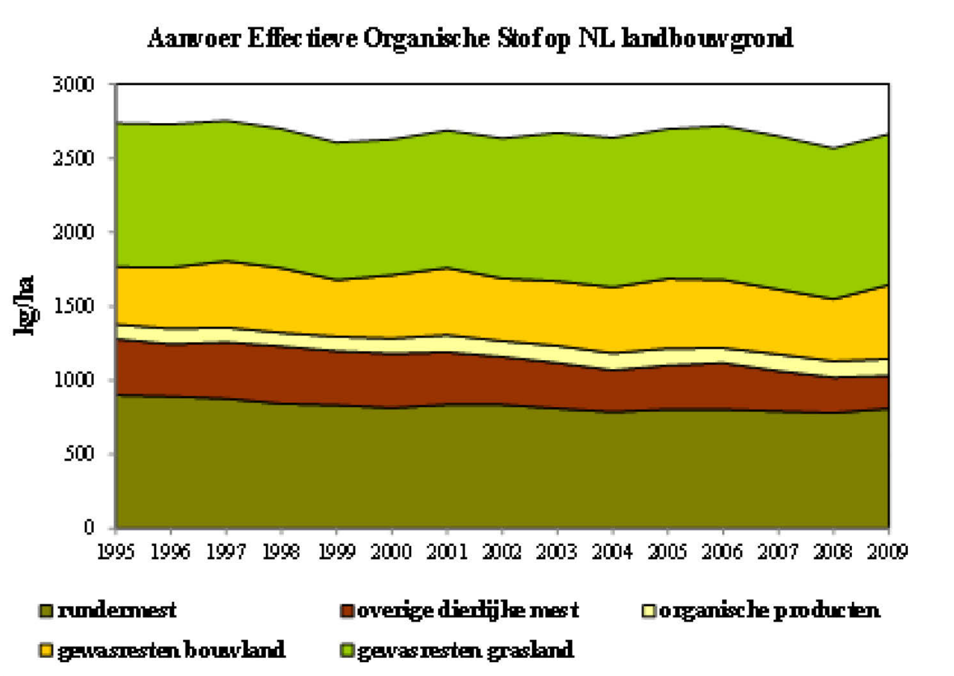

Figure 12. Input of EOM per ha agricultural land in the Netherlands (Schils et al., 2012).

2.3.3 Uncertainty

With the model STONE 2.4 (Groenendijk *et al.*, 2013), calculations have been performed specifically for this study (February 2014). STONE is a Dutch emission model linking spatial databases of soils, climate and management with crop and soil process calculations to assess N and P emissions towards surface and groundwater and includes a SOM module for calculating SOM dynamics in the Netherlands (Appendix V). Results in Table 8 show that the acreage of agricultural grassland and arable land in the Netherlands is almost the same as compared to the output of the model MITERRA-NL (Table 7b) and that the total SOC stock is comparable (although as a result of a slightly higher SOC stock in grassland compensated by a lower SOC stock in arable land). However, a very large difference exist in the estimated amount of grass residues which is >2 times higher as calculated by STONE 2.4. Background of this higher estimate is the crop model QUADMOD (Ten Berge *et al.*, 2000), which calculates grass residues based on (inter)national literature of total biomass production and grass yields. We decided to use a grass residue value of circa 3600 kg EOM ha^{-1} y^{-1} for grassland instead of 1950 kg from Table 7b. This “new” value was used further in the analysis of this study which is described below in section 3 and is also mentioned by Schils (2012) for 3-year old grassland. Due to this adjustment the average total EOM input at grassland increases from 3.60 to 5.25 ton ha^{-1} y^{-1} (see section 3.2.1), which equals circa 2.1% of the SOM stock in the upper 30 cm of grassland soils (instead of 1.5% from Table 7a).

Table 8. Total EOM inputs and SOC stocks of agricultural area in the Netherlands based on results with STONE 2.4

Inputs[1]	Mton EOM y^{-1}	Land use	Million ha	Mton SOC (0–25 cm)	Mton SOC[4] (0–30 cm)
Grazing manure	-	Grassland	0.98	120	133
Applied manure	1.91[2]	Cropland	0.97	71	79
Grass residues	4.43				
Crop residues	0.72				
Compost	-				
Total	7.06	Total	1.95	191	212
		Ratio input/stock[3]		1.9%	1.7%

1 *EOM inputs based on calculations of STONE 2.4 and the following humification coefficients: 0.3 for grass residues, 0.25 for crop residues, 0.4 for manure applied at arable land and 0.5 for manure applied at grassland.*
2 *Including grazing manure.*
3 *EOC input calculated by taking 50% of EOM.*
4 *Values of STONE were reported for 0-25 cm and were recalculated for 0-30 cm by assuming that 0-25 cm contains 90% of the stock of 0-30 cm.*

Another source of uncertainty concerns the estimation of the humification coefficients for every organic matter input. Below is an overview of different values found in literature with in general consensus according to different sources except for belowground residues, various slurry types, GFT compost and champost where differences between low and high values amount 0.1 or more. To illustrate the effect: a difference of 0.3 to 0.4 (e.g. "varkensdrijfmest") means a 33% higher or 25% lower EOM input. The many identical values (especially for crop/grass residues) seems to point at the situation that most of the sources originate from the same background values found in "older" literature, such as Kolenbrander (1969). It was outside the scope of this study to analyse the literature and trace the current values back to the original data/publications. However, we did not find many recent experiments aiming at establishing "new" values for the decay of fresh inputs in Dutch soils. Whether the conditions for decay in the soil have changed relative to some 30-40 years ago or whether the degradability of the current crop and grass varieties is different from those used before in the Netherlands is unknown (to our knowledge). Therefore it is not possible to assess the actual uncertainty of these humification coefficients. The methodology of estimating humification coefficients is also a source of uncertainty, where different periods have been used ranging from less than one year (and extrapolating to one year) to more than one year (and taking the average loss) to assess the humification coefficient. Some effort to find the causes of the differences and similarities of the values in Table 9 seems justified to get a better insight in the validity of these values for current situations.

Table 9. Overview of humification coefficients in different sources (1-6).

Source Type	1	2	3	4	5	6
Crop residues (aboveground); green biomass		0.20				0.20
Sugarbeet (leaves+top)	0.22				0.22	0.20
Cabbage	0.25				0.25	
Grass (leaves?)	0.25				0.26	
Green manure, incl. roots	0.30	0.30			0.30	0.25
Cereals (straw?)	0.31	0.35			0.31	0.35
Belowground crop residues	0.35	0.40			0.30	0.35
Slurry	0.40					
Bovine slurry			0.70	0.45	0.40	
Pig slurry			0.33	0.30	0.40	
Poultry slurry			0.33	0.44	0.40	
Manure (stable?)	0.50		0.60		0.50	0.50
Leaf residues		0.55				
Kitchen compost (Gft)	0.86	0.75	0.75	0.85	0.86	
Champost	0.91		0.50	0.80	0.91	
Green compost	0.96				0.95	

1 = Hendriks, 2011; 2 = Janssen, 2002; 3 = van Dijk et al., 2005; 4 = Velthof, 2004; 5 = INAGRO, 2011; 6 = Kolenbrander, 1969.

2.3.4 Conclusions

We have distinguished three main sources of organic carbon input to soils: 1) grass and crop residues, 2) animal manure and 3) compost. A large part of the original carbon input is lost by respiration within one year. The fraction OM remaining after one year is called the humification coefficient (hc) and ranges roughly from 0.2-0.4 for plant residues, 0.33-0.7 for animal manure types and 0.75-0.95 for compost. Many of these hc values seem to originate from the same publication(s) of about 40 years ago and due to uncertainty in the validity of these values for current situations, a more thorough investigation, including a comparison with data from other countries, and an update of the values is needed.

The effective organic matter (EOM) input is defined as the amount remaining one year after application to the soil and is assumed to contribute to the maintenance of the SOM. In the Netherlands grass and crop residues contribute 52-63%, animal manure 34-45% and compost 2-3% to the total EOM input. These values illustrate that residues and manure have a comparable effective input to agricultural soils in the Netherlands and that the input of compost is negligible at the national level (for specific fields however, e.g. bulb cultivation at dry sandy soils, the input from compost can be very substantial). The difference between the lower and higher estimates is primarily due to differences in the estimation of the amount of effective grass residues. MITERRA has estimated this value at 1.95 Mt y^{-1}, based on Velthof (2004), whereas other sources (Quadmod) use a value which is two times higher. This gives a very large difference in the EOM input per ha grassland (from 3.6 to 5.2 ton ha^{-1} y^{-1}) and should be analysed in more detail to find the right value.

Roughly 84% of total produced manure is applied to agricultural soils, because the remaining part is exported or incinerated in the Moerdijk energy plant (mostly poultry manure). Cereal straw is assumed to be harvested for a large extent, but part of this removed fraction may be applied to the soil via manure (consisting of animal excretion and bedding material). It is unclear whether this contribution is taken into account with the estimates of EOM content of manures and thus in the calculations.

2.4 Carbon output flows

2.4.1 Sources

In this section the main losses of SOM in the Netherlands are described. The substantial loss of organic carbon during the first year after application of organic matter to the soil of 5-80% (i.e. the difference between the original and the effective OM inputs) has already been dealt with in section 2.3 and will not be part of this section. The (other) main output flows are (1) respiration of existing SOM, (2) SOM leaching and (3) SOM loss with erosion. We did not find (national) data on OM loss by soil erosion and we assume that this loss is negligible in the Netherlands. Leaching of SOM occurs when dissolved OM is transported with water and leaves the top layer of the soil. We only found one source (results from calculations with STONE) with on average 7 and 18% SOM leaching relative to total fresh additions of OM, respectively for grassland and arable systems. No other data sources were checked for these values. However, if SOM under the soil depth of 30 cm is (slowly) decomposing and the amount of SOM below 30 cm remains constant, than inputs in the layer below 30 cm must occur. The amount of SOM beneath 30 cm can be significant (Table 1), but a large uncertainty exist in the relative respiration rate of this SOM. Due to lack of data we simply assumed in the analysis of this report that next to erosion also leaching is negligible, which probably is an underestimation.

Various sources have been used for a comparison of estimated relative loss rates of SOM by respiration. Some of these are more directly linked to experimental data (such as Kortleven, BLGG, HLB), whereas others are based on (dynamic) model calculations (RothC-26.3) with overall a wide variety of methodology, soil type, initial SOM level and soil layer. RothC-26.3 has been used in the climate yardstick of CLM (results described in this section) and also in MITERRA (results of SOM balance described in section 3). Most data sets refer to arable soils. Loss of SOM from peat(y) soils are not described here but some information can be found in section 2.2.3.

2.4.2 Results

Relative loss rate

Based on earlier work of Janssen, Yang developed an equation to describe the decomposition of organic materials including existing SOM (Yang, 1996; Yang and Janssen, 1997; Yang and Janssen, 2000; see also Pronk, 2007). In Janssen (2002) this equation is calibrated for SOM of a non-cultivated loam soil (parameters: R= 0.046; S = 0.315) based on data of Kortleven (1963). Figure 13 illustrates the development during the first 22 years of this soil. Parameter S allows for a decreasing relative loss rate as time proceeds, which is explained by the decomposition of easily degradable components during the early years which increases the share of more resistant components in later years. First year decay equals 4.5% according to this Yang equation whereas average decay of the first 22 years corresponds to a relative decomposition rate of 1.7% per year (Figure 13). This value is within the range given by Kortleven of 1.5% (sand) to 3.9% (clay) for different soils in the Netherlands with an average of 2.0% (Kolenbrander, 1969). The value is also close to the average value for sandy soils (1.8%) from an analysis of BLGG (Figure 14). The range of average values from BLGG of 1.8% (sand) to 3.2% (clay) matches well with the values of Kortleven, but the underlying methodology differs widely. Kortleven estimated an average value for the decomposition during the first circa 20 years by regression of a time series of SOM data. In the simple exponential decay function which was used by Kortleven for SOM, the relative rate is constant over years contrary to the methods of Janssen and Yang. The BLGG decomposition rates are based on a study of Hanegraaf *et al.* (in prep), where they used respiration experiments for 300 different soil and crop/land use combinations which started in spring and lasted for (only) three months. The measured amount of CO_2 was converted to a decomposition rate over one year. Corrections were made for the amount of fresh organic matter and temperature differences (not for sub-optimal moisture conditions in the field compared to the experimental conditions in the lab). The final equation for decomposition takes account of the organic carbon content, C:N ratio, pH and PMN (Potential mineralisable nitrogen). The final values for the decomposition factor are in principle valid for the sampled layer, which is 0-25 cm for arable land and only 0-10 cm for grassland. However, the experiments for Hanegraaf *et al.* (in prep) were based on the 0-20 cm layer for grassland soils and 0–30 cm for arable soils.

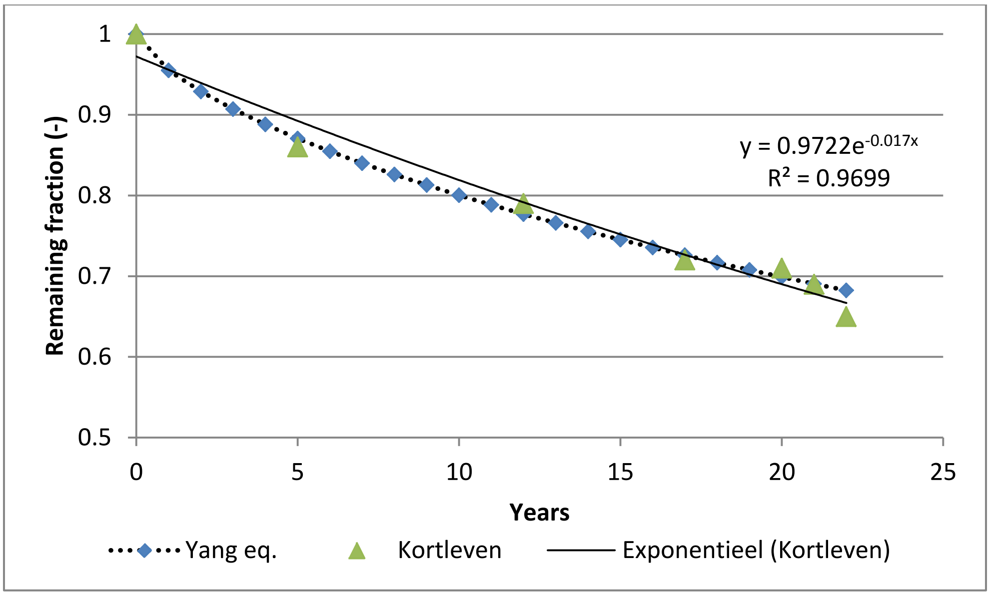

Figure 13. Remaining SOM fraction per year of an uncropped loam soil: data from Kortleven (green triangles), fitted with Yang equation (blue diamonds) and fitted by a simple exponential decay function (line with equation).

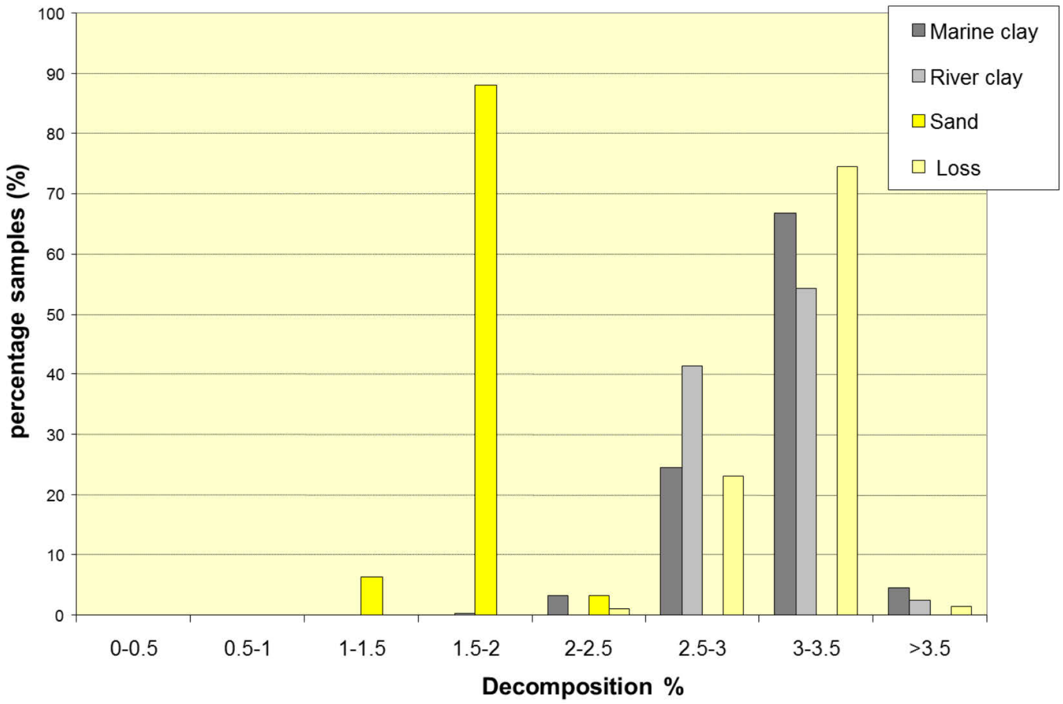

Figure 14. Distribution of decomposition factors, based on BLGG analysed soil samples, according to methodology of Hanegraaf et al. (in prep). Average decomposition factors are 1.8% for sand, 3.2% for marine clay, 3.1% for river clay and 3.1% for loss soils.

Recently, a calculation tool has been developed (Zwart *et al.*, 2013b) to calculate the SOM balance of crop rotations in the Netherlands. The calculation of the SOM loss through respiration in this tool is based on data from a long-term pot experiment of Wadman and de Haan (1997) and the derived decomposition factor only depends on the initial organic matter content (Figure 15: HLB OS balance). According to this calculation tool the relative loss rate may vary between 0.035 (at 1% initial SOM) and 0.009 (at 10% initial SOM). Obviously, when the SOM level is high due to high EOM inputs this negative correlation will not be appropriate. Apparently, this was not the case in the original experiment and high (initial) SOM levels correlated well with low SOM loss rates, i.e. conditions or factors that have a negative effect on decomposition rate. It is unclear from which soil layer the SOM was taken and although some grassland soils were used the majority of the soils refer to crop land. In the HLB OS tool the relative loss rate of SOM is applied on the amount of SOM in 0-30 cm to calculate the total SOM loss which is compared with the total EOM input. If both are equal it is assumed that the amount of SOM remains unchanged.

Other tools use more detailed models like the RothC-26.3 model, e.g. CLM developed a carbon module for their climate yardstick (www.klimaatlat.nl) based on the RothC model. However, it is not possible to obtain directly the decomposition factor from this model, as it depends on the amount of C input, which determines the division of carbon over the different compartments. Nevertheless, we indirectly obtained some estimates of the decomposition factor, by running the RothC version from the Climate yardstick for two soil types and different OM contents, with zero C inputs. Figure 15 shows some derived decomposition factors for soils with various OM contents based on the two before mentioned tools.

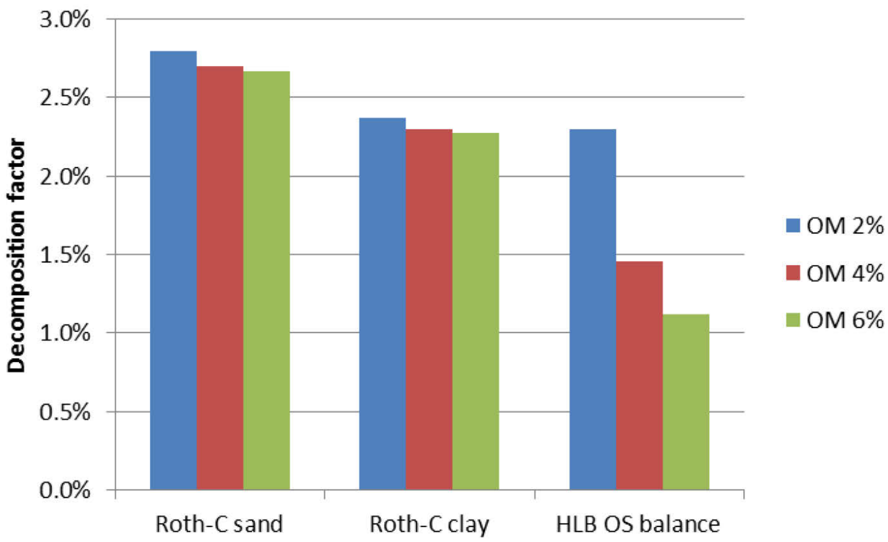

Figure 15. *Relative decomposition rate (y^{-1}) under various OM content for two different models, data are based on 0-30 cm layer. For HLB OS balance we assumed a bulk density of 1.4, 1.35 and 1.3 kg/dm3 respectively for the 2%, 4% and 6% OM soils.*

RothC clearly result in higher decomposition values for sand and lower for clay compared to the estimates from BLGG. Furthermore, the HLB OS tool shows a distinct difference as function of initial SOM level which is not the case with RothC. The values of HLB for SOM levels >2% are significantly lower than those of BLGG and RothC as used in the climate yardstick. It must be noted that although the same model is used in the climate yardstick (results in Figure 15) and in MITERRA (results in section 3), the results on decomposition will be different due to different inputs to run the model. RothC in MITERRA appears to have significantly lower relative loss rates compared to RothC in Figure 15, probably because in MITERRA RothC is run with realistic C inputs, which results in a different distribution of the initial SOM over a number of pools (see Appendix V) and consequently a different overall loss rate compared to the run without C inputs from the climate yardstick.

In Schils (2012) a range of relative loss rates is reported from 0.5% (sandy soils with >2% SOM) to 10% (dune sand; see also Table 4 in Pronk, 2007). Different values are given depending on soil texture, age, organic matter content and pH.

SOM loss rate

With relative loss rates and the amount of SOM in the top layer (0-25 cm), SOM loss/decomposition rates have been calculated for arable land and grassland per province (peat(y) soils excluded; Figure 16 & 17). In these Figures HLB_OM is compared with a simple 2% decay (the average value of Kortleven) and with an adjusted SOM loss equation (Adj_OM). In the original HLB tool an average temperature of 8° C was used for the estimation of the decomposition rate. This is too low for the Netherlands, where a current average temperature of 10° C would be more appropriate (see Appendix VI). We also replaced the average long term decomposition estimated with HLB_OM by the loss of C during the first year which e.g. should be compensated with fresh inputs to achieve equilibrium. This was done by developing "new" equations based on the same data set of Wadman and de Haan (1997). Both corrections lead to higher decomposition rates in the adjusted calculation (on average +39%; see results of HLB_OM and Adj_OM in Figures 16 & 17).

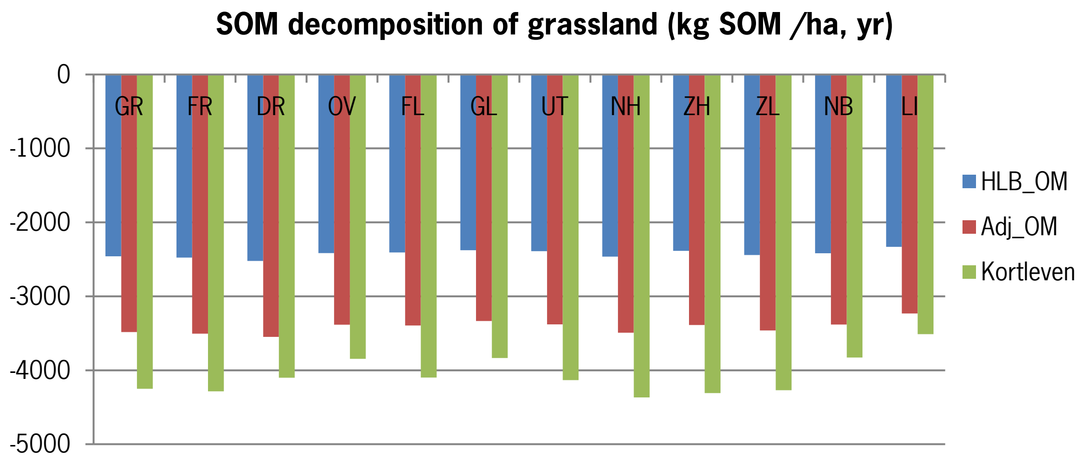

Figure 16. Decomposition of existing soil organic matter (kg ha^{-1} yr^{-1}; 0-25 cm) in grassland per province according to three calculations methods (for Kortleven simply one relative decomposition rate of 2% was used). Peat(y) soils were excluded.

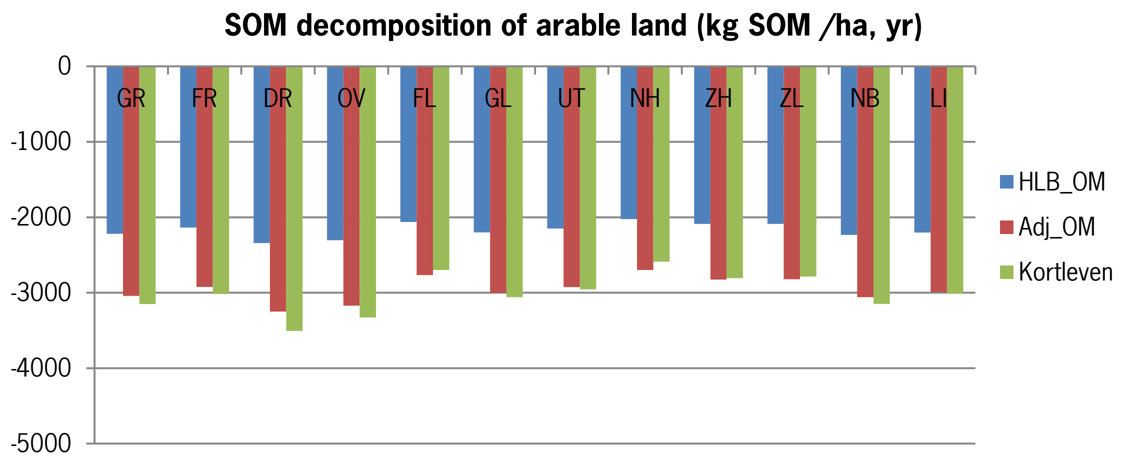

Figure 17. Decomposition of existing soil organic matter (kg ha^{-1} y^{-1}; 0-25 cm) in arable land per province according to three calculations methods (for Kortleven simply one relative decomposition rate of 2% was used). Peat(y) soils were excluded.

For arable land the results of Adj_OM are almost identical to the 2% loss of Kortleven (area-weighted relative difference = -1%). The results of the HLB tool are clearly lower (-36% relative to 2% loss). For grassland soils the 2% loss rate results in the highest SOM loss with on overall averaged -15% for Adj_OM and -40% for HLB_OM relative to 2% loss. Contrary to arable land, 2% loss and Adj_OM differ which may be related to the higher SOM percentage in grassland soils that leads to lower relative loss rates in Adj_OM as was found in Wadman & de Haan (1997).

2.4.3 Uncertainty

A considerable uncertainty exists in the estimation of the relative SOM loss. Firstly, the time period over which the loss is determined differs. Both the analysis based on Kortleven and the HLB tool use long-term average values, whereas the calculation of Adj_OM and RothC refer to the loss of the first year and the methodology of BLGG extrapolates data from a three-month experiment to a whole year. In balancing the SOM loss with EOM input the first year loss of SOM should be taken because in practice organic matter is applied each year. The Yang equation calibrated for the loam soil (Figure 13) clearly illustrates the difference between first year loss of 4.5% and the 20-year average loss of 1.7%. In Janssen (2002), another model calibrated with the same data, resulted in a first year loss of 3.3%. Secondly, data are derived in various ways ranging from CO_2 measurement in a lab to SOM measurements of samples taken from fields left uncropped for many years. It is difficult to assess the uncertainty related to these different types of measurements. If the soil is disturbed, e.g. in a lab experiment, this may affect the results. Thirdly, different factors are used to distinguish different conditions, like BLGG with distinct values per soil type (e.g. 1.8% versus 3.2% for sand and clay, respectively) and RothC that also adjusts for soil texture but with a much lower effect (sand with 2.3% versus clay with 2.6%). Wadman and de Haan (1977) found a significant correlation between initial SOM and average SOM loss (which is used in the HLB tool), but data from Kortleven did not support this and instead Kolenbrander (1969) reports that the results of Kortleven correlates negatively with C:N ratio. The large uncertainly in the assessment of SOM development was also illustrated by a comparison of different models for SOM dynamics with a >6–fold difference between minimum and maximum accumulation after equilibrium was reached (de Willigen *et al.*, 2008). This large difference was due to the different process equations of the models, because the same soil temperature, texture, moisture condition and pH was used and the same types of crop residue input (green leaf and straw). Fourthly, SOM is not well defined. A practical definition refers to all organic material in the soil with an age >1 year (which links with the calculation of effective organic matter; see 2.3.1), but in taking a soil sample, part of the organic material may be younger which cannot always be easily determined. “Contamination” of SOM with this younger material of e.g. plant residues can significantly affect the overall decay rate, and thereby the estimation of the relative decay rate of SOM due to the much higher decay of young organic material. In some methodologies the final relative loss rate is corrected for this effect (e.g. BLGG).

An additional uncertainty in calculating the SOM balance is the soil layer for which the relative loss rate is applied. For arable land mostly 0-25 cm is used (related to the average ploughing depth) but the HLB tool uses 0-30 cm and the original RothC model is based on 0-23 cm. In grassland standard measurement depth of SOM is only 10 cm, which makes it more difficult to estimate in practice the total SOM loss that should be compensated by fresh inputs. Moreover, as most data originate from arable soils, results of the application of these estimated relative loss rates for calculation of grassland SOM dynamics may be more uncertain compared to arable soils.

2.4.4 Conclusions

Reported variability of relative SOM loss rates by decomposition is high due to various conditions of e.g. soil texture, initial organic matter content, manure history and pH (Schils, 2012, Pronk, 2007). Uncertainty of estimated / calculated loss rates for the same conditions is also high up to a factor of almost 4 as illustrated for loam/sand soils in this report (compare relative loss rate of HLB tool of 1.2% with the 4.5 % of the Yang equation). Methodologies to determine SOM loss differ in time period, measurement, soil layer, relevant covariates and resulting equations, which all add to the uncertainty. Various tools are available for the farmer to calculate the amount of organic matter input (from plant residues, manure, compost etc.), required for an equilibrium of current SOM. Probably, these tools give different results and not one method or model gives the best prediction for all situations. In other scientific areas (such as climate and crop yield prediction) an ensemble of models is used to estimate uncertainty but also because the average of a number of models proved to be a better predictor for a wide variety of situations than any single model separately. For SOM dynamics this "ensemble modelling" could also be a good way to bring practical and scientific knowledge together and offer an integrated answer to predicting SOM as function of inputs, climate and soil conditions.

2.5 Recent trends

2.5.1 Sources

Two sources were used to illustrate the development of SOM in the Netherlands during recent years. One is based on measurements during the period of 1984-2004 (Reijneveld *et al.*, 2009) and the other one results from calculations with the model Stone 2.4, applied to the Netherlands for the period 1981-2010 (Groenendijk *et al.*, 2013). The measurements refer to the soil layers 0-25 cm (arable and maize land) and 0-5 cm (grassland) and the calculations with STONE are performed for 0-25 cm (all land use types: i.e. grassland, arable land, maize land and nature). In STONE 2.4, land use is kept constant and the same area is modelled during the whole period, whereas the measurements refer to combinations of land use and region and throughout the years data from different fields were combined because fields were not geo-referenced.

2.5.2 Results

Table 10 contains the data of Table 2 in Reijneveld *et al.* (2009) with two extra columns calculated: "*t-values*" and "*b/mean*". The column "*t-values*" shows the level of statistical significance of the slope (or average change during the period) and in more than 50% of the combinations of land use and region the change is statistically not significantly different from zero. There is only one combination with a statistically significant loss of -1% of the mean SOM level (grassland on north marine clay). All remaining situations show a positive change ranging from 0.2% to 1.0%.

Table 10. Results from analysis of Reijneveld et al. (2009) on trends in SOC stocks during 1984-2004.

Regions	**Land use**	**Mean SOC (g/kg)**	**Slope b (g/kg,y)**	**(±se)**	**R2**	*t-values*	*b/mean (%)*
marine clay, north	Grassland	57	-0.55	0.16	0.46	*-3.44*	*-1.0%*
	Arable land	13	-0.02	0.04	0.01	*-0.50*	*-0.2%*
marine clay, south-west	Arable land	12	0.03	0.02	0.13	*1.50*	*0.3%*
Marine clay, central-west	Arable land	21	0.18	0.12	0.11	*1.50*	*0.9%*
Riverine clay, central	Grassland	53	0.37	0.17	0.25	*2.18*	*0.7%*
Peaty clay, north	Grassland	155	-0.98	0.81	0.09	*-1.21*	*-0.6%*
Peaty clay, west	Grassland	88	-0.27	0.28	0.06	*-0.96*	*-0.3%*
reclaimed peat, north-east	Grassland	70	-0.07	0.36	0	*-0.19*	*-0.1%*
	Arable land	63	0.08	0.1	0.04	*0.80*	*0.1%*
sand, south	Grassland	24	0.18	0.05	0.47	*3.60*	*0.8%*
	Arable land	17	0.01	0.02	0.02	*0.50*	*0.1%*
Loess, south	Grassland	33	0.34	0.11	0.39	*3.09*	*1.0%*
	Arable land	13	0.02	0.01	0.10	*2.00*	*0.2%*
Netherlands	Grassland	43	0.10	0.06	0.16	*1.67*	*0.2%*
	Arable land	20	0.08	0.02	0.39	*4.00*	*0.4%*
	Maize land	23	0.23	0.05	0.58	*4.60*	*1.0%*

Note: Trends are significantly different from 0 if t-score >2 or <-2 (p=0.05). These situations have been highlighted in the Table in red.

With the model Stone 2.4 the SOM dynamics in the top soil of four land use types were calculated and aggregated to represent the trends in the Netherlands (Figure 18). A significant positive trend was found on grassland, a significant negative trend for arable land and a neutral trend for maize land.

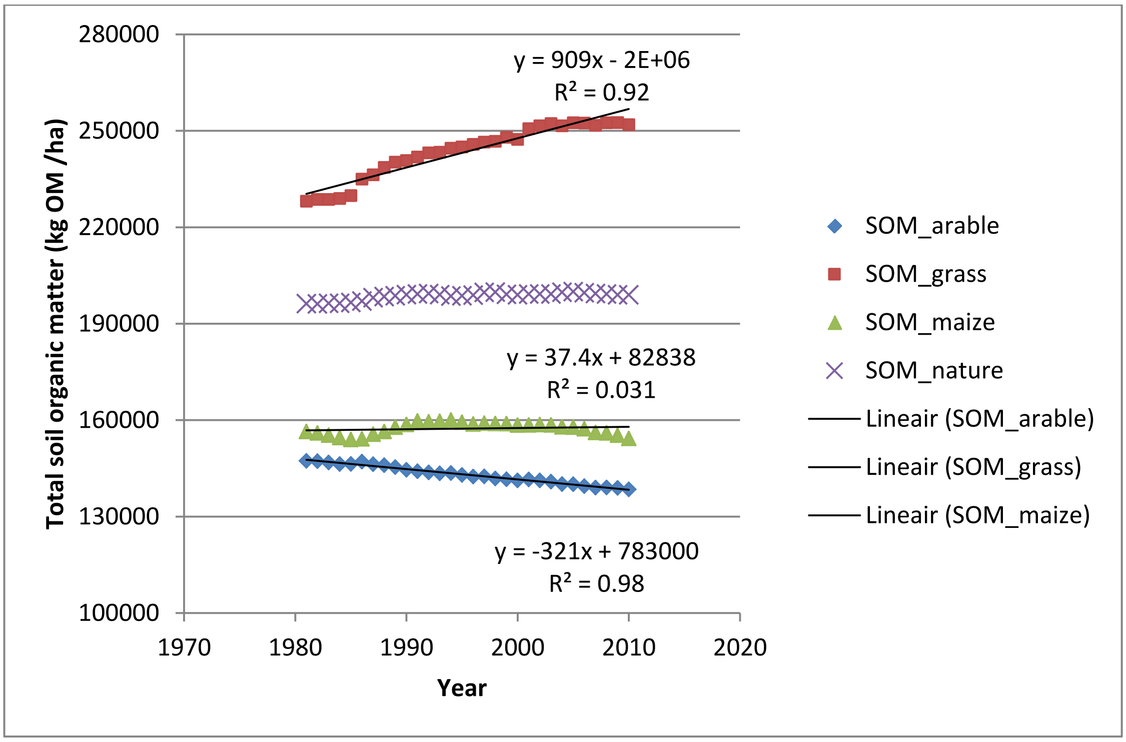

Figure 18. Calculated trends in soil organic matter by STONE_2.4 (kg ha^{-1}; 0-25 cm).

According to both Reijneveld's data and Stone 2.4, SOM in grassland soils (0-5 cm and 0-25 cm, respectively) has increased with on average 0.2-0.4% per year during the 80s and the 90s. For arable soils a difference in estimated trend is clearly present with a positive change in Reijneveld and a negative change calculated by Stone 2.4. Based on data of maize land from Reijneveld a significant positive change occurred whereas Stone 2.4 has estimated a zero trend. Maize is often cultivated in rotation with (temporal) grassland. This has not been modelled by Stone 2.4 (only continuous, permanent cultivation of each land use) but will have affected the data of Reijneveld (only land use at the moment of sampling is determined). Mixing Stone plots of permanent grassland and continuous maize will decrease the trend for grassland an increase the trend for maize land and results of both sources may become more similar. Carbon stock values of the three land use types are reasonably comparable between these two sources.

Table 11. Summary results from both sources.

	Change (% to mean)		Stock (ton C/ha; 0-25 cm)	
Source	Reijneveld *et al.* (2009)	Stone 2.4	Reijneveld *et al.* (2009)	Stone 2.4
Land use				
Grassland	0.23%	0.37%	129[1]	122
Arable land	0.40%	-0.22%	65	71
Maize land	1.00%	0.02%	75	79

[1] *Assuming that 43 g/kg in the 0-5 cm also holds for 0-25 cm in grassland soils.*

2.5.3 Uncertainty

The data of Reijneveld *et al.* (2009) are not based on sampling the same field regularly during the whole period and the calculations of Stone 2.4 assume continuous cultivation (without grassland renewal). Both lead to errors which cannot easily be assessed. Moreover, the grassland data of Reijneveld are produced from sampling only the 0-5 cm top soil which is small part of the active SOM in grassland soils. Nowadays, the sampling depth has been increased to 0-10 cm which is an improvement but still considerably less that the sampling depth in arable soils (0-25 cm). Grassland SOM receives less attention compared to that of arable soils, because generally the input of EOM is higher and critical SOM levels in grassland do usually not occur. However, this may not be true for specific fields or farms where grassland farming could profit from higher SOM levels. This also holds for arable/maize farming: although for the whole of the Netherlands data of Reijneveld report a positive trends, on specific fields/farms too low SOM levels may occur (see e.g. Hanegraaf *et al.*, 2009).

2.5.4 Conclusions

Based on measurements during 1984 and 2004, the majority of the combinations of land use and region has either no significant change (trend is neutral) or has a positive change (SOM is increasing) and in only one situation a negative change was measured (SOM is decreasing). Overall for the Netherlands only positive trends were detected. In almost all situations the change was less than +/- 1% of the mean SOM level. Stone 2.4 calculates an increasing trend for permanent grassland, neutral trend for continuous maize and a negative trend for arable land. Especially this negative trend for arable land compared to the positive trend in the data of Reijneveld *et al.* (2009) asks for further study. With changing future climate (temperature, precipitation) and increasing regulation on manure application the situation for the coming decades can differ from that of recent years.

3. Assessment of high risk areas

3.1 Introduction

To assess the areas that are under potential risk of too low soil carbon stocks we used two different approaches. The first approach (3.2.1) was based on simple balance equations of effective OM inputs (crop residues, manure and compost) minus output (OM decomposition, i.e. loss by respiration). For the OM decomposition we used three different equations to calculate the SOM decomposition and resulting balances were compared with results from the dynamic model RothC as incorporated in MITERRA-NL (see below). This approach of calculating the SOM balance of one year resembles the available simple tools for practical farmer advice, e.g. the HLB tool developed for the 'Productschap akkerbouw'. Inputs were derived from MITERRA-NL at postal code level and the current SOM levels from LSK and the soil map. For the second approach (3.2.2) we used RothC to calculate the soil carbon balance. For both approaches the carbon input from crop residues and manure (incl. grazing manure) was derived from MITERRA-NL and calculations were done for each crop at the 4 digit postal code level with current SOM level based on a combination of LSK data and the soil map of the top soil (0-25 cm). Compost was not (yet) included in the second approach, as the parameterisation for the C fraction data of compost was not available in RothC. However, a preliminary estimation of the effect of compost was made in the SOM balance approach. Both approaches were only applied for mineral soils in the Netherlands, as RothC cannot simulate well the carbon dynamics of peat(y) soils.

3.2 Results

3.2.1 Simple balance equation

In the simple balance equation both the loss of existing SOM for one year and the annual input of EOM were determined and compared. A negative value for the balance indicates a declining SOM level (SOM loss > EOM input), whereas a positive value points to the opposite (EOM input > SOM loss). Loss of SOM is calculated:

a. with a constant 2% relative loss rate, according to "*Kortleven*",
b. by the HLB tool with a relative loss rate depending on initial SOM level (downloaded 8-02-2014, denoted with "*HLB_OM*") and
c. by the improved version, again with the relative loss rate depending on initial SOM level ("*Adj_OM*" ; see also discussion in section 2.4.2), based on original data of Wadman & de Haan (1997).

Data on SOM losses at province level were already given in section 2.4 (Figure 16 & 17). These three have been compared to the balance calculated with RothC (via MITERRA-NL). All results of the balance equations are illustrated below at province level, but calculated in more detail (inputs: crop areas and manure application at postal code level and existing SOM level: see resolution of Figure 4b, left pane). The results illustrated in Figure 20 and Table 12 are based on the same calculations as those from Figures 21-22 in section 3.2.2. A final comparison is made with the balance of "*RothC*" after correction for the effect of compost application ("*RC+compost*"). The latter has simply been performed by adding the amount of EOM input with compost at province level to the balance of "*RothC*" and is therefore not available at the higher resolution of the other four approaches.

EOM inputs are calculated with crop areas and yields, combined with humification coefficients for crop residues, with animal numbers, excretion data per animal type and humification coefficients for manure types and estimated compost application and their humification coefficients (see section 2.3). As discussed in section 2.3 the input with grass residues have been increased (compare Figure 19, right side with Figure 10 left side: approximately 1.6 ton EOM per ha more grass residues).

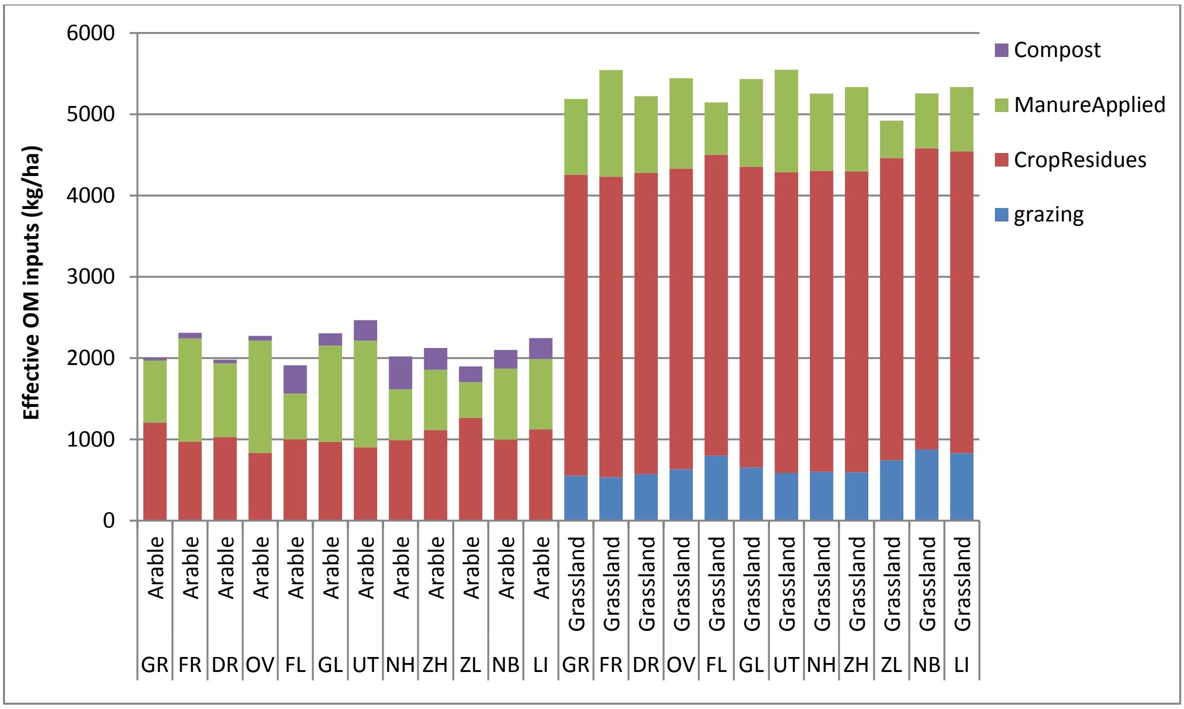

Figure 19. Effective organic matter inputs (kg ha^{-1} y^{-1}) for arable land and grassland per province.

Total EOM inputs are on average 2 ton ha^{-1} y^{-1} on arable soils and 5 ton ha^{-1} y^{-1} on grassland soils (Figure 19) and are equal for each calculation method. Combined with the estimated SOM losses, all balances for grassland are positive at the province level (Figure 20, upper part). With HLB_OM the highest values are found due to the calculation of the lowest loss rates. Next come the Adj_OM balance results which are lower than HLB_OM due to the correction of the relative loss rates (resulting in higher loss rates than those of HLB_OM), but the relative loss rates of Adj_OM are still lower for each province than the constant 2% ("*Kortleven*"). The relative loss rates of RothC are on average also lower than 2%, but not in the provinces Drenthe, Overijssel, Noord-Brabant and Limburg. The aggregated total increase of SOM in the top soil ranges from 1.3 (2% loss rate) to 2.9 (HLB_OM) ton ha^{-1} y^{-1} on grassland soils in the Netherlands (Table 12), which equals approximately 0.7% and 1.5% of the current SOM amount. These results are clearly higher than those from Reijneveld *et al.* (2009) in Table 10.

For arable soils the balances per province are negative in most situations, except for some results calculated with HLB_OM and with RC+compost. Again HLB_OM has the least negative values, due to the calculated low relative loss rates. Contrary to the grassland soils above, the balance results of RothC are clearly less negative compared to the 2% loss rate (due to on average 1.6% loss rate) and the results of Adj_OM are on average equal to the 2% loss rate with variations of lower and higher values among provinces. The correction with compost per province shows only modest effects in Groningen, Friesland, Drenthe and Overijssel, whereas it significantly increased the balance in the other provinces with even positive instead of negative values in Flevoland, Noord-Holland and Zuid-Holland as a result. The aggregated total increase of SOM in the top soil ranges from -0.9 (2% loss) to -0.08 (HLB_OM) ton ha^{-1} y^{-1} on arable soils in the Netherlands (Table 12). Compost application at arable soils increased the SOM balance calculated with RothC on average with 0.2 ton ha^{-1} y^{-1} (from -0.38 to -0.18 ton ha^{-1} y^{-1} in Table 12).

The aggregated values of the SOM balances for arable and grassland soils together in the Netherlands is for each method used in this report positive and ranges from 0.2 (2% loss rate) to 1.4 (HLB_OM ; see agricultural area in Table 12).

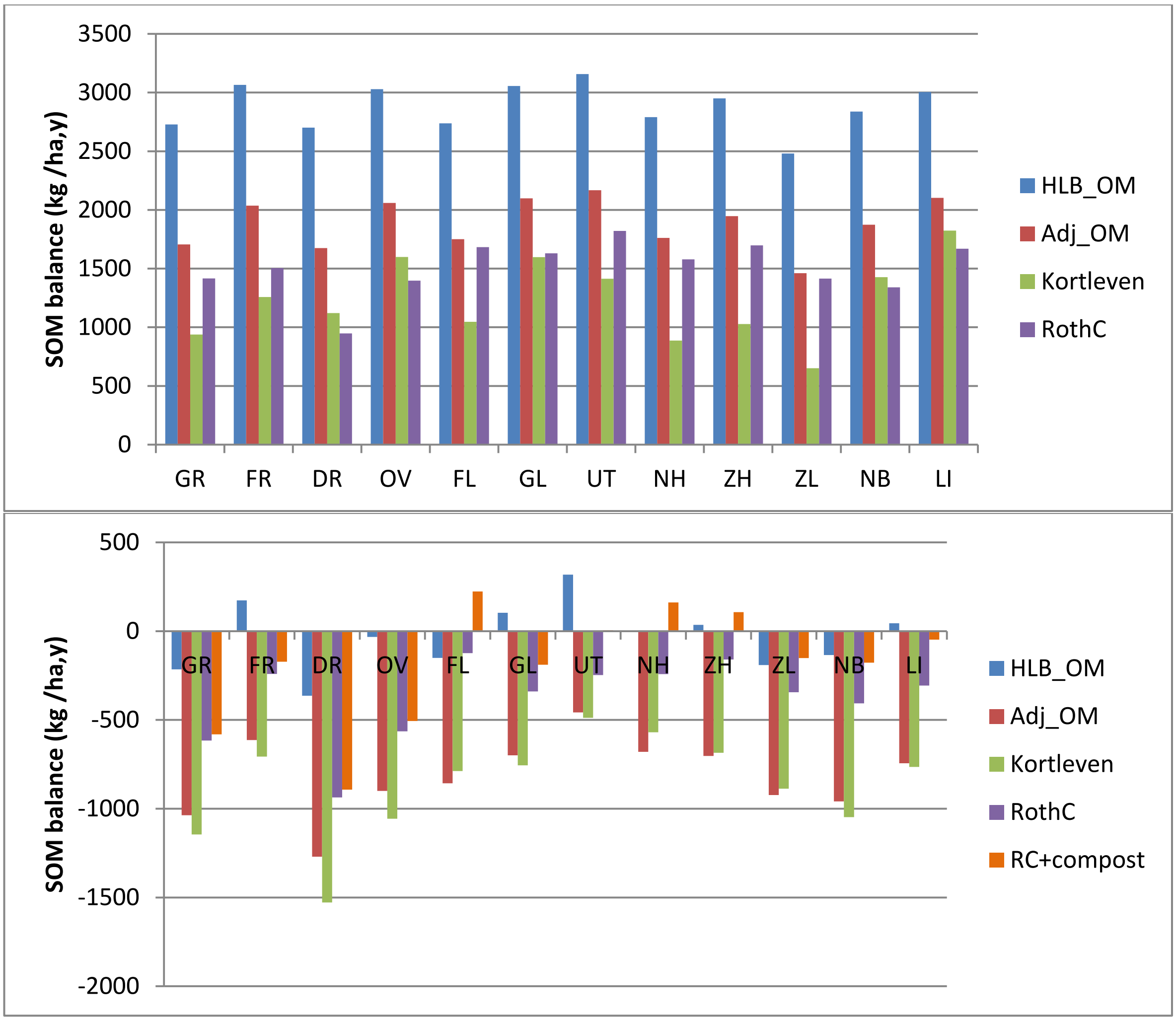

Figure 20. The calculated soil organic matter balances per province in the Netherlands of grassland soils (upper part) and arable soils (lower part). Soil layer: 0-25 cm and methods only applied to only mineral soil types.

Table 12. Soil organic matter balance (kg ha^{-1} year^{-1}) of arable and grassland soils in the Netherlands, assessed by the simple balance approach (i.e. effective organic matter input – decomposition soil organic matter).

Land use	HLB_OM	Adj_OM	2%_Kortleven	RothC	RothC+compost
Arable	-79	-863	-906	-378	-180
Grassland	2947	1959	1349	1495	
Agriculture	1406	522	201	541	642

3.2.2 Model RothC

Previously the MITERRA model used the soil carbon stock change approach from the IPCC 2006 guidelines to calculate soil carbon stocks. For this study the RothC model was incorporated in MITERRA-NL for calculation of the soil carbon balance. RothC (version 26.3) is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process and was used to calculate the current soil organic carbon balance and the steady state soil carbon stock based on current inputs (see also Appendix IV). For the initial carbon content we used the soil carbon stocks based on the Dutch LSK data (Figure 6 and Table 5) and soil map for arable and grassland soils.

We applied two methods to assess high risk areas with RothC. For method A we assessed the SOC balance using RothC and compared these with the soil carbon stocks and defined risk classes. For method B we calculated also the steady state SOC stock and the time it would take to reach the steady state.

Method A

Figure 21 shows the maps of the calculated soil carbon balance for arable land and grassland. For arable land the SOC balance is close to zero or slightly negative. Only in the north-east (Veenkoloniën) and in some dune sand areas in Noord Holland more negative SOC balances are found. Although the peat and peaty soils were excluded from the analysis, there are also sandy soils with still a high SOM content from small peat layers or former peat layers that are mixed into the soil profile. This results on higher SOM contents than would be expected on the basis of climate, soil type and C inputs. This is a possible reason for the strong negative SOC balances in the Veenkoloniën. For grassland the SOC balance is almost every positive, especially on the clayey soils. Figure 22 shows the combined SOC balance for arable and grassland, which gives a more realistic picture in those areas where crops are grown in rotation with temporary grassland (see also discussion in section 3.3). The overall SOC balance is positive for agricultural land in the Netherlands, however, certain areas still have a negative SOC balance; these are mainly areas on poor sandy soils under arable land.

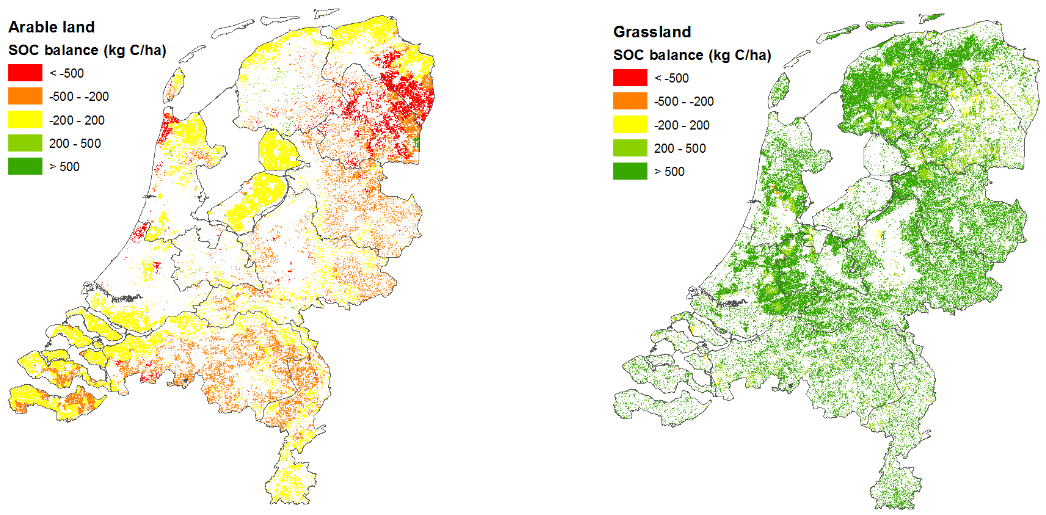

Figure 21. Calculated soil organic carbon balance (kg C ha^{-1}y^{-1}) for arable land (left) and grassland (right) in the Netherlands. SOC balance is calculated by the input of organic material (residues and manure) and the first year decay of existing soil organic matter (0-25 cm).

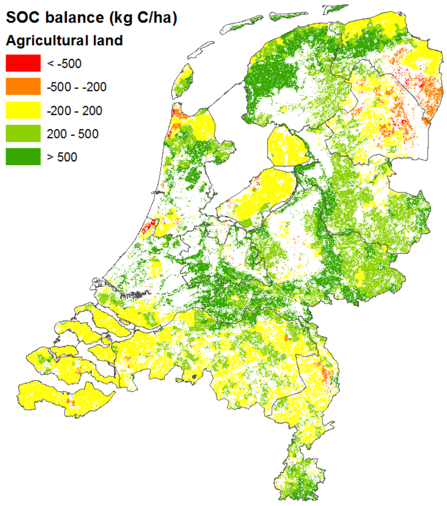

Figure 22. Calculated soil organic carbon balance (kg C ha^{-1} y^{-1}) for agricultural land use in the Netherlands (combination of the two maps in Figure 21).

To come to a risk map we defined three risk classes, low, medium and high, which are determined by a threshold for the SOC stock and the SOC balance (Table 13), These thresholds have been arbitrary defined as 1.5% organic carbon (~3% OM) for the SOC stock and -0.5 ton C/ha and -1.0 ton C/ha for the SOC balance. The resulting SOC risks maps are shown in Figure 23. According to these risk classes all grassland is in the low risk class and most of the arable land as well. For arable land areas in Northeast Netherlands have a medium risk and a few areas in the dune sands have high risk.

Table 13. Chosen thresholds for soil organic carbon stock (SOC, %) and first year soil organic carbon balance (%, relative to SOC stock) to define three risk classes (High, Medium and Low).

SOC stock (%) (0-25 cm)	**SOC balance (ton ha^{-1})** (0-25 cm)	**Risk value**
Low: <= 1.5	<= -0.5	High
	-0.5 <> 0.0	Medium
	>= 0.0	Low
High: > 1.5	<= -1.0	High
	-1.0 <> -0.5	Medium
	>= -0.5	Low

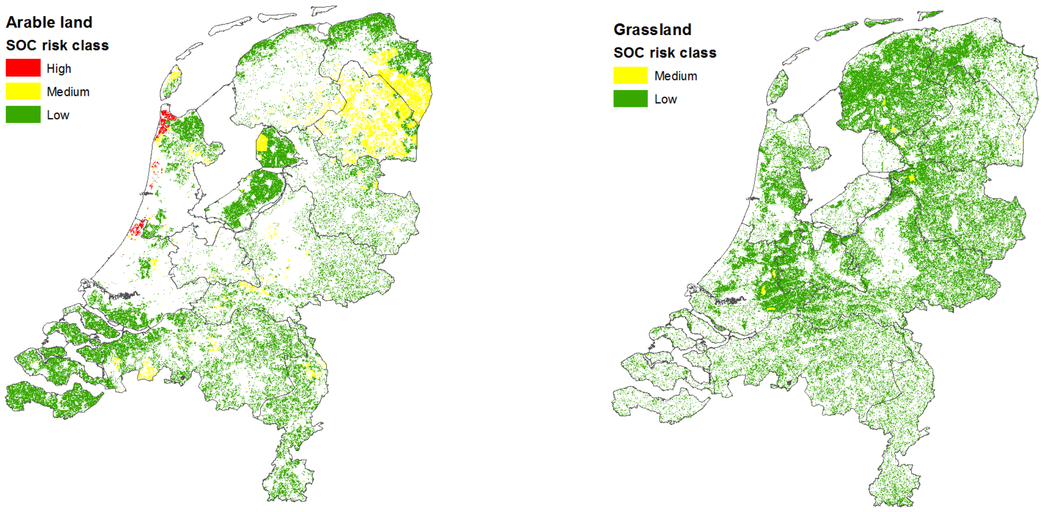

Figure 23. *Estimated risk classes (H, M or L) for arable land (left) and grassland use (right) in the Netherlands.*

Method B

For method B we also used RothC, but instead of expressing risk in terms of the SOC balance, we used the time to reach a certain carbon content threshold as risk indicator. First RothC was used to calculate the steady state SOC stock, based on the current carbon inputs. Second we determined the time it would take, in case of a negative SOC balance, to reach the threshold of 1.5% SOC (both for arable and grassland). We did not run RothC dynamically over time, because this was not yet implemented in MITERRA due to budget constraints. Therefore it was not possible to simulate the time it would take to reach the steady state condition. However, we did make a time estimation based on the current SOC balance, simply assuming a linear increase in SOC until the steady state is reached (Table 14). Although this is a large simplification, which underestimates the time to steady state, as changes in SOC are slowing down when equilibrium is reached, it still offers the possibility to compare the different regions in the Netherlands in terms of risk time.

Figure 24 shows the SOC risk map expressed in time to reach the 1.5%OC threshold. For grassland most of the areas have a positive SOC balance and are not under risk. For a few areas with a negative SOC balance, it will still take more than 100 years until the 1.5% OC threshold is reached, which can be considered as a low risk. For arable land the picture is different. A few areas, mainly dune sand areas, are already below the 1.5% OC threshold. In the more clayey soils the SOC balance is on average positive, indicating no SOC risk, but in most areas the SOC balance is (slightly) negative. For most areas it will take at least 50 years until the 1.5% OC threshold is reached, but in few areas, especially in Noord Holland, it might even take less time. Although these results are based on model simulations, with large uncertainty in the quantification of the risk time, still these results do give a good insight which areas are more vulnerable to SOC loss compared to other regions. This might help policy makers to target specific policies/measures for certain areas.

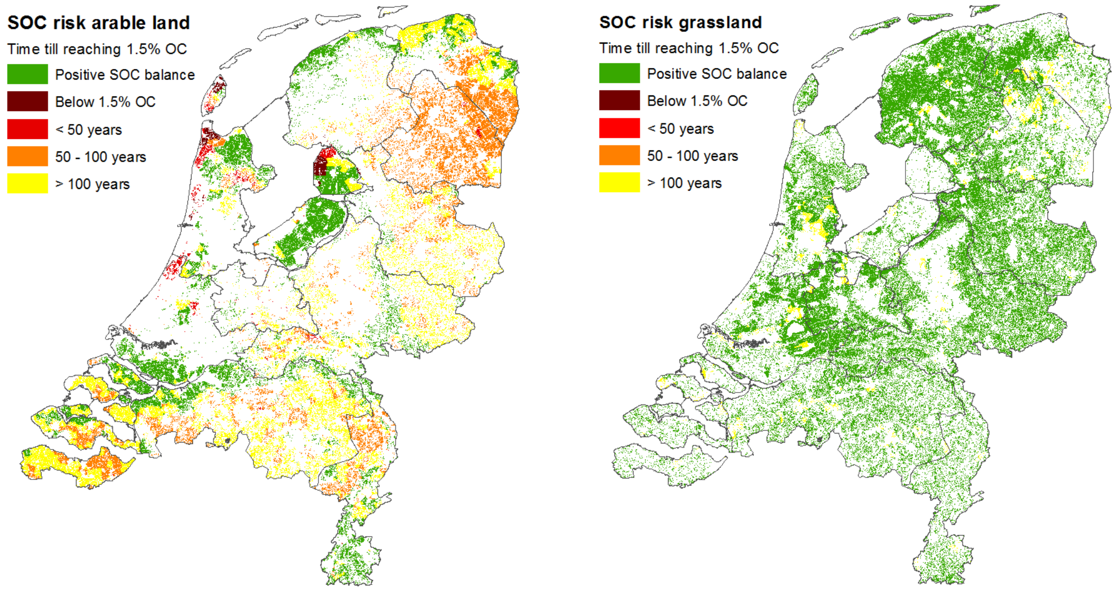

Figure 24. Calculated risk as time to pass the 1.5% SOC content for arable land (left) and grassland use (right).

Table 14. Initial SOC (derived from LSK), modelled steady state and SOC balance by RothC (all in ton C/ha) and time till steady state (derived by simply dividing the difference between steady state and initial SOC by the SOC balance).

Province	**Arable**				**Grassland**			
	Steady state	Initial SOC	SOC balance	Time (years)	Steady state	Initial SOC	SOC balance	Time (years)
GR	64.6	78.7	-0.31	46	193.9	106.2	0.71	124
FR	74.5	75.4	-0.12	8	200.4	107.1	0.75	124
DR	60.4	87.7	-0.47	58	167.1	102.5	0.47	136
OV	69.5	83.2	-0.28	49	184.3	96.1	0.70	126
FL	69.9	67.5	-0.06	39	208.5	102.4	0.84	126
GL	69.8	76.5	-0.17	39	197.6	95.8	0.81	125
UT	68.6	73.9	-0.12	43	215.6	103.3	0.91	123
NH	62.1	64.7	-0.12	21	207.4	109.2	0.79	124
ZH	71.0	70.2	-0.08	10	211.5	107.7	0.85	122
ZL	63.8	69.6	-0.17	34	197.7	106.8	0.71	129
NB	70.7	78.7	-0.20	40	181.9	95.7	0.67	129
LI	71.4	75.3	-0.15	25	187.9	87.8	0.83	120

3.3 Uncertainty

SOM balance at province level

Results above have been illustrated and separated for arable crops and grassland. However, in the agricultural practice of the Netherlands temporal grassland is often grown in rotation with arable crops while this area is usually classified as arable land opposite to grassland with mainly permanent grass cultivation (in the latter category grassland can be renewed by ploughing grassland followed by resowing with grass). We have estimated the effect on the results for the SOM balance of arable land if a part of the grassland balance would be combined with the balance for arable crops. We have used data on the total area of temporal grassland per province (taken from Basis Registratie Percelen) and made an area weighted sum of the SOM balances calculated for arable crops and grassland separately (see results in Table 12). This analysis does not alter the results for (permanent) grassland, only the area will decrease because the part of total grassland that is temporal is now added to the area of arable crops to estimate total arable land. Due to data limitation we could only apply this method on province level with temporal grassland values ranging from 9% in Friesland to 43% in Noord Brabant and an overall 20% as average for the Netherlands. Figure 25 shows that the SOM balances become less negative and that in much more situations for HLB_OM and RC+compost positive balances are calculated instead of a negative balance (compare with Figure 20, lower part). For the Netherlands as a whole results are presented in Table 15 and show that the arable land balance becomes near zero for RothC and RC+compost, is clearly positive for HLB (+0.4 ton SOM ha^{-1} y^{-1}), but still remains negative for the other two models with circa -0.5 ton SOM ha^{-1} y^{-1} (Adj_OM and 2% of Kortleven). In addition, there is uncertainty in the amount of straw that is returned to the field, which might not all be comprised in the manure input.

Table 15. Soil organic matter balance (kg ha^{-1} y^{-1}) of arable and arable plus temporary grassland soils in the Netherlands, assessed by the simple balance approach (i.e. effective organic matter input – decomposition soil organic matter).

Land use	HLB_OM	Adj_OM	2%_Kortleven	RothC	RothC+compost
Arable	-79	-863	-906	-378	-180
Arable+20% [1]	392	-423	-548	-89	78

[1] *Arable+20%: estimated value if the balance of 20% of grassland area (Table 12) is added to arable balance. The 20% refers to temporary grassland that is assumed to be grown in rotation with arable crops (on average 80% of total grassland area is permanent in the Netherlands, but varies per province; different values per province were used; source: BRP data).*

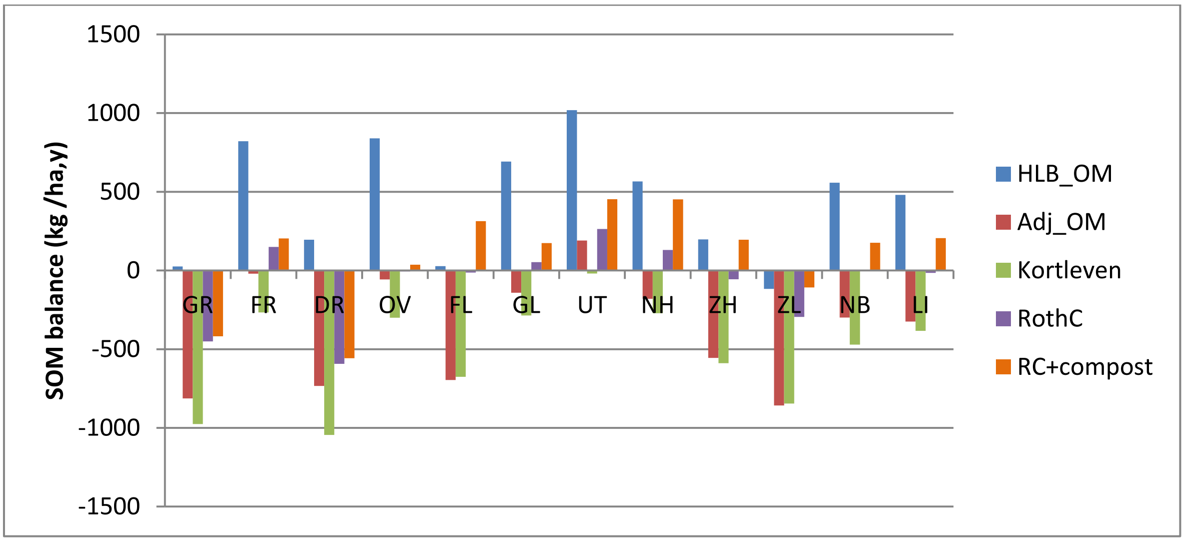

Figure 25. The soil organic matter balance per province in the Netherlands of arable soils land with temporary grassland as part of the arable land (layer: 0-25 cm and only mineral soil types).

There are specific situations in the Netherlands which differ considerably from the mainstream situation (e.g. dune sand with reported (very) high SOM loss rates and EOM input rates; Pronk *et al.*, 2007). These situations have not been adequately described by the various models in this study because they represent more extreme conditions that fall outside the average range for which the models were developed. This is a general phenomenon that may occur when models are used that should cover a wide range of situations but in which outliers are less well presented. It adds to the general uncertainty of our results but specifically points to careful further use and in-depth examination of what we have presented in this report, especially for local situations.

Temperature effects

In RothC, HLB_OM and Adj_OM temperature affects the rate of SOM decomposition, where usually air temperature is used as proxy for soil temperature. In general higher temperatures cause higher decomposition rates leading to lower SOM levels (if "all else being equal") or requiring more inputs to maintain SOM levels. The effect of a rise in temperature of +2 °C on the decomposition and ultimate SOC balance has been calculated with RothC for the Netherlands (Figure 26). By comparing these results with those from Figure 21, it becomes visible that more areas on arable land have more negative balances (the yellow colour has almost disappeared whereas the orange and red have increased) and that for grassland more areas with around zero balance appear at the expense of areas that had a clear positive balance. Overall the annual balance decrease with approximately 290 kg C ha^{-1}. It must be noted that a 2 °C increase may also change the availability of inputs (e.g. by higher productivity), however this effect has not been taken into account in this study due to high uncertainty about its value.

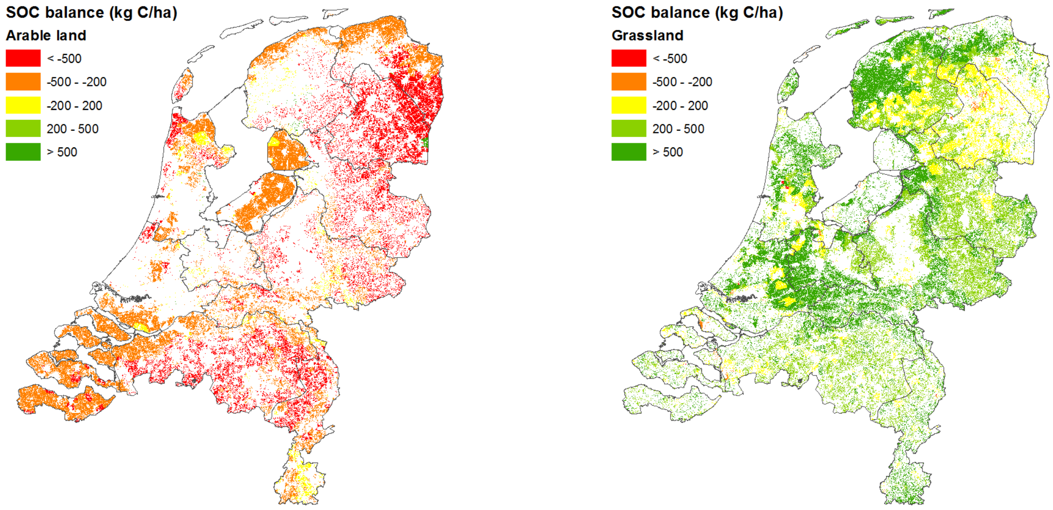

Figure 26. *Effects of +2 °C on SOC balance of arable land and grassland (compare with Figure 21). Temperature increase is only applied on model parameters of decomposition (no effect on production of crop and grass residues has been taken into account).*

De Willigen *et al.* (2008) presented a figure that illustrates the differences in the effect of temperature according to seven different SOM models (Figure 27). This graph is constructed by recalculation of the original temperature function of each model with all factors equal one at 9 °C. The blue dots which are close to the light blue line for values between 5 and 15 °C are added to the Figure of de Willigen *et al.* and represent the function of RothC. Uncertainty about the effect of temperature becomes visible by the deviation among the functions when temperature is lower or higher than the "standard' value of 9 °C. To illustrate this uncertainty: at 12 °C (+2 °C relative to current long term average of 10 °C; see Appendix VI), RothC assumes an increase in decomposition rate of 27% which is 20% more than calculated by Minipb (increase of only 7%). The differences in SOC balances illustrated above when comparing Figure 26 with Figure 21 would thus be much smaller if the temperature function of Minipb would have been used. It was beyond the scope of our study to look for the background of the different temperature functions but the example above clearly shows that further investigation into these differences is recommended.

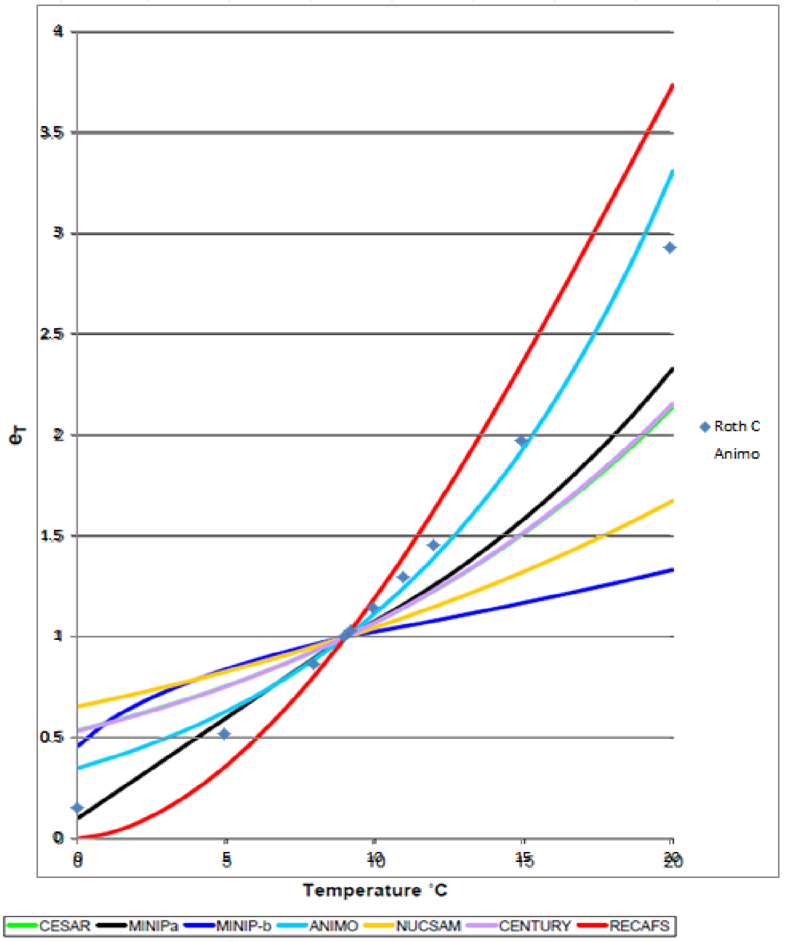

Figure 27. Temperature response of the different SOC models (Source: de Willigen et al., 2008).

3.4 Conclusions

Our different approaches for calculating the SOM balance are consistent in predicting a positive balance on grassland and a negative balance on crop land. However, if crops are grown in rotation with temporal grassland and the effect of compost is taken into account, some models result in positive SOC balances, while others still calculate negative balances for arable land. It was also shown that models differ significantly in their values for the positive or negative balance due to differences in estimated decomposition rate of the initial SOM. The HLB tool (available for farmers on the internet) is illustrative for estimating low decomposition rates of both land use types (mainly caused by assuming a temperature that is too low), whereas the (constant) 2% decomposition rate is the highest with intermediate values from Adj_OM and RothC. This is remarkable because the 2% refers to a long-term average and a higher rate is expected during the first year's decay on which the simple balance equation is based. Differences lead to either relatively high (HLB tool) or low (2% rate) values for the SOM balance. There are many drivers that affect the decomposition rate, which are difficult to quantify (such as temperature and characterisation of current SOM in relation to decomposition and input history; the effect of grassland renovation once every 5 to 10 years). Besides the decomposition rate, also the soil depth which is chosen in the calculation adds to the uncertainty of the balance. In practice it is not well-known which part of the soil should be selected in combination with the fresh OM inputs, especially at grassland where currently only the top 10 cm of the soil is sampled for a SOM analysis.

Only with RothC a more detailed map of the SOC balance was made at postcode level. Balances from grassland areas are positive and those from arable land mostly negative with some very negative (dune areas in Noord Holland and in the North east part of the Netherlands). Results for arable land do not match the conclusion from Reijneveld *et al.* (2009), but the direction is consistent with results from simulations with Stone 2.4 (Table 11). According to the temperature function of RothC, a 2 °C temperature rise may require an extra 600 kg EOM input per ha to compensate for the higher decomposition which is +11 and +27% of the current EOM inputs on grassland and arable land respectively (only based on temperature effects on decomposition rate). This also illustrates the sensitivity of the results to the assumed effect of temperature which may differ a lot among different models.

The SOC balance results were used in constructing risk maps to illustrate which areas in the Netherlands are most vulnerable for declining SOM up to critical low SOM levels. Two methods have been applied: a qualitative one with high, median and low risk assessments by combining threshold levels of first year SOC balance decline and critical current SOC levels and a quantitative one with a proxy estimation of the time 'required' to reach a certain (low) threshold value in SOC level with current inputs. Both methods are consistent and point to the same arable areas which were already highlighted above by having a large negative SOC balance. In this study a 1.5% SOC (~ 3% SOM) was chosen as critical low value, but in literature not much is known quantitatively about lower threshold levels for good functioning soils as a function of local conditions.

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Appendix I.
Comparison of LSK and LUCAS data

LUCAS (Land Use/Cover Area frame statistical Survey) is a harmonised survey across all Member States to gather information on land cover and land use. Estimates of the area occupied by different land use or land cover types are computed on the basis of observations taken at more than 250,000 sample points throughout the EU. By repeating the survey every few years, changes to land use can be identified. In 2009, the European Commission extended the periodic LUCAS survey to sample and analyse the main properties of topsoil in 23 Member States of the EU. This topsoil survey represents the first attempt to build a consistent spatial database of the soil cover across the EU based on standard sampling and analytical procedures, with the analysis of all soil samples being carried out in a single laboratory. Approximately 20,000 points were selected out of the main LUCAS grid for the collection of soil samples. A standardised sampling procedure was used to collect around 0.5 kg of topsoil (0-20 cm). The samples were sent to an accredited laboratory where a range of chemical and physical soil properties were analysed. SOC content (g C kg^{-1}) was measured by dry combustion (ISO 10694:1995). More details about the survey and the data can be found in Tóth *et al.* (2013). In 2012 also samples from Romania and Bulgaria were collected and currently being analysed. A new monitoring survey is foreseen in 2015. The benefit of LUCAS data is that it is recently observed data and there is a clear link to land use and to lesser extent land management.

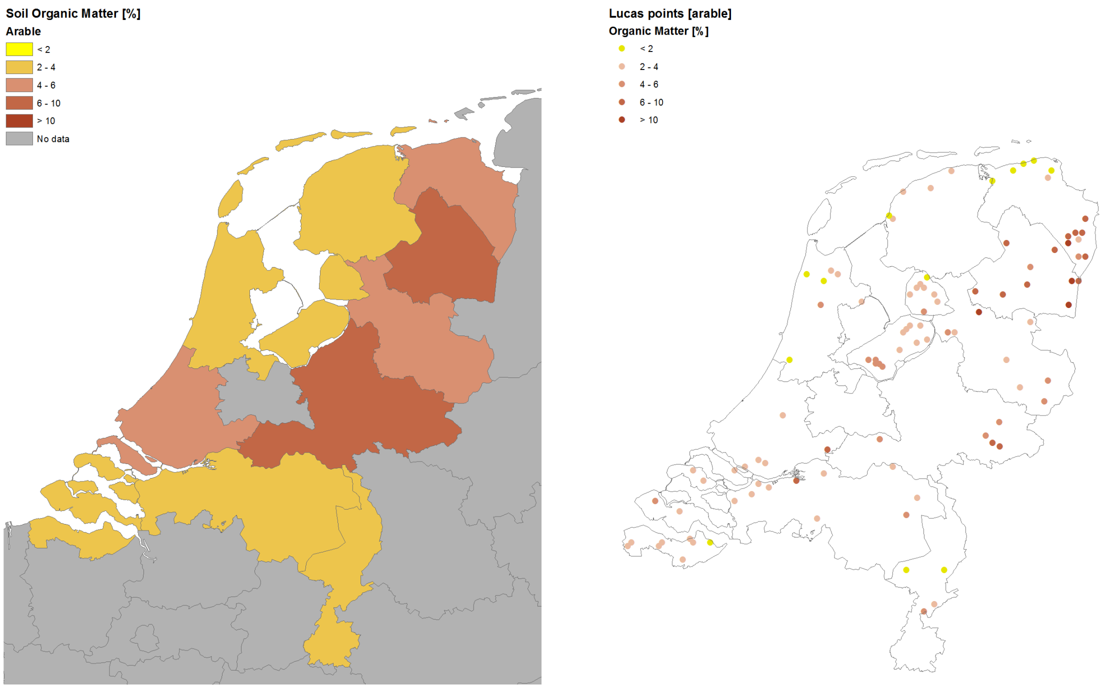


Figure I-1. Soil organic carbon content for arable soils based on LUCAS data, left average per province and right the individual sample points.

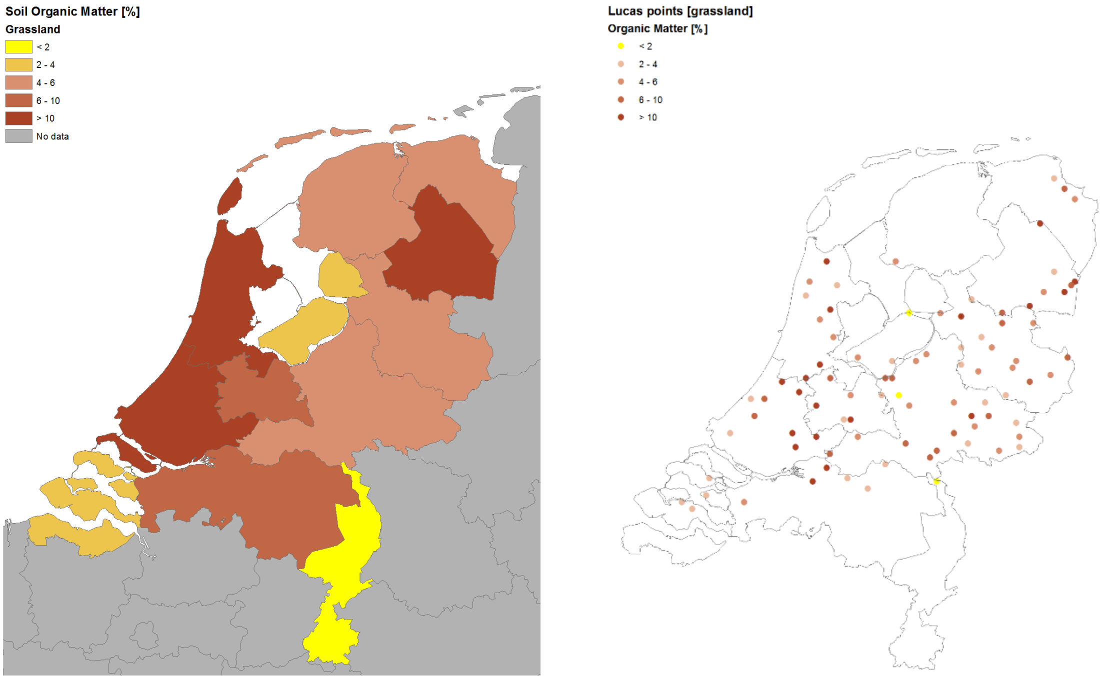


Figure I-2. Soil organic carbon content for grassland soils based on LUCAS data, left average per province and right the individual sample points.

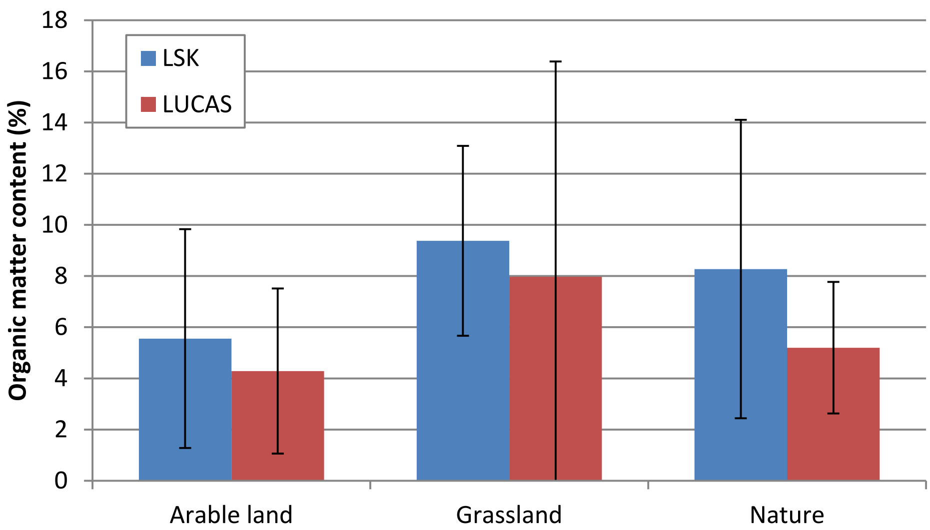
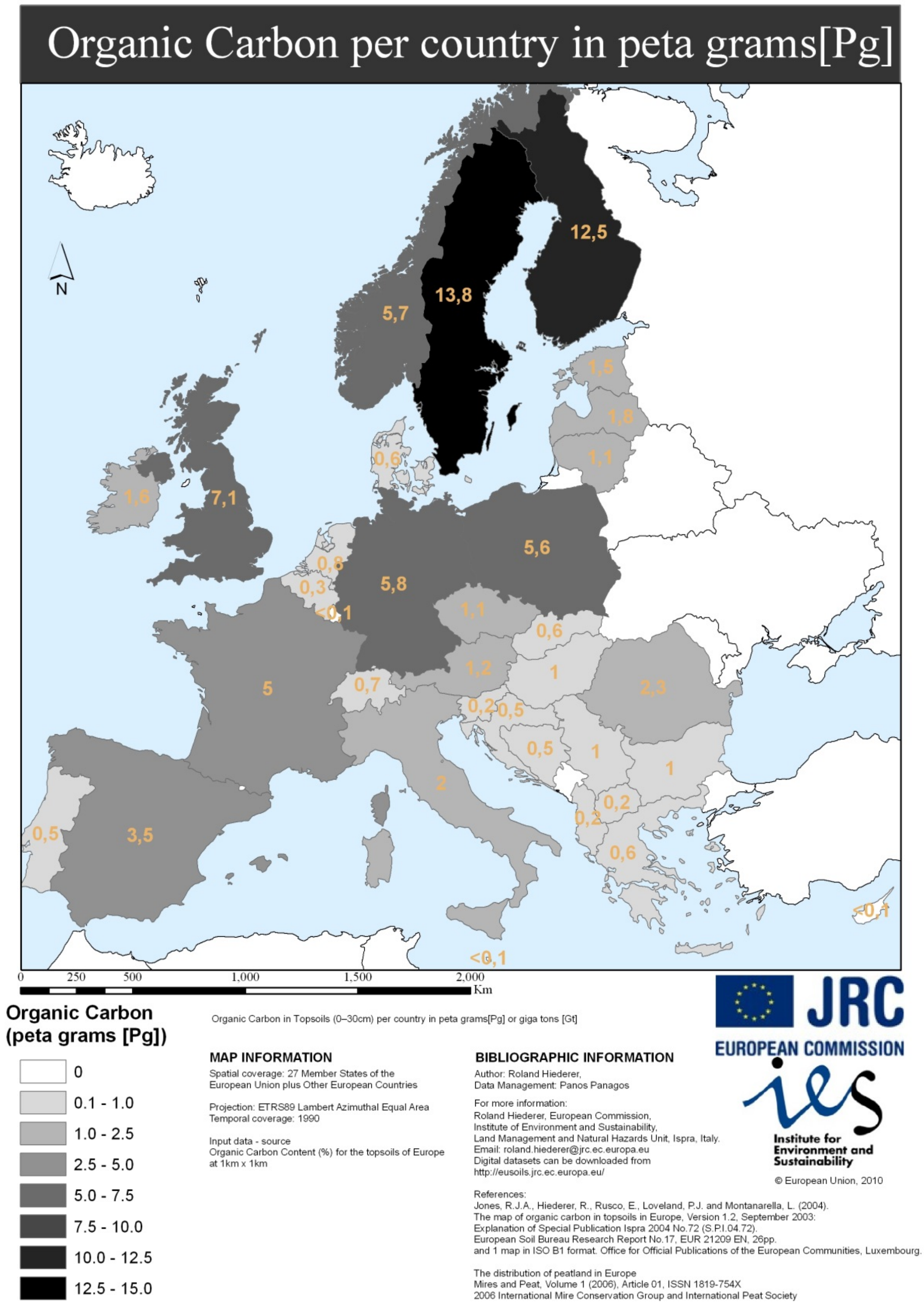


Figure I-3. Comparison of soil organic matter content from LSK and LUCAS soil data. Data are representative of the 0-20 cm layer. Error bars indicate the standard deviation.

The LUCAS data shows on average lower soil organic matter contents compared to the LSK data. However, the variance is large and differences are probably not significant (not tested). The total number of sampling points for LUCAS (about 200) for the Netherlands is not sufficient to obtain accurate results at province level. Since LSK was sampled at the end of the nineties and LUCAS was sampled in 2009, there might be a trend of lower SOM levels in the Netherlands, but these differences are probably not significant.

Appendix II.
Estimation of national organic C stocks

Source: http://eusoils.jrc.ec.europa.eu/ESDB_Archive/octop/octop_data.html



Appendix III. Supplementary data on stocks

Table III-1. Soil organic carbon content (ton C ha-1) and total amount (Mton C) in the top 30 cm per province and for the Netherlands. Area refers to the part of each province, i.c. grasslands, arable land and nature (based on Figure 4b).

	LSK + soil map			HWSDa		
Provinces	Area (km^2)	ton C/ha	Mton C	Area (km^2)	ton C/ha	Mton C
Friesland	2784	127	35	3415	113	39
Groningen	1957	115	22	2385	138	33
Drenthe	2296	130	30	2569	170	44
Noord-Holland	1694	109	18	2414	103	25
Overijssel	2728	116	32	3197	116	37
Flevoland	1160	89	10	1402	30	4
Gelderland	3970	96	38	4770	66	31
Zuid-Holland	1686	124	21	2484	93	23
Utrecht	982	123	12	1259	95	12
Noord-Brabant	3753	96	36	4541	69	31
Limburg	1603	92	15	1935	63	12
Zeeland	1414	85	12	1693	29	5
Nederland	26026	108	282	32066	92	296

Table III-2. Average carbon stock (ton C/ha) per soil type and land use.

Soil type	**Grassland**	**Cropland**	**Nature**
Brikgrond	78	76	82
Eerdgrond	88	71	96
Kalkhoudende zandgrond	59	54	34
Kalkloze zandgrond	87	76	57
Leemgrond	89	82	112
Moerige grond	146	162	171
Oude kleigrond	81	84	61
Podzol grond	116	108	92
Rivierklei grond	111	85	138
Veengrond	189	163	242
Zeekleigrond	114	81	112

Table III-3. SOM stock and SOM content based on the 0-25 cm topsoil, derived from LSK data. These data were used for the calculations of the decomposition factor and SOC dynamics with MITERRA and RothC.

	Arable land		**Grassland**	
Soil type	**SOM stock (ton/ha)**	**SOM content (%)**	**SOM stock (ton/ha)**	**SOM content (%)**
Brikgrond	132	3.7	134	3.8
Eerdgrond	120	4.2	148	4.3
Oude kleigrond	144	4.3	139	4.3
Leemgrond	125	3.5	150	4.4
Kalkloze zandgrond	132	3.8	151	4.6
Moerige grond	275	13.1	251	13.4
Podzol grond	182	5.5	199	6.4
Rivierklei grond	140	4.4	190	7.3
Veengrond	271	19.3	321	22.5
Zeekleigrond	135	4.2	197	7.4
Kalkhoudende zandgrond	85	2.3	103	3.0
Onbepaald	159	5.8	210	9.5

Appendix IV.
Additional information on inputs

Table IV-1. Crop properties used in calculations with MITERRA, data are based on Zwart et al. (2013) and Vleeshouwers and Verhagen (2002).

Crop	Effective OM input (kg/ha)	Eff OM incl. straw (kg/ha)	Harvest index
Permanent grassland	3975		0.44
Temporary grassland	2575		0.44
Natural grassland	3975		0.44
Fodder maize	660		0.67
Grain maize	2200		0.46
Corn cob mix	1900		0.46
Winter wheat	1640	2630	0.46
Spring wheat	1630	2590	0.46
Spring barley	1310	1940	0.46
Winter barley	1570	2350	0.46
Sugarbeet	1275		0.69
Consumption potato clay	875		0.69
Seed potato clay	875		0.69
Starch potato	875		0.69
Consumption potato sand	875		0.69
Seed potato sand	875		0.69
Vegetables	600		0.50
Grasseed	2300		0.20
Onion	500		1.00
Bulbs	500		1.00
Fallow	500		
Nurseries	919		0.85
Pulses	650		0.69
Apples	2956		1.00
Pears	2956		1.00
Luzerne	1550		0.50
Other crops	600		0.50
Other seeds	1000		0.50
Triticale	1600	2530	0.46
Rapeseed	975	1800	0.69
Strawberry	300		0.50
Rye	1020	1500	0.46
Other fruits	2956		1.00
Oats	1570	2470	0.46
Green manure	1000		0.30
Fibres	660		0.92
Sunflower	1000		0.46
Fodder beet	1275		0.69
Other cereals	1400		0.46
Wine	2956		0.70
Miscanthus	3695		0.44
Switchgrass	3695		0.44
Willow	2956		0.85

Table IV-2. *Manure properties used in calculations with MITERRA, data are based on BLGG and NutriNorm.*

Manure type	**OM (g/kg)**	**CN-ratio**	**Eff. OM (g/kg)**	**Humification coefficient**
dunne mest				
Rundvee	64	7.8	30	0.47
Vleesvarkens	43	3.0	18	0.42
Zeugen	25	2.5	10	0.40
rosekalveren	71	6.3	30	0.42
witvleeskalveren	17	3.3	5	0.29
vaste mest				
Rundvee	152	14.3	85	0.56
Varkens	153	9.7	65	0.42
leghennen mestband	416	8.1	190	0.46
leghennen mestband droog	427	6.3	190	0.44
kippen strooiselmest	359	6.4	230	0.64
Vleeskuikens	419	6.5	183	0.44
Kalkoenen	427	9.2	230	0.54
Paarden	160	17.4	125	0.78
Schapen	195	11.1	105	0.54
Geiten	174	8.8	90	0.52
Nertsen	293	5.2	95	0.32
Eenden	237	13.3	105	0.44
Konijnen	332	17.7	185	0.56
Champost	211	13.9	89	0.42
GFT compost	242	9.5	183	0.76
Groen compost	179	17.9	190	1.06

Appendix V.
SOM dynamics models used in this study

A. Summary description of Animo 4.0 (part of STONE)

Copied from: Renaud, L.V., Roelsma, J. and Groenendijk P., 2006. *User's guide of the ANIMO 4.0 nutrient leaching model.* Wageningen, Alterra, Alterra Report 224. 191 pp. 65 Fig.; 24 Tab.; 35 Ref.
http://www2.alterra.wur.nl/Webdocs/PDFFiles/Alterrarapporten/AlterraRapport224.pdf

Theoretical background of the ANIMO model

A comprehensive model description is given in Groenendijk and Kroes (1999) and Groenendijk *et al.*, (2005).
A summarized description for the carbon, nitrogen and phosphorus cycles has been summarized in the subsequent section.

Carbon, nitrogen and phosphorus cycle

The transformation processes described are all part of the carbon, nitrogen or phosphorus cycle. These cycles have been modelled according to *Figure 1 (carbon), 2 (nitrogen) and Figure 3 (phosphorus, not shown here)*. These three figures show the interrelation between the cycles. The figures contain a horizontal line that indicates either the soil surface or the top boundary of the system described. Parameters mentioned above this line indicate actions concerning additions to and removal from the soil system. Below the horizontal line, the principal parameters of the soil system are shown with four kinds of organic matter in the centre of the soil system. These four kinds of organic matter are:

- a fresh organic matter pool: root and crop residues and organic parts of manure added to the soil;
- a dissolved organic matter pool: organic matter in solution from fresh organic matter or humus;
- an exudate pool: dead root cells and organic products excreted by living roots;
- humus/biomass: consists of dead organic matter and of living biomass and is formed from part of the fresh organic matter, root exudates and dissolved organic matter.

The organic material added to the soil may vary strongly from composition and quality. To express differences in quality, the fresh organic matter can be sub-divided into different fractions, each with its own decomposition rate, N-content and P-content. In this way, it is possible to distinguish between materials with their own specific characteristics. In the ANIMO model, the rate variables for organic matter transformation are adjusted for the responses on temperature, moisture, pH and oxygen status; the nitrification rate is corrected for influences of temperature, moisture and pH.

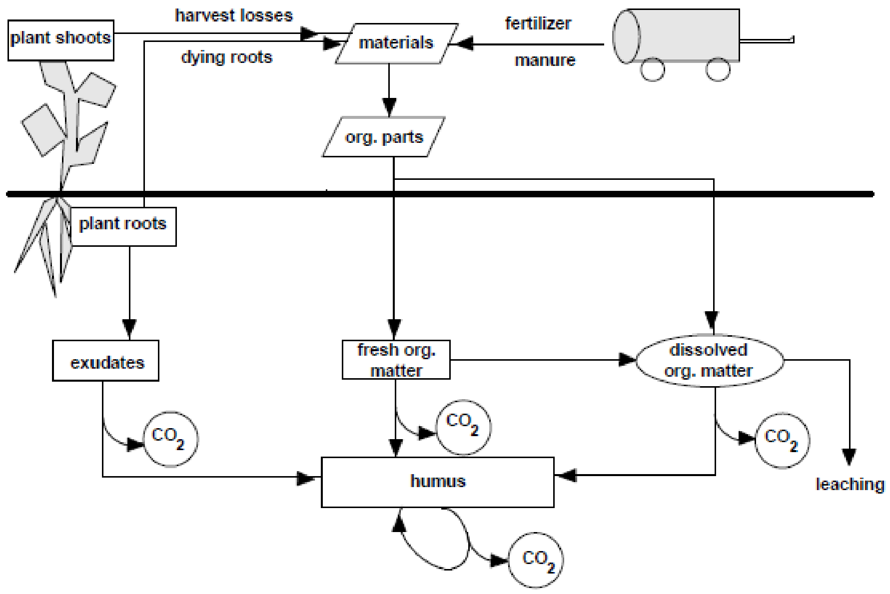


Figure 1. Representation of the Carbon cycle in ANIMO.

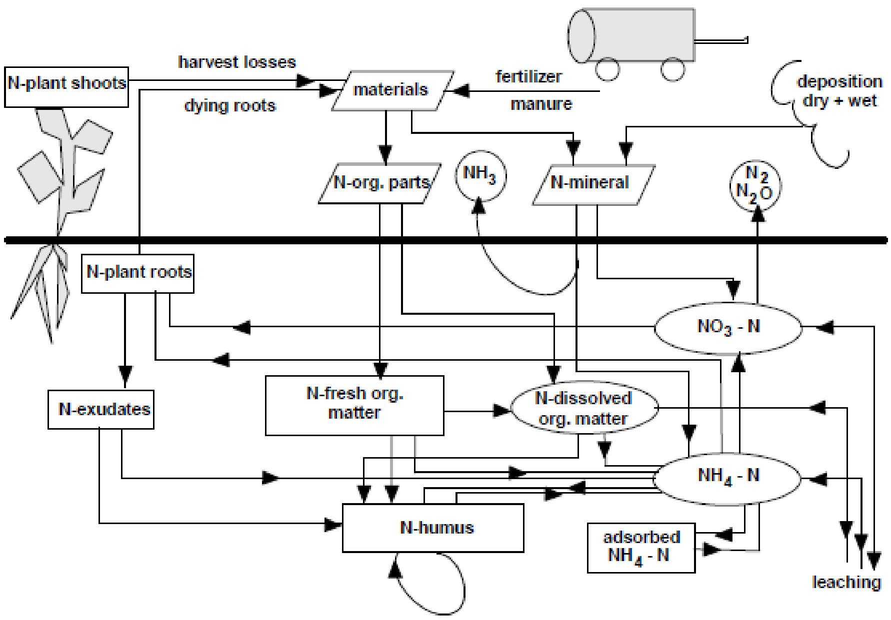


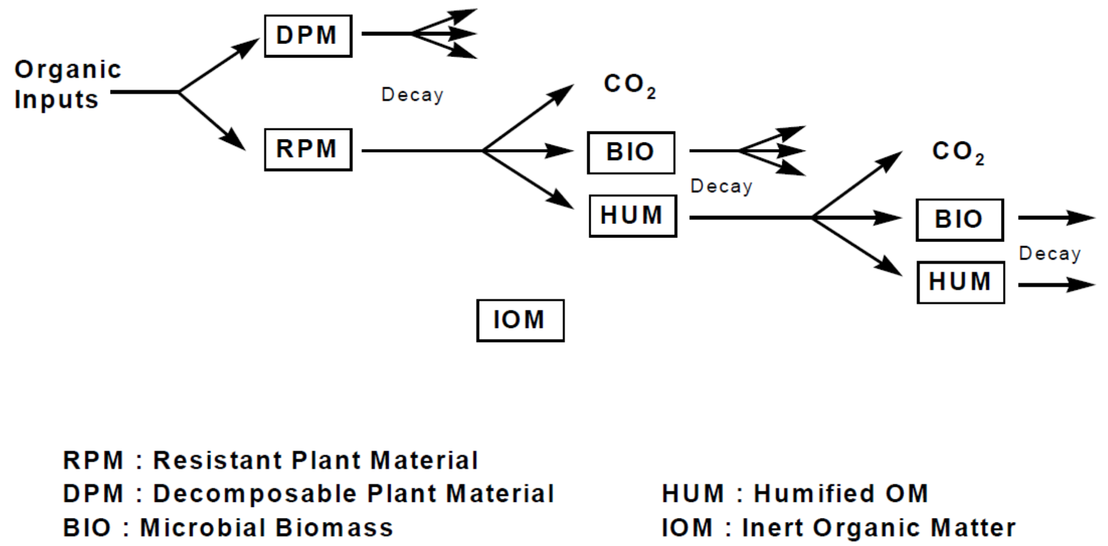
Figure 2. Respresentation of the Nitrogen cycle in ANIMO.

B. Summary description of RothC (version 26.3)

RothC (version 26.3; Coleman and Jenkinson, 1999) is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic carbon (ton C ha^{-1}), microbial biomass carbon (ton C ha^{-1}) and Δ14C (from which the radiocarbon age of the soil can be calculated) on a years to centuries time scale. Soil organic carbon is split into four active compartments and a small amount of inert organic matter (IOM) in RothC. The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition. RothC requires the following input data: 1) monthly rainfall (mm), 2) monthly open pan evaporation (mm), 3) average monthly air temperature (°C), 4) clay content of the soil (as a percentage), 5) an estimate of the decomposability of the incoming plant material – the DPM/RPM ratio, 6) soil cover (is the soil bare or vegetated in a particular month), 7) monthly input of plant residues (ton C ha^{-1}), 8) monthly input of manure (ton C ha^{-1}), and 9) soil depth (cm). Initial carbon content can be provided as an input or calculated according to long term equilibrium (steady state).

In this study RothC was used to calculate the current soil organic carbon balance and the steady state soil carbon stock based on current inputs. For the initial carbon content we used the soil carbon stocks based on the Dutch LSK data and soil map for arable and grassland soils.

Figure 1 - Structure of the Rothamsted Carbon Model



From: Coleman and Jenkinson, 1999.

Appendix VI.
Average temperatures in the Netherlands

Source: KNMI website.

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