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Mitigation

Soil carbon dynamics and variability at the landscape scale: its relation to aspects of spatial distribution in national emission databases

R.W. de Waal | F.K. van Evert | J.G.J. Olivier
B. van Putten | C.J.E. Schulp | G.J. Nabuurs

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Authors

R.W. de Waal [1] , F.K. van Evert [2], J.G.J. Olivier [3], B. van Putten [4], C.J.E. Schulp [5] , G.J. Nabuurs [6]

1 WUR-Alterra
2 WUR-PRI
3 PBL
4 WUR-Biometris
5 LAD
6 EFI

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Summary

Summary in Dutch

In het ME3–project zijn enkele belangrijke bijdragen geleverd aan een verder invulling van de schattingen van emissie en vastlegging van koolstof op een nationale schaal voor de sector landgebruik, landgebruiksverandering, en bosbouw (Land Use, Land Use Change and Forestry, LULUCF) van Nederland. De bijdragen omvatten een analyse van de onzekerheid in de berekeningsmethode die wordt toegepast voor de nationale rapportage van de LULUCF-sector onder het VN-klimaatverdrag, een overzicht van makkelijk toepasbare steekproefstrategieën, een verbetering van het inzicht van de ruimtelijk variabiliteit op landschapsschaal en hoe deze gegevens in te brengen in de rapportage in het kader van de nationale Emissie Registratie. Allereerst worden simpele en overzichtelijke en eenvoudig toepasbare statistische procedures gepresenteerd. Daarbij is gestreefd naar een optimale verhouding tussen resultaat en inspanning. Wat betreft de ruimtelijke variabiliteit is er allereerst gekeken naar de relatie tussen de in de minerale bovengrond (Soil Organic Carbon, SOC) en daarop liggende ectorganisch humus (Forest Floor Carbon, FFC) vastgelegde koolstof en boomsoortenkeuze op enkele locaties in het pleistocene zandgebied. Tevens is er onder andere aan de relatie tussen leeftijd van de opstand, regulier beheer en andere invloeden aandacht besteed.
Verder zijn aan de hand van enkele simulaties de gevolgen van bedrijfsmatige keuzen voor een melkveehouderij en een akkerbouwbedrijf voor de balans van koolstof en broeikasgas doorgerekend. De rol van historisch landgebruik op de vastgelegde koolstof in de bodem komt eveneens aan de orde. Analyses zijn uitgevoerd aan de hand van enkele voorbeeldgebieden uit het zandgebied van midden en het noordoosten van Nederland. Het historische landgebruik blijkt daarbij van een belangrijke verklarende factor te zijn voor de variabiliteit in de koolstofbalans. Het vierde hoofdstuk behandelt het neerschalen van de gegevens en de onzekerheden die daarbij ontstaan ten behoeve van de nationale Emissie Registratie. De onzekerheids analyse van Tier 1 en Tier 2 zijn daarbij met elkaar vergeleken.

Summary

In the ME3 study some important steps are taken for refinement of the estimates for the National System for the Land Use, Land Use Change and Forestry (LULUCF) sector of the Netherlands. This is accomplished by providing sampling designs (chapter 2), by improving insight in soil carbon spatial variability on a landscape scale in relation to management and its history (chapter 3), and incorporation of results from LULUCF studies, amongst other of the uncertainty estimates for the calculation methods used for the LUCLUCF sector, into the Netherlands Greenhouse Gas Emission Inventory and the National Inventory Report for the UN Climate Convention, which are made and updated by the National Emissions Registration (chapter 4). In the first chapter some simple and easily applicable sampling designs are presented along with simple statistical test procedures. The sample designs are optimized in their balance between results and effort or costs. Furthermore, some simulations of the consequences of management choises on a diary farm- and some arable farms systems for the sequestration of carbon and the emissions of greenhouse gasses are performed.

With respect to the spatial variability, first of all, the report focusses on the gap in knowledge on soil and forest floor carbon stocks (SOC and FFC respectively) in relation to tree species in two forested sandy areas in the Netherlands. Also management related items as stand age, forest management

are given some attention. The role of historical land use in the soil carbon balance is highlighted in the next paragraph (3.3). The influence on the soil carbon stock and its variability is examplified for some sandy areas in the central and north eastern part of the Netherlands. This historical landuse turns out to be an important explaining factor in the soil carbon stock. Chapter 4 discusses the aspects of downscaling of results of the ME3 project into the estimation of the national Emission Registration. The uncertainty analyses of Tier 1 and Tier 2 have been compared.

1. Introduction

Slowing down of the human-induced climate change and reducing its effects is the great challenge of our time. Investigation of the global carbon cycle is, in this respect, of great importance. How much greenhouse gases are emitted, with which rate they are fixed as carbon, in which pools, and how strong is the influence of management, are some of the prime questions to be answered. These answers help to decide about the right measures to be taken.
Countries annually have to submit a national greenhouse gases and carbon budgets inventory to the UNFCCC (United Nations Framework Convention on Climate Change). For the carbon budget this means that for a detailed level of land use type stratification, annual budgets of all greenhouse gases will have to be assessed to a level of high certainty for all following pools: aboveground biomass, belowground biomass, coarse woody debris, litter and soil organic matter. This requires innovations in inventory based carbon budgetting, which can distinguish between all these pools, improves the spatial accuracy, and which delivers algorithms to downscale the National Emissions database. The IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (LULUCF) requires countries to report their main national emissions and sinks at a high certainty level, even at a high spatial distribution. In order to do this, a National System for greenhouse gas reporting of the LULUCF sector has been set up (Wyngaert et al. 2007, 2008)
The relation between biospheric sinks research and the official greenhouse gas emission inventory compiled by the national Emission Registration has been very weak in the past. This hampered upscaling of point level results and also hampered downscaling of the national scale data. The official national Emission Registration (ER) system consists of emissions/sinks figures at national level and regional emission maps. These maps are compiled by down-scaling national emissions per source category using spatial distribution information of different types: point source locations, line source data, thematic maps for distribution of diffuse sources and grid maps for grid-based emissions. The quality of the down-scaled emissions has not been assessed. Furthermore, current information used for the within-country distribution is outdated or even missing for some sources.

In the Netherlands the soil carbon pool (SOC) is the largests but also the most uncertain pool. Understanding the spatial and temporal variation of the SOC dynamics in relation to history and management is of crucial importance both scientifically as for the inventory of greenhouse gases. The Netherlands currently lacks an ongoing monitoring scheme for SOM of both agricultural landuse and forestry. The present knowledge is based on a relatively small number (few hundred) of rather old samples, gathered from a combination of databases and ad-hoc research projects. The figures from these sources show forestry as a sink and agricultural land use as a source of carbondioxide (Table 1.1). The agricultural land use on a national scale involves much vaster areas then the area coverede with forest. In terms of C-sequetrations Table 1.1 shows that that despite the restricted area covered with forests that the influence on the rural C-balance is of importance. Changes in this three main land use categories in the Netherlands account for 10 to 15% of the total emissions of greenhouse gasses (Olivier et al., 2005).

Table 1.1.
C-sequestration and emission in the Netherlands in 2000 and 2030 in two scenario's for Europe's rural areas (Schulp et al. 2008a).

	area (km²)			C-sequestration / emission (Gg.jr-1)		
	2000	**2030 A**	**2030 B**	**2000**	**2030 A**	**2030 B**
arable land	10.898	10.908	8.950	- 137	- 170	- 102
grassland	13.904	13.760	13.809	+ 153	+ 104	+ 161
forest	3.819	3.206	4.113	+ 264	+ 195	+ 290
total	**28.621**	**27.874**	**26.872**	**+ 280**	**+ 129**	**+ 349**

This project (ME3) is one of the mitigation projects performed within the framework of BSIK-KvR. Together with the ME1 and the ME2 project this project aims to contribute on a long range to increase the knowledge of biochemical processes in the climate systems (http://www.climatexchange.nl/projects). In the ME3 studies we assess important steps for the National System for the LULUCF sector: both by providing sampling designs and simple statistic procedures (chapter 2), improving insight in soil carbon spatial variability in relation to management and its history (chapter 3) and by deriving and setting up direct links to the National Emissions Registration (chapter 4). In Figure 1.1 the main objects of the ME3-project are showed. The project has links to the ME 1 and ME 2 projects. The ME 1 project is engaged in intergrated observations and modelling of greenhouse gas budgets at the ecosystem level; the ME 2-project in greenhouse gas budgets at a national level in the Netherlands.

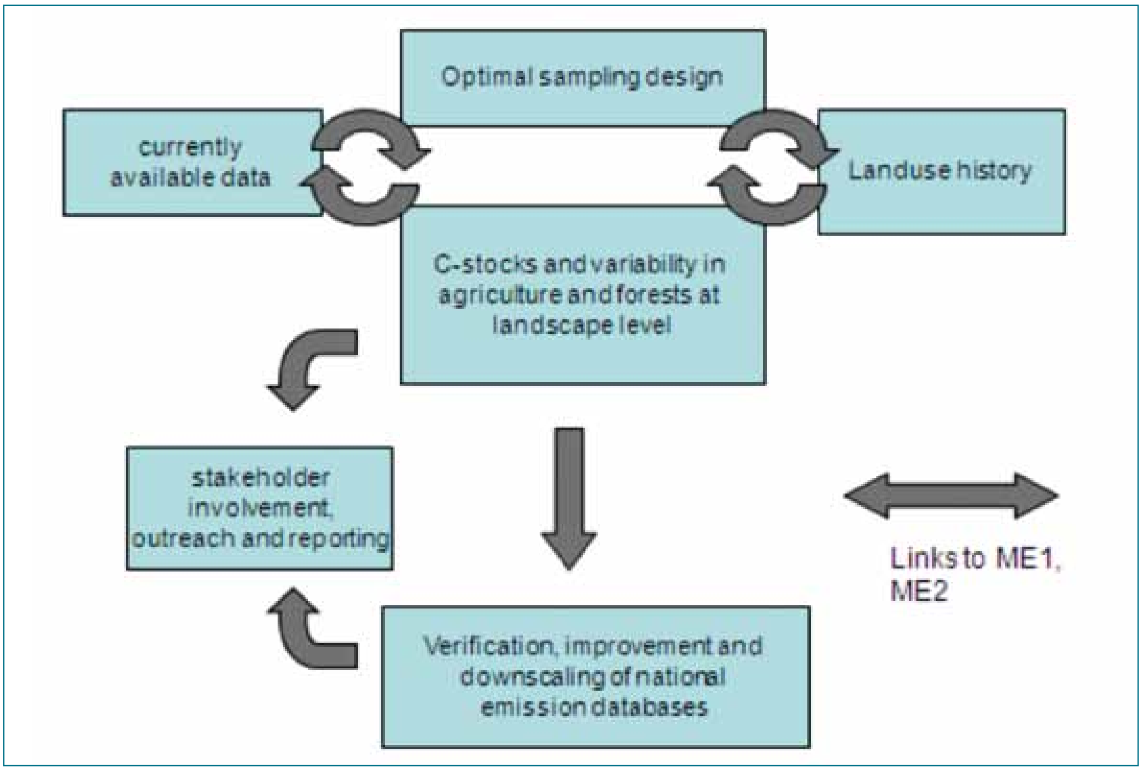

Figure 1.1.
Fields of engagement of the ME-3 project.

2. Working on an optimal design

In carbon sequestration research, quantitative methods play an important role, not only in model selection and model evaluation, but also in optimal design of experiments and allocation of observations.

In Nabuurs et al. (2008a), uncertainty is studied through sensitivity and uncertainty analyses of CO_2FIX which is a user friendly forest, forest soils, and wood products carbon accounting model. Analyses are applied to a Central European managed Norway spruce stand and a secondary tropical forest in Central America. Sensitivity analyses show that parameters exhibiting highest influence on carbon sequestration are carbon content, wood density and current annual increment of stems. Three main conclusions arise from this investigation: (1) parameters that largely determine model output are stem parameters, (2) depending on initial state of the model, perturbation can lead to multiple equilibrium, and (3) the standard deviation of total carbon stock is double in the tropical secondary forest for the wood density, and current annual increment. The standard deviation caused by uncertainty in mortality rate is more than 10-fold in the tropical forest case than in the temperate managed forest. Even in a case with good access to data, the uncertainty remains very high, much higher than what can reasonably be achieved in carbon sequestration through changes in forest management.

In Van Putten and Amézquita (2008), various approaches are discussed of modelling and extrapolation in tropical soil carbon sequestration. Among others, it is argued that an approach based on statistical methodology is to be preferred above commonly used Process Based Simulation modelling techniques.

Van Putten *et al*. (2009) show that in the identification of the 'best' Land Management System with respect to soil carbon sequestration potential, the choice of experimental design is of crucial importance for making correct statistical inference at low costs. As a starting point for our considerations, we take the ever valid notions of replication, randomization and blocking, as formulated by Sir R.A. Fisher who originally developed Analysis of Variance (ANOVA) and is deservedly viewed as the father of modern Experimental Design and Statistical Analysis. In experiments that compare treatments of different plots, blunt application of traditional statistical tests like ANOVA to field observations, can be highly misleading, but it seems that many researchers are not aware of that. (Hulbert 1984, Anselin & Griffith 1988 and Kozak 2009). The fundamental problem is a misperception of the notion of randomization. The treatments are the quantities that need to be randomized and the plots that receive treatments in a randomized manner are the so-called experimental units. Although it is good practice to sample each plot by more than one observation, it is incorrect to treat the individual observations as experimental units as they can be viewed at best only as pseudo-replications. Full recognition of the notions of randomization and replication implies that plots are treated as experimental units, and observations per plot consequently need to be aggregated. This aggregation can be conducted physically, by so-called composite sampling, leading to one observation per plot. This technique, although it reduces laboratory costs substantially, does not reveal any within plot variation. Instead, we advocate 'statistical aggregation' of observations at the plot level, taking into account their spatial correlation. We give evidence that some types of commonly used experimental design, are not appropriate at all for the comparison of treatments, like Design 1, shown in Figure 2.1 in plan form. In Design 1, treatments *A, B, ...* for instance could be various land use systems that are to be compared with respect to the resulting level of carbon stock.

Any statistical inference on treatment effects is impossible as differences in resulting carbon level can be attributed not only to differences between treatments but also to differences between the plots that existed before the experiment (e.g., a landscape gradient).

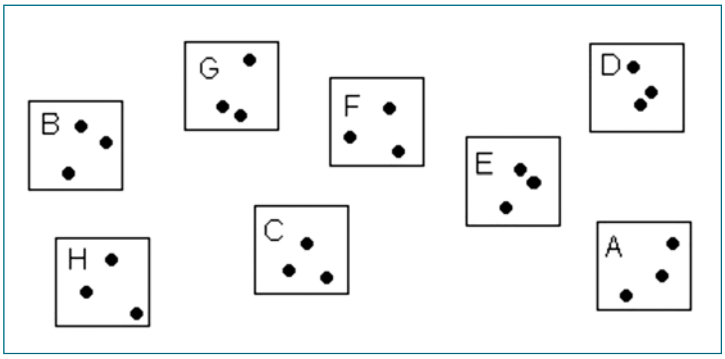

Figure 2.1.
Plan form of an experiment to compare treatments A,B,... . The number of plots and treatments is equal, so that each of the treatments is applied in exactly one of the plots. The dots represent the locations where observations were taken.

A better choice I s Designs 2, depicted in Figure 2.2, consisting of a number of plots that each represent one experimental unit. Treatment *A* is randomly assigned to some plots and treatment *B* is applied to the remaining ones. Observations per plot are sampled systematically or randomly.

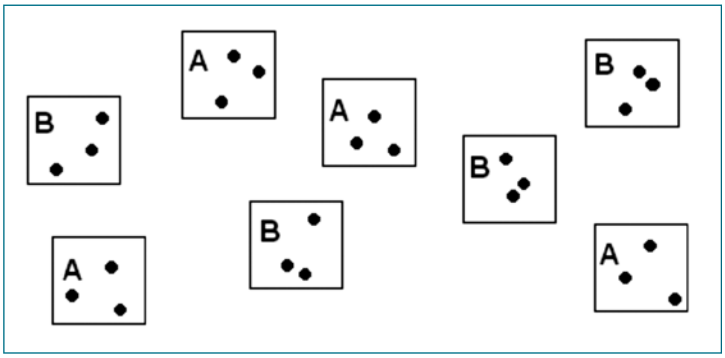

Figure 2.2.
Design 2 of an experiment to compare treatments A and B. Four plots were randomly assigned to treatment A and the remaining four received treatment B. The dots are observations.

If there is considerable variability between the plots, the detection of a possible treatment effect is less likely. When much variability is present, Design 3 in Figure 2.3 could be considered more appropriate as the principle of blocking is used. Each of the plots serves as a block, being divided into two parts that received treatments *A* and *B* following randomization. Observations per sub-plot are sampled systematically or randomly. In this experimental design, in principle even relatively small differences between treatments *A* and *B* can be detected by comparing the two treatments for each pair, especially for homogeneous blocks.

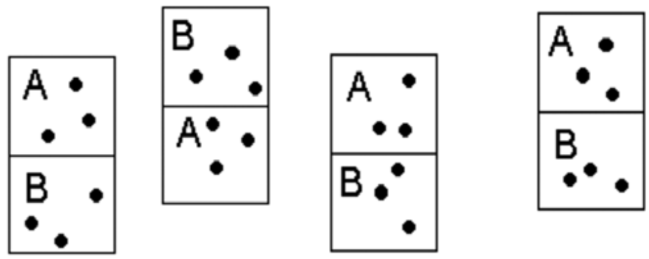

Figure 2.3.
Design 4 of an experiment to compare treatments A and B. Each of four plots has been sub-divided, and for each plot treatment A was randomly assigned to one of the sub-plots, whereas the other sub-plot received treatment B. The dots are observations.

Although Designs 2 and 3 in principle are adequate for the comparison of treatments, they are commonly misused in a subsequent 'statistical' analysis, in which experimental data are processed numerically by ANOVA. In practice, this approach is likely to lead to 'significant' results and it is tempting for a researcher to use this kind of analysis.

As Designs 2 and 3 are both truly replicated, they enable a correct statistical inference on treatments, provided that spatial dependence is carefully accounted for.

Instead of the design-based modelling, the model-based approach appears a natural setting for the comparison of treatments. We derived the Best Linear Unbiased Estimator (BLUE) for the mean of an (undivided) plot, given a spatial dependence structure under the assumption of a stationary isotropic process. For an estimator of the plot mean, the effective number of observations has been defined as the number that is left after their spatial dependence has been removed. Examples have been given for the calculation of the BLUE for the mean of a plot, and also for the calculation of the effective number, under an additional spherical model assumption. For a plot subdivided into two parts, the BLUE of the difference of means is derived. Also a general notion of global regression kriging has been given, of which both the undivided and divided plot are special cases.

The developed techniques allow adequate statistical inference, which is demonstrated in some simple experimental designs, under various model assumptions, both in case the treatments are randomly assigned to (undivided) plots, and in case the treatments are randomly assigned to subdivided plots. In all resulting test statistical test procedures, the effective number of observations appears to play a crucial role. All proposed statistical tests are based on Normality assumptions, apart from a distribution-free test that in the case of subdivided plots is applicable under very mild model assumptions.

Statistical tests developed in van Putten et al. (2009), are based on Best Linear Unbiased Estimation techniques, and have optimal power. Mathematical-statistical proofs are supplied in various Appendices of the paper. The presented methods have a general applicability. More elaborated information on this subject is also to be found in Van Putten et al. 2010 and Olieman et al. 2010.

3. Carbon dynamics and variability in land use and forestry

The Dutch sand area comprises three-quarters of the Dutch forests, making it an important area for sequestration of carbon. Most of this landscape was subject to different degrees of degradation in the past, resulting in large areas of heathland and even drift sands. Over the last century, the landscape has changed drastically, due to large-scale afforestations and conversion to agricultural areas. In this chapter we investigate how the landuse history and past and current management influence the carbon dynamics in the soil and litter layer. Section 3.1 focuses on forests, studying the relationship between soil organic carbon (SOC) as well as the forest floor carbon (FFC) and management of the forest. Section 3.2 focuses on farmland, studying the effects of management practices in a representative farming system on the soil organic carbon as well as on the emission of greenhouse gases. The availability of historic information makes the sandy area very suitable to study the influence of historical land use on the actual carbon stock in the soil. Section 3.3 discusses the possibilities of upscaling the carbon balance of the land use carbon relation.

3.1 Carbon dynamics in forests

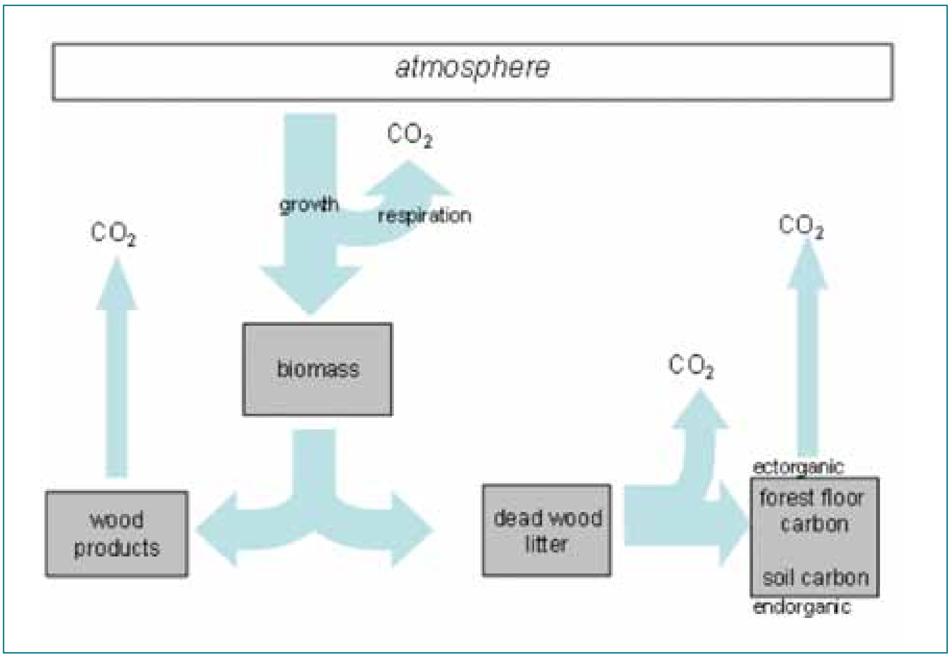

Figure 3.1.
CO_2 sequestration in forests.

In forests, differences in management and forest stand age are assumed to influence the carbon balance (Dale, 1992; Johnson and Curtis, 2001; Jandl et al., 2007). Management includes interventions like harvesting, thinning and fertilizing as well as the choice of tree species (Figure 3.2). In Dutch circumstances harvesting, thinning and fertilizing are of minor importance compared to other European countries (Nabuurs et al., 2008). Tree species affect soil carbon stocks besides dead wood and root activity mainly by the amount and quality of organic matter input through litter fall. Litter fall has large effects on the carbon stock on poor soils, which affects in particular the storage in the litter layer (Figure 3.3 and 3.4). The influence of specific tree species on carbon stocks in the mineral soil is less clear (Binkley and Valentine, 1991; Vesterdal and Raulund-Rasmussen, 1998; Jandl et al., 2007).

In a study of two sample areas in the cover sand region of the Netherlands the effect of tree species is investigated in managed as well as in non-managed stands. The results of this study have been published in (Schulp et al., 2008b). Also, the complete sampling strategy and description of the sample treatment is described in (Schulp et al., 2008b). The poor, acid cover sand and the slightly loamy sands of the ice pushed ridges are besides young drift sand the most common sites in the forested areas of the Netherlands.

Within the two sample areas 10 sample plots for each stand were selected. Each stand has a comparable soil and relief, the same age and species and the same management. Within each plot a mixed sample has been taken of ten stratified samples. The mixed sample with a known volume and weight was analysed on organic matter and carbon. A comparison of the carbon stocks was made between the different species (Figure 3.3).

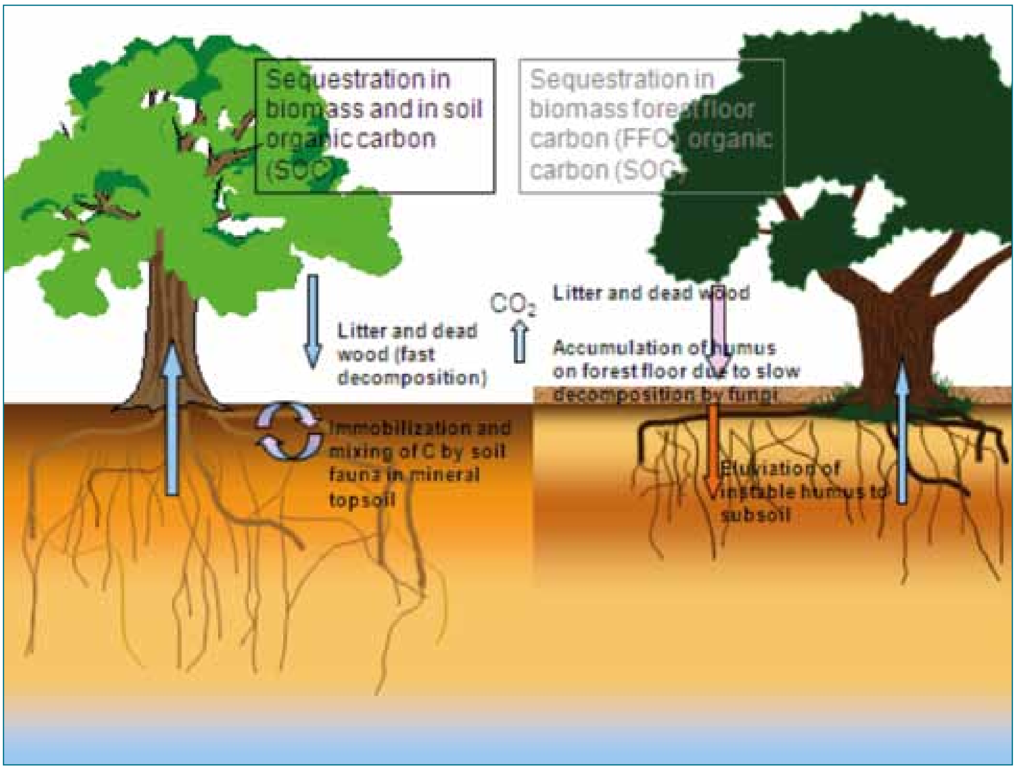

Figure 3. 2.
Sequestration of carbon in dependency of tree species.

Sample size was estimated based on differences in SOC and FFC content between tree species in other studies (Ladegaard-Pedersen et al., 2005). Sampling was carried out in June - August 2006. In each stand, 10 plots of approximately 100 m^2 were located randomly. In each plot one profile description of the mineral soil up to 1.2 m in depth was made and vegetation was described. We registered if there were signs of recent management in the plot, such as thinning, fresh sawing litter, tree harvesting etc. We observed whether plots were disturbed by wild boars and the disturbed area was measured. One bulk density sample of both the 0-10 cm and 10-20 cm layers of the mineral soil were taken in each plot with a soil core sampler.

In each plot ten points were chosen randomly along a 1x1 m grid. At these points, samples of forest floors and mineral topsoil with a fixed area were taken with a 35 cm^2 monolith profile sampler (Wardenaar, 1987). This sampling device is constructed particularly for forest floor and mineral topsoil description and for sampling with minimal disturbance of the forest floor. Forest floor was described (Table 2; Van Delft et al., 2006). Root density was estimated by counting the visible roots and estimating their size. From mineral soil, 0-10 cm and 10-20 cm layers were sampled. From the forest floor, all horizons that could be distinguished separately with sufficient thickness were individually sampled. If horizons were too thin to sample, either the F1 and F2 were combined (abbreviations in Table 2) and the Hr and Hh were combined, or the F1 was sampled separately and the F2+H horizons were combined. All horizons together are referred to as the forest floor. In case L material was present on top of the sample, this was removed. Twigs or dead wood in the F or H remained in the sample, the presence of twigs and dead wood was registered. Composite samples were made in each plot over all samples and points, per forest floor horizon, or group of horizons, to decrease the effects of short-distance spatial variation.

In October 2006, the L horizon was sampled at five locations per stand using a 50 x 50 cm frame. L thickness was measured at ten random locations per sample.

Samples were dried for 24h at 105°C. The dried forest floor and mineral soil samples were weighed for calculation of bulk densities. Mineral soil samples were sieved through a 2-mm sieve to determine the stone content (Table 1). Samples were pre-treated according to NEN5751 (Nederlands Normalisatie Instituut, 1989) and carbon content was determined with a Leco dry combustion element analyzer.

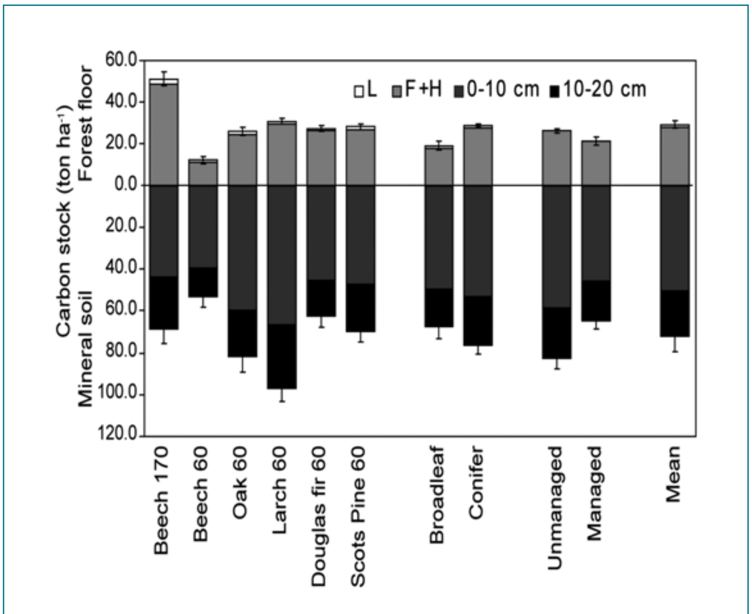

Figure 3.3.
SOC and FFC on the ice pushed ridges of different stands.

For some tree species managed and non-managed, old and young was compared in the slightly loamy area. The tree species involved are Douglas fir, Scotch pine, Oak, Beech and Larch. As a result, different tree species under otherwise similar circumstances have significantly different carbon stocks in both the forest floor and the mineral topsoil. In a larch stand the largest carbon stocks were observed: 29.6 ton per ha in the forest floor and 97.1 ton per ha in the top 20 cm of the mineral soil. The young beech stand had the lowest carbon stocks: 11.1 and 53.3 ton per ha on the forest floor and in the mineral topsoil respectively (Figure 3.3). Carbon stocks were significantly altered by the management intensity. Plots with signs of recent management activities like thinning or harvesting had lower carbon stocks in forest floor and mineral topsoil than unmanaged plots. Comparison of the young beech with the old beech stand shows us the influence of age of the stand on the carbon stock in both the litter layer as the mineral topsoil. On non-calcareous sandy soils the difference shows itself mainly in the above ground stock, on richer soils the storage in the mineral topsoil will dominate (Den Ouden & Verheyen 2010). Figure 3.4 shows the above ground storage in a more or less natural development (without harvesting) of a Scots pine forest into a oak dominated forest (Fanta et al. 2010). Not only the total amount changes but also amount of C stored in the more stabile , semi-permanent humus pool (Hh-layer).

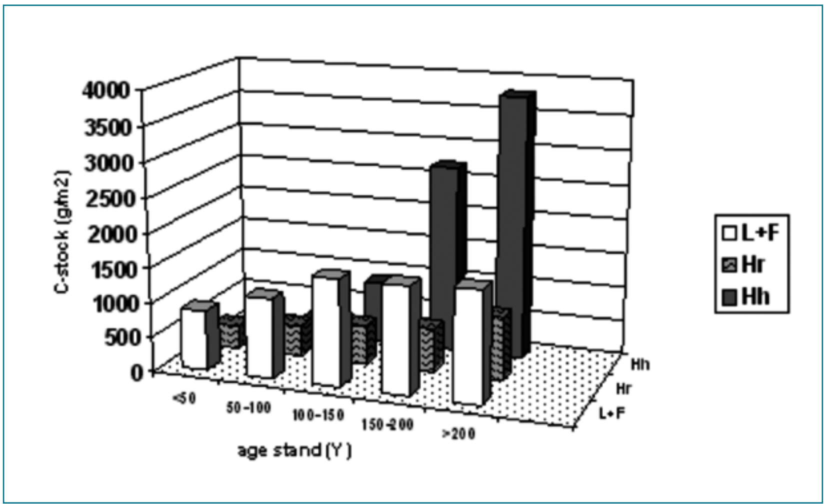

Figure 3.4.
Estimated C-stock in the different litter layers (F, Hr en Hh) in aging barely managed forests with Scots pine and of oak forests on poor sandy soils (Fanta & Siepel, 2010).

In addition with the same method a study has been performed on a poor sandy cover sand area with podzol soils and on stabilized drift sands. On the cover sands Larch, Douglas fir and Scots pine stands, between 60 and 70 year of age have been sampled. In the drift sand area a more than 100 years old oak thicket also has been sampled.

The differences in C-stocks between the tree species were comparable with the results of the study on the ice pushed ridge (figure 3.5). The C-stock under Larch on the poor cover sands, however did not differ significantly from those under Douglas fir and Scots pine. Comparison between the stocks of the same tree species of the different areas shows that the total carbon stock (SOC and FFC) is higher on the somewhat richer ice pushed ridges. Although the forest floor carbon stock (FFC) is clearly higher on the poor sites, the higher SOC of the more loamy sites tips the scale in favour of the latter (Figure 3.3).

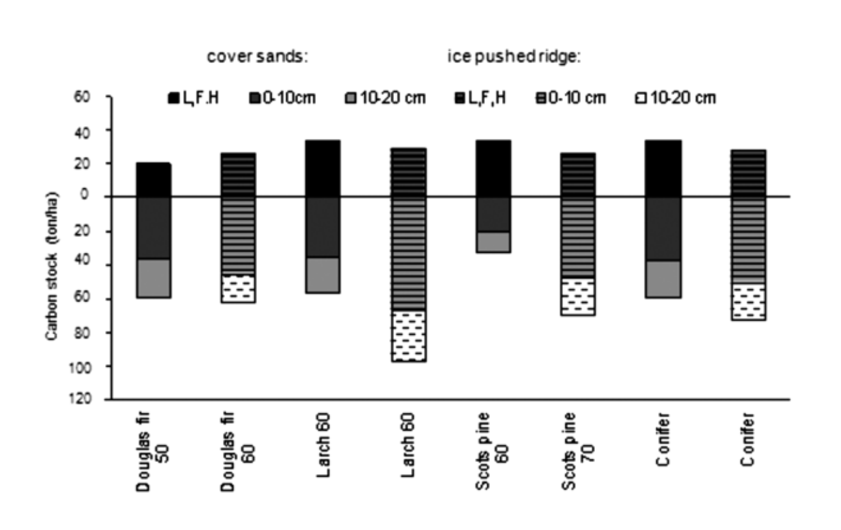

Figure 3.5.
C- stock on the cover sand area and the loamy ice pushed ridge.

This difference is presumable caused by the higher productivity, and therefore the higher litter input on the richer ice pushed ridges. The significant differences stresses the importance of distinguishing site types, which are more than differences in soil alone, while establishing the carbon balance on a national scale.
The old oak thickets on the drift sands showed another source of variability, typical to Dutch forests. Some plots were almost totally ploughed by rooting wild boars, while only one plot did not show any disturbance. This comparison indicated a rather large difference in total C-stock between the rooted and non-rooted areas, although this could not be supported statistically. Further research is of importance in areas that suffer periodically of overpopulation of wild boar.

Conclusions and discussions

Apart from site differences in climate, soil and hydrology, on a more detailed scale, the trees species, the management and the stand age are important for the C-sequestration in the forest. Management of the Dutch forests serves a multiple purpose of which harvesting of wood is only of minor importance. Recreation, Biodiversity, and recently C-storing are the major goals. This means in a lot of cases that conifer forests develop in a more or less natural and gradual way into a natural mixed or broadleaf wood (Fanta & Siepel 2010). Besides forest or conifers and also oak and beech can be transformed by the forest managers into broadleaf stands with tree species with better decomposable litter as Ash, Maple, Lime, Elm and Hornbeam. Both processes means a change in litter decomposition and therefore C-fluxes. On the other hand there are some tendencies in transforming forests into heath land. Against 3800 km^2 forest about 500 km^2 is covered with heathlands in the Netherlands. Its not commonly known that heathlands can also store substantial amounts of C in its litter layers and mineral topsoil while aging (Bijlsma et al. 2008). The expensive management practice of sodding heathlands to keep the heather in a young and purple blooming stage seems to work, in a sense of C-storage (and biodiversity), counter productive. Despite the fact that a lot of (fragmented) field data are available on this subject, needs the C-storage in heath land further investigation. The effects of forest development, the (re)introductions of the rich broad leafs, heath management, and influences of wild boars probably are not very relevant on the national inventory; in studies on regional and sub-regional scale however they can be of substantial importance and need to be investigated.

On base of the results of the ME3 studies an improvement of the national estimations of the C-stocks in the mineral topsoil can be accomplished (Tabel 5.1) by taking into account the tree groups (77.4 ton ha-1 following the NIR; 69.7 in this study). The FFC stocks also can be improved. Especially the improved insight in spatial distribution of the FFC makes more accurate estimation of the loss of C as a result of deforestation possible.

3.2 Carbon and greenhouse gas dynamics in agricultural land use management

Agriculture contributes to climate change through emission of all major greenhouse gases (GHG's) from a variety of sources. For example, use of fossil fuels results in the emission of CO_2, manufacturing of fertilizers results in the emission of CO_2 and N_2O, keeping livestock results in the emission of N_2O and CH_4 (e.g. Steinfeld et al., 2006). Further, agricultural land may lose soil organic matter and thus emits CO_2 for a period of 100 – 200 years after it has been converted to agriculture. (e.g.. Jenkinson, 1991). On the other hand, agricultural land may in some cases also be managed in such a way that it becomes a sink of CO_2 contributing to mitigation of climate changes (Janzen, 2004; Lal, 2001). Emissions of all three GHG's are affected by agricultural management. Because a particular agricultural practice may have opposing effects on each of the greenhouse gases, the net effect of a measure or set of measures is hard to predict (e.. Freibauer et al., 2004). The objective of this work was to evaluate the effect of several plausible measures on emission of greenhouse gases. We investigated dairy farming as well as arable farming.

Modelling – dairy

We used modelling to quantify the net effect of measures. FarmMin is a model that quantifies carbon and nutrient flows on a dairy farm (Van Evert et al., 2003; Van Evert et al., 2007a; Van Evert et al., 2007b; Van Evert et al., 2008; Schut and De Haan, 2005). The model's primary purpose is to study the effects of management decisions on agricultural production and on externalities such as greenhouse gases emissions, carbon sequestration, nitrate leaching, and ammonia emission. FarmMin is suitable for addressing these questions because it uses simple yet realistic relationships to model the entire cycle consisting of using:

- The soil to enable crop growth and feed production;
- the produced feed for production of milk and growth of the cattle;
- the decomposition of organic matter from manure and crop residues after they have been applied to the soil.

Farmmin has been used in a number of studies, either to predict how farmers will respond to legislation (e.g. Schoumans et al., 2002); or to predict the effect of a proposed alternative management of the farm (e.g. Ketelaars et al., 2006). Farmmin has been corroborated using farm-level measurements (Smits et al., 2005) and its prediction of ammonia emissions has been compared with other models (Reidy et al., 2008).

Emission of CH_4 and N_2O is modelled in a simple manner by using emission factors (Schils et al., 2005). The evaluation of CO_2 fluxes, however, requires a more detailed description of the processes involved. To this end, the model of soil organic matter decomposition as given by Yang and Janssen (1997; 2000) was included in Farmmin. This model describes the decomposition of soil carbon and states that after an amount of organic matter has been added to the soil, the fraction of that material that can be recovered declines more or less exponentially with time. The model is expressed by the following formula:

$$C_t = C_o \exp(-R_9 t^{1-S}) \qquad [1]$$

where C_o = organic C added at t = 0, C_t = organic C remaining in the soil at time = t, R_9 = parameter for rate of decomposition at 9 °C, S = rate of ageing of the organic material. The model could be made responsive to temperature by adjusting R, but this is usually only done to account for the large difference that excists between temperate and the tropic climates. The model does not account for effects of the frequency of wetting and drying of the soil.

Mineralization of carbon and nitrogen occur in tandem and some of the mineralized C and N are built into microbial biomass. of Yang and Janssen was extended to describe the amount of N in organic form, either original, or in microbial biomass (Bos et al., 2007). This amount is a function of the C:N ratio of the original material, the C:N ratio of microbial biomass, the ratio of microbial assimilation and disassimilation, and time:

$$N_t = (N_o - C_o/r_{cnmic})\,(C_t/C_o)p + C_t/r_{cnmic} \qquad [2]$$

where N_o = organic N added at t=0, N_t = organic N remaining in the soil at time t=t, r_{cnmic} = C:N of microbial biomass, p = related to ratio of assimilation and disassimilation.

There is a discrepancy between Farmmin, which models equilibrium flows, and the model that expresses soil organic matter decomposition as a function of time. We resolved this discrepancy by running the organic matter model for a period of 50 years, after which the soil organic matter has practically reached the equilibrium that results from the new level of organic matter input to the soil.

Modelling of arable farming

Measures in arable farming that affect soil carbon stock and emission of GHG include selection of fertilizers and manures and the distribution of fertilizers and manures over the various crops in a rotation. We used the model Nutmatch (Bos et al., 2007), a mixed-integer linear-programming model, to simulate the effect of decisions about application of fertilizers and manures.

Crop growth is modelled as a function of available N through a dose – yield response curve. Response curves for the various crops are taken from the Dutch fertilizer recommendation manual. For each crop, the model chooses a N application rate from a discrete number of rates between recommended rate (highest yield) and 50% of the recommended rate.

Decomposition of organic matter and mineralization of N is modelled as described above for the dairy model. Uptake of N, leaching of NO_3, and offtake of N in harvested products are modelled. Economic return is maximized.

Scenarios of dairy farming

We identified four trends in the way dairy farms are managed that likely have an effect on greenhouse gases emission and soil carbon stocks (Table 3.1).

The first trend concerns the limits on application of manure. National governments as well as the EU are imposing ever stricter limits on the application of manure. Currently, the Nitrate Directive limits the application of manure. Many Dutch dairy farmers qualify for exemption from the application limits defined in the Nitrate Directive and are thus allowed to apply 250 kg N from manure per ha per year. However, this exemption is limited in time and it is possible that Dutch dairy farmers will have to comply with the Nitrate Directive's blanket limit of 170 kg N at some future time. Full details about regulations are given by (Van der Meer, 2008).

The second trend is the productivity of dairy cows. Milk productivity in The Netherlands has increased from 6500 kg cow^{-1} in 1989 to 7800 kg cow^{-1} in 2007 (Farm Accountancy Data Network, retrieved from http://ec.europa.eu/agriculture/rica/ on 22 February 2010). It is likely that this trend will continue to some extent.

The third trend is a decrease in the number of hours of grazing during the summer. Grazing leads to some loss of feed through trampling and it may lead to higher NH_3 emissions, nitrate leaching, and inefficient use of manure N. Not too long ago, dairy cows were kept outside all summer, but in the period from 1997 to 2010 the percentage of milking cows that is grazed day and night declined from 48% to 20 %. During the same period the percentage of milking cows that is kept inside all day increased from 8% to 26%
(http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=70736NED&D1=a&D2=0&D3=a&HD=080411-1115&HDR=T&STB=G1,G2, retrieved on 26 October 2011).

The fourth trend concerns the productivity of grassland. Nationwide average grassland productivity is currently 12 t ha^{-1} (Ten Berge et al 2000), but it is our judgement that productivity on well-managed grassland can be as high as 15 t ha^{-1}. The discrepancy between attainable and actual productivity can be explained in part by the quota system for milk; for many farmers it is not useful to increase the productivity of their grassland as long as the quota system limits the amount of milk they are allowed to produce. The upcoming end of the quota system, combined with the availability of new methods to monitor and manage grassland productivity (e.g. Schut et al., 2006) make it likely that grassland productivity will increase significantly in the decades to come.

Table 3.1.
Scenarios used in the dairy modelling.

Measure	**Scenario values** (In chronological order of trend) (Current value in bold)
Application limit on manure N	No limit, **250**, 230, 210, 170 kg N ha^{-1} yr^{-1}
Dairy cow productivity	6, 7, **8**, 9 t head^{-1} yr^{-1}
Grazing	20, **8**, 0 hours day^{-1}
Grassland productivity	**12**, 13, 14, 15 t ha^{-1} yr^{-1}

For each scenario, the model is run with fixed inputs grass and maize acreage, soil fertility, parameters for crop and livestock production functions, number of animals, milk and meat production of cows and growth rate of young stock, grazing regimes and prices of feeds, fertilizers and products. The boundary conditions of the system, as given by regulations, are defined. Then, numerical optimization is used to find the combination of values for the remaining inputs that leads to the lowest cost to the farmer. In this study, we optimized the distribution of available feedstuffs over dairy cows, heifers and calves, the dose of N fertilizer on grass and maize, and the fraction of produced grass that is ensiled.

Scenarios – arable

We represented arable farming on the sandy soils in the Netherlands through six idealized representations of real farms. Three idealized farms use field crops such as winter wheat, potatoes and sugar beets; three others are more intensive farms that produce high-value vegetable crops. We investigated the effect of greater reliance on slurries and composts for all (idealized) farms; in addition, we considered incorporation of straw and use of a green manure for the first two farms (Table 3.2).

Table 3.2.
Scenarios used in the arable modelling.

Farm	Crops	Area (ha)	Measures
NON1	potatoes winter wheat sugarbeet, maize, rapeseed	90	green manures plow straw of grain more manure/ less fertilizer
NON2	potatoes sugar beet winter wheat	80	green manures plow straw of grain more manure/ less fertilizer
ZON1	spinach, potatoes, salsify, maize, sugar beet, carrots	30	more manure/ less fertilizer
VGG4	leeks lettuce	22	more manure/ less fertilizer
VGG5	leeks broccoli, fennel, cabbage	14	more manure/ less fertilizer
VGG6	asparagus + marigold, strawberry, leeks	16	more manure/ less fertilizer

Results – dairy

Simulated GHG emissions are depicted in Figure 3.6. Emissions of the greenhouse gases CH_4 and N_2O on a per-hectare basis are affected by the productivity of cows and by the hours of grazing. Methane emission by cows is directly related to the intake of energy. A high productivity means that fewer cows are needed for a given amount of milk and thus that maintenance metabolism takes up a smaller fraction of the total energy intake by cows. Thus, at a given level of milk production per ha, an increase in the milk production per cow leads to a decrease in emission of CH_4.

A decrease in grazing leads to an increase in methane emission and a decrease in N_2O emission. But with much less grazing at present than in the past, this factor will be relatively unimportant. Eliminating grazing altogether (from the present situation of 8 hours of grazing per day, during 180 days per year) results in an increase in methane emission from 369 to 382 kg CH_4 ha^{-1}, equivalent to in increase from 8,481 to 8,776 kg CO_2-equivalent ha^{-1}, and it results in an decrease of N_2O emission from 8.1 to 6.8 kg N_2O-N ha^{-1} yr^{-1}, equivalent to a decrease from 3,747 to 3,150 CO_2-equivalent $ha^{-1} yr^{-1}$.

Soil carbon stock (Figure. 3.7) is affected by manure application limit and by the productivity of grass. When there is no application limit, soil organic matter reaches an equilibrium of 4.02%. The value corresponding to the current application limit of 250 kg N ha^{-1} is 3.80%. The value corresponding to the EU's limit of 170 kg N ha^{-1} is 3.63%. It is likely that after many years of heavy fertilization, soils are currently close to the value corresponding to no application limit. Thus, if the limit does indeed become 170 kg, a reduction of soil C stocks of up to 9.7% will result.

Soil carbon stock is also affected by the productivity of grass. Raising the productivity of grass (on clay) from its current level of 11556 kg ha-1 to 14556 kg ha^{-1} would result in an increase of soil carbon stock from 3.80% to 3.98%, an increase of 4.7%.

A change in soil carbon stock implies a (temporary) flux of CO_2. When the changes in soil carbon stocks above are averaged over 50 years, decreasing the manure application limit will lead to an average CO_2 emission of 352 kg CO_2 ha^{-1} yr^{-1} for each of the 50 years. Likewise, raising the productivity of grass will lead to a CO_2 sequestration of 154 kg CO2 ha^{-1} yr^{-1}.

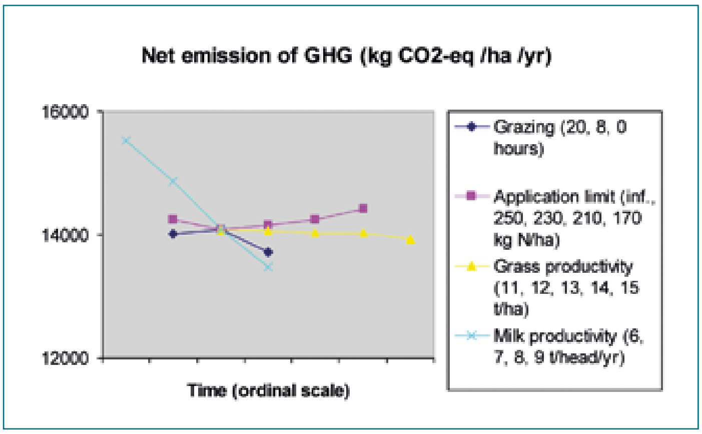

Figure 3.6.
Net emission of GHG emission (kg CO_2-eq ha^{-1} yr^{-1}) as simulated under various dairy farming scenarios.

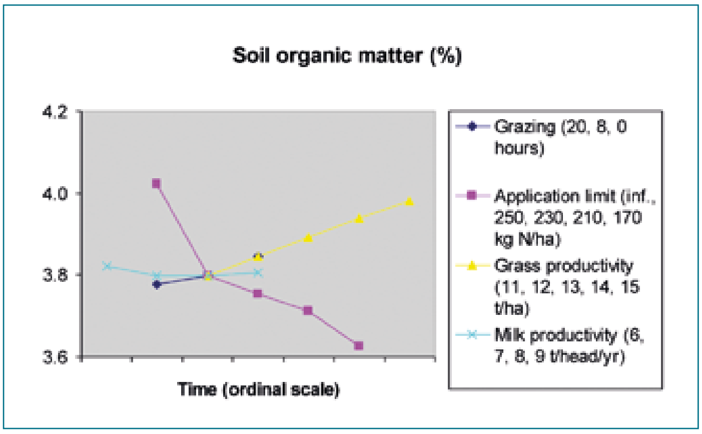

Figure 3.7.
Soil organic matter (%) as simulated under various dairy farming scenarios.

Results – arable

Selected modelling results are shown in Figure 3.8. The two vegetable farms emit more N_2O than the other farms but they increase the soil OM. N_2O emission is related to the crop residues that are produced; the increase in soil OM results because the organic matter from planting pots is included.

Modelling results for several scenarios for the NON1 farm are presented in Figure 3.9. These scenarios can be expected, more or less in the order in which they are given, to lead to more organic matter in the soil. The Figure shows that the increase in soil OM is achieved by applying less mineral fertilizer and much more organic fertilizer. This results in higher N surplus and this is part of the reason for the higher emission of N_2O. But if the emission of N_2O is expressed in CO_2-equiv. and added to the emission or sequestration of CO_2 from change in soil organic matter, the effect of the various scenarios is small (Fig. 3.10). Scenario's give similar results for the other farms and are not shown.

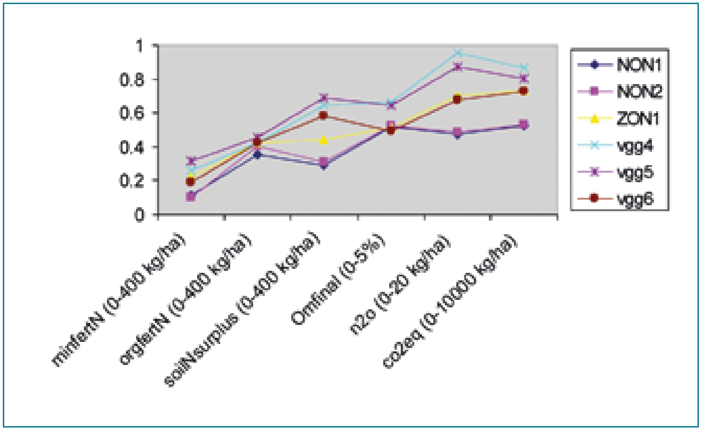

Figure 3.8.
Model results for the six idealized farms with the base scenario. From left to right, six performance indices are plotted (the vertical axis has a different scale for each index). Indices are: minfertN = the amount of N (kg N ha^{-1} yr^{-1}) applied in the form of mineral fertilizer, orgfertN = the amount of N (kg N ha^{-1} yr^{-1}) applied with manures, soilNsurplus = the amount of mineral N (kg N ha^{-1} yr^{-1}) from fertilizers or decomposition of organic matter that is not taken up by the crop, Omfinal = % organic matter in the soil at the 50 year point that we consider; in these simulations, we start with 3% and two of the vegetable farms end up with more but in the other farms there is a loss of soil OM; n2o = emission of N as nitrous oxide (kg N ha^{-1} yr^{-1}), this includes N_2O formed from transformation of leached nitrate, co2eq = net emission of CO_2 equivalents (kg CO_2 ha^{-1} yr^{-1}), resulting from loss (or gain) of soil organic matter expressed as CO_2, and add to it the emission of N_2O in CO_2 equivalents.

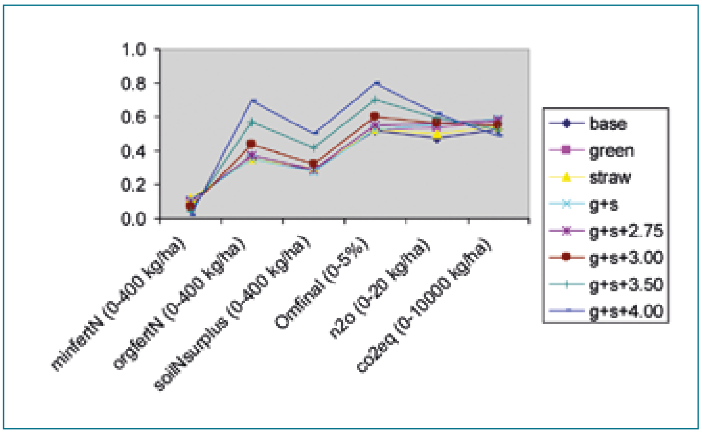

Figure 3.9.
Modelling results for several scenarios for the NON1 farm. The scenarios are as follows: base scenario, base + green manure, base + incorporation of wheat straw, base + green manure + incorporation of straw, and four scenarios in which a minimum soil OM percentage was imposed as an additional constraint.

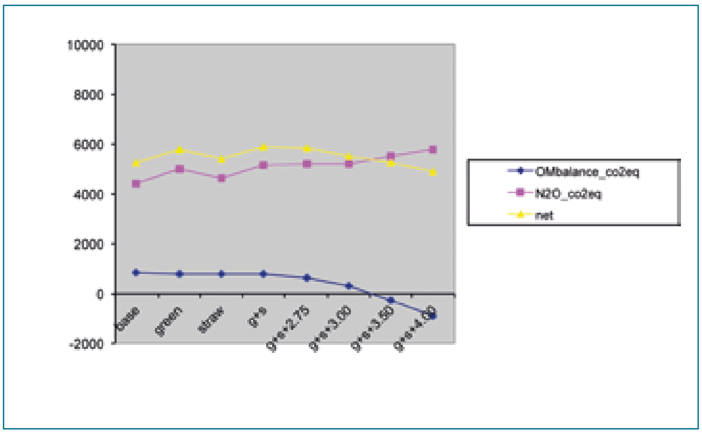

Figure 3.10.
Emission of GHG expressed in kg CO_2-equivalents ha^{-1} yr^{-1}. Shown are emissions or sequestration resulting from changes in soil organic matter content, emission of N_2O, and the sum of these two.

Conclusions and discussion

The dairy farm simulations presented show that for the management measures that we have chosen, the effect on GHG emission is more important than the effect on soil carbon stocks. Therefore, the contribution of dairy farming to climate change can be limited most effectively by reducing the emission of GHG. Increasing the productivity of dairy cows is an effective strategy for reduction of GHG emissions. Of course, highly productive dairy cows have a higher replacement rate so the effect will be partly offset by the GHG emissions associated with raising more young animals; this was not included in our simulations.

Carbon sequestration is increased by increasing the amount of organic matter put into the soil. The simulations quantified the magnitude of this effect for the dairy farm where organic matter input into the soil takes the form of manure and crop residues. Increasing the productivity of grass increases the amount of crop residue (roots, harvest losses) and is an effective strategy for carbon sequestration. Manure application limits are currently high and have been higher in the past. This has resulted in high soil carbon stocks. When these limits are reduced, this will tend to a decrease soil carbon stock.

The model describes the effect of agricultural management on soil carbon stock. However, non-agricultural management such as draining peat soils greatly increases decomposition of soil organic matter (Veenendaal et al., 2007). This effect is larger than anything that can be achieved by agricultural management.

Carbon sequestration in arable farming is not easily achieved in the scenarios that we simulated. The effect of adding more organic matter to the soil through a green manure may be outweighed by higher N_2O emission from the green manure. Anyway, the CO_2-flux resulting from CO_2 sequestration is temporary – it ceases when the new equilibrium has been reached.

Green manure reduces nitrate leaching, but the presence of fresh green matter may give rise to N_2O emission. Emission factors are uncertain with large variations reported.

Livestock farming and arable farming are linked through the exchange of feed and manure. The two types of farming must be considered in tandem when assessing climate change effects. In this study we have not done this.

3.3 Soil carbon variability and historical land use.

Land use influences dynamics of soil organic carbon (SOC). Formation of SOC is a slow process and as a result, it should be expected that the past land use influences present-day SOC stocks. Indications for such relations have, indeed, scarcely been found, e.g. Verheyen et al. (1999) and Sonneveld et al., (2004). Using knowledge on past land use thus could potentially improve insight in SOC variability and therefore could help improve SOC and greenhouse gas inventories. However, the impact of the past land use on SOC dynamics and resulting present-day SOC variability is hardly ever quantified. We explored the impact of long-term land use on SOC dynamics, assessed to which extent the past land use explained SOC variability in a number of case studies, and explored if knowledge on long-term land use could help improve upscaling of SOC and FFC stocks to national scale.

Impact of historical land use on SOC dynamics

Sensitivity of SOC stocks for land use history was tested with the RothC model. RothC simulates SOC built-up in the topsoil using clay content, precipitation, temperature, amount of carbon input from vegetation and manure, and the decomposability of the carbon input (ratio of decomposable to resistant plant material, DPM/RPM ratio). The RothC model is widely used to simulate SOC stocks under a wide range of environmental conditions and a wide range of management systems and scales varying from plot scale to European scale. We simulated SOC stocks for a case study in the central Dutch sand area (Veluwe). Two historical land use systems and two contemporary land use systems were simulated for 200 years, followed by 200 years of high-input present-day agriculture (Table 3.3). Soil, weather and carbon input data were quantified based on several data sources (for details see Schulp & Verburg, 2009).

Table 3.3.
Land use systems used to analyze impact of long-term land use on SOC dynamics.

Land use system	Vegetation C input (ton ha^{-1} yr^{-1})	Manure C input (ton ha^{-1} yr^{-1})	References
High-input historical land use	1.44	5.2	Van Zanden, 1985; Spek, 2004.
Low-input historical land use	1.76	0	Spek, 2004; Van Meeteren, 2007; Aerts, 1989 ; Coleman, 1999.
High-input modern land use	3.27	2.4	Statistics Netherlands, 2008; LEI, 2005
Low-input modern land use	2.60	0.2	Statistics Netherlands, 2008; LEI, 2005; Van Zanden, 1985

Results

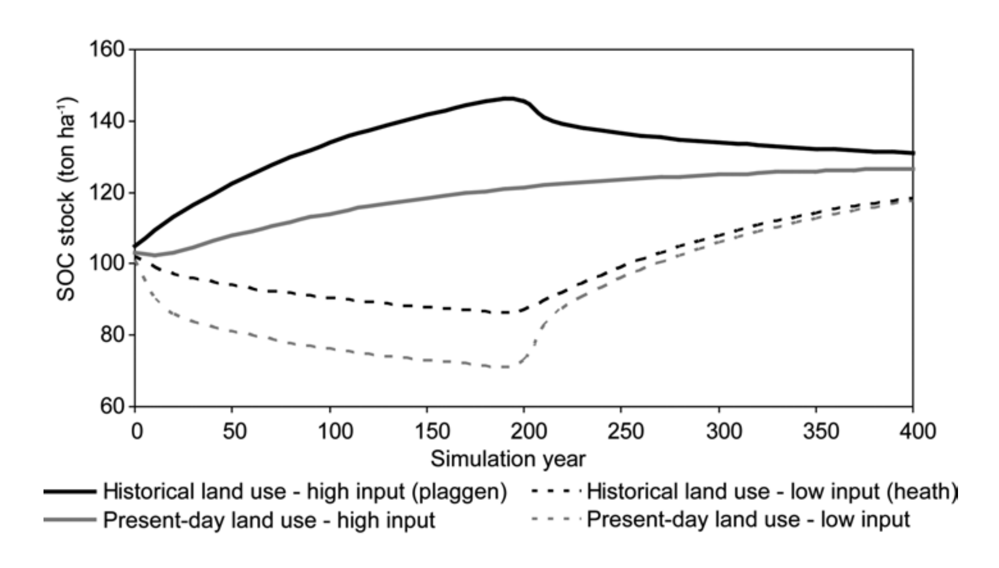

Figure 3.11.
Temporal changes of SOC stocks under contrasting land use systems. From year 200 onwards, conversion of all four land use systems into high-input present-day agriculture is simulated.

Modelling changes of SOC stocks under two contrasting historical land use systems resulted in SOC stock differences of 67% after 200 years (Figure 3.11). From year 200 onwards, we simulated conversion of both land use systems to high-input modern agriculture. SOC stocks then started to converge, resulting in a SOC stock difference of 24% in year 300. Contrasting present-day land use systems have a similar effect on SOC stocks; the difference between high-input and low-input systems was 66% after 200 years and a difference of 20% lasts in year 300. Both disturbed heathland and low-input agriculture resulted in a SOC stock decrease. The difference between the low-input systems is at maximum 19% and quickly decreased after conversion to high-input agriculture. The results suggest that although land use has strong impact on SOC stocks, significant differences only emerge after several decades of unchanged land use and differences between high-input and low-input systems will last decades after conversion to identical land use.

Impact of historical land use on spatial variability of SOC stocks at multiple scales

Because land use needs a long time to influence SOC dynamics and effects of different long-term land uses lasts a long time after conversion to identical present-day land use, it can be expected that historical land use still influences present-day spatial variability of SOC stocks as well. This was tested at different resolutions and extents.

In a case study in the northern Dutch sand area (Nieuwleusen) a detailed reconstruction of the land use history since the first reclamation for agriculture was made. Using a dataset with soil organic matter (SOM) contents from a 1:10.000 soil mapping (Scholten, 1996) the relationships between historical land use and SOM contents were explored at 50m-200m-500m resolution (for details see Schulp & Veldkamp, 2008).
In four case studies across the Dutch sand area (Nieuwleusen, Achterhoek, Veluwe, Den Bosch) a reconstruction of the land use history since 1850 was made using several existing national-scale datasets. Using datasets with soil organic matter (SOM) contents from 1:10.000 soil mappings (Leenders, 1992; Dekkers, 1997; Scholten, 1996; Van der Werff, 1999), relations between historical land use and SOC contents were explored within each site and over all sites. For details see (Schulp, 2009).

Results

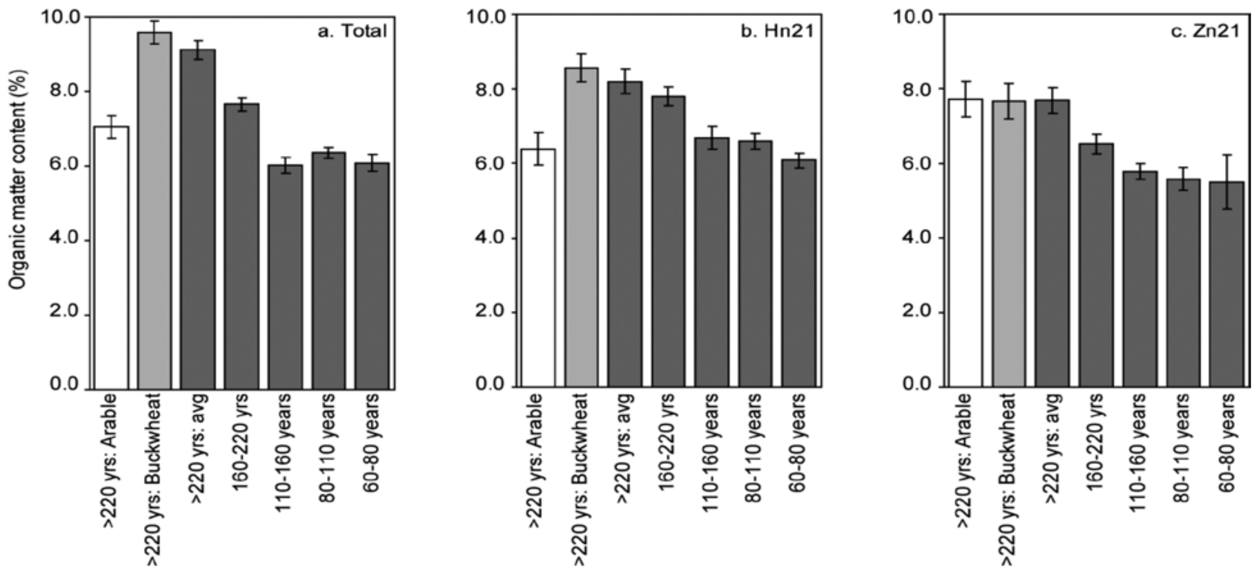

Fig. 3.12.
SOM contents (%) in the Nieuwleusen site for different reclamation age groups for the complete study area (a) and for the main soil types: Gleyic podzols (Hn21, b) and Humic gleysols (Zn21, c). Error bars indicate the SEM.

Table 3.4.
Effect sizes of determinants for SOM content at different resolutions.

Determinants	Resolution		
	50m	200m	500m
Reclamation age	0.37	0.47	0.56
Land use in 1780	0.37	0.44	0.38
Land use in 1850	0.45	0.49	0.53
Land use in 1900	0.20	0.15	0.16 [ns]
Land use in 2000	0.15	0.50	0.75
Permanent grassland	0.04 [ns]	0.19	0.25

[ns] **Effect is not significant at $p<0.05$.**

Table 3.5.
Associations with SOC content (R^2) per site and for the total dataset.

Independent variables	Site				
	Nieuwleusen	Achterhoek	Veluwe	Den Bosch	All sites
	Associations with SOC content – Determinants separately				
Site factors					
Land use history					
Reclamation type	14%	1%	2%	3%	17%
Land use 1900	15%	4%	3%	8%	2%
Present-day land use and management					
Land use 1999	0% *	1%	1%	3%	1%
Permanent grassland	0% *	0% *	1%	1% *	0%
OCeff input by crops per zip code region	19%	4%	0%*	1%	2%
OCeff input by livestock per zip code region	16%	0%*	1%	3%	2%
OCeff input by crops per municipality					6%
OCeff input by livestock per municipality					9%
	Associations with SOC content – Multivariate regressions				
Site factors-Reclamation type	40%	19%	14%	16%	20%
Site factors-LU 1900	39%	20%	11%	18%	12%
Site factors-LU 1900 – Reclamation type	41%	21%	14%	-	21%
Site factors-LU2000	-	19%	-	-	10%
Site factors-LU2000-OCeff	41%	20%	-	18%	11%
Site factors-LU1900-Recl. type-LU2000	-	-	-	-	21%
Site factors-LU1900-Recl. type-LU2000-OCeff	42%	21%	-	21%	21%

* Not significant at $p<0.05$.
– No significant R2 increase upon adding a variable.

On the Nieuwleusen site, at high resolution, historical land use is better for explaining SOM contents than present-day land use while at low resolution the effect of present-day land use is stronger.

When four sites were analysed separately, also lower percentages explained variance of SOC contents were seen when present-day land use was used. When explaining SOC contents over all sites, the scale of the database used to explain SOC contents matters. The detailed high-resolution databases (Land use 1999, permanent grassland, land use 1900) explained less variability than the aggregated databases (OCeff input per municipality, reclamation type). Best to explain SOC contents over all sites was a combination of site factors and historical land use.

Upscaling of SOC stocks using long-term land use as a variable

To conclude from the previous paragraphs, Long-term land use shows a stronger association with SOC stocks than present-day land use. In national-scale inventories of SOC stocks, present-day land use is however commonly used as an upscaling variable while long-term land use is never used for that purpose. Based on the results presented in the previous paragraphs we presume that at national scale using the long-term land use as an explaining variable might improve SOC inventories. In the Netherlands the current SOC inventory is based on an upscaling using soil and groundwater class as variables. We assessed if a national-scale inventory of SOC stocks for the Dutch sand area could be improved using the results from the landscape-scale case studies.

We assessed if factors that explained SOC variability in the case studies also explained SOC variability in a national-scale SOC dataset (Visschers, 2007). With the factors that came out to be relevant at national scale, SOC stocks were upscaled from the national-scale SOC point dataset to the complete Dutch sand area. All upscaled maps were validated by calculating a root mean square error (RMSE) using a jack knifing approach. Also an RMSE for the state-of-the art Dutch SOC map was calculated. RMSE's of the alternative upscalings were compared with the RMSE of the state-of-the-art SOC map, both for the total SOC stock as for the spatial variability (for details, see Schulp et al, 2010).

Using soil and reclamation type for upscaling SOC stocks from points to the agricultural Dutch sand area instead of soil and groundwater improved the estimate of the total SOC stock by 5%. In the forests at the Dutch sand area, using tree group (conifers versus broadleaves) additional to soil and groundwater for upscaling improved the estimate of the total SOC stock by 9%. The estimate of the total forest floor carbon stock was improved by 30% using tree species, age group and soil fertility for upscaling.

When mapping SOC stocks using soil and reclamation type for the agricultural area and tree group additional to soil and groundwater in forests (Figure 3.13), the RMSE of the SOC stock was improved in around 60% of the area (Figure 3.14). Especially in areas with a varied long-term land use including the long-term land use as an upscaling variable was beneficial.

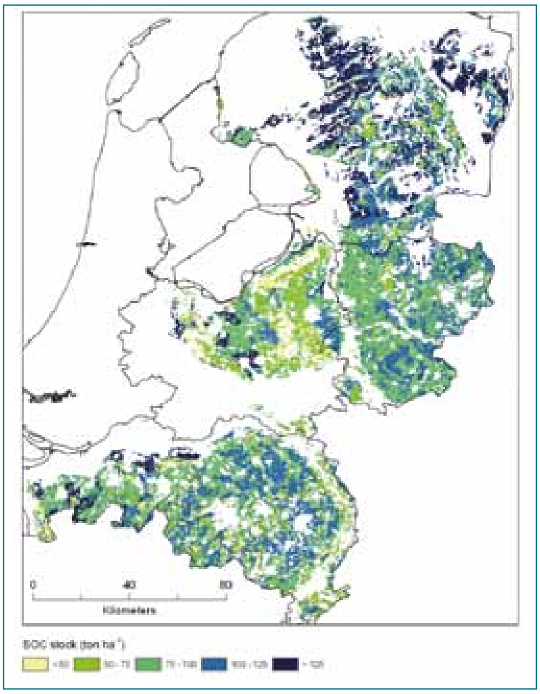

Figure. 3.13.
New map of the SOC stocks in the Dutch sand area, including long-term *land use as an upscaling variable.*

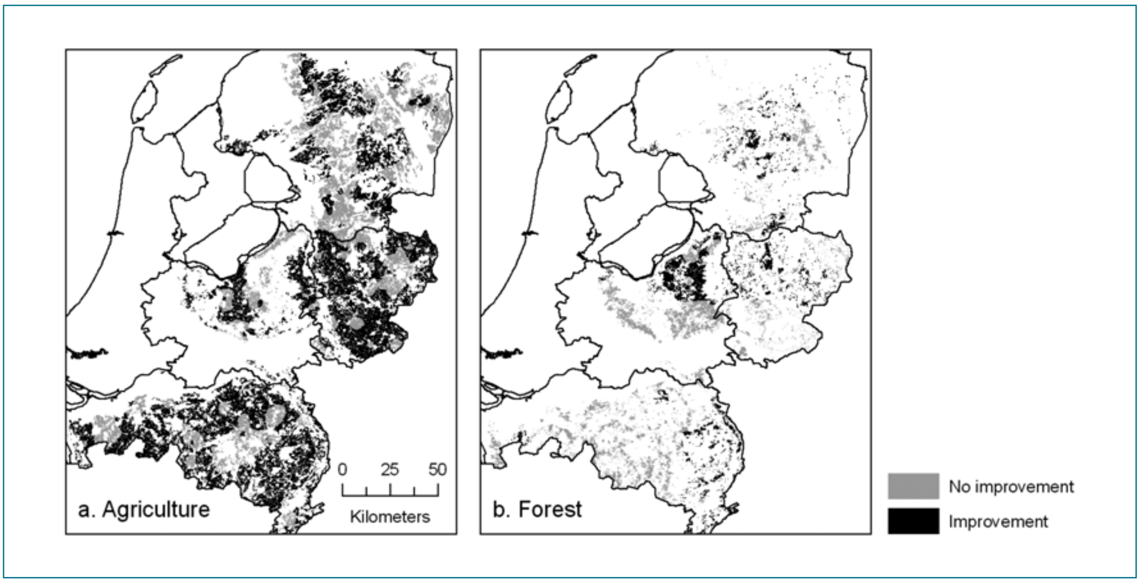

Figure. 3.14.
Areas where fig c improved the current Dutch SOC map.

Synthesis

- Long-term land use explained a larger percentage of SOC variability than present-day land use.
- Causality between long-term land use versus present-day land use: it takes a long time before land use influences SOC stocks and it takes a long time before a new land use has overwritten effects of past land use.
- Relevance of scale: at high resolution, long-term land use explained more SOC variability than present-day land use. At coarser resolution, present-day land use explained more SOC variability. Reason: difference in scale of historical and present-day land use.
- Different effects in different case studies: Interactions between biophysical landscape and the long-term land use.

4. Improvement and downscaling of national emissions database

The Netherlands signed the United Nations Framework Convention on Climate Change (UNFCCC), and, therefore, is bound to report its greenhouse gas emissions annually in a National Inventory Report (NIR). Within the framework of this NIR, an annual uncertainty assessment is made for both national total annual emissions and the trend, from the base year 1990 (1995 for F-gases) to the current year.

The PBL report by Olivier et al. (2009) documents uncertainty estimates used in the assessments performed for the NIR 2006 and (minor) updates made in the later submissions (2007 and 2008). Here, the uncertainty estimates made for all sources of emissions and sinks in the LULUCF sector, developed within this project, have been incorporated (http://www.pbl.nl/en/publications/2009/Uncertainty-in-the-Netherlands-greenhouse-gas-emissions-inventory). These uncertainty estimates for all elements of the LULUCF sector have also assisted in prioritising inventory improvements for this sector.

Uncertainty estimates were made using the simplified IPCC Tier 1 uncertainty analysis following the Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance*. In addition, assumptions and results of two more comprehensive analyses are presented in Ramirez et al. (2006), based on IPCC Tier 2 Monte Carlo assessments. These Tier 1 and Tier 2 assessments were used for identifying areas for improvement within the emissions inventory. Both studies showed that Tier 2 and Tier 1 uncertainty analyses, using similar underlying uncertainty data, resulted in similar magnitudes of overall uncertainty calculations, both for level and trend uncertainty. Therefore, using Tier 1 as the main method for uncertainty analysis in the NIR is justified, also because it is unlikely that the uncertainties will change quickly over the years. A summary of this work is presented in Ramirez et al. (2008).

Another contribution to the estimation of LULUCF emissions/sinks is an improved treatment of soil carbon in the national inventory. Results of this project have been used to include in the emission/sink calculation methodology data for calculation of the soil carbon changes.

For estimating soil carbon stocks in the national inventory, the “LSK/HGN” method as described in Groot et al. (2005) is used. When the land use changes, all carbon that is present in the soil is transferred to the new land use type and does not change to an other equilibrium. Therefore, the carbon content under a certain land use type only changes due to area changes. Based on the soil map combined with soil profile details based on LSK it is possible to produce a map and achieve a spatially explicit picture of the carbon stocks in the topsoil, using the following formula:

$$SOC(1990\text{-}2000),s1 = \sum_{i}^{n} (\text{Os x Bulk density x average C content x Topsoil})/n$$

with:

SOC (1990-2000),s1 = soil organic matter in the period 1990-2000 for soil unit S1 in ton C ha-1

Os = organic substance level in dry ground (%)

Bulk density = kg m-3 dry ground

Average C content = kg C kg-1 o.m. (default is 0.5)

Topsoil = thickness of the topsoil in metres (default is 0,3 m)

N = number of soil samples in soil unit S1

Total change in carbon content in mineral soils in the Netherlands:

$$\Delta C(c, \text{mineral}) = \sum_{s} [(SOC(1990\text{-}2000) \text{ x } A]$$

with

ΔC(c, mineral) = annual change in carbon content in mineral soil (ton C y-1)

SOC(1990-2000) = stock of soil organic substances in the relevant year (ton C ha-1)

SOC(0-T) = soil organic matter stocks in T years for the relevant inventory (ton C ha-1)

T = inventory period in years

A = land area of a specific land use (ha)

S = varying and differentiated soil types

The relevant data and calculations can lead to changes in the areas of specific land use, and to changes in the carbon levels and follow the IPCC requirements concerning methodologies and concepts. The years 1990 and 2000 are based on observations of land use. The values for the period in between are obtained through linear interpolations, and the values for the years after 2000 are obtained via extrapolation. More detailed descriptions of the methods used and emission factors can be found in the protocols on www.greenhousegases.nl.

The uncertainty of the Dutch analysis of carbon levels depends on the collec¬¬tive factors with which the calculations are implemented (calculation of the organic substances in the soil profile and the conversion to a national level) and the land use and land use change data (topographical data). In Table 4.1 the parameters and uncertainty estimate are given. Thus, the uncertainty of the change in carbon content in mineral soil can be calculated at:

Uncertainty ΔC(c, mineral) = √ { (5%)2 + (25%)2 + (10%)2 + (10%)2 + (25%)2 } = 38%

The information on the spatial distribution of the emissions and sinks as compiled in the ME projects has not been used for the Netherlands' Pollutant Release and Transfer Register (PRTR) compiled and managed by the national Emission Registration, but may be evaluated at a later stage to conclude which improvements can be made with respect to the spatial quality of the emissions and sinks.

Table 4.1.
Parameters and uncertainty estimate for 'soil carbon'.

Factor	Uncertainty estimate	References
OM content	5%	Groot et al. 2005, page 24.
Bulk density	25%	Calculated using pedotransfer functions (Groot et al, 2005). Estimates of uncertainty (expert judgment): Peat: 25%, Clay: 10-25%, Sand: 10%.
C content of OM	10%	50% is used as average value, but is assumed to vary between 45% and 55%.
Thickness of soil	10%	Expert judgment: estimated augering = up to 30 cm. So ± a few centimeters = ± 10%.
Area of land use type on a certain soil type	25%	Depends on uncertainty land use maps (5%; expert judgement) and uncertainty in soil data ((Kuikman et al. 2003) give max. 80% accuracy for these data). à 50% is probably too high à 25%.

The methodology for assessing the carbon sources and sinks in forests as applied for the Netherlands forests has also been used by PBL for evaluating the quality of global estimates for CO_2 emissions related to forests and other vegetation (Van der Werf et al., 2009).

5. Discussion and conclusions

In general the results of the ME3 studies contribute to an improvement of the National inventory of C and GHG's. By involving factors as tree species, age of stands, former landuse and agricultural management estimations can be improved. On a regional scale even more progress can be gained. On this level however more studie and survey is needed. Moreover a lot of usefull data are not yet available or accessible. Especially the data on FFC are strongly fragmented and need to be made available.

Optimal designs

With respect to the study on soil carbon sequestration potential, the choice of experimental design is of crucial importance. In chapter 2 the optimization between correct statistical inference and low costs is presented. In all resulting statistical test procedures, the effective number of observations appears to play a crucial role. All proposed statistical tests are based on very mild model assumptions for both normal and free distribution. The principles of an optimal design presented here have been applied, among others in the inventory and processing of the carbon stocks in different stands presented in chapter 3. The used designs are relatively simple en can generally be applicated.

Carbon Dynamics in forests

By relating carbon stocks in topsoils and on forest floors (ectorganic humus layer) on properties as tree species, management, age of stand a further refinement on the variability of the carbon stocks on a landscape scale can be accomplished. Of course the choice of tree species and indirectly the stand age are connected with the kind of management. A commercial management, focussed on harvesting, implies often other choices then a management that's focused on carbon-sequestration. To optimize between a fast growth rate (biomass production), desired species by the market, and an optimal tree age is often not optimal for carbon sequestration. Harvesting means interruption not only of the accumulation of the biomass but also the accumulation in the litter layer (Penman et al. 2003, Wyngaert et al., in prep.). On the other hand is a management focussed on biodiversity- and recreation not always the most desired in terms of functioning as a carbon sink. In the Netherlands harvesting is only a secondary goal. This means that a more or less natural development or an on recreation and biodiversity based management has to be expected in which tree species and stand age are important factors. In Schulp et al. (2008c) it is concluded that a differentiation in conifers and broad leafs could narrow down the variability in estimating the carbon stocks in forests. One has to be aware that this is true for most of the common tree species. For ecological reasons some other broad leaf tree species are expected to gain importance as replacement for oak, beech and conifers. These trees (a.o. ash, maple and lime) distinguish themselves by a very different behaviour concerning litter decomposition (Hommel et al. 2007).

The effects on C-stocks of the forest floor and the mineral topsoil need further investigation. For inventory of carbon stocks on a national scale however differentiation in conifers, litter forming broad leafs (Oak and Beech) and rich broad leafs (Ash, Maple, Hornbeam, Lime tree) would probably be sufficient to cope with variability. Combined with information on biomass dynamics in the forest and the use of models like CO2FIX (Schelhaas et al. 2004) a better estimation on a national scale as well on a regional and even sub regional scale can be obtained. However there are influences not included in this study which need further investigation. For example more supplementary study of the relation between stand age and forest history on one side and the mitigation potential on the other side is needed.

Also further investigation of for example the effect of overpopulation of wild boars in extended fenced areas in the Netherlands on the carbon stock can contribute to a further refinement of the estimation of carbon stocks in the forests. Additional research in other regions with different landscapes with different soils, for example the coastal dune area and the limestone and loess area in the south of the Netherlands could result in a further improvement of carbon estimations on a more detailed scale. Local studies (Bijlsma et al. 2009) indicate that an inventory of the sequestration of CO_2 in semi natural environments outside forests like extended heathlands could be performed in nearly the same way.

Agricultural land use management

A more reliable estimation of the national and regional carbon balance needs the involvement of an inventory of farm systems. The contribution of dairy farming to climate change can be limited most effectively by reducing the emission of GHG. Increasing the productivity of dairy cows is an effective strategy for reduction of GHG emissions. Increasing the productivity of grass in less intensive farming systems increases the amount of crop residue (roots, harvest losses) and is an effective strategy for carbon sequestration. Carbon sequestration in arable farming however is not easily achieved in the scenarios that are presented in this report. The effect of adding more organic matter to the soil through green manure may be outweighed by higher N_2O emission from the green manure. Moreover the CO_2-flux resulting from CO_2 sequestration is only temporary – it ceases when the new equilibrium has been reached. Another important aspect is application of manure. Limits to the quantity of manure that can be applied are currently high but have been higher in the past. This has resulted in high soil carbon stock. When these limits are reduced, this will tend to a decrease of soil carbon stock. In the Dutch examples of modern and very intensive dairy and arable farms not much improvement is to be gained in terms of carbon stocking and reductions of emissions of greenhouse gases by intensifying the farming system. In other European regions however, with less intensive farm systems the profit could be more substantial.

An additional remark has to be made about effects of farm management in relation to other factors. The relevance of farm management depends on the landscape. For example, in the western peat areas of the Netherlands where dairy farming is by far the dominant farming system, the effect of large scale hydrological management out-weights the effects of the farm management. Draining peat soils leads to decomposition of organic matter at a rate that is far higher than can be mitigated by any agricultural measure. Livestock farming and arable farming are linked through the exchange of food and manure. In this study the two types of farming are not considered in tandem when assessing climate change effects. Some improvement could be accomplished here. Simulation of other farming systems could improve our estimations of the GHG and carbon balance on regional and national scale.

A last remark must be made on the use of Farmin in respect to expected climate changes. The model gives insight in how much can be gained from a respect of GHG-emissions by application of different farm management systems. The model though cannot answer questions like what changes in emissions can be expected following rise or fall in temperature, rain or CO_2-concentrations.

Historical land use

Addition of information on former land use can provide in a further improvement on inventories in rural areas in carbon dynamics. The ME3-study gives a good insight in the profit to be gained and the methods which are at our disposal for applying it on other landscapes in other countries. The investigation of the influence of historical land use in the study areas prove that long-term land use explains a larger percentage of SOC variability than present-day land use. It takes a long time before land use influences SOC stocks and it takes a long time before a new land use has overwritten effects of past land use. Also the scale is relevant. At high resolution, long-term land use explained more SOC variability than present-day land use. At coarser resolution, present-day land use explained more SOC variability. This is caused by discrepancy in scale of historical and present-day land use. Further variability can be caused by interactions between biophysical landscape and the long-term land use. Refining of the sequestration balance needs however also in this case, study of the influence of former land use in other landscapes. The method used in this project could well be adapted for studying other western European landscapes.

One has to be aware that application of the mere figures in most other countries and regions in Europe is not to be recommended because of different abiotic circumstances, landscapes and management practices in each region. The methods however are applicable in other regions and countries, but one has to realize that in the Netherlands the availability of regional and national data bases on a suitable scale, especially on soils and land use history, is rather high. This availability may be restricted or even absent in other EU-countries.

Uncertainty and downscaling

Uncertainty estimates for the calculation methods made for all sources of emissions and sinks in the LULUCF sector were developed within this project and have been incorporated in the NIR 2006 and (minor) updates made in the later submissions (2007 and 2008). They have been used for the overall uncertainty assessment of the total GHG inventory to identify the large areas of uncertainty in share and trend of GHG sources and sinks. These uncertainty estimates for all elements of the LULUCF sector have also assisted in prioritising inventory improvements for this sector.The estimates for the calculation methods used for the LUCLUF sector have been documented in more details in a separate PBL report (Olivier et al. 2009). Here, the uncertainty estimates emissions and sinks in the LULUCF sector, developed within this project, have been incorporated.

Another contribution to the estimation of LULUCF emissions/sinks is an improved treatment of soil carbon in the national inventory. Results of this project have been used to include in the emission/sink calculation methodology data for calculation of the soil carbon changes (Tabel 1.1 p. 5 and the calculation of the National SOC stocks (Tabel 4.1). As far as improvement and downscaling for the balances on a national scale Tier 1 and Tier 2 uncertainty analyses are compared. These studies shows us that for the NIR the use of Tier 1 analysis is still justified as the main approach onto both level and trend uncertainty. For estimating soil carbon stocks in the national inventory, the "LSK/HGN" method as described in Groot et al. (2005) is used. When the land use changes, all carbon that is present in the soil is transferred to the new land use type and does not change to an other equilibrium. Therefore, the carbon content under a certain land use type only changes due to area changes. Based on the soil map combined with soil profile data it is possible to get an more accurate overview of the carbon stock in the topsoils.

General conclusion is that National estimates can be improved (Tabel 5.1). On a regional scale even more improvement can be achieved. Accuracy of the SOC maps can be increased with 19-23% in about 60% of the Dutch sand-areas (Schulp 2009). For the FFC a substantial improvement can be accomplished for half of the sandy area.

Tabel 5.1.
Ton ha^{-1} SOC stock and national SOC stock (Mton) per land use type as found in the NIR and in the ME3-study (Schulp 2009, 2010).

Land use type	Mean SOC stock (ton ha^{-1})		Total SOC stocks (Mton)	
	NIR	Schulp 2009	NIR	Schulp 2009
Cropland	105.5	103.3	53.7	52.5
Grassland	106.6	103.2	30.4	29.4
Other agriculture	96.2	94	8.1	7.9
Forest	77.4	69.7	20.3	16.1
Total			112.4	105.8

The research on the spatial variability of carbon dynamics on a landscape scale contribute to a further improvement of inventory of carbon and greenhouse gases. The information on the spatial distribution of the emissions and sinks as compiled in the ME projects has not been used for the Netherlands' Pollutant Release and Transfer Register (PRTR), but may be evaluated at a later stage to conclude which improvements can be made with respect to the spatial quality of the emissions and sinks in the national GHG inventory. The methodology for assessing the carbon sources and sinks in forests as applied for the Dutch forests has also been used by PBL for evaluating the quality of global estimates for CO_2 emissions related to forests and other vegetation (Van der Werf et al., 2009).

Scientific output

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Climate changes Spatial Planning

Climate change is one of the major environmental issues of this century. The Netherlands are expected to face climate change impacts on all land- and water related sectors. Therefore water management and spatial planning have to take climate change into account. The research programme 'Climate changes Spatial Planning', that ran from 2004 to 2011, aimed to create applied knowledge to support society to take the right decisions and measures to reduce the adverse impacts of climate change. It focused on enhancing joint learning between scientists and practitioners in the fields of spatial planning, nature, agriculture, and water- and flood risk management. Under the programme five themes were developed: climate scenarios; mitigation; adaptation; integration and communication. Of all scientific research projects synthesis reports were produced. This report is part of the Mitigation series.

Mitigation

The primary causes for rising concentration of greenhouse gases (GHG) in the atmosphere are fossil fuel combustion, land use and land use change (deforestation). Yet our understanding of interactions between land use (change) and climate is still uncertain. Climate changes Spatial Planning contributed to the development of a system that allows both the best possible 'bottom-up' estimate of the GHG balance in the Netherlands, as well as independent verification 'top-down'. This system supports better management, i.e. reductions of GHG emissions in the land use sector. In this context it addressed a.o. the possibilities and spatial implications of second generation biomass production.

Programme Office Climate changes Spatial Planning

P.O. Box 1072
3430 BB Nieuwegein
The Netherlands
T +31 30 6069 780

c/o Alterra, Wageningen UR
P.O. Box 47
6700 AA Wageningen
The Netherlands
T +31 317 48 6540
info@klimaatvoorruimte.nl

www.climatechangesspatialplanning.nl