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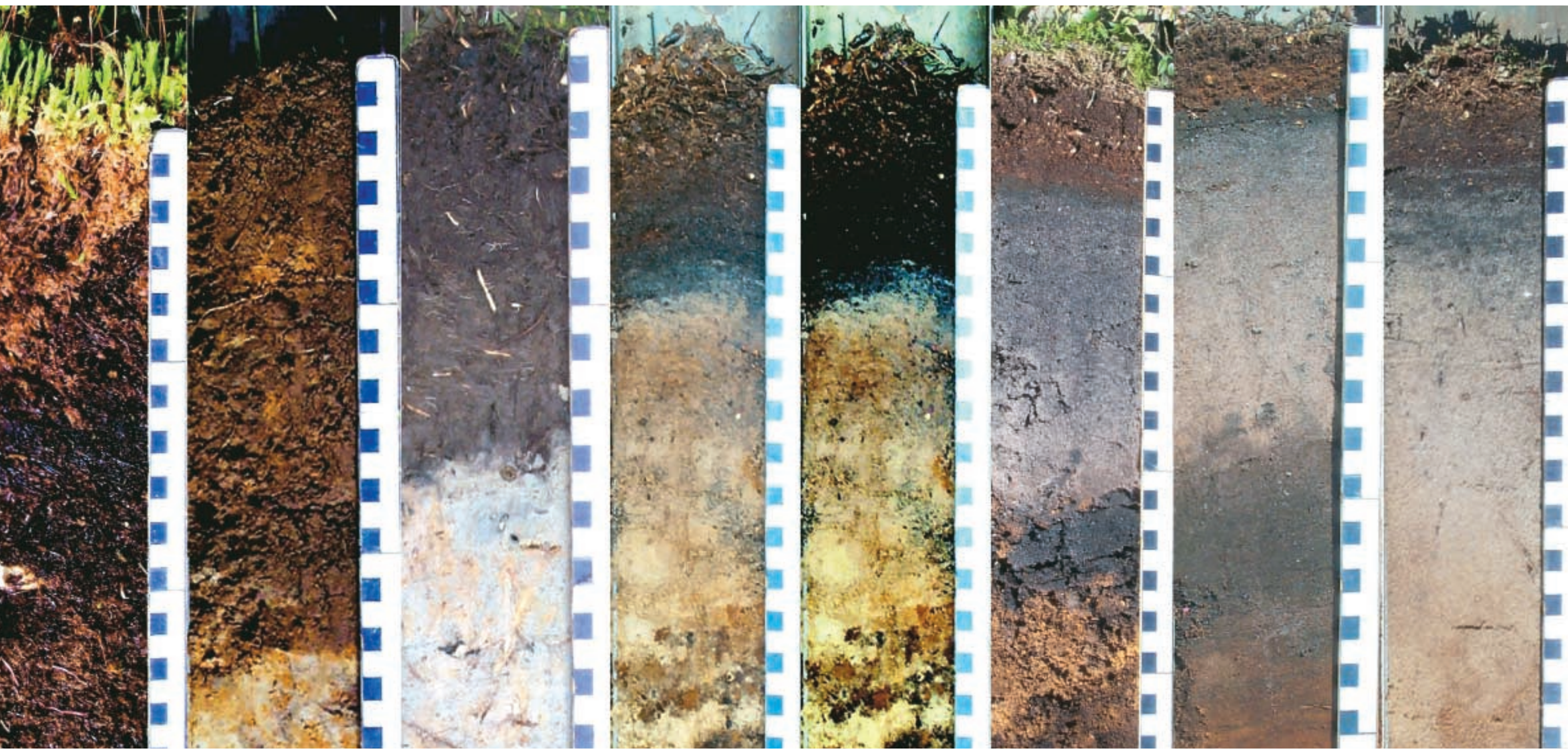
# Separation of direct and indirect effects on carbon sequestration and C stocks: an inventory of methodologies

Jan Verhagen & Peter Kuikman (red.), Ton Gorissen, Jan Willem van Groenigen, Gert Jan Nabuurs, Raymond Jongschaap, Bart Kruijt, Isabel van Wyngaerde, Annemieke Smit, Cees van den Berg, Bert van der Werf, Kor Zwart & Reind Visschers



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Jan Verhagen[1] & Peter Kuikman[2] (red.), Ton Gorissen[1], Jan Willem van Groenigen[2], Gert Jan Nabuurs[2], Raymond Jongschaap[1], Bart Kruijt[2], Isabel van Wyngaerde[2], Annemieke Smit[2], Cees van den Berg[2], Bert van der Werf[2], Kor Zwart[2] & Reind Visschers[2]

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# 1. Introduction

At the Marrakech Conference Of Parties (COP) the United Nations Framework Convention on Climate Change (UNFCCC) formulated the following request to the IPCC:

*To develop practicable methodologies to factor out direct human-induced changes in carbon stocks and greenhouse gas emissions by sources and removals by sinks from changes in carbon stocks and greenhouse gas emissions by sources and removals by sinks due to indirect human-induced and natural effects (such as those from carbon dioxide fertilization and nitrogen deposition), and effects due to past practices in forests (pre-reference year), to be submitted to the Conference of the Parties at its tenth session; (Decision 11/CP.7 3(d), Page 55).*

The rationale behind this text is simple: the additional effect of activities to reduce emissions is rewarded excluding possible positive or negative effects resulting from other human induced activities and natural effects which influence the emission of greenhouse gasses.

Although the rationale and question are simple to define an answer is not. As the question was formulated in a policy arena the consequences for the science arena were not clear at the time the issue was put on the agenda. Untangling the numerous factors leading to an increase in the carbon stock or reduction of emission is not a trivial matter, let alone when also the nature of agent and effects over larger timescales should be included in the equation.

In this report a start is made with unravelling the issue with an inventory of possible methods, and their applicability, to separate the direct and indirect effects in relation to carbon sequestration in agricultural land use and managed forest ecosystems. It provides an inventory of methodologies to separate direct and indirect effects and uncertainties and areas for future research are identified.

During the execution of this study it became clear that hardly any literature was available on the matter of separating direct and indirect effects. A detailed literature review on processes and the interaction with climate and management was conducted. Parallel to this literature review a framework to list and evaluate several methodologies was created. During the creation of the framework the project came in a deadlock and the project was halted for some to discuss on how to move forward.

In the same period the IPCC released a workshops report that looked at the separation of direct and indirect effect. The key conclusion was that the scientific community cannot currently provide a practicable methodology that would factor out direct human-induced effects from indirect human-induced and natural effects for any broad range of LULUCF activities and circumstances (IPCC, 2003).

IPCC (2003) continues to conclude that in many circumstances the direct effects of ARD activities on carbon stocks and greenhouse gas emissions and removals will be much larger than the sum of indirect human-induced and natural effects, and the non-linear interactions among all effects.

After consultation with LNV it was decided to 'restart' the project with the aim to see whether available long-term dataset e.g. TAGA (Kooistra & Kuikman, 2003) and forest data could provide more insight in the dynamics of organic matter. In addition simulation models will be used to mimic the dynamics and explore possible management options and the contribution of N deposition to the carbon budgets of forest and agro ecosystems.

Getting the data out of TAGA was more problematic than first anticipated. Moreover the two selected experiments (IB0013) at Borgercompagnie reclaimed peat soil (dalgrond) and an experiment on a clayey soil at Ammerzoden (PR1255) were not complete enough to allow simulation of the experiment.
Parallel to the TAGA, the still ongoing *De la Lande Cremer* experiments (Zwart, in prep.) and recently collected data from 'Sturen op nitraat' (DWK-programme) were added.

For forestry only one long-term experiment was available (Japanese larch) data was limited to above-ground biomass production. The effect of nitrogen deposition on a *Pinus sylvestris* stand was simulation using CENTURY.

At the time it was anticipated that the data could be used for projects within the DWK climate programme: rol en kosten 3.4 and carbon in soils. Due to changes in research priorities these projects have been reformulated.

The report is written for policy-makers at LNV (the Dutch Ministry of Agriculture, Nature and Food Quality) involved in GHG emissions from land use and in assessing mitigation measures to reduce these emissions. The more detailed literature review (Gorissen & Visser, 2004) is written for a scientific audience.

This study was carried out within the program 'Knowledge development round monitoring of carbon sequestriation and integration of climate-adaption in LNV policy courses' financed by the Dutch Ministry of Agriculture, Nature and Food Quality.

# 2. Purpose and limitations of the study

The study was conducted in two parts. The first part of the study provides an inventory of possible methods, and their applicability, to separate the direct and indirect effects in relation to carbon sequestration in agricultural land use and managed forest ecosystems. It does not address trade off with other $N_2O$ and $CH_4$. It is a first assessment as no clear literature exists on the matter.

We will address a limited number of effects: i) carbon dioxide fertilization; ii) nitrogen deposition; iii) past practices in forests; iv) temperature; v) precipitation; and in less detail vi) radiation levels; vii) flooding, and vii) fire and the impact on the C stock.

The range of temporal and spatial scales at which processes occur and the scales at which management interacts with these processes are not included in this study.

The second part of the study looks at the long-term experiments in forest and agricultural systems and tries to identify and simulate the effects of management on the carbon stocks and fluxes from these systems.

## Inventory of methodologies

Methodologies used to determine C stocks and changes of these stocks were grouped into two major categories (Table 1). For each methodology a short review is presented providing basic information:

- Short description of the method
- Scale & uncertainties
- The link with direct and indirect
- Strong and weak points of the method.

*Table 1. Two methodological groups.*

| Measurements | Models |
|---|---|
| Soil & plot experiments | Soil crop models |
| Crop inventory | Forest models |
| Soil inventory | |
| Forest inventory | |
| Large scale flux measurements | |

The scales distinguished in this study are:

i. *Lab*: this scale allows control and manipulation of environmental factors.
ii. *Plot*: at this scale processes and farm and forest management practices can be tested. Some control and manipulation of environmental factors (e.g. $CO_2$, water, fertilizer) is possible
iii. *Field*: at this scale processes and farm and forest management practices are tested on practical application and adequacy. It is complementary to the plot scale and may include coarse control of some (e.g. water, fertilizer) environmental factors. This scale is typical for farm operations.
iv. *Stand*: the equivalent of field in forest systems.
v. *Farm*: Level of decision making in agriculture. Most statistical and economic data are collected at this level.
vi. *Landscape*: mosaic of different types of land use. Remote sensing and large scale flux measurements are techniques used to collect data at this scale.

A range of methods, operating at different scale, exists change measuring and estimating stocks and flux of carbon and other greenhouse gasses. Only a few of these are linked to the scale of management (plot and field). In the following sections we will discuss several methodologies. See also: Kuikman *et al.*, 2003 and Nabuurs *et al.*, 2003.

## Long-term experiments

Long- term datasets and models have been used to evaluate soil organic matter dynamics in agricultural and forest soils. The data collected in long-term experiments could provide important insight in the role of management and the variability of the carbon stocks and fluxes related to weather conditions.

Well documented long experiments are an important source of information on the carbon dynamics of agricultural systems. Polwson and Poulton (2003) argue that the relevance of these experiments is greatly enhanced when soil and plant samples are archived. In the Netherlands the TAGA archive contains descriptions and results of over 20 000 field experiments and includes 250 000 soil samples and over 50 000 crop samples. Kooista and Kuikman (2003) came to the conclusion that TAGA offers great opportunities to explore carbon sequestration options in agriculture.

Short-term experiments in agriculture are available from ongoing research such as Sturen op Nitraat (a Dutch nitrate management research programme), which may provide information on the current status of soil carbon in these systems.

In combination with dynamic simulation models these long-term and short-term data sets can be used to explore the effect of various management options on the carbon balance.

Long-term forestry experiments are less well documented. Only one long-term experiment was found. The data was limited to the documentation of forest management and the effects on above-ground biomass.

The Forest Intensive Monitoring Coordinating Institute (FIMCI) which started as an initiative to contribute to a better understanding of the impact of air pollution and other factors on forest ecosystems has grown to a full scale monitoring programme which collects data at the plot scale on weather, atmospheric deposition, soil chemistry and vegetation. FIMCI currently includes 862 plots in 31 countries (512 in the EU and 350 outside the EU). This monitoring network could be used for model exploration and validation of the carbon budget of forests.

# 3. Direct and indirect effects

The assignment at hand requires a clear understanding of what is meant by direct human induced, indirect human induced, and natural effects in relation to changes in carbon stocks. It is difficult to define the exact boundaries of direct and indirect effects as the effects are complex, interrelated, non-linear, and strongly variable over time.

Direct effects are related to measurements aiming at carbon sequestration. As such, direct effects are in fact no more than farm of forest management activities aiming at managing the size of the carbon stock or carbon fluxes. Measuring or quantifying the impact of management on the C stock is complex trying to separate the indirect effects of environmental factors like $CO_2$ concentration; N deposition is even more so.

## Carbon sequestration

Crops capture $CO_2$ from the atmosphere via photosynthesis. In agriculture and forestry the crop is harvested and in some cases crop residues are returned to the soil. In most European soils the carbon stocks have been depleted because conventional management doesn't aim at maintaining the carbon stock. Carbon is lost mainly via the decomposition of soil organic material, but extreme cases related to fire, floods and storms may cause removal of the C stock via destruction of topsoil and vegetation.

The carbon stock can be increased via two pathways. Firstly by increasing the input via soil and crop management or addition of organic material. Secondly by reducing the loss of soil organic matter, e.g. via changes in soil and water management.

Area expansion favouring land use types that can store relatively large amounts of carbon is also an efficient way to increase the carbon stock of a region.

Decision 11/CP.7 3 provides some idea on the direction but does not provide an exhaustive list of effects that should be included. The minimum set that should be included based on the decision is:

i. carbon dioxide fertilization
ii. nitrogen deposition
iii. past practices in forests

The challenge to separate direct and indirect effects requires a detailed understanding of the processes involved. Some processes may be simply additive, others synergistic (more than additive) or even antagonistic (less than additive). Gorissen & Visser, 2004 provide a more detailed summation of the underlying processes and options to model these processes.

Additional to the three effects identified above, changes in temperature, precipitation, radiation, flooding frequency and fire frequency will influence the C cycle. How these effects have influenced and will influence the carbon cycle in relation to management is not clear. We will briefly discuss the effects and how they interact with the C cycle.

### Carbon dioxide fertilization

Carbon dioxide ($CO_2$) is needed for plants to grow. In $CO_2$-rich environments plants grow faster, and absorb more carbon. This effect is know as the $CO_2$ fertilization effect. The enhanced plant growth also leads to higher inputs to the soil, both processes contribute to an increased C fixation. The effect of $CO_2$-rich environments on the C dynamics in the soil is less clear. The decomposition of plant material by soil microbial biomass decreases, most likely through changes in the quality of plant material (Gorissen & Visser, 2004).

## Nitrogen deposition

Carbon nitrogen is a crucial element for plant growth, increased levels of nitrogen will increase the primary production of agro-ecosystems provided that other factors are not limiting. As with carbon, the logic is that the enhanced production levels result in higher amounts of carbon stored in the standing biomass and in higher input to the soil.

## Past practices/age

The age structure of a forest determines the effect of e.g. carbon dioxide fertilization and nitrogen deposition. Trees of different age respond differently to stimuli. Age also is a factor in the decomposition rate of soil organic matter, in general the rate decreases as the material ages.
In Europe, most soils are out of equilibrium as they have been affected by past land use / management practices. Management practices affecting GHG emissions from agricultural areas include changes between arable and grassland, grassland and forest, etc., crop land management such as tillage and rotations, fertilizer use, legumes, the type of fertilizer applied, the farm management pattern, grassland management such as ley systems (cut or grazed) (Smith *et al.*, 2004).

## Temperature

Temperature is a main driver of crop and soil processes, in general an increase in temperature will accelerate these processes. For agricultural crops this would mean that plants mature faster and total biomass production decreases; turnover of soil organic matter would be accelerated thus reducing the soil carbon stock growth.

## Precipitation

Changes in precipitation, as does temperature, will have an impact on total biomass production and turnover of soil organic matter. The total soil water content and drying-wetting cycles affect soil organic matter dynamics, changes in timing and amount of rainfall will affect carbon sequestration. In general decomposition rates of soil organic matter are reduced under suboptimal (too wet, too dry) conditions.

## Radiation

Changes in radiation are related to changes in cloud cover. Changes in radiation levels will have a minor impact on the production levels of plants.

## Flooding, fires, storms

Flooding and fires can destroy entire landscapes and are part of natural cycles. Both are strongly influenced by human activities related to land use. Fire clearly has a negative effect on the carbon balance. Flooding may result in a removal of the topsoil.

The above listed effects are merely a summation the descriptions and do not take into account interactions between the various effects. The table below summarizes the drivers, the indirect effects, the impact on the agro-ecosystem, and the relation to carbon sequestration in terms of input, output and stock.

*Table 2. Summary of drivers, indirect effects, impact and relation to carbon sequestration.*

| Driver | Indirect effect | Impact | Relation to C sequestration |
|---|---|---|---|
| Climate Change increased $CO_2$ | $CO_2$ fertilization | Changes primary production / litter production | C input |
| N Volatilization (sources: industry, cars, agriculture, …) | N deposition | Changes primary production / litter production and decomposition of organic matter. | C input and C output |
| Climate change | Temperatures | Changes primary production and decomposition of organic matter | C input and C output |
| Climate change | Precipitation | Changes primary production and decomposition of organic matter | C input and C output |
| Climate change | Radiation | Changes primary production and dynamics of microbial biomass | C input and C stock |
| Climate change | Weather-induced extremes (e.g. fires, floods, erosion, pests and diseases) | Decimates primary production / removal of topsoil | C stock |
| Past practices/ management/land use | Age structure | In soils C storage capacity may increase – risk of high flux when disturbed<br>Forest age determines the impact of external drivers. | C stock and C output |

The direction and order of magnitude of the impact of the effects on the carbon stocks and fluxes critically depends on the local situation. Three important issues related to the size and direction of the effects are discussed in some more detail.

## Interconnected processes

When turning to soil processes and organic matter it is clear that the carbon (C) and nitrogen (N) cycles are strongly linked (Figure 1). In managed systems the relative balance between the two cycles is disturbed via soil and crop management. Ploughing and N fertilizer application are clear examples of such disturbances.

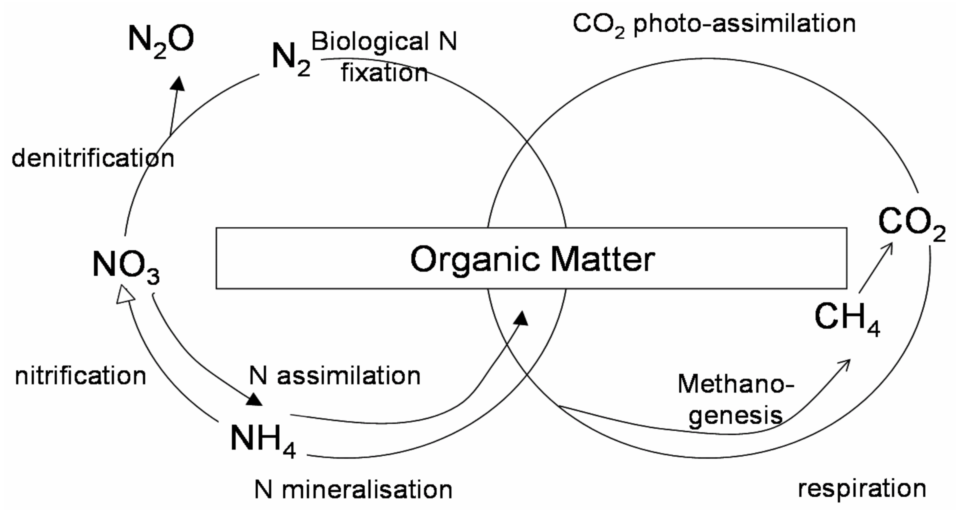


*Figure 1. The C and N cycle in terrestrial systems (Oenema et al., 2001).*

In fact the system is more complex as the phosphate (P) and sulphur (S) cycles are other biogeochemical cycles which are connected to the C cycle. As plants depend on these elements fertilizer applications also include P and S. The biological and chemical processes linking these cycles are also depending on water. The water cycle, which can be managed via irrigation and groundwater level control, is obviously also a crucial factor in crop production.

In managed systems, affecting one cycle may have an immediate effect on another cycle but constraints only show up when such constraints are lifted. An N fertilizer application will have an effect in systems that are not limited by other elements such as P or perhaps more evident by water or the acidity or pH of the soil. As the processes in the cycles, although connected, have different rates, the timing of the effects on e.g. the C cycle is difficult. It is exactly these combinations that make it impossible to produce a clear and direct answer to the posed question of separating direct and indirect effects.

Separation of the effect of e.g. nitrogen fertilizer applied by farm management and nitrogen deposited through the atmosphere is impossible. At best an estimation of an integrated effect can be made based on the total amounts of nitrogen supplied to the system.

The constraints related to the absolute amount available and the amount relative to other elements and the state of the system (e.g. pH, water) are not new. Modelling approaches such as QUEFTS (Jansen *et al.,* 1990) take a four-step balance approach to arrive at a fertilizer recommendation. CENTURY (Parton *et al.*, 1987) and PlantSyst on the other hand aim at modelling the biogeochemical cycles of carbon, nitrogen, phosphorus, and sulphur on a monthly time scale.

# Scale and accuracy

Scale is another complicating factor; decision II/7 doesn't state at which scale or at what precision the effects should be separated. Both scale and accuracy will determine which method is most appropriate.
Looking at managed terrestrial ecosystems, the logical scale is the unit of management which normally is the field level for agriculture (arable + grassland) and stand level for forestry.

Ecological processes occur at all temporal and spatial scales. Direct effects are, however, linked to the scale of interaction between human activities and the environment. For agricultural systems this is the farm field, for forestry this is the stand. Indirect effects, e.g. N deposition, are not linked to a particular scale.

The heterogeneity of land and land management and practical reasons, e.g. data availability, will in most cases not allow a very detailed approach. Up-scaling activities or the effects of activities from field or stand to the landscape is difficult. When moving from field to landscape, the link with management is lost, time scales change and the error and uncertainty changes as the processes and associated data change. In this study the trade off between scale, and accuracy will be named for the different methodologies.

*Table 3. Area information for agriculture, forest and nature in the Netherlands.*

| Year | Agriculture ($km^2$) | Forest ($km^2$) | Nature ($km^2$) | Total land ($km^2$) |
|---|---|---|---|---|
| 2000 | 23111 | 3501 | 1334 | 33784 |

*Source: CBS/StatLine*

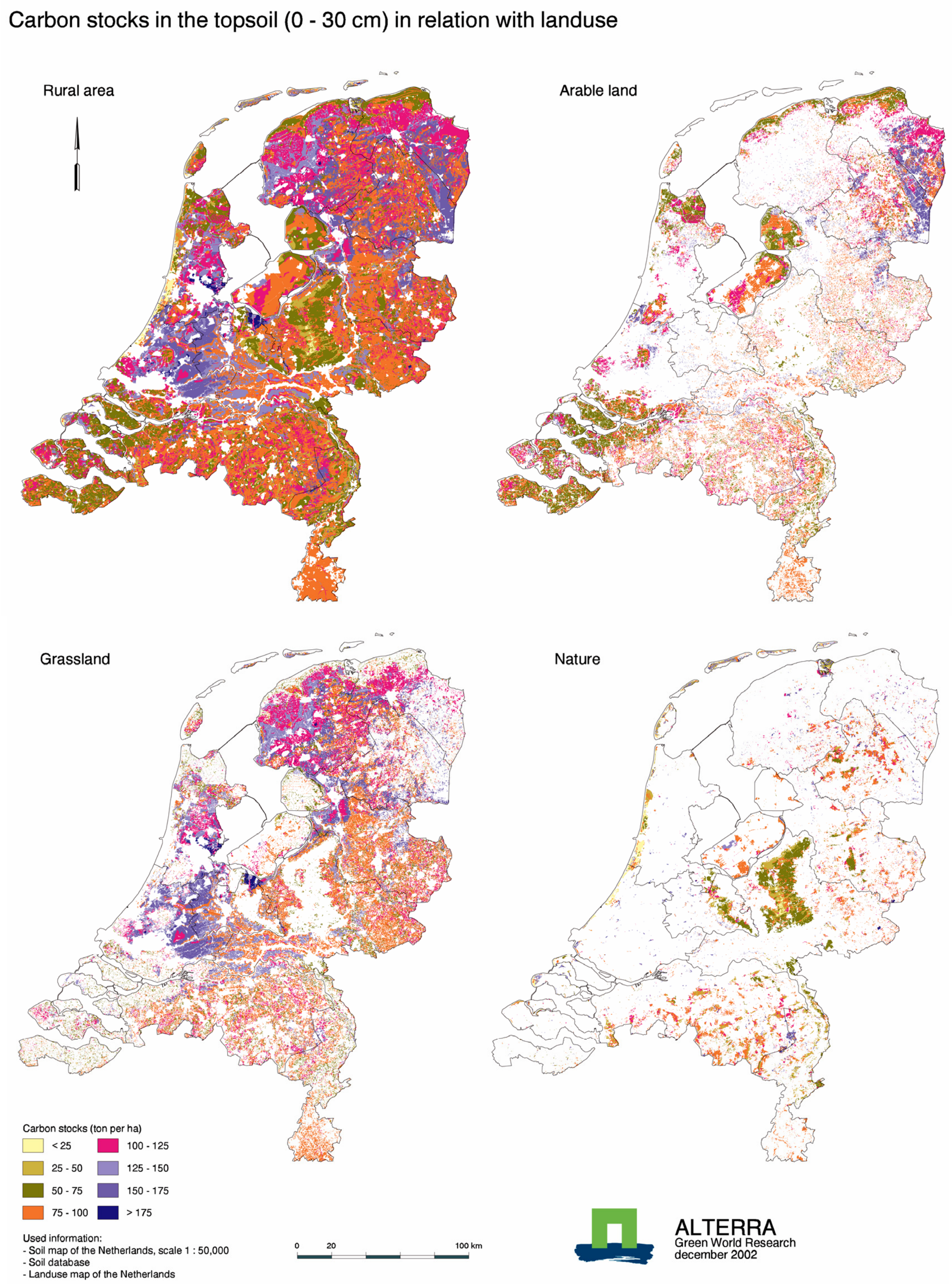


*Figure 2. Carbon stocks in soils in the Netherlands (0 – 30 cm) on the basis of the Soil Map of the Netherlands, scale 1 : 50 000, the Dutch Soil Monitoring (LSK) database and the land cover database of the Netherlands (LNG3); in all soils (top left) and soils in arable land (top right) grassland (bottom left) and nature areas (bottom right) (from Kuikman et al., 2003).*

Another source of error is the area estimation for the different land use types and the spatial allocation. For the Netherlands agriculture is clearly the dominant land use type (Table 3). Using soil and land cover databases a first estimation of the carbon stocks in the soil was made by Kuikman *et al.*, 2003 (see Figure 2). From this figure the relatively high importance of agricultural land (arable and grassland) is clear. Both the area and amounts of carbon in the soil exceed those of soils in nature and forest areas.

No direct information, however, is available by which management activities can be assigned to land areas. Moreover, the temporal variability of farm and field level activities provides an extra layer of uncertainty. The uncertainties and variability of estimations of C for agricultural land are considerable when compared to other land uses (Janssens *et al.*, 2003).

# Management

Farm management is mainly directed at influencing the N and water cycles, which in turn has an effect on the C cycle. Several management activities that also influence the C cycle are listed in Table 4. In forest management options are limited and are mainly related to managing the standing biomass (Table 5).
In both systems, besides soil and other environmental conditions, the start and duration of the activity determine its effect. The age effect is clear for trees, but also for soils the duration and initial conditions determine the impact on the C balance.
Increasing the carbon stocks at a given location can be done in two ways: increasing carbon input and stabilizing or decreasing carbon output. For both forest and agricultural management, several management activities and the principle applied to manipulate the carbon cycle are listed in the Tables 4 and 5.

*Table 4. Measures and the impact on carbon stocks and fluxes in agricultural soils (after Freibauer et al., 2003).*

| Measure | Impact | Potential seq. rate (t $CO_2$ $ha^{-1}$ $y^{-1}$) | Estimated uncertainty (%) |
|---|---|---|---|
| Crop-land | | | |
| Zero-tillage | Reduce losses | 1.42 but see reference | > 50% |
| Reduced-tillage | Reduce losses | < 1.42 | >> 50% |
| Set-aside | Area expansion | < 1.42 | >>50% |
| Perennial grasses and permanent crops | Increase production | 2.27 | >50% |
| Deep-rooting crops | Increase production | 2.27 | >50% |
| Animal manure | Increase input | 1.38 | > 50% |
| Crop residues | Reduce losses | 2.54 | > 50% |
| Sewage sludge | Increase input | 0.95 | >50% |
| Composting | Increase input | 1.38 or higher | >>50% |
| Improved rotations | Reduce losses/increase production | >0 | Very high |
| Fertilization | Increase production | 0 | Very high |
| Irrigation | Increase production/reduce losses | 0 | Very high |
| Bioenergy crops | Increase production/substitution fossil fuel | 2.27 | >>50% |
| Extensification | Reduce losses | 1.98 | >>50% |
| Organic farming | Reduce losses/increase input | 0-1.98 | >>50% |
| Convert arable to woodland | Increase production | 2.27 | >>50% |
| Convert arable to grassland | Increase production | 7.03 ± 2.08 | 110% (2.3 to 11.2) |
| Convert grassland to arable | Increase losses | -3.66 | >>50% |
| Convert permanent crops to arable | Increase losses | -3.66 | >>50% |
| Convert woodland to arable | Increase losses | -? | ? |
| Grassland | | | |
| Increase in the duration of grass leys | Reduce losses | 0.4-1.8 | ? |
| Change from short duration to permanent grasslands | Reduce losses | 1.1-1.5 | ? |
| Increase of fertilizer on nutrient-poor permanent grassland | Increase production | 0.7 | ? |
| Intensification of organic soils with permanent grassland | Reduce losses/increase production | -3.3-4.0 | ? |
| Livestock management | Reduce losses | ?? | ?? |
| Cutting method and frequency | Reduce losses | ? | ? |
| Fire protection | Reduce losses | ?? | - |
| Revegetation | | | |
| Abandoned arable land | Area expansion/reduce losses | 2.27 | >>50% |
| Farmed organic soils | | | |
| Protection and restoration | Reduce losses | Up to 17 | Range 0–17. Spatial variability high |
| Avoid row crops and tubers | Reduce losses | 0 | >50% |
| Avoid deep ploughing | Reduce losses | 5 | >50% |
| Shallower water table | Reduce losses | 5-15 | >50% |
| Convert arable to grassland | Increase production | 5 | >50% |
| Convert arable to woodland | Increase production | 2-5 | >>50% |
| New crops on restored wetlands from arable | Increase production | 8-17 | >50% |
| New crops on restored wetlands from grassland | Increase production/reduce losses | 3-12 | >50% |
| Sheep grazing on undrained peatland | Reduce losses | >8 | >50% |
| Abandon for conservation | Reduce losses | >8 | >50% |

*Table 5. Measures and the impact on carbon stocks and fluxes in forest soils.*

| Measure | Impact |
|---|---|
| Changes in rotation length (production period) | Changes in primary production / litter production |
| Change in regeneration system | Changes in primary production / litter production |
| Intensity | |
| Thinning frequency | |
| System: selection / systematic thinning | |
| Concentrate on high quality stems | |
| Diameter target thinning/ future tree approach | |
| Change in thinning regime | Changes primary production / litter production |
| Harvesting | Reduce losses |
| Low-impact harvesting (min. disturbance / damage) | Conservation of carbon stock in soil |
| Minimum cutting diameter | |
| Quantity / Timing (given by goals, prices and demand for wood products, alternative materials | |
| Degree of salvaging | |
| Species / provenance change | Changes in primary production / litter production |
| 'Better' species mixture (exotic vs indigenous (genetically)) | Changes in primary production / litter production |
| Incorporation of better adapted species/ provenances/ genetically improved plant material) | |
| Afforestation of former agricultural lands | Area expansion |
| Water management | Changes in primary production / litter production and decomposition of organic matter |
| Irrigation/drainage | |
| Leave forested lake sides/ water sides | |
| Assign temporary water storage (swamp) forests | |
| Soil management | |
| Fertilization (Ca, Mg, K, ) | Changes in primary production / litter production and decomposition of organic matter |
| Minimum disturbance at regeneration | Decomposition of organic matter |
| Leave logging slash/ burn slash/ push slash on rills | |
| Plant nitrogen fixers | |
| Reduction of erosion | Reduce losses |
| Pest control | Regulate biomass production |
| Different tree species/mixtures of species | |
| Wood import regulations / constraints, spraying | |
| Fire control / prevention | Reduce losses |
| | Reduce losses |
| Increasing frequency of intentional fire | |
| Fire to be incorporated into thinning, species choice ... | |
| Control of storm damage | Reduce losses |
| To be incorporated into thinning, species choice, soil management, spatial, vertical and spatial diversity, location of stands in the landscape, tree allometry | |
| Reduction of forest degradation / Degraded systems restoration | Reduce losses |
| Control of overexploitation, erosion, grazing, fuel wood gathering, etc. | |

# 4. Inventory of methodologies

## Soil and plot/field experiments

The various ways in which changes in the soil C stock can be quantified are listed in Table 1. They are discussed below. First, carbon stocks can be measured by sampling soils and analyze organic and inorganic C. An attempt can be made to follow these stocks in time in order to quantify C losses or gains. The main drawback is the low discrimination level as a result of the high levels of ‘old’ soil C in relation to possible sequestration rates. Therefore, longer survey periods are needed (> 10 y). The big advantage is the relatively simple sampling procedure and sampling processing, and the fact that C sequestration is measured in the most direct way possible.
To overcome the low level of detection mentioned above, the soil C pool can be separated into more labile and more recalcitrant SOM pools. Whereas different management practices will not lead to sudden qualitative and quantitative changes in the recalcitrant SOM pools, changes in the labile pools can be pronounced within a short period of time. The soil microbial biomass represents only a minor pool of soil organic matter (< 1%) but it can be very effective as an early indicator of larger changes in carbon stocks in time. Alternatively, physical (size and/or density) or chemical fractionation of the soil organic matter pool can be used to follow C through the successive SOM pools (e.g. Six *et al.*, 1998).
Instead of fractionating the SOM pool into younger and older fractions, the new C can be labelled using either stable ($^{13}C$) or radio ($^{14}C$) isotopes, and tracked into the soil. Stable isotopes are more expensive to acquire and analyze than radioisotopes, but their environmental safety often makes them the more practical option for field experiments. In $CO_2$ fertilization experiments, $^{13}C$ labelling may occur automatically, since the natural gas used for $CO_2$ fertilization is often strongly depleted in $^{13}C$. In other studies, the naturally occurring differences in $^{13}C$ concentrations between C3 and C4 plants may be used (e.g. by adding maize residue on ‘C3 soil’). A new and relatively inexpensive technique involves labelling crop using leaf fertilization with $^{13}C$ enriched urea. Using a radioactive technique like $^{14}C$ labelling has the advantage that background $^{14}C$ values approach zero and discrimination levels between ‘old’ and ‘new’ C are therefore extremely low.
Combining SOM fractionation (microbiological, physical or chemical) with isotope tracing may be especially powerful in order to quantify C sequestration in the soil (Hungate, 1996; Magid *et al.*, 1996) and to quantify decomposition rates of the different soil organic matter fractions (Hassink, 1995).

### Fluxes

Carbon fluxes at the micro-scale can be measured using static chambers installed in a field or using pot experiments (Table 6). Within these closed chambers, $CO_2$ is accumulating during a preset time and the concentration is measured using a $CO_2$ analyzer. This method gives information about the total C emission from soil. However, the main drawback is that only the efflux from soils is quantified, not the influx. This can be overcome using plants in closed phytotrons while measuring net C uptake during the day and C emission during the night. The latter method can be combined with stable or radioactive isotope techniques.

On the micro scale (both field and laboratory experiments), separating between factors is relatively simple, since the environmental conditions (e.g. $CO_2$ and N fertilization, soil management) can be manipulated. However, without a sound experimental design (i.e. with controls and combinations of treatments), it will be difficult make this separation.

The interaction of $CO_2$ fertilization with many management measures is still largely unexplored, and a literature review is needed to summarize this information on the selected management measures and to map the knowledge gaps. Provided that much information on the effects of the selected management measures on C sequestration to feed existing or future models is missing, measurements have to be made to collect these data. The methods mentioned in Table 6 can be used to measure C stocks in soils that result from both natural variation, indirect or direct effects.

## Direct effects

Some effects of management measures on soil C stores have been reported in the literature, and they are listed in Table 4 and 5. Important extra issues are the consequences of both direct and indirect effects on emission of other greenhouse gasses such as $N_2O$ and $CH_4$. Soil management practices that increase C sequestration, such as reduced or zero-tillage, may lead to an increase in emission of these other gasses, thereby partly defying the purpose of these measures. (Literature search is needed to summarize knowledge on the effect of management measures on soil C stocks and, subsequently, on the interaction between the selected management measures and indirect effects).

## Indirect effects

In general, there may not always be a strict need to include all factors that cause indirect effects in an experiment unless this factor can be used as a management measure. Nitrogen may. e.g., cause indirect effects when entering an ecosystem by deposition, but may also exert direct effects when applied as a fertilizer. $CO_2$ will never be a management factor and thus, depending on the type and purpose of the experiment, it may not be included as a factor. For example, in a field experiment in which soil management factors are evaluated during 20 years, the increasing $CO_2$ concentration will affect all plots. A drawback of this approach would be the possibility of an existing interaction between $CO_2$ and the management measure that cannot be unravelled without $CO_2$ as an experimental factor. The same applies to other indirect effects like temperature, precipitation etc.
Below, several controlling factors are listed of indirect effects on C sequestration that can be quantified in laboratory, plot or field experiments.

### $CO_2$ fertilization

It has been suggested that C sequestration in the soil may offset a significant amount of higher atmospheric $CO_2$ levels (Gifford, 1994). Free Air Carbon Enrichment (FACE) or open-top experiments provide a way to quantify effects of elevated $CO_2$ concentrations on soil C dynamics, especially when combined with tracers. However, nutrient limitations in natural ecosystems may pose a problem. The aims of future studies should include the identification of these limiting factors, for example to prevent the selection of wrong management measures and to allow selection of the rights measures.

### N deposition

The mean nitrogen deposition in the Netherlands is still about 30 $kg \cdot ha^{-1}$. This will increase the primary production of ecosystems when other factors are not limiting. Therefore, this also increases possible carbon sequestration in organic matter. Many data are available on effects of management measures on soil nitrogen dynamics, on nitrogen dynamics and primary production (carbon uptake), and on interactions between (elevated) $CO_2$ and N.

### Temperature

The number of experiments on the effect of temperature on decomposition and mineralization processes in soil has been quite extensive. However, essentially no data are available on the significance of the interaction between (elevated) $CO_2$ and (increased) temperature for C sequestration in the soil. It may be hypothesized that changes in temperature, combined with changes in litter production under elevated $CO_2$, will lead to a change in the soil microbial community and, therefore, to a change in the C and N cycles.

## Precipitation

Total soil water content and drying-wetting cycles affect soil organic matter dynamics substantially. Changes in the amount of precipitation or precipitation patterns may therefore affect carbon sequestration. Data are available on soil water content, drying and rewetting of soils, and on soil carbon dynamics. The relation with rain events may be less clear.

*Table 6. Methods for quantifying C changes in the soil.*

| | Method | Strengths | Weaknesses |
|---|---|---|---|
| 1 | Measuring total soil C, incl. organic and mineral carbon | Permits measurement of changes in soil carbon stocks in time as a result of management | Changes difficult to measure because of heterogeneity at smaller measuring scales |
| 2 | Measuring soil microbial biomass | | |
| | Fumigation-extraction<br>Fumigation-centrifugation<br>Substrate Induced Respiration | Early indicator of changes | May not be representative for larger C pools in the soil |
| 3 | Measuring size of SOM fractions | | |
| | Chemical fractionation (chemical stability)<br>Size-density fractionation (biological stability) | Indicates stability of soil C | Models describing soil carbon dynamics not based on chemical fractions. Fractionation sometimes rather arbitrary |
| 4 | Measuring isotope dynamics | | |
| | $^{13}C$ natural abundance (e.g. depleted $CO_2$, replacement C3/C4 crops)<br>$^{14}C$ radiocarbon measurements | Enables to track new C into the system, precise measurements | Extrapolation to higher levels, environmental considerations radioisotopes |
| 5 | Measuring fluxes (micro scale) | On-line measurement | Uncertainty when converting to C stock changes |

# Forests inventories

Temporal variation of carbon balance in forest stands (Figure 3) is translated into spatial variation of sources and sinks (Figure 4).

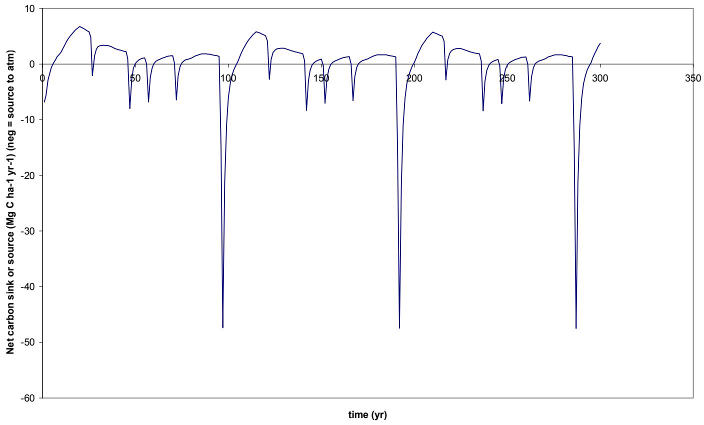


*Figure 3.* *Net annual fluxes in one stand of Norway spruce during three rotations of each 100 years: long periods of a net sink alternate with short periods with a large source. (X axis: time, Y axis: net carbon sink or source (Mg C $ha^{-1}$ $yr^{-1}$) (when negative = source to atmosphere)*

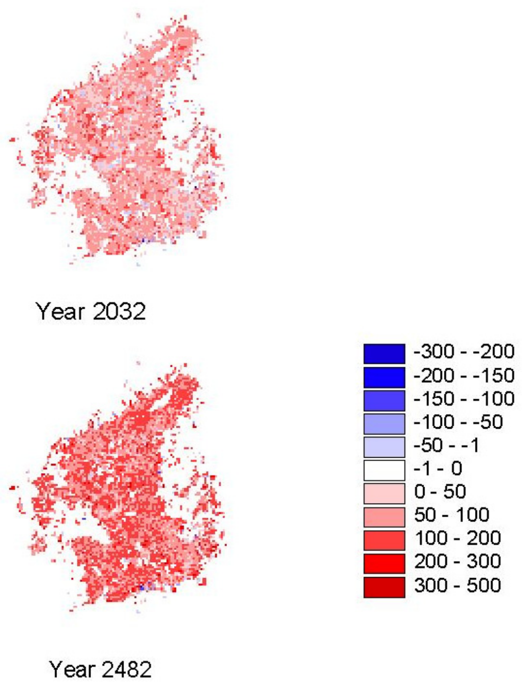


*Figure 4.* *Spatial variation of sinks.*

In order to capture the spatial variation forest inventories are ideally based on a sampling design. Depending on desired accuracy, pre information, diversity, and available funds, the sampling design and intensity is determined.

## Three-phase sampling

The first sampling phase is carried out with photographic documents. It consists of using a grid to examine areas (per forest type). The second phase involves a field check of the findings of the photo-interpretation on a subsection of the points drawn by lot from the phase one sample.
The third phase consists in taking measurements at 'forest use points' in the phase-two sample. Different criteria are assessed in (sometimes) 25 m radius sample plots on the land surrounding each point. See Veluwe landscape for sampling intensity in the Netherlands

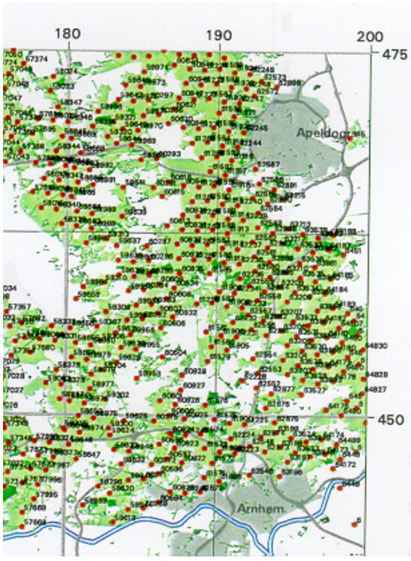


*Figure 5. Sampling design of Dutch forest inventory (systematic: 1 plot per every 100 ha).*

## What is measured on all trees (of over 5 cm diameter) in a sample plot?

Each tree is measured in detail, which makes it possible to calculate the volume of usable timber and its annual growth rate. Two methods may be used. The first involves calculating this volume based on measurements recorded for each tree. It is applied in cases where the IFN calculation centre does not have enough previous measurements in its database to build a cubic volume rate. The second, based precisely on the application of these volume rates based on measurements of the overall height of each tree and the circumference at a height of 1.30 m, is applied in all other cases.
Needless to add, both methods presuppose that the measurements required for timber volumes with bark have been previously made: assessment of the circumference at the base of the stump and at a height of 1.30 m, diameter at a height of 2.60 m, height at the cut, and overall height, and lengths and diameters of standing top timber. Added to this, for calculating the volume increment of the timber, are the thickness of the rings over a radius for the past five and ten years, the thickness of the bark at 1.30 m, and development of the height over the last five years.

Additional parameters make it possible to break down volumes based on use qualities, the status of the tree in the stand, and its age class. In all, almost 30 codes may be applied to just one tree. At the same time, stumps of felled trees or trees that have been dead for less than five years within the perimeter of the 15 meter sample plot are recorded and measured to assess the volume of logged wood and the death rate of the trees.

Forest inventories are specifically designed to supply statistically sound measurements of timber stocks and growth across large, heterogeneous regions. Field measurements exist for more than a million plots across the Northern Hemisphere, and measurements extend back decades in many countries. Comprehensive national forest inventories have not been conducted in most tropical countries, although there have been a few regional surveys (e.g., Brown & Lugo 1992, Phillips *et al.*, 1998). In most northern countries, total wood volume can be estimated with 95% confidence to within 1-5% of the mean (Powell *et al.*, 1993, Köhl & Päivinen, 1997, Shvidenko & Nilsson, 1997).

# Crop inventories

The Farm Accountancy Data Network, carried out by LEI, annually collects, since 1986, economic data on crop and livestock agriculture at the county or regional level. The portal to this data is http://statline.cbs.nl/ which is part of the website of the Centraal Bureau voor de Statistiek (CBS). LEI reports every year on yields and farm income for all farming sectors in the Netherlands (see e.g. Bont & Knijf, 2003).

This data is linked to the Geografisch Informatiesysteem Agrarische Bedrijven (GIAB), a geographical database on agricultural enterprises. This information system provides a country-wide overview of the agricultural enterprises present in the 'Landelijke Service Regelingen van Ministerie van LNV LASER' and the animal health service (GD).

At the European level crop yield data for the different countries of the EU are available via EuroStat, the statistical office of the European Commission http://europa.eu.int/comm/eurostat/. The data from the Netherlands are derived from the above-mentioned databases.

In general, crop data is readily available and of high quality. Management information is, apart from fertilizer application, not documented. Separating effects of management from indirect human-induced effects is virtually impossible with these data. Lobell & Asner (2003) were, however, able to separate the effect of climate and management to trends in agricultural yield for the USA. Limiting to temperature they found that changes in climate have played a significant role in determining yield trends at the county level, and that gains due to non-climatic factors (e.g. new varieties, better management) were about 20% lower than previously assumed (Lobell & Asner, 2003).

# Soil data

A digitized soil map coupled to measured soil information is available for the Netherlands (De Vries, 1999; De Vries *et al.*, 2003 and www.bodemdata.nl). For all soil units a description of a representative soil profile with reference to collected and measured soil data is available. The data was collected during a time span of thirty years, starting in 1960 and stored in the Dutch Soil Database (BIS). Basic soil physical and soil chemical data such as texture, organic matter content, pH and land use information are available. The data is not georeferenced and re-sampling the location is not possible as this information was not recorded.

To accommodate the changing needs and the need for more detailed additional soil information a sampling strategy to update, complete and improve the underlying soil information stored in BIS was developed (Finke *et al.*, 2001; De Gruijter *et al.*, in prep). The Dutch Soil Monitoring Network (DSMN) was carried out from 1990 till 2001. A total of 1392 soil profiles were described and sampled for chemical analysis including analysis of soil organic matter content (Kuikman *et al.*, 2003)

For forest soils a separate monitoring programme exists (FIMCI). This European scale monitoring system includes the collection of detailed chemical information on forest soils and soil litter.

A European scale soil map, based on the national soil maps of the individual countries was recently compiled (http://eusoils.jrc.it/msapps/Soil/SoilDB/SoilDB.phtml). Linked to this soil map is the Soil Geographical Data Base of Europe at Scale 1:1,000,000. Both are the result of a collaborative project involving all European Union and neighbouring countries.

# Large scale flux measurements

## Principles and limitations

Eddy correlation is a direct measurement technique aimed at assessing the total exchange of carbon, water or energy between the land surface and the atmosphere at the 'patch' scale, usually through the deployment of automated sensitive instruments at the top of a tower extending well above the surface. The use of this technique has been dramatically gaining support over the past ten years. The method was initially used by micrometeorologists since the mid-sixties as a method to collect (usually day-time) flux data for only a few 'golden' days (Shuttleworth *et al.*, 1984). The aim of such research was to assess atmospheric properties close to the earth's surface and also to calibrate land surface physiological exchange models. In the mid-nineties, eddy correlation started to be implemented for continuous long-term monitoring by ecologists through the efforts of projects and networks such as HAPEX, BOREAS, EUROFLUX, AMERIFLUX and FLUXNET (http://daacl.esd.ornl.gov/FLUXNET/), and through the exemplary studies of, for example, Wofsy *et al.* (1993), Moncrieff *et al.* (1997) and Valentini *et al.* (2000). With the still expanding global-scale network of towers, this technique has now matured to be used as an operational monitoring option for carbon and water fluxes. In the near future, many of these towers will be linked into remotely accessed, on-line monitoring networks aimed at policy definition and carbon balance assessment. Despite its success, there are still several conceptual and practical problems to be solved and the method should only be seen as one of several other constraints in determining carbon budgets. The following will explore the scope of usefulness and limitations of eddy correlation.

The basic principle of eddy correlation is that the average net transport of energy or matter through a horizontal plane above a surface is estimated by measuring rapid fluctuations of vertical air motion, together with concurrent scalar air properties (momentum, temperature or gas concentrations). The product of these does in principle lead to the net transport through the upper cross section of an imaginary control volume containing the vegetation of interest. Over tall vegetation, it is also necessary to measure the concentration changes underneath the sensor to account for exchange between vegetation and canopy air that did not (yet) cross the sensor level. The method, however, assumes that we can close the mass balance of the volume, implying horizontal homogeneity, horizontal terrain and flow, and absence of adjective fluxes through the sides of the volume. In many cases, this assumption does not hold, for example during calm night conditions when substantial emission fluxes can be missed by the method, and an assessment is needed of how sensitive measured fluxes are to deviations from basic assumptions. In practice there are still substantial discrepancies between eddy correlation results and those from repeated inventory studies of biomass and other organic material in ecosystems.

If assumptions are sufficiently met, the method estimates the carbon exchange between surface and atmosphere for an area of several hectares to square kilometres upwind of the sensor, depending on measurement height. This exchange includes the activity of all components of the ecosystem: autotrophic and heterotrophic soil respiration as well as photosynthesis and respiration of above-ground biomass. This is an advantage since no complex scaling-up procedure is required, but this is for the same reason a disadvantage, as component processes are not resolved and their role in ecosystem functioning cannot be assessed separately.

Alternatively, it is possible to base and eddy correlation system on a low-flying, slow aircraft. In this way, the method can cover much more area and investigate heterogeneity. In this approach, mapping spatial variation is gained at the expense of continuity in time. However, high costs and conceptual problems relating to non-stationarity in the measurements preclude it as a routine method.

The cost aspect is also a limitation to eddy correlation in general. The initial cost of a tower and equipment are relatively high, although prices are falling. The costs of maintenance are neither insignificant, as a site visit is usually required a few times per month and time-consuming breakdowns do occur. However, the benefits are also large: a substantial area and all component processes covered by each instrument. Also, many improvements are being made to make the method more robust, cheap and efficient.

## Applications

One of the important advantages of eddy correlation, also in terms of cost efficiency, is that the high time resolution makes it especially suitable for scaling up. No other method provides fluxes at seasonal, monthly, daily or hourly scale. This information makes it possible to calibrate process-based models for specific land cover types, sensitive to edaphic and environmental variables that are more readily accessible. Thus, one eddy correlation measurement series at one point, and even more a network of such series like FLUXNET, can deliver reliable estimates of carbon exchange for an area that is vastly larger than the tower 'footprints', because the models can be used to scale up measurements.

To study the relative importance of direct and indirect effects of vegetation on the atmosphere's carbon balance, eddy correlation is mainly useful in extensive, natural vegetation or forest plantations. Its high time resolution allows studying detailed responses to changes in climate or management, classified as either direct or indirect effects (e.g. Amazon logging: Miller *et al.*, 2002). Similarly, paired studies can be carried out, comparing different management conditions or climates (Zegveld study: Synthesis FLUXNET data: Groen, 2002). Because of its rather extensive footprint, the method is less suitable to monitor carbon exchange in spatially small-scale experiments. However, one such experiment is being planned in the Mediterranean, where rainfall exclusion and irrigation effects on ecosystem fluxes will be studied (MIND: Migleitta *et al.,* 2002).

## Future

In the future, eddy correlation will probably develop into several directions. First, the number of sites, climates and vegetation types covered, as well as the time series lengths, will be extended. Conceptual problems will be solved, partly by designing additional measurements and using complex terrain flow models. But most importantly, ways will be developed to integrate this method with several other carbon flux measurement methods, to achieve a multiple constraints assimilation method, giving the best possible estimate of carbon exchange for patches to regions.

# Soil-crop models

Soil-crop models are a valuable tool in scientific research and decision support for global environmental change and crop rotation management. Numerous models have been developed; here we discuss only two: CESAR a simple model and PlantSyst a mechanistic simulation model.

The CESAR (Vleeshouwers & Verhagen, 2002) model (Carbon Emission and Sequestration by Agricultural land use) has been developed to simulate changes in the carbon content of plant production systems. The model includes the effects of crop (species, yields, and rotations), climate (temperature, rainfall, and evapotranspiration) and soil (carbon content and water retention capacity) on the carbon budget of agricultural land. The CESAR model focuses on carbon stocks and fluxes in soil organic matter. The model calculates carbon input into the soil from plant residues, and carbon output from the soil by decomposition of the accumulated organic matter in the soil.

PlantSyst (Jongschaap *et al.*, in prep) uses (simple) algorithms based on physical, physiological and biochemical laws of individual processes that are seized in separate and exchangeable modules. For fallow or for field crop rotation systems, the model governs water fluxes (precipitation, irrigation, run-off, evaporation, transpiration, seepage and drainage), nitrogen fluxes, soil organic matter pools, turnover of dead plant material, (in-)organic fertilization, wet and dry deposition, leaching, root nitrogen uptake by mass flow and diffusion). The organic matter module is the VERBERNE model (Verberne *et al.*, 1990). Light interception and thermal heat accumulation directs crop growth and development. Thermal heat units refer to canopy temperatures, which may differ from air temperatures due to water stress. Light interception of the canopy is steered by a vertical nitrogen profile, which differs between crop types in shape and concentration. Crop nitrogen profiles may vary seasonally due to hampering nitrogen uptake. Management interactions comprise ploughing (date, depth), incorporation and turn-over of organic fertilizer (date, rate, type) and the application of inorganic fertilizer (date, rate, type), sowing (rate, depth), irrigation (date, rate) and harvest (date, method). Crops currently included in the model are wheat, sugar beet, potato, barley, rape seed and maize. Calibration parameters identified by sensitivity analyses are established for various sites in temperate regions in Europe. Comparison of model predictions with independent data demonstrates the model's accuracy in different environmental settings.

Natural, direct, and indirect human-induced factors may all affect the emissions and removals of greenhouse gases from terrestrial ecosystems. Distinguishing between these effects is a significant issue in the design of accounting systems. For agricultural areas, however, models like CESAR and PlantSyst may be used to tackle this problem. These models allow evaluation of the separate contribution of:

Direct human-induced effects, caused by e.g.:
- application of farm-yard manure,
- green manure crops,
- leaving behind crop residues in the field,
- reduced tillage,
- change of land cover.

Indirect human-induced effects, caused by e.g.:
- increasing agricultural production by crop breeding and improved crop management,
- rising atmospheric $CO_2$ concentration due to human-induced emissions,
- rising temperature owing to climate change.

Natural effects, caused by e.g.:
- interannual variation in weather conditions.

In an earlier study (Vleeshouwers and Verhagen, 2001) CESAR was used to calculate changes in soil organic matter in relation to management of carbon into the soil via crop residues (non-harvested crop biomass) and extra additions of organic matter (e.g. through farm-yard manure). The output of carbon from the soil depends on soil temperature and moisture content, and on the tillage method. The effects of the following trends or measures were evaluated for arable fields in Europe:
- Application of farmyard manure. Farmyard manure was applied at an annual rate of 35 t per ha. The organic matter content of farmyard manure was 14% (Janssen, 1992), and the humification coefficient was estimated at 0.50 (Kolenbrander, 1974).
- Leaving behind cereal straw in the field. In cereals, the straw that is usually harvested for several purposes may be left in the field to increase the amount of soil organic matter. The average effect on the amount of soil organic matter depends on straw yields but also on the proportion of cereals in the crop rotation.
- Reduced tillage. Soil tillage stimulates the decomposition of soil organic matter, mainly because of aeration of the soil. Reducing soil disturbance by shallow tillage or no tillage, therefore, decreases the decomposition rate of soil organic matter. From data presented by Smith *et al.* (2000a) it was assumed that reduced tillage lowers the decomposition rate of soil organic matter by 25%.
- Change of land cover. The conversion of arable fields to grassland was evaluated in model simulations.
- Rising $CO_2$ concentration in the atmosphere. The amount of total crop biomass increases with increasing $CO_2$ concentration. The annual increase was estimated at 0.2% (Goudriaan & Unsworth, 1990).
- It was assumed that the increase also applies to the amount of crop residues. It was also assumed that the decomposition of organic matter in the soil is not affected by the elevated $CO_2$ concentration in the atmosphere (Sadowsky & Schortemeyer, 1997; Van Ginkel *et al.*, 1997).
- Rising temperature owing to climate change. The effect of rising temperatures on the decomposition of soil organic matter was calculated using a climate scenario in which the temperature rises by 3 °C in the 21st century. The possible effect of temperature on other factors (e.g. yield) was not included.

In the simulations, the measures were assumed to start in 2000. The annual net effect in the commitment period 2008-2012 was calculated according to IPCC (2000). The results of model calculations in which the above-mentioned measures and trends were evaluated for arable fields in Europe are shown in Figure 6.

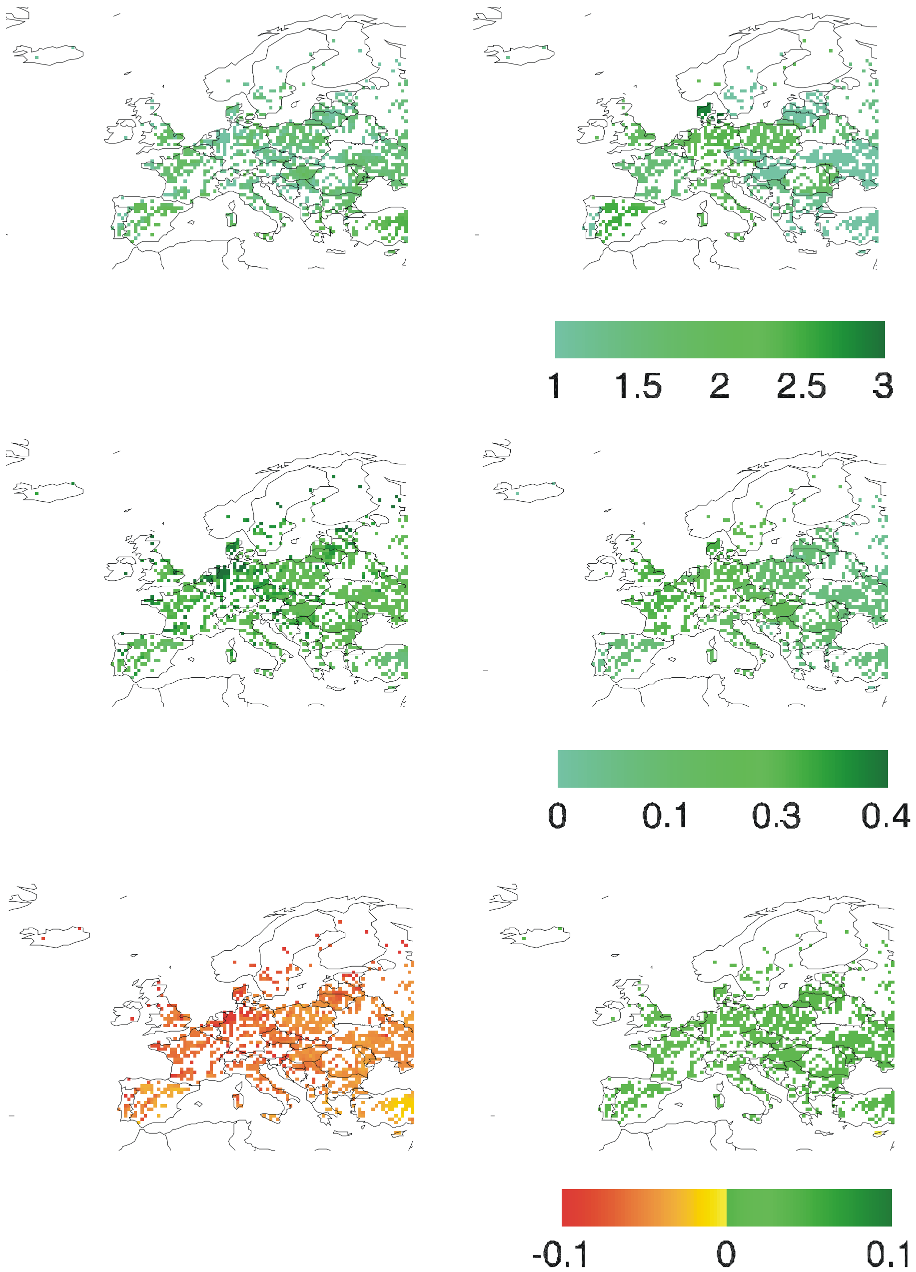


*Figure 6.* *Estimated average annual net effect on the carbon content of soil organic matter in arable fields in the commitment period 2008-2012 (tC ha-1 y-1): (a: top left) application of farm-yard manure, (b: top right) conversion into grassland, (c: center left) reduced tillage, (d: center right) leaving behind cereal straw, (e: bottom left) rising temperature, (f: bottom right) rising atmospheric $CO_2$ concentration. Note that to be able to discern spatial differences, different color scales were used in different maps.*

This preliminary study shows that rising temperatures and $CO_2$ have a relatively small effect when compared to farm operations.

## Forest models

Century is a simulation and process model used to understand grassland and agro-ecosystem dynamics including forests. The purpose of the model is to analyze soil organic matter dynamics in response to changes in management and climate. The model uses monthly time steps for simulations of up to several thousands of years to examine the flows of carbon, nitrogen and phosphorus.

Data required for input are:

- monthly mean maximum and minimum temperatures;
- mean precipitation;
- soil texture and soils depth;
- vegetation types and $CO_2$ levels.

The output contains information on carbon and nitrogen fluxes, net primary production and soil organic matter. The spatial extent of the model is regional.

For above-ground biomass the CO2FIX (Mohren & Klein Goldewijk, 1990) was developed. This model, updated by Nabuurs *et al.* (2001) and applied by Masera *et al.* (2001), was used to evaluate the carbon sequestering potential of forestry projects.

## Summary

There is no clear methodology that allows for separation of direct and indirect effects. At best a combination of experiments/measurements and models will allow a first estimation of the contribution to the carbon balance of the different indirect effects. As age of soil organic matter and forest age play a role in the impact on the carbon balance and the fact that effects are non-linear and not additive it will not be possible to factor out all different effects and their individual contributions. The difference in C sequestration related to the indirect effects is expected to be low.

From a practical point, the information on farm and forest management operations (timing, location) is only available for well-described experiments. Up-scaling of this information can be done via farm and forest typologies at the cost of accuracy of the information. Given that management is the overriding factor in the carbon budget in these agricultural systems (excluding disasters like fires, storms) it is likely that the indirect effects are well within the margins of error of any practical system aiming at separating direct and indirect effects. For forest ecosystems the contribution of N deposition seems to be significant as a growth-determining factor.

A combination of controlled soil and plot experiments with simulation models is the most likely candidate to estimate the direction and order of magnitude of the impacts of direct and indirect effects on the carbon balance.

*Table 7. Overview of methods and models.*

| Methodology<br>Measurements | Scale | Information | Linked to indirect effect |
|---|---|---|---|
| Soil & plot experiments | Plot/Field | Primary production<br>Litter production and decomposition of organic matter | $CO_2$ fertilization<br>N deposition<br>Temperature<br>Precipitation<br>Radiation |
| Soil inventory | National European | Carbon stocks | $CO_2$ fertilization<br>N deposition |
| Crop inventory | Farm<br>National | Primary production | $CO_2$ fertilization<br>N deposition<br>Temperature<br>Precipitation<br>Radiation |
| Forest inventory | National<br>European | Primary production<br>Age structure | $CO_2$ fertilization<br>N deposition<br>Temperature<br>Precipitation<br>Radiation<br>Age structure |
| Large scale flux measurements | Landscape | Primary production | $CO_2$ fertilization<br>N deposition<br>Temperature<br>Precipitation<br>Radiation |
| Models | | | |
| Soil crop models | Plot/Field | Primary production<br>Litter production and decomposition of organic matter | $CO_2$ fertilization<br>N deposition<br>Temperature<br>Precipitation<br>Radiation<br>Age structure |
| Forest models | Plot/Stand | Primary production | $CO_2$ fertilization<br>N deposition<br>Temperature<br>Precipitation<br>Radiation<br>Age structure |

# 5. Experimental data

## Possibilities of using long term forest growth data for separating direct and indirect effects

Cees van den Berg, Bert van der Werf and Gert Jan Nabuurs

The aim was to test the suitability of forest growth and yield measurements for separating direct and indirect effects. In order to do so, all readily available measurements regarding height, diameter and volume growth for Japanese larch (*Larix kaempferi*) in the Netherlands were used. Japanese larch was chosen because it is a fast growing species that is known to be responsive to different sites, and because a large data set was available.

Two sub-aims were set:
1. Is it possible to derive the influence of management and environmental circumstances on increment through regression analysis
2. Has growth of Japanese larch in the Netherlands changed over time; where the year 1960 is used as the separating year between two periods; 1960 is used because it is generally seen as the start for rapid economic growth and associated higher N deposition.

In this study we used as responses variables: height, diameter and (derived) volume increment with the following eight explanatory variables for forest type (age), environment (soil type, groundwater class, temperature, precipitation, $CO_2$ concentration, and Nitrogen deposition) and management (thinning percentage). A total of 234 recordings were made (Table 1, Appendix I) over a period of 65 years (1925 – 1990). This time frame is characterized by low N deposition until 1960 and high N deposition after 1960.

Analysing the growth data as recorded before 1960 versus after 1960, showed that diameter and volume increment of Japanese larch -when corrected for age effects - have significantly increased in the Netherlands. This suggests that environmental circumstances as N deposition and $CO_2$ concentration determine to a significant extent the growth trends of Japanese larch when the intrinsic growth dynamics are cancelled out. However, the explanation of height and diameter growth of all explanatory variables was still only around 50%, and its causality not proven.

The only management variable for which we had data (thinning), was significantly explanatory only for diameter growth. The latter is logical, as thinning concentrate growth on a reduced number of trees, mainly showing as increased diameter growth of the individual trees. However, we cannot derive what proportion of growth has been caused by direct effects and what by indirect.

Despite the clear value of historic data for scientific purposes we need to be cautious in extrapolation of results. The selected plots and their recordings were never set up for this aim and are not necessarily representative for forests in the Netherlands as they do not cover all age classes and environmental circumstances were not continuously monitored. Remarkably, management was only recorded in a limited way.

In summary, no conclusive result can be presented. When removing the age effect the study revealed a significant, but maybe not causal, contribution of N deposition and $CO_2$ concentration to the growth of Japanese larch. Thinning could be linked to diameter growth, the large variation indicates that the relation is uncertain. The effect of management in forest systems seems to be limited.

# Analyses of selected documented long term experimental field trials on carbon and nitrogen management in agriculture

Jan Willem van Groenigen

The TAGA archives (available at Alterra) contains descriptions and results (and in some cases even soil samples) of over 20 000 field experiments in the Netherlands. 250 000 soil samples and over 50 000 crop samples are part of the archives. Kooista & Kuikman (2003) came to the conclusion that TAGA offers great opportunities to explore carbon sequestration options in agriculture. Triggered by those findings it was decided to explore the TAGA archive and extract relevant long term experiments and extract relevant reports.

A number of experiments was identified and the data was extracted. All experiments reported organic matter in relation to N supply. Because of this data on carbon is difficult and very time consuming to extract. Another complicating factor was the fact that no bulk densities are reported which prevents a quantitative analysis of carbon stock dynamics in the soil.
The data suggests that soil carbon is highest in grassland, followed by arable field fertilised with farm yard manure and lowest at fields using inorganic manure. Less is know about the effect of the different types of organic manure, although it seems that compost and peat, high resistant organic material, have a large positive effect on soil carbon.

A first scan of the available reports yielded some 7 reports of field trials which can be used for further study (see Appendix II).

1. In TAGA, a fair number of experiments have been identified that need further detailed studying the carbon cycling; despite omissions in measurements and inadequacies in statistical design, these experiments may allow for conclusions on carbon cycling to be drawn that are otherwise not available today from short term experimentation
2. Almost all experiments report on humus content rather than carbon content and were focussed on qualitative and quantitative aspects of agricultural production and nitrogen mineralization. Carbon dynamics have sofar not seriously been examined from these data and experiments
3. All identified historical experiments relate to arable land and some have include arable ley rotations (3 years grassland and 3 years of arable land); experiments on permanent grassland have not been identified
4. In all reports and measurements bulk densities of soil have not been taken into account and only changes in humus contents are provided; this renders evaluation of carbon dynamics in soil difficult and only approximations of changes in carbon contents can be extracted; further research is required to check whether the original data do contain data on bulk densities indeed.
5. From the experiments is shows that carbon sequestration is highest in the rotations with grassland and larger than in arable farming with manure or other organic amendments and larger than for mineral fertilizer application. Many experiments report strong increases in organic carbon for arable ley rotations as was anticipated
6. On any differences in organic carbon in soil as a result of different organic amendments is less known; the only long term experiment reports on a strong positive effect of peat followed by compost additions.

# Analyses of organic matter dynamics in soils in the 'Sturen op nitraat' projects

Annemieke Smit

The 'Sturen op nitraat' project was designed to assess the relation of management and nitrate leaching in sandy areas. For this a large number of data was collected over a period of 4 years. Organic matter data was measured at the start of the project at 478 locations on 34 farms. We tried to assess the relation between soil type, groundwater level and landuse with carbon in the topsoil.

The focus in this project was on nitrate leaching and therefore the 34 farms and sites were located on sandy and loss soils. The total of 478 points samples in a stratified sampling scheme with three factors: soil organic matter content, groundwater table and crop (grass, mais, arable crops).

Highest carbon contents were found in the arable fields, carbon levels in grassland were significantly lower. This pattern is contrary to what is normaly found (as e.g. in TAGA) and unexpected (Table 2, Appendix III). Soil type and groundwater level can not explain the differences in soil organic matter content.

Several hypothese were formulated:

1. Inadequate soil sampling with different depths for grassland versus arable land
2. Historical land use with arable farms on naturally richter soils including higher organic matter or on anthropogenic soils with human induced soil carbon accumulation from elsewhere
3. Land use changes as measurements for soil carbon were only provided for in 2000 and previous or subsequent land use may well have differed
4. Recent changes in groundwater management now enables farmers to use former wet natural grassland for arable farming and rotations
5. Non reprensentative sampling i.e. some very high organic matter (peat) soils were included

Non of these hypotheses could be tested and validated in the course of this project and results have not been explained yet. However, when arable land on sandy soil contains relative large amounts of carbon, poor management of these soils result in losses of carbon that need to be accounted for. This is worthwhile examining further.

# Soil organic carbon accumulation - simulation of De la Lande Cremer/Zwart experiments

Raymond Jongschaap and Kor Zwart

In the Netherlands no ongoing long term field experiments are available where data on changes in soil carbon storage are collected. Data from a variety of past and discontinued long term experiments are available via reports and publications. Data from many former experiments are archived in the TAGA (Technical Archive on Soils and Crops) at Alterra (see Appendix III).

In 1961 at the Research Institute for Soil Fertility (IB) in Groningen, the Netherlands an experiment was started by De la Lande Cremer to monitor organic matter decomposition rates related to different types and levels of application of organic material (Zwart, unpublished). We have analysed these experiments and simulated the organic matter dynamics in relation to organic matter management using a dynamic simulation model PlantSys (Jongschaap *et al.*, in press) for two soil types (clay and loam soil) and five treatments of organic amendments. The model was validated against measured organic matter data from 1961-1988.

The simulations produce similar patterns of organic matter contents for a range of different initial states which is promising; however decomposition rates may have been underestimated. The simulation results follow the theoretical patterns: organic applications with higher C/N values tend to increase the soil organic matter content the most and additional nitrogen applications increase decomposition processes lowering C/N in the organic pools.

The extremely high application rates of 1000 kg N $ha^{-1}$ are largely leached to the ground water. Leaching is even more pronounced in the loamy soil with lower soil moisture holding capacity and higher drainage rates. This results in a relatively lower effect of the additional nitrogen applications on organic matter accumulation.

The simulated control values show a decrease in soil organic matter contents of 0.02 % $y^{-1}$ for low, and 0.04 % $y^{-1}$ for high initial organic matter contents for the situations with high initial organic matter contents (Figure 6, Appendix IV). These values are in agreement with the observation in the 'De la Lande Cremer' experiments.

The calibrated model was used to explore the fate of more realistic application rates of soil organic matter application of 15 – 60 ton manure per hectare. Results for the model explorations demonstrate that fixed application rates with fixed C/N ratios show much less variation in soil organic matter contents than the De la Lande Cremer experiments. With regards to FYM applications, yearly application of Chaff/Straw resulted in higher increase in soil organic matter for both soil types, reaching stable situations eventually.

For FYM applications, application rates higher than 30 t ha $y^{-1}$ resulted in a small increase of soil organic matter contents in the clay soil, whereas for the loamy soil, lower FYM application rates resulted in increased soil organic matter contents. This can be explained by the fact that loamy soil types are relatively dryer, resulting in reduced decomposition rates.

Although soil types and climate set the obtainable levels for soil organic matter contents, management factors (like application rates and C/N of the organic material) determine the direction of change and are the main source of variation. Temperature and precipitation are of minor importance.

# Fluxes - combining flux data and a process based model to separate direct from indirect effects

Isabel van den Wyngaert and Bart Kruyt

One way of separating the directly human-induced effects from the indirect effects and other changes in carbon uptake is to use well-calibrated models of the carbon cycling in ecosystems (see Appendix V) like CENTURY. This model can be run to represent situations with and without human actions and thus direct human induced effects can be separated from indirect effects at the impact of different processes can be calculated (i.e. N deposition and thinning in a forest).

In general, there was a strong relation between initial rate of carbon accumulation and increased nitrogen deposition both in the vegetation and in the soil. Higher rates of carbon accumulation resulted in higher carbon stocks for nitrogen deposition values up to 2.5 g N $m^{-2}$ $year^{-1}$ (see also Makipaa *et al.*, 1998). In the CENTURY runs used in this paper, nitrogen input higher than 2.5 g N $m^{-2}$ $year^{-1}$ does not increase the final amount of carbon accumulated in the system. The higher initial production rates lead to a faster accumulation and the 'equilibrium value' is reached earlier. Nitrogen was clearly not limiting anymore to either vegetation or soil micro-organisms.
For nitrogen input higher than 3 g N $m^{-2}$ $year^{-1}$ the amount of nitrogen leaching from the system in equilibrium to deeper ground water increased linearly with the nitrogen input (Figure 2.7 in Appendix V).

The process-based biogeochemical model CENTURY simulated ecosystem response to varying levels of nitrogen deposition as an example of an indirect human induced effect. The simulations showed a strong effect of nitrogen on carbon accumulation rate in young, nutrient-poor systems on sand with nitrogen deposition values up to 2.5 g N $m^{-2}$ $year^{-1}$. Eventual (theoretical) equilibrium carbon stocks were also strongly determined by nitrogen input for levels of nitrogen deposition below and up to currently occurring values (regions with low nitrogen deposition in the Netherlands). From about 3 g N $m^{-2}$ $year^{-1}$ carbon stocks did not increase further with increasing nitrogen deposition, but there was a strong increase in leaching from the system; carbon storage equilibrium values were reached sooner only.

Thinning reduces the storage of carbon in the system and these reductions are larger than the relative amounts removed. A 20% thinning every 10 years could almost halve eventual equilibrium carbon stocks for nitrogen limited conditions. The loss of production through increased nitrogen limitation was smaller, however, than the loss of production through loss of leaf area, and even in situations with ample nitrogen supply thinning lead to large (up to 37%) reductions in carbon stocks. The effect of thinning increased when nitrogen input dropped, and this most probably reflects the loss of nutrients from the system in increasingly nutrient-limited conditions.

# 6. Conclusions and recommendations

At the Marrakech COP the UNFCCC requested the IPCC to *develop practicable methodologies to factor out direct human-induced changes in carbon stocks and greenhouse gas emissions by sources and removals by sinks from changes in carbon stocks and greenhouse gas emissions by sources and removals by sinks due to indirect human-induced and natural effects (Decision 11/CP.7 3(d)*. The rational behind this text is simple: the additional effect of activities to reduce emissions is rewarded excluding possible positive or negative effects resulting from other human induced activities and natural effects which influence the emission of greenhouse gasses. The range of temporal and spatial scales at which processes occur and the scales at which management interacts with these processes are not included in this study. The study deals with $CO_2$ and not with $CH_4$ or $N_2O$.

In this report we begin to unravel this issue with an inventory of possible methodologies and their applicability, to separate the direct and indirect effects in relation to carbon sequestration in agricultural land use and managed forest ecosystems (Gorissen & Visser, 2003; chapter 4 this report).

Although the rational and question are simple to define it has proven difficult to achieve:

- *Definition* – the question was formulated in a policy arena the consequences for the science arena were not clear at the time the issue was put on the agenda.
- *Complexity at concept level* – unravelling the numerous factors leading to an increase in the carbon stock or reduction of emission is not a trivial matter, let alone when also the nature of agent and effects over larger timescales should be included in the equation.
- *Management overrules natural processes* – in many circumstances the direct effects of ARD activities on carbon stocks and greenhouse gas emissions and removals will be much larger than the sum of indirect human-induced and natural effects (IPCC, 2003).
- *Complexity at the process level* – the non-linear interactions among all effects and various time scales.

In this report we first have addressed a selection of effects: i) carbon dioxide fertilization; ii) nitrogen deposition; iii) past practices in forests; iv) temperature; v) precipitation; and in less detail vi) radiation levels; vii) flooding and vii) fire and the impact on the C stock.
For two reasons it was more problematic than anticipated: (i) the existing literature evidence is weak as too few databases from long term experimentation or monitoring exist and (ii) knowledge of C and $CO_2$ fluxes are poorly understood due to difficulties in the methodologies. In other words, we do not sufficiently know which relevant parameters to measure and how frequently to facilitate detailed process modelling. During the first phase of the project IPCC (2003) concluded that *the scientific community cannot currently provide a practicable methodology that would factor out direct human-induced effects from indirect human-induced and natural effects for any broad range of LULUCF activities and circumstances*. This was inline with our findings and prompted us to, in consultation with LNV, to reformulation of the final part of the project.

In the second part of this report we focussed on long term experiments in forest and agricultural systems to identify and simulate the contribution of management on the carbon stocks and fluxes from these systems. Several sources were used, i.e. TAGA for agricultural land use (Kooistra & Kuikman, 2003), Larch plantations for forest ecosystems (Jansen *et al.*, 1996)) and recent 'Sturen op Nitraat' measurements for agriculture. The re – analysis of data from TAGA was time consuming and not all relevant data were direct available from records. The analyses revealed several unexpected C dynamics in response to the documented management such as decreases in organic matter concomitant with continued additions of organic matter. Most experiments in TAGA have certainly not been designed to monitor changes in organic carbon in soil and many not even as long term experiments. Management factors such as application rates and C/N of the organic material are the main source of variation in soil organic carbon as shown in long term experiments from De la Lande Cremer and overrule traditional factors such as temperature and precipitation (Appendix IV).

The analysis of growth data of Larch plantations was inconclusive. When removing the age effect of trees and forest, a significant but maybe not causal relation between N deposition,$CO_2$ concentration and the growth of Japanese larch was found. The effect of management in forest systems seems to be limited, but was hardly investigated here because of a lack of management data.

The effect of nitrogen deposition on a *Pinus sylvestris* stand was simulated using CENTURY. The conclusion on the prime impact of management and N deposition on forest carbon accumulation was sustained. Equilibrium levels of organic matter in soil depend on the long term nitrogen additions (mainly deposition) and may take up to 1000 years to be achieved and depend on management (thinning).

Clearly separating direct from indirect human induced effects is a scientifically difficult issue and given our current scientific understanding today is difficult to achieve. Drawing clear conclusions is therefore not possible. Main reason for this lies is the complex nature of carbon allocation in ecosystems primarily as result of management. Many non – linear interactions have been identified. Usually, managing resource availability (N or P) has more pronounced impact on carbon stores and carbon fluxes than does $CO_2$ concentration or temperature.

Only if we improve our understanding and predictability at process levels of our management of ecosystems we may expect to factor out natural causes from human impact. This will inevitably be done using simulation models. Such models require regional or local data for validation and verification purposes. In the Netherlands, such ongoing long term field trials and experiments are not available anymore. Many European countries too bring long term field trials to a halt. In this perspective, reported and well documented experiments are of high value and bring immediate possibilities for parameterization and validation of simulation models. In some cases archived samples may allow for re – analysis while in other cases experimental results not reported sofar are still available from archived datasets. These options have not been examined fully.

For practical reasons such models need to be simple as simple models require fewer and more universal parameter estimates. Such scientific achievements require major efforts and include analyzing existing data or executing long term experiments or monitoring sequences.

Future activities include development and acceptation of simple rules such as using (regional) cut – off values (default 1 or 5 or 10% of all effect is indirect and larger fraction is direct effect based on the observations that management overrules natural impacts). This would certainly hold for agricultural activities and ecosystems. In forest ecosystems in the Netherlands the reversed may hold as N deposition may overrule forestry management. However, this N deposition is in fact related to agricultural or industry and traffic management.

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# Appendix I.
# Possibilities of using long-term forest growth data for separating direct and indirect effects

Cees van den Berg, Bert van der Werf and Gert Jan Nabuurs

## Introduction

The decision of a forest owner to plant a certain tree species determines to a large extent the net carbon balance of that site for many decades because each tree species and management regime have their own specific temporal evolution of carbon stocks and fluxes (Figure 1). Some tree species grow fast but reach their maximum biomass and age rather soon, others can continue to build up biomass for much longer times. These intrinsic dynamics are influenced by human beings, but also by environmental circumstances. An example of human impacts (direct impacts) can be seen in Figure 1 where the forest owner has decided to clear fell the Scots pine at 90 years age. The owner of the beech stand decided to clear fell at 150 years, which gives a very different time evolution of the carbon balance. Environmental circumstances (indirect impacts) again influence these dynamics, e.g. N deposition and increased atmospheric $CO_2$ may alter the slope of the carbon stock increase in the beginning, or may alter the maximum level that is reached. Thus indirect impacts may actually change site productivity.

The interest in being able to separate these direct and indirect impacts is a fundamental scientific issue, but has recently been given a policy interest through the text in the Marrakesh accords (see the overall introduction of the main report) (IPCC, 2003).
One option to separate direct and indirect effects may be available in the data derived from long-term forest growth and yield measurements. These regular measurements of diameter, height and number of trees in permanent plots were carried out in many Western countries starting often in the 1920's and continuing to the present day. If we were able to combine these data with auxiliary data sets on management and environmental circumstances, these data may provide a part of the solution on separating direct and indirect effects.

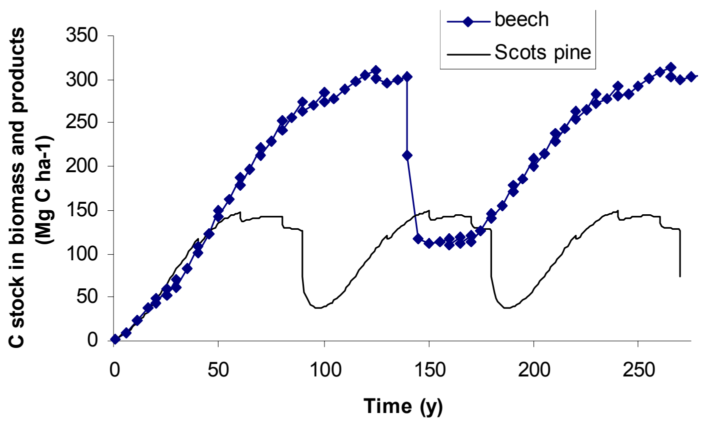


*Figure 1. Typical carbon stock development of living biomass and products for a beech and a Scots pine stand of 1 ha in the Netherlands as assessed with CO2FIX based on yield table data.*

# Aim and set-up

The aim was to test the suitability of forest growth and yield measurements for separating direct and indirect effects. In order to do so, all available measurements regarding height, diameter and volume growth for Japanese larch (*Larix kaempferi*) in the Netherlands were used. Japanese larch was chosen because it is a fast growing species that is known to be responsive to different sites, and because a large data set was available.

Two sub-aims were set:

1. Has growth of Japanese larch in the Netherlands changed over time, where the year 1960 is used as the separating year between two periods? The year 1960 is used because it is generally seen as the start for rapid economic growth.
2. Is it possible to derive the influence of management and environmental circumstances on increment through regression analysis (All Subsets Regression; Stepwise Forward Selections).

# Methods and data

Height, diameter and (derived) volume increment were used as response variables.

The following explanatory variables were available:

1. Age — germination year as recorded in growth and yield data
2. Soil type — derived from soil map 1 : 50000
3. Groundwater class — derived from soil map 1 : 50000
4. Temperature — temperature sum of the monthly means (average for the Netherlands)
5. Precipitation — sum (mm) (average for the Netherlands)
6. Thinning percentage — volume of thinnings (% of the growing stock) per plot
7. $CO_2$ concentration — atmospheric $CO_2$ concentration (ppm) (global average)
8. Nitrogen deposition — (kg N/ha.y) (average for the Netherlands)

The data for Japanese larch were derived from 72 plots that were recorded at 1 to 3 year intervals. In total 234 recordings were made (Table 1). Most of them are on Veldpodzol (poor sandy, moist podsols). The data recordings covered the period 1925 to 1990. For growth and yield research, the raw field data of height and diameter were processed to e.g. basal area, volume increment, growing stock, thinning volume, etc.

*Table 1. Stand characteristics of the data.*

| Number of plots | Age (y) | Number of recordings | Soil type | Groundwater class |
|---|---|---|---|---|
| 60 | 10 – 66 | 233 | Veldpodzol | 3,5,6 |
| 6 | 10 – 38 | 33 | Haarpodzol | 7 |
| 3 | 20 – 50 | 14 | Enkeerd | 7 |
| 2 | 14 – 50 | 13 | Duinvaag | 7 |
| 1 | 30 – 55 | 9 | Vlakvaag | 5 |
| 72 | | 234 | | |

## Growth and yield plot recordings

Figure 2 displays the basic data on height increment by age, and Figure 3 by year of recording. The age effect of decreasing growth with age is visible in Figure 2. It also shows that most recordings were done on trees varying from 20 to 50 years. Figure 3 shows that most recordings were done between 1940 and 1970. Some new plots in young stands were established after 1970, showing up as the individual lines around 1980.

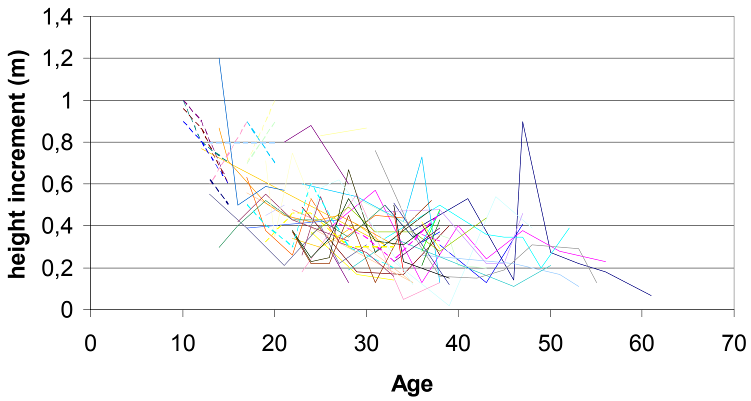


*Figure 2.* *Height increment of the dominant trees by age for each plot as available from the growth and yield data for Japanese larch.*

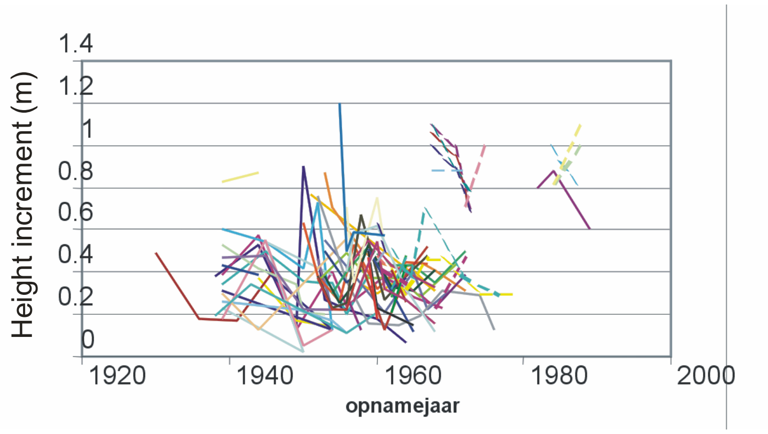


*Figure 3.* *Height increment of the dominant trees per plot by recording year for each plot as available from the growth and yield data for Japanese larch.*

## Temperature data

Temperature sum data of the monthly average show that a small increase has taken place since 1900 (Figure 4). A non-significant increase took place if the periods before and after 1960 are compared. The average annual sum of the data before 1960 amounts to 111.1, while after 1960 it amounts to 112.9. KNMI (2000) however reports a 0.7 °C increase in average year temperature for the Netherlands for the last two decades in comparison to the period 1900-1920.

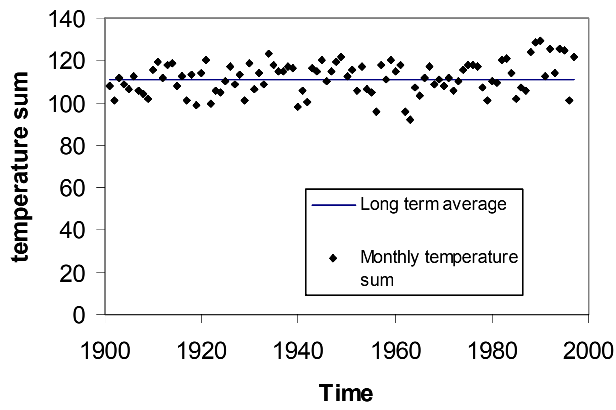


*Figure 4.* *Monthly average temperature sum per year.*

## Precipitation data

A significant increase in annual precipitation took place. Before 1960 the average was 766 mm, and after 1960 it amounts to 849 mm/y (Figure 5) (Fprob < 0.001). This is confirmed by the Dutch averages as presented in KNMI (2000) and by Boxel and Cammeraat (1999).

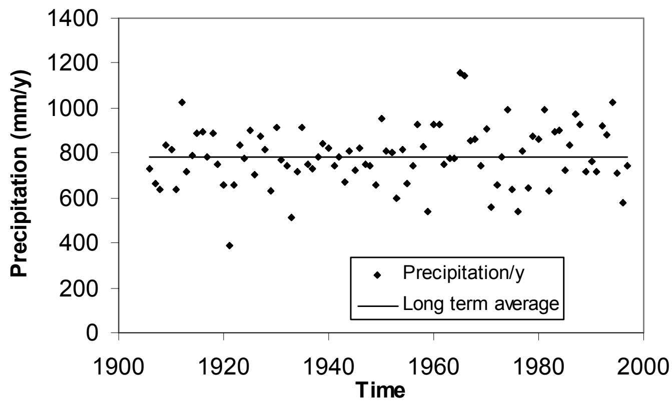


*Figure 5.* *Annual sum of precipitation.*

## Management data: thinnings

As explanatory variables for management, only the thinnings were available in the growth and yield recordings. All other management aspects as site preparation, planting or seeding, and fertilization were not recorded systematically and had to be left out of the analyses. Thinning intensity is expressed here as the percentage of the growing stock volume that is removed per thinning event. A non-significant change in thinning intensity was found for the period before 1960 versus after 1960. Before 1960 the thinning intensity amounted to 11% of growing stock per thinning event, after 1960 it amounted to 9% (Fprob. 0.06).

## Carbon dioxide concentration

The carbon dioxide concentration as measured at Mauna Lowa, Hawaii was used as another environmental explanatory variable. Mauna Lowa was used as it is the longest running measurement period. Since 1958 it increased from 316 tot 353 ppm at present. Based on these measurements, values for the period 1900 – 1958 were extrapolated (Figure 6). Although exact $CO_2$ concentrations for the Netherlands will be slightly higher, the trend is the same and therefore the Hawaii values can be used.

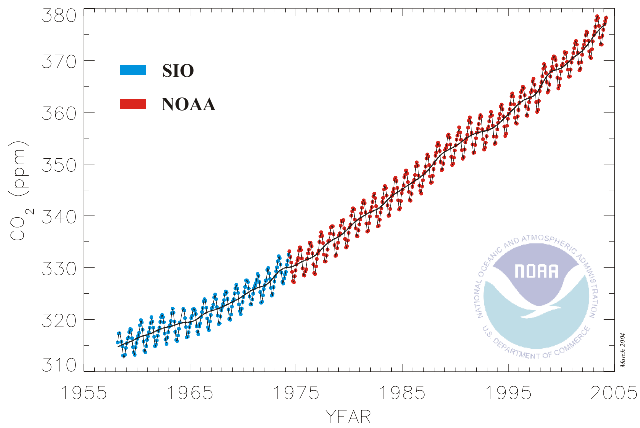


*Figure 6.* *Mauna Loa Monthly Mean Carbon Dioxide. Atmospheric carbon dioxide monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography (SIO, blue), data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA, red). A long-term trend curve is fitted to the monthly mean values. Principal investigators: Dr. Pieter Tans, NOAA CMDL Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678, Pieter.tans@noaa.gov, and Dr. Charles D. Keeling, SIO, La Jolla, California, (616) 534-6001, cdkeeling@ucsd.edu.*

## Nitrogen deposition data

Individual nitrogen deposition trends for each growth and yield plot were not available. Therefore one average nitrogen deposition trend was used as the last environmental explanatory variable. The nitrogen deposition in the Netherlands has strongly increased after 1960 (Figure 7), but is curbed after the 1980's due to measures taken in agriculture and the transport sector.

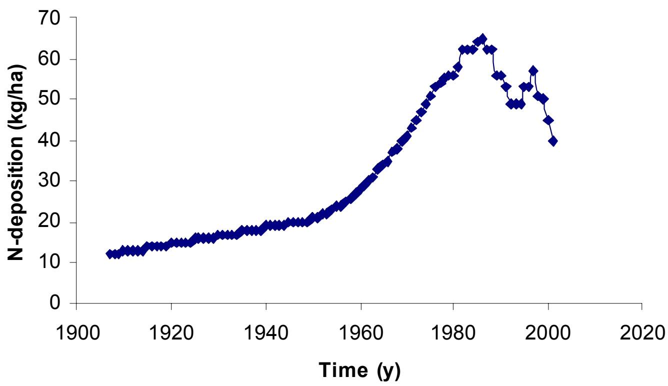


*Figure 7.* *Average N deposition over time for the Loobos site (pers comm. Bobbink).*

## Statistical analyses

For the first aim a simple variance analysis was applied to the data recorded before 1960 and those recorded after 1960. Correction for age effect was applied.
To assess the dependence of height, diameter and volume increment to environmental changes or management and possible interactions (second aim), linear regressions were applied (All Subsets Regression; Stepwise Forward Selections). Correction for age effect was applied.

# Results

## Analysis of growth change and site influences

A significant increase in diameter and volume increment was found for Japanese larch in the Netherlands for the period after 1960 (Table 2), showing a small correlation to nitrogen deposition (Figure 8).

*Table 2. Increment in height, diameter and volume during the periods before 1960 and after 1960.*

| Period | Height increment (cm) | se **) | Diameter increment (cm) | se | Volume increment ($m^3$/ha.y) | se |
|---|---|---|---|---|---|---|
| Before1960 | 40 | 18 | 0.29 | 0.16 | 10.2 | 5 |
| After1960 | 42 | 21 | 0.49 | 0.21 | 11.9 | 4 |
| Significance | NS (Fprob = 0.2)*) | | S (Fprob = < 0.001 | | S (Fprob = < 0.001 | |

**) S = significant*
*NS = not significant*
***) se = standard error*

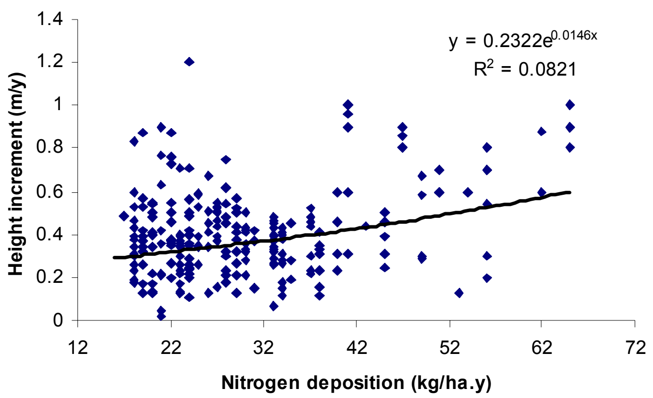


*Figure 8. Height increment by nitrogen deposition.*

Relevance of soil and groundwater class for height, diameter, and volume growth were tested in a variance analysis (Tables 3, 4, 5).

*Table 3. Height increment (m) by soil and groundwater class.*

| Soil type | Groundwater class (gt) | | | |
|---|---|---|---|---|
| | 3 | 5 | 6 | 7 |
| Veldpodzol | 0.48 | 0.35 | 0.45 | 0.36 |
| Haarpodzol | | | | 0.43 |
| Enkeerd | | 0.38 | | |
| Duinvaag | | | | 0.39 |
| Vlakvaag | | | | 0.29 |
| Significance | Gt: S (Fprob = <0.01) | | soil: NS | |

**) S = significant*
*NS = not significant*

*Table 4. Diameter increment (cm) by soil and groundwater class.*

| Soil type | Groundwater class (gt) | | | |
|---|---|---|---|---|
| | 3 | 5 | 6 | 7 |
| Veldpodzol | 0.32 | 0.35 | 0.45 | 0.38 |
| Haarpodzol | | | | 0.31 |
| Enkeerd | | 0.25 | | |
| Duinvaag | | | | 0.22 |
| Vlakvaag | | | | 0.37 |
| Significantie | Gt: S (Fprob = <0.01) | | bodem: S (Fprob=<0.01) | |

**) S = significant*
*NS = not significant*

*Table 5. Volume increment ($m^3$) by soil and groundwater class.*

| Soil type | Groundwater class (gt) | | | |
|---|---|---|---|---|
| | 3 | 5 | 6 | 7 |
| Veldpodzol | 15.5 | 11.9 | 11.7 | 10.1 |
| Haarpodzol | | | | 10.5 |
| Enkeerd | | 11 | | |
| Duinvaag | | | | 11.1 |
| Vlakvaag | | | | 8.8 |
| Significantie | Gt: S (Fprob = <0.01) | | bodem: NS | |

**) S = significant*
*NS = not significant*

Groundwater class significantly affects all three growth variables while soil type only has significant influence on diameter increment.

## Regression analysis for separating direct and indirect effects

Tables 6, 8 and 10 present the results of the significance of each individual explanatory variable on the growth variables, while Tables 7, 9 and 11 present the results of the stepwise forward selection giving the best explanatory model. Based on the latter, parameters were estimated and used for predictions of growth by either nitrogen deposition (Figure 9) and $CO_2$ concentration (Figure 10). These predictions were made for an average age of 29 years, an average temperature sum and an average thinning percentage.

*Table 6. Explanation of the individual explanatory variables on height growth.*

| Explanatory variable | % explanation | Fprob: (< 0.05 is significant) |
|---|---|---|
| N deposition | 41 | < 0.01 |
| Groundwater class (Gt) | 41 | 0.04 |
| $CO_2$ concentration | 40 | 0.02 |
| Soil type | 40 | 0.1 |
| Precipitation | 40 | 0.1 |
| Temperature sum | 40 | 0.1 |
| Thinning percentage | 39 | 0.7 |
| Period (before/after 1960) | 39 | 0.9 |

*Table 7. Explanatory variables in order of decreasing significance forming the best explanatory model for height growth.*

| Explanatory variable | Fprob: (< 0.05 is significant) | Total explanation: 48% |
|---|---|---|
| Age | < 0.001 | |
| N deposition | 0.004 | |
| Soil | 0.02 | |
| Groundwater class | 0.02 | |
| Period | 0.02 | |
| $CO_2$ | 0.28 | |
| Temperature sum | 0.27 | |

*Table 8. Explanation of the individual explanatory variables on diameter growth.*

| Explanatory variable | % explanation | Fprob: (< 0.05 is significant) |
|---|---|---|
| Age | | |
| N deposition | 48 | <0.001 |
| Period | 38 | <0.001 |
| $CO_2$ | 33 | <0.001 |
| Soil | 29 | 0.02 |
| Thinning | 29 | 0.005 |
| Groundwater class | 28 | 0.09 |
| Precipitation | 26 | 0.5 |
| Temperature sum | 26 | 0.6 |

*Table 9. Explanatory variables in order of decreasing significance forming the best explanatory model for diameter growth.*

| Explanatory variable | Fprob: (< 0.05 is significant) | Total explanation of the model: 51% |
|---|---|---|
| Age | <0.001 | |
| N deposition | <0.001 | |
| Soil | 0.03 | |
| Thinning percentage | 0.02 | |
| $CO_2$ | 0.2 | |

*Table 10. Explanation of the individual explanatory variables on volume growth.*

| Explanatory variable | % explanation | Fprob: (< 0.05 is significant) |
|---|---|---|
| Temperature | 12 | 0.001 |
| N deposition | 12 | 0.001 |
| Groundwater class | 11 | 0.01 |
| Soil | 9 | 0.08 |
| Period | 7 | 0.3 |
| $CO_2$ | 7 | 0.4 |
| Precipitation | 7 | 0.9 |
| Thinning | 7 | 1.0 |

*Table 11. Explanatory variables in order of decreasing significance forming the best explanatory model for volume growth.*

| Explanatory variable | Fprob: (< 0.05 is significant) | Total explanation of the model: 23% |
|---|---|---|
| Age | < 0.001 | |
| Temperature | < 0.001 | |
| N deposition | < 0.001 | |
| Groundwater class | 0.008 | |
| Soil | 0.06 | |
| $CO_2$ | 0.1 | |

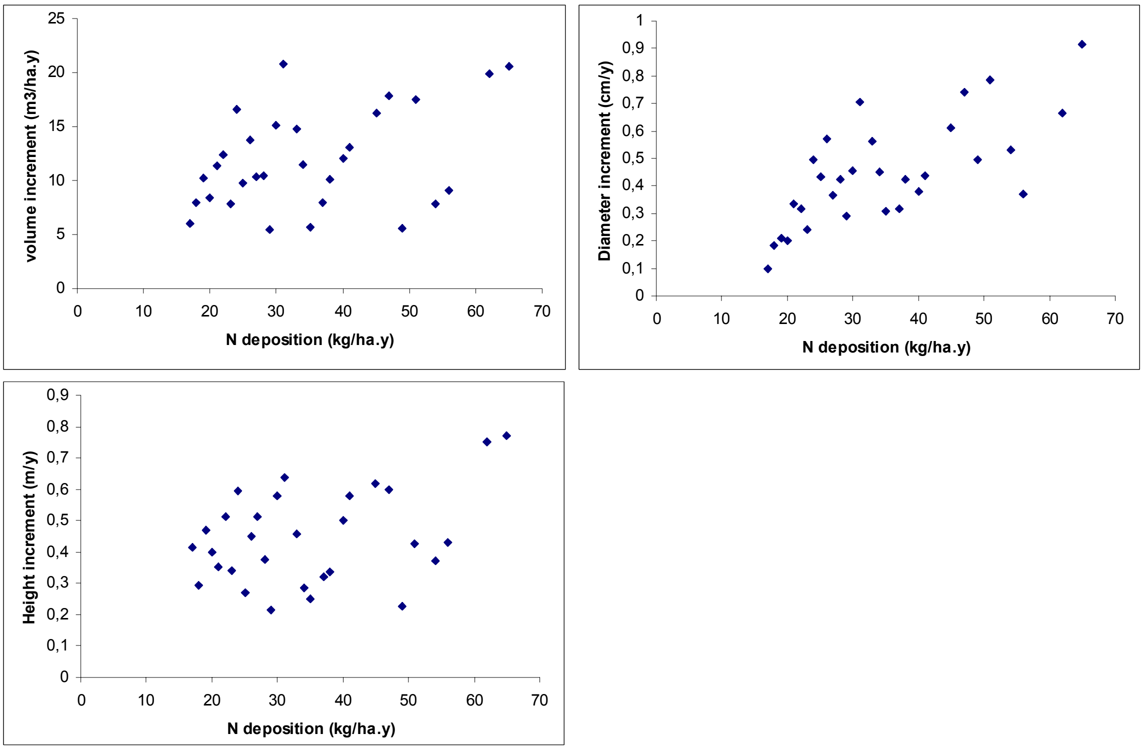


*Figure 9.* *Predictions of volume, diameter and height growth as explained by nitrogen deposition based on the best explanatory models. The large spread in estimates shows the relatively small explanation by nitrogen alone.*

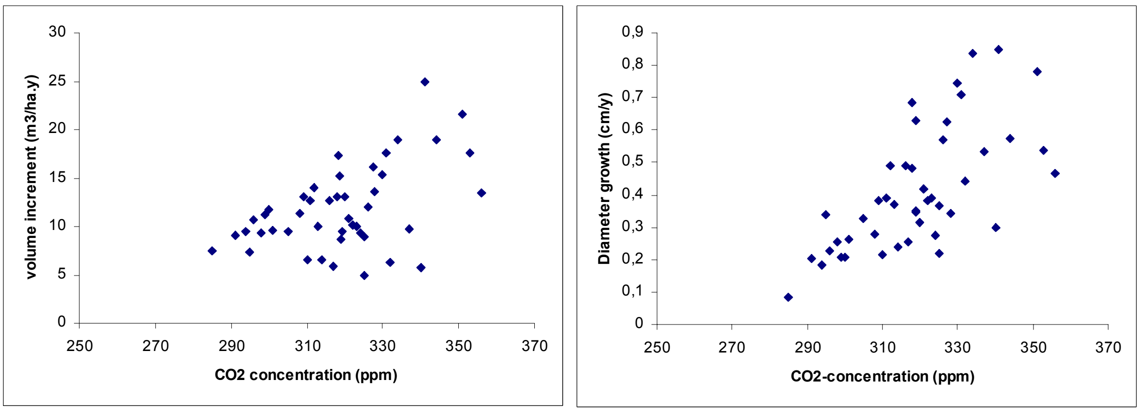


*Figure 10.* *Predictions of volume and diameter growth as explained by $CO_2$ concentration based on the best explanatory models. The large spread in estimates shows the relatively small explanation by $CO_2$ alone.*

# Discussion and conclusion

The analyses as presented here must be taken with great caution because data regarding the explanatory variables were derived from a variety of sources and often not from the exact location of the measurement plot. This sets great limitations to the present analysis. Only thinning percentage was recorded in the measurement plot as the only management-related variable.

Analysing the growth data as recorded before 1960 versus after 1960, showed that diameter and volume increment of Japanese larch -when corrected for age effects - have significantly increased in the Netherlands. When canceling out the intrinsic age dynamics of tree growth, this study mainly found N deposition and $CO_2$ concentration to be of significant importance in explaining growth of Japanese larch. The only management variable for which we had data (thinnings) was significantly explanatory only for diameter growth. The latter seems logical, as thinnings concentrate growth on a reduced number of trees, mainly showing as increased diameter growth of the individual trees. However, the growth predictions based on the best explanatory model showed large variations, suggesting that only a small proportion of the variation was indeed explained by the model.

What does this mean for:

**a.** the suitability of growth and yield plot data for separating direct and indirect, and

**b.** the proportion between direct and indirect?

**Re a.**

Historic growth and yield plot data are of great value as such. However, for the type of research as done here they also have their limitations. These plots and their recordings were never set up for this aim. They are not necessarily representative, do not cover all age classes, and environmental circumstances were never recorded. Remarkably, the management was recorded in a limited way too. Although some of the missing data might be retrievable, for some of it this is now impossible (e.g. N deposition over time at the exact site). This means that these types of analyses will always have their limitations. Even with a large additional effort aimed at retrieving local explanatory data (maybe in combination with tree ring analyses) does not give the full picture. Such a set-up was part of the RECOGNITION project (Karjalainen *et al.*, 2004) which still had its limitations. http://www.efi.fi/projects/recognition/

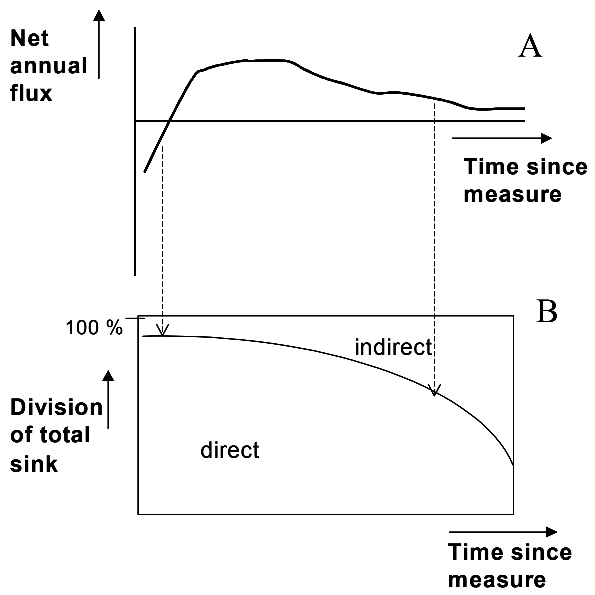


*Figure 11. A possible approach for separating direct and indirect effects. A management measure is carried out at year 0 and has a sink impact as given in the top graph 'A'. The B graph then suggests how the sink in time can be assigned to direct impact of human-induced measures versus indirect impacts. It is likely that the direct impact declines over time, as the relative impact of weather variability, $CO_2$ fertilisation and N deposition increases (Nabuurs, 2004).*

**Re b.**

The results as presented here suggest that environmental circumstances as N deposition and $CO_2$ concentration determine to a significant extent the growth trend of Japanese larch when the intrinsic growth dynamics are cancelled out. However, the explanation of height and diameter growth of all explanatory variables was still only around 50%, and its causality not proven. Bascietto *et al.* (2004) use a comparable set up where they analyse bio-mass data of a chronosequence of spruce stands. They conclude that the recent young stands contain significantly more biomass than what the presently old stands contained when they were young. This may indicate a site productivity change, but is still no basis for separating direct and indirect effects. The same goes for our set-up: we cannot conclude now what proportion of growth has been caused by direct effects, and what by indirect effects. i.e. the separating line in the 'B' graph of Figure 11 cannot be fixed on the basis of these results. However, we gained indications that the indirect effects are large and significant.

# Literature

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# Appendix II.
# Een beknopt overzicht van mogelijk interessante historische proeven m.b.t. C-vastlegging in de bodem

Jan Willem van Groenigen

In dit overzicht vindt u de resultaten van een korte historische inventarisatie van langlopende proeven die ons mogelijk iets kunnen leren over potentiële koolstofvastlegging in de bodem. Eerst wordt een overzicht gegeven van de proeven Pr 1255 te Bommelerwaard en Pr 0013 te Borgercompagnie, waarvan gegevens uit het TAGA archief zijn geanalyseerd. Vervolgens wordt er een overzicht gegeven van 8 veelbelovende rapporten die geselecteerd zijn uit een 40-tal publicaties over langlopende proeven. Bij het overzicht is steeds kort aangegeven wat de opzet van de proef is, hoe lang de proef liep en wat de conclusies waren. Dit overzicht kan mogelijk dienen als leidraad voor een vervolg-literatuurstudie waarin de rapporten en onderliggende data gedetailleerd worden bestudeerd.

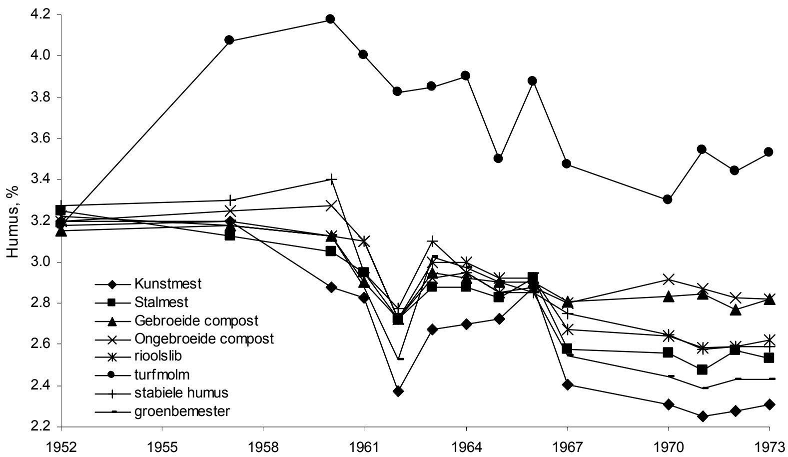
Een aantal voorlopige conclusies kan getrokken worden:
1. Er is een aantal proeven gevonden die dermate uniek zijn in opzet en looptijd dat deze zeker extra studie verdienen. Alhoewel er aan statistische opzet en de uitgebreidheid van de bepalingen meestal wel wat ontbreekt, kunnen er waarschijnlijk toch conclusies uit getrokken worden die vandaag de dag met kortlopende proeven niet te trekken zijn.
2. Vrijwel alle proeven rapporteren het humusgehalte slechts als ondersteunende data, en zijn gefocussed op kwantiteit en kwaliteit van landbouwproductie en stikstofleverend vermogen van de grond. De C-gehalte-data zitten dus over het algemeen 'verstopt' in de verslaglegging en is tot nu toe nooit serieus wetenschappelijk geanalyseerd.
3. Alle historische langlopende proeven hadden betrekking op bouwland, met mogelijk kunstweide (3 jaar grasland na 3 jaar bebouwing). Er zijn geen proeven gevonden op permanent grasland.
4. In bijna alle rapporten wordt geen bulk density vermeld, maar wordt uitsluitend het verloop van het humusgehalte getoond. Dit maakt het onmogelijk om C-voorraden in de bodem exact the kwantificeren, alhoewel het humus-gehalte wel een indicatie geeft. Evt. verder onderzoek zou zich ook moeten richten op het terugvinden van evt. wel gedane bulk density metingen.
5. Het voorlopige beeld dat ontstaat m.b.t. C-vastlegging in de bodem is kunstweide >> stalmest/organische toe-voegingen > kunstmest. Meerdere proeven rapporteren een sterke toename in organische stof bij kunstweide.
6. Over de verschillen tussen soorten organische toevoegingen is veel minder bekend – de enige langdurige studie vermeldde een groot positief effect bij turfmolm, gevolgd door compost.

## 1. Proef pr 1255: Bommelerwaard

Gedurende 21 jaar (van 1952 tot 1973) liep er in de Bommelerwaard een proef waarbij het effect van verschillende organische bemestingen op humusgehalte in de bodem en opbrengst van het gewas (rotatie graan, bieten, aard-appelen) werd gevolgd. De volgende behandelingen werden onderscheiden:
1) Kunstmest
2) Stalmest
3) VAM gebroeide compost
4) VAM ongebroeide compost

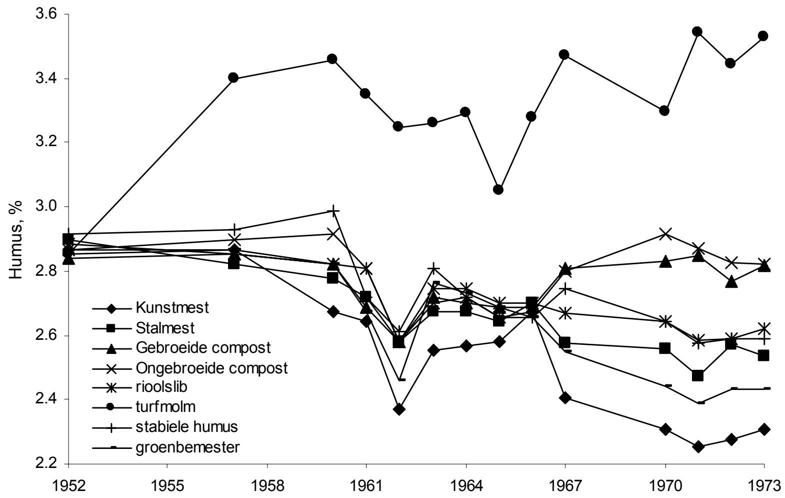
5) Rioolslib
6) Turfmolm
7) Stabiele humus
8) Groenbemester

Het materiaal is in de periode 1952 – 1967 om de twee jaar toegediend in variërende hoeveelheden. Van 1967 t/m 1974 ieder jaar in halve hoeveelheden. Van 1974 t/m 1980 is de hoeveelheid stalmest verviervoudigd, en zijn de andere behandelingen aangepast tot een vergelijkbare organische-stofgift. De proef is opgezet in viervoud. Over opbrengst en N-opname in het gewas zijn allerlei data beschikbaar. De bodemdata zijn helaas veel beperkter. Van 14 jaren binnen de periode zijn er humusmetingen beschikbaar (Figuur 1), de periode vanaf 1974 is in deze fase nog niet geanalyseerd, alhoewel er geen sprake lijkt van een trendbreuk.

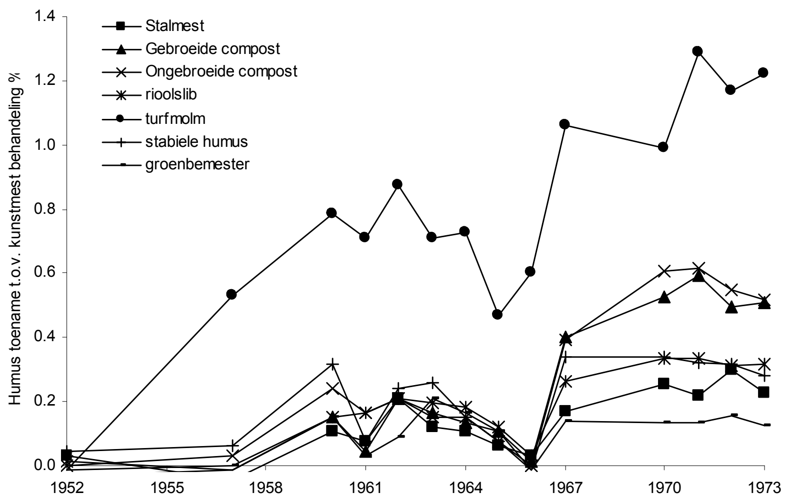



*Figuur 1. Het verloop van het humusgehalte binnen proef Pr1255 voor de verschillende behandelingen. Data zijn niet gecorrigeerd voor de overgang naar een andere humusbepaling vanaf 1976.*

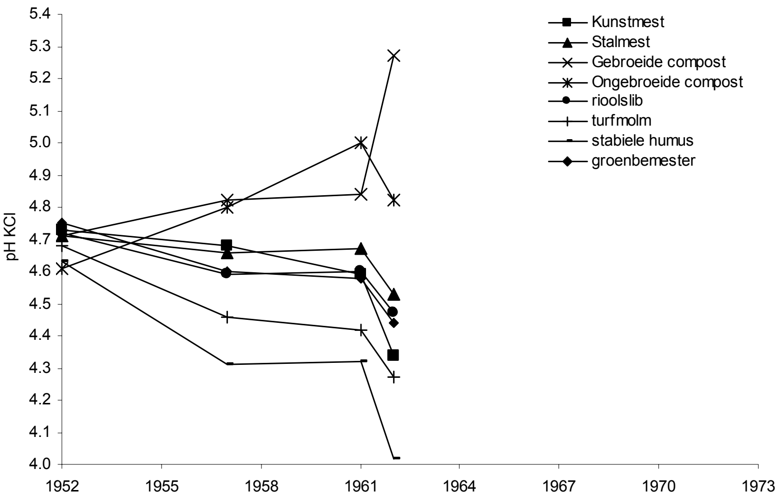
Tot en met het jaar 1966 is er een andere methode gebruikt om humusgehalte te bepalen ('elementair') dan daarna ('oxidatie'). Systematische verschillen tussen de twee methodes ('oxidatie' had systematisch lagere waarden dan 'elementair') zijn gecorrigeerd m.b.v. lineaire regressie, waardoor alles nu in 'oxidatie'-equivalenten staat vermeld in Figuur 2.
Turfmolm leidt als enige tot een duidelijke stijging in het humusgehalte, van 2,9% tot 3,5% (Figuur 2). Alle andere toevoegingen resulteren in een lager humusgehalte. Het is echter waarschijnlijk dat dit gedeeltelijk een artefact is dat terug te voeren is op veranderd management.




*Figuur 2.* *Het verloop van het humusgehalte gedurende proef Pr1255 voor de verschillende behandelingen. Data zijn gecorrigeerd voor de overgang naar een andere organische-stofbepaling tussen 1966 en 1967.*




*Figuur 3.* *Het verloop van het humusgehalte gedurende proef Pr1255 ten opzichte van het humusgehalte bij de kunstmestbehandeling. Data zijn gecorrigeerd voor de overgang naar een andere organische-stofbepaling tussen 1966 en 1967.*




*Figuur 4. Het verloop van de pH-KCl voor verschillende behandelingen in proef Pr1255. Er zijn geen metingen beschikbaar van na 1962.*

Er zijn grofweg drie periodes te onderscheiden gedurende de proef:

1) 1952 – 1960: een sterke stijging van humusgehalte in de turfmolmbehandeling die gedurende de hele proef blijft bestaan.
2) 1960 – 1967: een aantal plotselinge dips en stijgingen die wellicht uit veranderd management verklaard kunnen worden.
3) 1967 – 1973: een verdere uitsplitsing van het humusgehalte naar het type organische toevoeging, waarbij turfmolm >> compost > rioolslib ≈ stabiele humus ≈ stalmest > kunstmest.

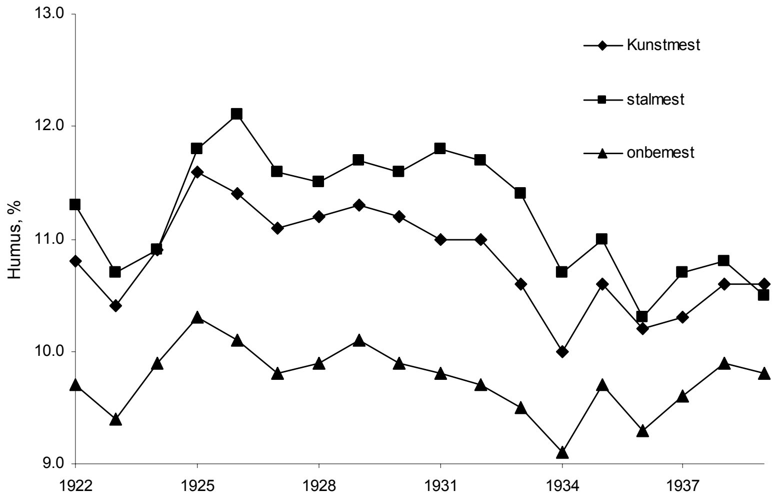
De sterke dip in het jaar 1962 is waarschijnlijk niet anders te verklaren dan door iets als dieper ploegen, waardoor een verdunning optrad. Om dit probleem deels te ondervangen, wordt in Figuur 3 het humusverloop t.o.v. de kunstmestbehandeling uitgezet. T.o.v. deze behandeling neemt het humusgehalte bij alle organische toevoegingen toe, waarbij gebroeide en ongebroeide compost het meest effectief zijn na turfmolm.
De weinige additionele bodemdata geven weinig indicaties over de reden waarom turfmolm tot zo'n grote humustoename leidt. De ontwikkeling van pH (Figuur 4) is in ieder geval voor turfmolm en (on)gebroeide compost radicaal verschillend.
Het grootste manco in deze dataset is het ontbreken van bulk density data over de meetperiode en het ontbreken van een duidelijke diepteaanduiding van de monstername (nu uitsluitend 'bouwvoor').

Een paar afsluitende vragen en conclusies:

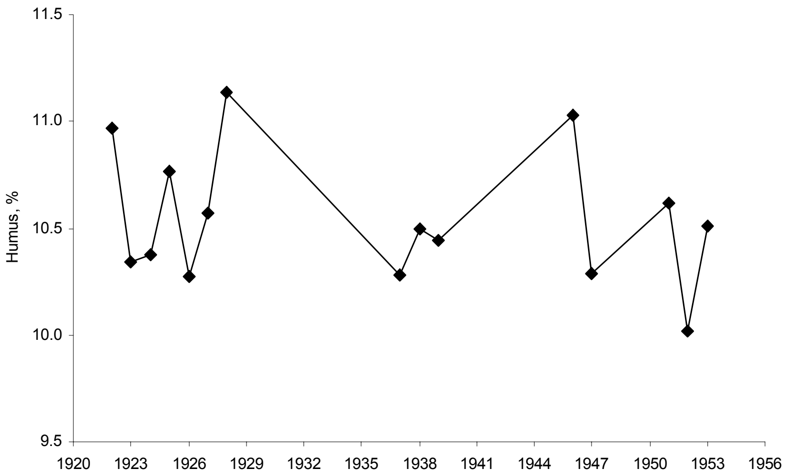
- turfmolm leidt in deze proef duidelijk tot de hoogste humustoename in de bodem – kunstmest tot de laagste.
- het effect van verschillende analysemethoden voor humusgehalte kan deels worden ondervangen door correctie m.b.v. lineaire regressie.
- kunnen we uit verdere analyse van turfmolm afleiden waarom juist deze toevoeging leidde tot een sterke toename in het bodem-C?
- kunnen we uit verdere analyse van de gewasopbrengsten in deze proef misschien iets zeggen over de aanvoer van bodem-C via residu?
- hoe verhouden de hoeveelheden toegediende N zich voor de verschillende behandelingen? Blijft turfmolm ook de topper als hiervoor wordt gecorrigeerd?
- meer documentatie (nog niet goed bestudeerd) over deze proef is te vinden in het rapport 'huisvuilcompost en zuiveringsslib als organische meststoffen voor bouwlandgewassen op een zware rivierkleigrond in de Bommelerwaard, in vergelijking met stalmest, groenbemesting en turfmolm', van S. de Haan en J. Lubbers. Hierin worden nog aanvullende metingen tot begin jaren '80 gerappporteerd.

## 2. Proef Pr 0013: Borgercompagnie

Gedurende 45 jaar (van 1922 t/m 1967) liep er op proefbedrijf Borgercompagnie een serie proeven die met name betrekking hadden op vorm van bemesting (organisch vs. kunstmest) en, na de oorlog, op de invloed van pH op gewasopbrengst.




*Figuur 5. Verloop van het humusgehalte onder verschillende behandelingen gedurende het eerste gedeelte van proef IB 0013.*




*Figuur 6. Het gemiddelde verloop van het humusgehalte in de periode 1920- 1953 voor proef IB 0013.*

De rotatie is over het algemeen aardappelen / rogge /haver. Voor de oorlog zijn er met name data over het humus-gehalte, na de oorlog zijn er meerdere proeven aangelegd, met name voor pH en bekalkingsproeven, soms ook meststoffen (chilisalpeter vs. zwavelzure ammoniak) of groenbedekking. Alleen voor de jaren 1922 en 1924 zijn er bulk density metingen gedaan, waardoor een goede berekening van de C-voorraad in de bodem wederom niet mogelijk is. Verder zijn er in de perioden 1922-1936 en 1937-1939 verschillende coderingssystemen gebruikt voor de verschillende veldjes, en lijkt na de oorlog de hele verkaveling van de proef te zijn veranderd. Het is dus niet mogelijk om b.v. het humusverloop van 1 behandeling gedurende de hele periode te laten zien. Figuur 5 laat het humusverloop gedurende het vooroorlogse deel van de proef zien voor 3 behandelingen. Het feit dat er al direct verschillen zijn tussen koemest, kunstmest en geen bemesting doet vermoeden dat de behandelingen al enige tijd waren geïnstalleerd voor de metingen begonnen. Gedurende de periode daalt het humusgehalte met name in de jaren ‘30 sterk. Dit lijkt ook weer het gevolg van veranderd management (b.v. dieper ploegen). Een aantal metingen van na de oorlog laat ook geen duidelijke trend zien in het gemiddelde humusgehalte (Figuur 6).

## 3. Historisch literatuuroverzicht

| | | |
|---|---|---|
| *Titel* | : | Enkele resultaten van het grondonderzoek van het bemestingsproefveld op zandgrond bij gebroeders Ter Haar te IJhorst, staande onder leiding van de proefveldcommissie in Overijssel |
| *Auteurs* | : | D.J. Hissink en J. van der Spek |
| *Proefnummer* | : | |
| *Instituut* | : | IB |
| *Jaar* | : | 1935 |
| *Looptijd proef* | : | 1911 – 1935 (24 jaar) |
| *Opzet proef* | : | 4 veldjes met (i) stalmest, (ii) kunstmest, (iii) kunstmest + mergel, (iv) half kunstmest, half stalmest. Organische-stofmetingen 6 keer tussen 1923 en 1935. |
| *Conclusie m.b.t. bodem C* | : | Duidelijke toename humus bij stalmest (tot gehalte 9,7%) t.o.v. kunstmest (6,9%). Bekalken lijkt ook positief effect te hebben. |
| *Problemen met data(analyse)* | : | Proef niet gerepliceerd, geen humusgehalte gemeten bij aanvang proef, bulkdichtheid alleen in 1925 gemeten, bodemmonsters op verschillende manieren genomen. |
| *Bruikbaarheid data* | : | Lange proef met duidelijk positief effect van stalmest, duidelijke verschillen, ook in bulkdichtheid. |

| | | |
|---|---|---|
| *Titel* | : | Bemesting met stalmest op een herontgonnen veenkoloniale grond gedurende 25 jaren |
| *Auteurs* | : | F. Riem Vis |
| *Proefnummer* | : | Pr 800 |
| *Instituut* | : | IB |
| *Jaar* | : | 1971 |
| *Looptijd proef* | : | 1944 – 1971 (27 jaar) |
| *Opzet proef* | : | Proef op een in 1934 herontgonnen grond. Gedurende 27 jaar (misschien langer?) wordt opbrengst (aardappelen, rogge) vermeld bij verschillende hoeveelheden stalmest, daarbovenop N-trappen. Precieze opzet is niet vermeld, staat in Kortleven (1970). Uit dit rapport ontstaat echter de indruk van een degelijk opgezette proef. |
| *Conclusie m.b.t. bodem-C* | : | Gedurende 15 jaar constant, daarna een afname van humusgehalte met gemiddeld 0.16% per jaar. Een vergelijking met andere veenkoloniale gronden en een discussie van de specifieke problemen met humus op deze gronden is bijgevoegd. Normaal volgt op ontginning een periode van (i) toename organische stof vanwege menging veenkluiten en minerale bodem; (ii) consolidatie humusgehalte, en (iii) achteruitgang van humusgehalte. Deze afzonderlijke fasen komen soms dichtbij elkaar voor, soms zelfs in dezelfde proef. Over het algemeen ging de stijging sneller dan de afname:<br>Gedurende de proef steeds betere aardappelopbrengst – met name door betere N-benutting. |
| *Problemen met data* | :. | Onduidelijk – moet blijken uit precieze opzetbeschrijving. Waarschijnlijk is bulk density niet gemeten, maar dit is niet helemaal zeker. |
| *Bruikbaarheid data* | : | Heel interessant, met name voor ontgonnen gronden, opzet lijkt goed, moet nog wel gecheckt worden. |

| | | |
|---|---|---|
| *Titel* | : | Samenvattend verslag over 9 jaar van een bodemvruchtbaarheidsproefbedrijf op zavelgrond in Noord-Friesland |
| *Auteurs* | : | G.J. Wisselink |
| *Proefnummer* | : | Onderdeel van interprovinciale proefserie 22, proefbedrijf NF 662 |
| *Instituut* | : | IB |
| *Jaar* | : | 1961 |
| *Looptijd proef* | : | 1949 - 1957 |
| *Opzet proef* | : | Bedrijf schakelt over van een gardeniersbedrijf (pootaardappelen) naar meer gemengde bouw. 3 behandelingen: (i) geen organische mest, (ii) zoveel mogelijk organische mest, (iii) wisselbouw (3 jaar kunstweide, 3 jaar bouwland). Behandelingen gerepliceerd over bedrijf. |
| *Conclusie m.b.t. bodem C* | : | Weinig verandering in humusgehalte behandeling 1, in 2 met 0,10% gestegen, behandeling 3 0,5% over 6,5 jaar. Conclusie: vooral kunstweide helpt. |
| *Problemen met data* | : | Geen bulk density vermeld, relatief korte periode. |
| *Bruikbaarheid data* | : | Veel data over samenstelling mest, oogst, etc. Gerepliceerd op een min of meer random manier. Duidelijk effect kunstweide. |

| | | |
|---|---|---|
| *Titel* | : | Verslag over het verloop der humusgehalten gedurende zestig jaren in een onbebouwde zandgrond |
| *Auteurs* | : | J. Kortleven |
| *Proefnummer* | : | Pr 1 (vanaf 1951 Pr 1265) |
| *Instituut* | : | IB |
| *Jaar* | : | 1970 |
| *Looptijd proef* | : | 1904 – 1967 (63 jaar) |
| *Opzet proef* | : | Kunstmatig gecreëerde grond bij stichting IB 1904. Gedeeltelijk onbebouwd, planten steeds verwijderd, helft met fosfaat bemest, andere helft onbemest. In 1951 werd het onbemeste deel opgesplitst in (i) onbebouwd, geen stalmest, en (ii) onbebouwd, stalmest. Het bemeste deel werd (iii) bebouwd, geen stalmest en (iv) bebouwd, stalmest. Proef wordt in 1967 overgebracht naar nieuwe locatie IB, waarna dit rapport stopt. |
| *Conclusie m.b.t. bodem-C* | : | In de periode 1911 – 1950 neemt het humusdeel in het het onbegroeide deel met 0,8% af, het begroeide deel stijgt 0,1%. In de periode 1950 – 1967 is het effect van bemesting groter dan dat van bebouwing. Een stijging van 0,34% in begroeid zonder organische mest, een stijging van 0,43% in onbegroeid met organische mest. |
| *Problemen met data* | : | Niet gerepliceerd, in de oorlog hebben er tanks door de proef heen gereden, wat resulteerde in onduidelijke verplaatsing van grond. Geen bulkdichtheid. |
| *Bruikbaarheid data* | : | Zeer lange looptijd, duidelijk effect van niet bemesten. |

| | | |
|---|---|---|
| *Titel* | : | Proeven met stadsvuilcompost II |
| *Auteurs* | : | J. Kortleven |
| *Proefnummer* | : | diverse |
| *Instituut* | : | IB |
| *Jaar* | : | 1970 |
| *Looptijd proef* | : | Een groot aantal proeven, meestal in de periode tussen de oorlog en publicatie-datum. Veel proeven met een looptijd van 10-20 jaar. |
| *Opzet proef* | : | Een veelheid aan proeven met compost, o.a. over invloed op humusgehalte, N- levering en vergelijking met andere organische bemesters. |
| *Conclusie m.b.t. bodem-C* | : | Veel proeven rapporteren een duidelijke stijging gedurende een aantal jaren, en daarna een plotselinge stabilisatie. Compost wordt over het algemeen als beter gezien dan andere organische additieven. |

| | | |
|---|---|---|
| *Problemen met data* | : | Nog onduidelijk – dik rapport met veel data dat nadere studie behoeft. Wel een verandering in de compostsamenstelling in de periode (veel minder 'huishoudkool'). |
| *Bruikbaarheid data* | : | Veel data over compost, lange proeven. Moet meer bestudeerd worden. |

| | | |
|---|---|---|
| *Titel* | : | De bodemstructuur op de drie organische-stofbedrijven |
| *Auteurs* | : | A. Pelgrum |
| *Proefnummer* | : | |
| *Instituut* | : | IB |
| *Jaar* | : | 1976 |
| *Looptijd proef* | : | 1951 – 1973 (22 jaar) |
| *Opzet proef* | : | Drie bedrijven in de Noordoostpolder, startende vanuit eenzelfde beginsituatie, met (i) alleen kunstmest, (ii) zo veel mogelijk groenbemester, (iii) wisselweide. |
| *Conclusie m.b.t. bodem-C* | : | Wisselweide gaf duidelijk de minste afname (van 3,0 tot 2,62%), kunstmest de meeste (van 3,0 tot 2,17%). |
| *Problemen met data* | :. | Metingen pas vanaf 1968 gerapporteerd. |
| *Bruikbaarheid data* | : | Geen herhaling, maar door unieke uitganssituatie toch redelijk goede vergelijkbaar. Ook bulk density data gerapporteerd voor de laatste jaren, alsmede andere fysische metingen. |

| | | |
|---|---|---|
| *Titel* | : | De uitkomsten van 9 proefpercelen met organische bemesting over een periode van 9 jaar |
| *Auteurs* | : | G.J. Wisselink en J. Lubbers |
| *Proefnummer* | : | Pr 1227, PO 317, U 684, U 685, U 709, ZL 1790, OB 3107, WB 1703, ZGr 790 |
| *Instituut* | : | IB |
| *Jaar* | : | 1963 |
| *Looptijd proef* | : | 1949 - 1958 |
| *Opzet proef* | : | Op 9 bedrijven met verschillende gronden door het hele land heen werd de invloed van (i) alleen kunstmest, en (ii) kunstmest + groenbemesting + stalmest op o.a. humusgehalte, opbrengst en vochtleverend vermogen bepaald. |
| *Conclusie m.b.t. bodem C* | : | Behandeling ii leidde in 9 jaar tot een gemiddelde verhoging van 0,2% humus, dit is een kwart van de totaal toegevoerde organische stof. |
| *Problemen met data* | : | Soms in tweevoud, meestal niet gerepliceerd. Niet zo'n heel lange proef. |
| *Bruikbaarheid data* | : | Consistent beeld over meerdere grondsoorten met zeer verschillende humus-gehaltes. |

| | | |
|---|---|---|
| *Titel* | : | Kwantitatieve aspecten van humusopbouw en humusafbraak |
| *Auteurs* | : | J. Kortleven |
| *Proefnummer* | : | Diverse |
| *Instituut* | : | IB |
| *Jaar* | : | 1963 |
| *Looptijd proef* | : | |
| *Opzet proef* | : | Met name een modelleerstudie, maar met waardevolle data en (met name) referenties naar langdurig experimenteel werk op het gebied van humusgehalte. |
| *Conclusie m.b.t. bodem C* | : | |
| *Problemen met data* | : | |
| *Bruikbaarheid data* | : | Referenties moeten worden nagetrokken voor mogelijke extra interessante data. |

| Humus stijgt (i) | | Humus blijft gelijk (ii) | | Humus daalt (iii) | |
|---|---|---|---|---|---|
| proef no. | stijging per jaar % | proef no. | humusgehalte % | proef no. | daling per jaar % |
| Pr 3 | 0,18 | Pr 3 | 6,9 | Pr 8/9 | 0,19 |
| Pr 927 | 0,21 | Pr 10 | 6,8 | Pr 19 | 0,05 |
| Pr 1502 | 0,17 | Pr 13 | 11,0 | Pr 120 | 0,09 |
| IB 7 | 0,15 | Pr 30 | 25,2 | Sappemeer | 0,47 |
| Pr 935 | 0,38 | Pr 800 | 8,7 | Pr 800 | 0,16 |
| Pr 935 | 0,47 | Pr 935 | 16,6 | | |
| Pr 1047c | 0,43 | Pr 934 | 22,6 | | |
| Pr 1048a | 0,67 | Pr 1041 | 14,8 | | |
| Pr 1051 | 0,47 | Pr 1051 | 9,6 | | |
| gemiddeld | 0,35 | gemiddeld | 13,6 | gemiddeld | 0,19 |

# Appendix III.
# Data-analyse Sturen op Nitraat

Annemieke Smit

## Introductie

Doel van dit deelonderzoek was te kijken of er uit de gegevens van Sturen op Nitraat meer te halen was dan er nu binnen dat project wordt gedaan. Er zijn in het eerste meetseizoen behoorlijk wat metingen gedaan aan organische-stofgehaltes, maar die zijn bij latere statistische analyses niet relevant gebleken voor de regressiemodellen.
In onderstaande tekst wordt uitgewerkt welke gegevens over organische stof in het project Sturen op Nitraat zijn verzameld. Verder worden de organische-stofgehaltes van verschillende gewasgroepen vergeleken en worden er nieuwe vragen opgesteld.
Hierbij is vooral het verschil tussen grasland en bouwland of maïsland interessant. Ten slotte zullen enkele overwegingen worden gegeven.

## Sturen op Nitraat - gegevensverzameling

Voor het project Sturen op Nitraat (StopNit) zijn in de jaren 2000- 2004 metingen uitgevoerd aan bodem en grondwater. Het doel van deze meetcampagnes was het verzamelen van steekproefgegeven, waarmee empirische modellen moeten kunnen worden afgeleid waarmee de regio-, bedrijfs- en perceelsgemiddelde nitraat-concentratie in het bovenste grondwater kan worden afgeleid. Het moet tevens mogelijk zijn de voorspelnauwkeurigheid van de modellen te kwantificeren.

De focus van dit project lag dus duidelijk op nitraatuitspoeling. Dit betekent dat er ook vooral op zandgronden en in lössgebieden naar bedrijven is gezocht. In totaal zijn er 34 bedrijven geselecteerd, verdeeld over melkveehouderij en akkerbouw, die allen deelnemers waren aan andere projecten, zoals Koeien & Kansen, Telen met toekomst, BIOM, BIOVEEM, Praktijkcijfers II.

Er werden 478 meetpunten (proefplekken) geloot volgends een vooraf vastgestelde stratificatie, verdeeld over alle bedrijven. Bij het ontwikkelen van de stratificatie waren drie onderscheidende factoren voor nitraatuitspoeling onderscheiden: bodemorganische stof, vochtgehalte en gewas. Deze drie factoren zijn vertaald naar strata:

- Bodemgroepen:
  - L: Loss
  - Z1: zand met veel org stof of dikke bovengrond
  - Z2: zand met relatief veel org stof en hoog leemgehalte
  - Z3: overige zandgronden (podzolgronden)
- Gt-groepen:
  - Gt1: GHG <40 cm –mv
  - Gt2: GHG tussen 40 en 80 cm –mv
  - Gt3: GHG > 80 cm -mv
- Gewas:
  - (g) Gras
  - (m) Maïs
  - (b) Akkerbouwgewassen in 4 groepen

Op basis van bodemkaarten met grondwatertrappen en bedrijfsgegevens met gewassen zijn de punten geloot. In het veld is vervolgens gecontroleerd of het punt werkelijk tot het toegekende stratum behoorde.

In onderstaande figuur zijn de locaties van de bemonsterde bedrijven weergegeven.

*Uit: Gegevensverzameling Sturen op Nitraat (Smit et al., 2003).*

Op ieder meetpunt (proefplek) zijn meerdere metingen uitgevoerd:

- Nmin in 3 meetlagen (3 - 4 meetseizoenen)
- Nitraat in grondwater/bodemvocht
- Bodemprofielbeschrijving (inclusief org-stof% per horizont) +classificatie
- Denitrificatie in 6 laagjes
- Bouwvoor → analyses N en C, mineralisatie, denitrificatie
  ‼ Let op de **bouwvoor** is voor grasland 0-10 cm en voor bouwland 0-25 cm

# Analyse van de gegevens en aannames

De metingen aan organische-stofgehaltes zijn uitgevoerd in het eerste meetseizoen. De meeste proefplekken zijn in het najaar van 2000 bemonsterd, aangevuld met enkele proefplekken in het voorjaar van 2001. Van ieder meetjaar is uitgebreide informatie beschikbaar over de bedrijfs- en perceelsgegevens (gewas, aanvoer en afvoer van N), maar de voorgeschiedenis is voor de meeste bedrijven niet bekend. Op basis van de gegevens in 2000 is wel op te maken welke gewas er in dat seizoen op het perceel stond, maar het is bijvoorbeeld niet te zeggen of de aanwezigheid van gras betekent of het om blijvend grasland gaat of om tijdelijk grasland. Om toch een onderscheid te kunnen maken is de aanname gedaan dat proefplekken, die gedurende de hele looptijd van het project (en indien bekend ook in 1999) onder gras hebben gestaan zeer waarschijnlijk blijvend grasland zijn (g). Proefplekken waarop in de periode 2000 (of 1999) tot 2003 zowel gras als maïs heeft gestaan, zijn bij een andere groep ingedeeld (g/m). Zo is er ook een groep met alleen maar maïs (m), een groep met alleen maar akkerbouwgewassen (b) en een groep waar zowel akkerbouwgewassen, maïs als gras is verbouwd gedurende de looptijd van het project (b/g/m).

Bij de laboratoriumanalyses aan de monsters van de proefplekken zijn alle gemeten parameters weergegeven in gehaltes. De omrekening naar voorraden is alleen uitgevoerd voor de Nmineraal in de bodemlagen. Hiervoor is gebruik gemaakt van een berekende dichtheid op basis van een in het veld geschat organische-stofgehalte. Hiervoor zijn de volgende formules gebruikt:

Dichtheid vaste fase (g/cm$^3$) =1/((org stof% /100)/1,17+(1-(org stof%/100))/2,67) [1]

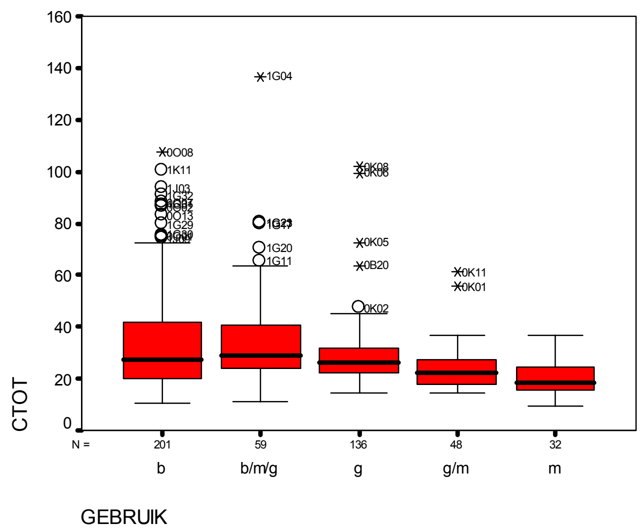
Porievolume = 0,28+0,555*((org stof%/100))^0,36 [2]

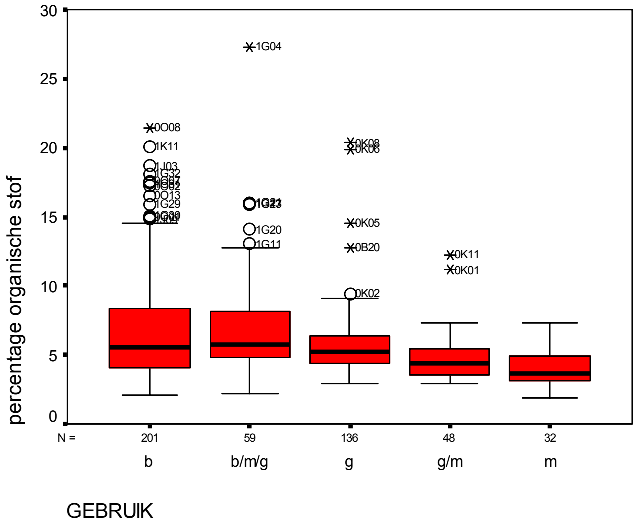
Bulkdichtheid = (1-porievolume)*dichtheid vaste fase [3]

Deze methode lijkt een zeer ‘vage’ en onbetrouwbare te zijn; toch blijkt uit verdere discussies dat ook het direct meten van de dichtheid tot vele praktische bezwaren kan leiden. In grasland zal de dichtheid door het jaar heen redelijk constant blijven, maar in bouwland spelen tijdstip van bemonsteren en de precieze locatie een belangrijke rol. In deze analyse is het Ctotaal-gehalte in de bouwvoor zoals dit in het laboratorium is bepaald volgens de Kurmies-methode (Houba *et al.*, 1997) omgerekend tot een koolstofvoorraad met behulp van de bulkdichtheid van de laag 0-30 cm, zoals hierboven is beschreven. Om een vergelijking te kunnen maken van voorraden tussen grasland en bouwland zijn beide voorraden opgeschaald tot een laag van 30 cm, uitgaande van een constant Ctot-gehalte over deze diepte.

# Resultaten

In onderstaande figuur zijn de boxplots van de C-gehaltes in de bouwvoor per gewasgroep weergegeven. De box geeft de 25 en 75 percentiel-waarde aan en de zwarte streep de mediaan. De proefplekken binnen de groepen g, g/m en m vallen vrijwel allemaal binnen melkveehouderijbedrijven, terwijl de proefplekken van de gewasgroepen b en b/m/g vooral op de akkerbouwbedrijven liggen.



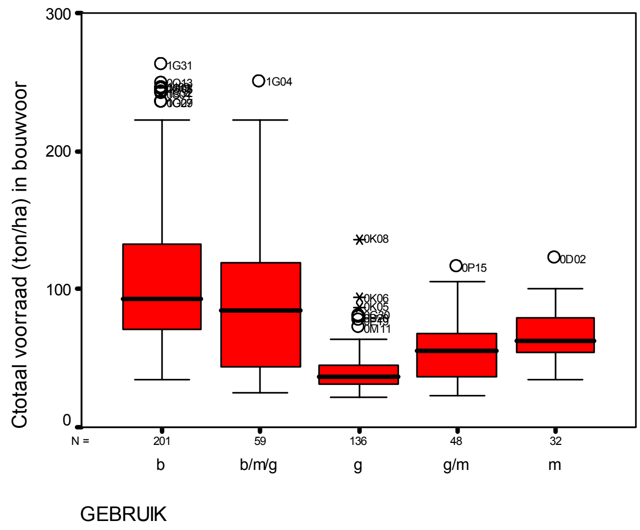



De gegevens van bovenstaande figuur zijn getoetst met een tweezijdige t-test. De resultaten van de test zijn weergegeven in Tabel 1. De gewasgroepen verschillen vrijwel allemaal significant van elkaar. Alleen de gewasgroepen b en b/m/g zijn niet significant verschillend.

*Tabel 1. Percentage organische stof voor de verschillende gewasgroepen. Significante verschillen zijn aangegeven met een * (p < 0,1) of ** (p < 0,05). L: Loss; Z1: zand met veel org stof of dikke bovengrond; Z2: zand met relatief veel org stof en hoog leemgehalte; Z3: overige zandgronden (podzolgronden); (g) Gras; (m) Maïs; (b) Akkerbouwgewassen in 4 groepen.*

| Groep | Gemiddelde | Std | Significant verschil met groep | | | | |
|---|---|---|---|---|---|---|---|
| | | | b | b/g/m | G | g/m | m |
| b | 6,77 | 3,92 | | - | ** | ** | ** |
| b/g/m | 7,31 | 4,36 | | | ** | ** | ** |
| g | 5,73 | 2,45 | | | | ** | ** |
| g/m | 4,82 | 1,83 | | | | | ** |
| m | 3,94 | 1,23 | | | | | |

De Ctotaal-gehaltes zeggen op zich niet veel over de voorraden koolstof in de bodem. In onderstaande grafiek zijn de voorraaden (ton/ha) in de bouwvoor weergegeven. Let op, het gaat hierbij om 10 cm bouwvoor in graslanden en 25 cm bouwvoor in proefplekken waar in 2000 maïs of een akkerbouwgewas stond. Dit gegeven maakt het moeilijk om een vergelijking te maken.




Daarom zijn de gegevens naar een vergelijkbare laagdikte opgeschaald (zie volgende figuur). Het is verrassend om te zien dat dan nog steeds de bouwlandproefplekken een hogere koolstofvoorraad (ton/ha) hebben dan de graslanden en dat de verschillen nog steeds significant zijn (Tabel 2).

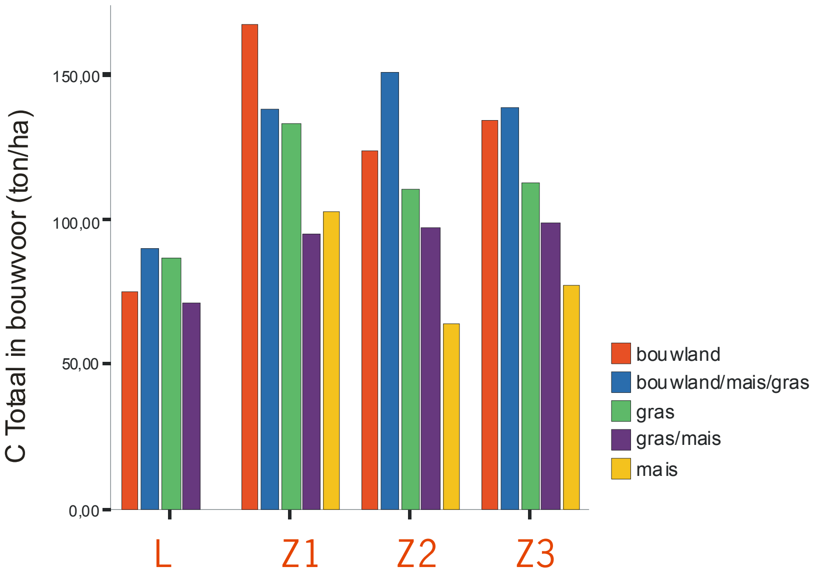
*Tabel 2.* *Ctot (ton/ha) voor de verschillende gewasgroepen. Significante verschillen zijn aangegeven met een * (p < 0,1) of ** (p < 0,05).*

| Groep | Gemiddelde | Std | Significant verschil met groep | | | | |
|---|---|---|---|---|---|---|---|
| | | | b | b/g/m | g | g/m | m |
| b | 5,21 | 3,04 | | * | ** | * | ** |
| b/g/m | 6,16 | 4,01 | | | ** | * | ** |
| g | 4,37 | 1,19 | | | | - | - |
| g/m | 4,41 | 2,78 | | | | | - |
| m | 4,14 | 1,43 | | | | | |

Voorraden organische stof zijn twee keer zo groot, uitgaand van een C-gehalte in organische stof van 50%.

## Mogelijke verklaringen voor een hogere voorraad C in bouwland

De hogere voorraden in bouwland ten opzicht van grasland kunnen in ieder geval niet het gevolg zijn van de aannames die zijn gedaan. Immers, voor grasland is alleen de bovenste 10 cm bemonsterd, die naar verwachting een hoger organische-stofgehalte heeft dan de daaronder gelegen 20 cm. Toch is de voorraad van de bouwvoor met 3 vermenigvuldigd om tot een laag van 30 cm te komen. Dit zal eerder tot een overschatting van het organische-stofgehalte leiden, dan tot een onderschatting. Daar staat tegenover dat in bouwland 25 cm is bemonsterd, hoewel aan het eind van het seizoen verwacht zou kunnen worden dat de bovenste laag van ongeveer 10 cm rijker is aan organische stof dan de rest (ongeveer 15 cm). Toch is deze laag in z'n geheel bemonsterd en van 25 naar 30 cm opgeschaald. Hier zou sprake kunnen zijn van een onderschatting, eerder dan een overschatting.

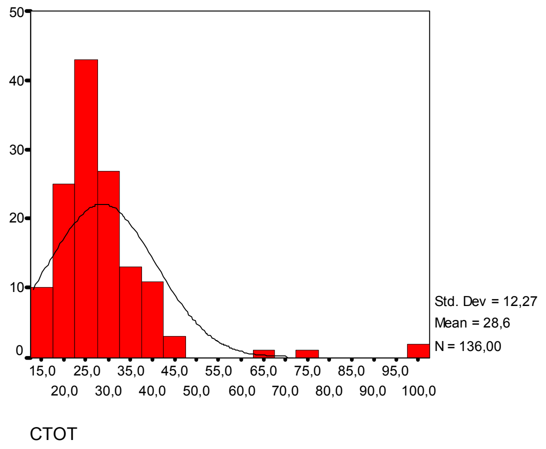


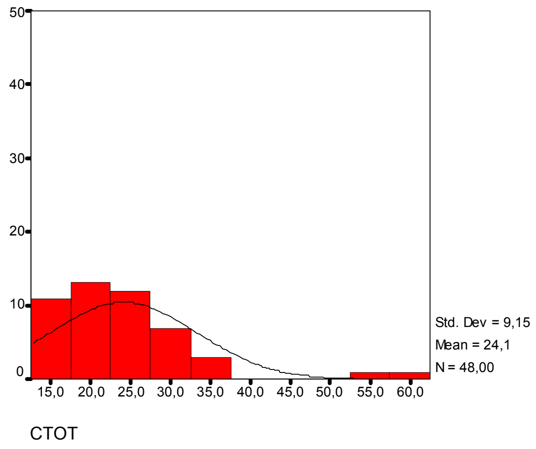

*C totaal in bouwvoor voor de verschillende bodems (L: Loss; Z1: zand met veel org stof of dikke bovengrond; Z2: zand met relatief veel org stof en hoog leemgehalte; Z3: overige zandgronden (podzolgronden)) en landgebruik.*

Het vermoeden bestond dat door de manier van berekenen van de dichtheid een mogelijke onderschatting van de voorraad in grasland is gemaakt. Immers onder grasland verwacht je een hoger organische-stofgehalte, als dat ook zo geschat wordt, zal door de berekening van de dichtheid een lagere dichtheid worden geschat, waardoor ook een lagere voorraad wordt berekend. Echter, uit de schattingen van het organische-stofgehalte van de bovenste 30 cm blijkt dat het gehalte op akkerbouwbedrijven (groepen b en b/m/g) hoger is dan op melkveehouderijbedrijven (gewasgroepen g, m en g/m).
Dan is er ook nog een mogelijkheid dat de akkerbouwbedrijven op de rijkere gronden liggen en de melkveehouderijbedrijven op de arme zandgronden. In onderstaande figuur is duidelijk te zien dat de C-gehaltes grofweg wel wat dalen van bodemgroep Z1 naar Z3, maar dat binnen alle bodemgroepen de gewasgroepen b en b/m/g de hoogste C-gehaltes hebben.
Het blijft er naar uitzien dat in Nederland de bouwland-gronden een hoger koolstofgehalte hebben dan de graslanden en dat is op z'n zachtst gezegd opvallend. Een mogelijkheid zou nog kunnen zijn dat de bouwlanden in het noordoosten van Nederland toch vooral op gronden terecht zijn gekomen waar altijd een hoger C-gehalte was. Deze gronden zijn voor akkerbouw zeer aantrekkelijk. In het zuidoosten van Nederland waren zulke bodems er veel minder en is er veel energie gestopt in het verrijken van de bodems door middel van potstalsystemen en zo. Bijvoorbeeld, de bodems in Meterik (tot voor kort proefbedrijf PPO) zijn tot 60 a 80 cm diep zeer rijk aan organisch materiaal dat onder andere in de vorm van mest en materiaal uit de omliggende bossen is aangevoerd. Deze gronden werden bij voorkeur niet voor beweiding gebruikt, omdat dat ook 'uit' kon in de armere omliggende gebieden. Of dit idee van een relatie tussen gebruik en organische-stofgehaltes ook kan worden getoetst is niet zomaarte zeggen, nadere oriëntatie daarover is nodig.

## Is er verschil tussen blijvend grasland en 'tijdelijk' grasland

Hier is onderscheid gemaakt tussen de punten die alle jaren grasland zijn geweest (aangemerkt als blijvend grasland) en punten die tijdens het project zowel grasland als maïsland zijn geweest (aangemerkt als tijdelijk grasland) (let op, niet al deze punten waren in 2000 ook daadwerkelijk gras, dat moet nog worden gedaan).
Er zijn niet duidelijk twee verschillende pieken te onderscheiden. In onderstaande figuren staan de verschillende grasgroepen afzonderlijk weergegeven. De linkerfiguur is blijvend grasland, de rechter betreft tijdelijk grasland.




## De invloed van de voorvrucht bij maïs

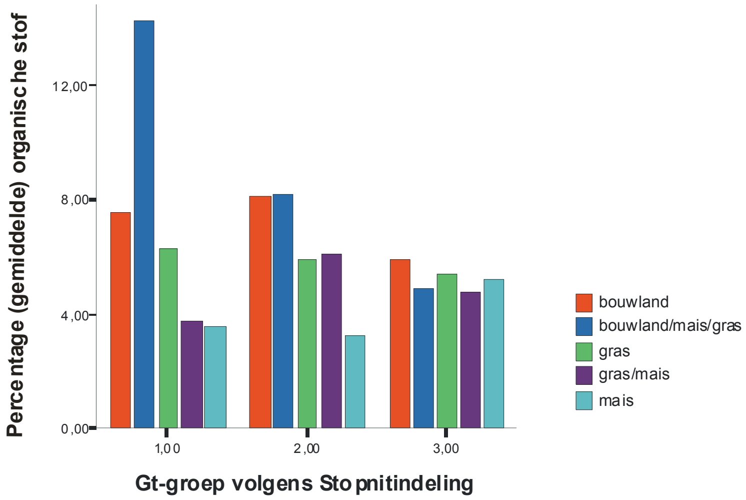
Hiervoor zijn de punten geselecteerd die in 2000 bij gewasgroep m horen en waarvan het gewas in 1999 bekend is. Per voorvrucht is bekeken wat het organische-stofgehalte was.

| Voorvrucht | N | Mean | Stdev |
|---|---|---|---|
| Onbekend | 37 | 3,73 | 0,94 |
| M | 29 | 4,89 | 1,74 |
| G | 7 | 4.91 | 1,15 |

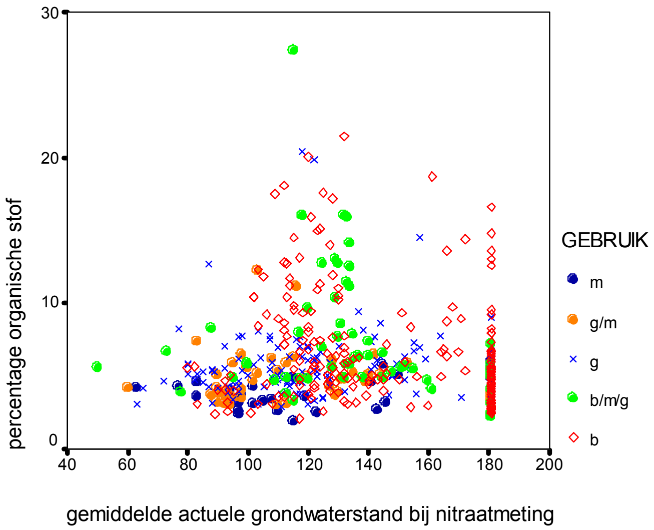
## De relatie tussen organische stof en Gt

Van alle proefplekken is in 2000 de Gt-groep bepaald op basis van bodemprofielkenmerken. Daarnaast is ieder jaar, tijdens de bemonstering van nitraat in het grondwater de diepte van het grondwater gemeten. In deze analyse zijn de metingen van de drie jaren per proefplek gemiddeld.

Eerst is gekeken of de gewasgroepen bij verschillende Gt-groep een ander organische-stofgehalte hebben. Dat blijkt het geval, waarbij opvalt dat b en b/g/m/ in Gt-groep 3 de laagste percentages hebben en gewasgroep m juist de hoogste. In Gt-groep 3 zijn de verschillen tussen de gewasgroepen nauwelijks meer zichtbaar.




In Gt-groep 1 is duidelijk dat de gewasgroep b/m/g en uitschieter in organische stof is. Het blijkt om 4 meetpunten te gaan, waarvan er 2 op een bodem liggen die is geclassificeerd als moerige beekeerdgrond. Hier zijn de organische-stofpercentages 27 en 18%. Zonder deze twee punten zou de groep niet meer opvallen en gemiddeld 7% organische stof hebben.




Er bestaat geen verband tussen het organische-stofgehalte en de diepte van het grondwater.

# Appendix IV.
# Simulation of De la Lande Cremer/Zwart experiments

Raymond Jongschaap and Kor Zwart

## Background

In 1961, an experiment was started at the Research Institute for Soil Fertility (IB) in Groningen, the Netherlands by *De la Lande Cremer* to monitor organic matter decomposition rates related to different types and levels of application of organic material. In 1967, this experiment was, together with the institute, relocated to Haren, the Netherlands. When IB and the Centre of Agrobiological Research (CABO) merged into Research Institute for Agrobiology and Soil Fertility (AB-DLO), the experiment was relocated to Wageningen, the Netherlands in 1998. (Zwart, unpubl.)

In this chapter we will analyse the experiments and try to simulate the organic matter dynamics in relation to organic matter management using a dynamic simulation model. The soil-crop simulation model PlantSys (Jongschaap at al., in press) was used to simulate carbon and nitrogen fate of organic applications that are incorporated in two soil types.

## Model description

Exchangeable modules for specific environmental processes form the PlantSys 1.1 simulation model. In any chosen composition, a calibration and validation procedure is mandatory for the model. Both calibration and validation procedures are demonstrated.
Details in the processes and methods used in PlantSys 1.1 can be separated in two domains: soil processes and crop processes. Because the experimental setup of the *De la Lande Cremer* experiment did not include a crop only, soil processes are considered in this study.

### Soil processes

The soil is represented as a vertical column, horizontally divided into distinctive soil horizons with specific physical and chemical characteristics. For each soil horizon, input data are needed on soil water holding capacities, organic matter contents, organic nitrogen contents, inorganic nitrogen contents, bulk density, and the quantity of remaining plant material from earlier crop growth. Other required input parameters are the initial carbon fraction in the stable organic matter pool and in the decomposable, structural and resistant plant material pool. Turnover rates controlling the organic matter dynamics are influenced by soil temperature and soil moisture contents.

*Table 1. Simulated organic matter pools, composition, carbon-nitrogen ratios and turnover rates (Verberne et al., 1990).*

| Pool | Composition | C/N | Turnover rate ($d^{-1}$) |
|---|---|---|---|
| Decomposable plant material | carbohydrates and proteins | 6 | 0.2 |
| Structural plant material | hemi-cellulose and cellulose | 150. | 0.1 |
| Resistant plant material | lignin and hemi-cellulose | 100. | 0.02 |
| Labile organic matter | - | 15. | 0.03 |
| Stable organic matter | - | Var | 0.000015 |

## Water fluxes

The soil water balance, affecting the decomposition of organic matter, is calculated on a daily basis. Precipitation, irrigation, run-off, run-on and infiltration occur at the boundary layer between soil and atmosphere. Precipitation rates and irrigation rates are daily input for the simulation model. As an option, run-on of surface water can be simulated as a surplus fraction of precipitation rates. From the aggregate, the run-off rate is subtracted. Run-off rates depend on the sum of precipitation and irrigation rates and infiltration capacity of the topsoil layer, as described by Breman and De Ridder (1991, p.338-348).

Water removal by transpiration (Penman, 1948; 1956) occurs in rooted soil layers only. The root surface fraction in a specific soil layer (compared to total root surface) determines how much of the daily transpiration demand is requested from the specific soil layer. If in a layer the soil water request exceeds the available soil water, deeper soil layers are depleted. Daily crop growth rates are reduced if water request from the soil cannot be fulfilled. Relatively dry topsoil hampers water removal by evaporation. Depending on soil type, evaporation removes water from deeper soil layers. Water transport between layers only takes place in downward directions. A water table and capillary rise are not taken into consideration in PlantSys 1.1.

## Carbon and nitrogen fluxes

Carbon enters the soil system by organic fertilization and via dead crop material (leaves and roots). Roots are incorporated in the appropriate soil layers, while leaf litter enters the 1st soil layer. At harvest crop residues may be removed or ploughed into the soil. Depending on the carbon-nitrogen ratio, crop residues and dead plant material are distributed over the organic matter pools, each with their own turn-over rate and microbiological efficiency factor.

Carbon can leave the simulation system by crop removal (harvest) and by $CO_2$ emissions as result of the inefficiency of microbiological processes for carbon and nitrogen incorporation into the soil organic matter pools.

Nitrogen enters the soil system by (in)organic fertilization, via dead crop material (leaves and roots) and by wet and dry deposition. Inorganic fertilizers enter the $1^{st}$ soil layer and dissolve in the available soil moisture as nitrate ($NO_3^-$), where it becomes available for other processes. Inorganic fertilizers of different nature have different rates for dissolving into the soil moisture. Organic fertilizers are added to the $1^{st}$ soil layer, and may be ploughed into deeper layers. According to the carbon-nitrogen ratio of the organic fertilizer and of root and leaves litter, the application rate is distributed over resistant, structural and decomposable plant material pools, each with their own turn-over rate and microbiological efficiency factor to the organic matter pools. Mineralization from and immobilization to organic matter pools are steered by soil moisture and soil temperatures, carbon-nitrogen ratios of the organic matter pools and the plant material pools. Nitrate transportation to deeper soil layers takes place by downward soil moisture transport. Nitrogen can leave the soil via volatilization, leaching and by crop uptake.

# Experimental set-up

## Soils

Two soil types were included in the experiment: a heavy clay (soil type A) and loam (soil type B). Both soil types were initially low in organic matter contents. For simulation purposes they were brought to high values for organic matter contents. Twenty-five cm of each soil was placed on 100 cm white sand in a bottom-less container with a diameter of about 0.62 m or 0.6 $m^2$ per container. Table 2 summarises the soil characteristics and interpretations for input into the simulation model.
The differences between soil type A and B can be found in the carbon-nitrogen ratios of stable organic matter (SOM). Carbon-nitrogen ratios decrease with decreasing soil particle size (Cameron and Possner, 1979; Amato and Ladd, 1980; Anderson *et al.*, 1981).

*Table 2. Topsoil and subsoil layer characteristics with interpretations for simulation.*

| Description | Unit | Topsoil A | Topsoil B | Subsoil |
|---|---|---|---|---|
| Soil compartment | (cm) | 0-25 | 0-25 | 25-125 |
| Thickness | (cm) | 25. | 25. | 100. |
| Characterization | (-) | Heavy clay | Loam | Sand |
| SOM[a)] fraction | (-) | 0.55 | 0.55 | 0.55 |
| Organic Matter[b)] | (%) | 2.10 / 5.17 | 0.80 / 5.17 | 0.002 |
| Carbon[b)] | (%) | 1.22 / 3.00 | 0.46 / 3.00 | 0.001 |
| Organic N[b)] | (%) | 0.122 / 0.30 | 0.03 / 0.20 | 0.00005 |
| CN ratio SOM | (-) | 10. | 15. | 20. |
| Bulk density | (g $cm^{-3}$) | 1.2 | 1.5 | 2.0 |
| WC saturation | ($cm^3$ $cm^{-3}$) | 0.5400 | 0.3940 | 0.3950 |
| WC field capacity | ($cm^3$ $cm^{-3}$) | 0.4929 | 0.2848 | 0.0647 |
| WC wilting point | ($cm^3$ $cm^{-3}$) | 0.3609 | 0.0939 | 0.0001 |
| WC air-dry | ($cm^3$ $cm^{-3}$) | 0.1767 | 0.0074 | 0.0000 |

[a)] *Fraction Stable Organic Matter (Verberne et al., 1990)*
[b)] *Simulations were performed for low and high organic matter contents*

## Treatments

The experiment consisted of 5 treatments with applications of different kinds of organic material to soil columns. The application rates per soil container (of 0.6 $m^2$) were:
(1) 1500 g Green Waste (GW) Lucerne,
(2) 1590 g Chaff/Straw,
(3) 795 g Chaff/Straw + 750 g GW Lucerne,
(4) 1590 g Chaff/Straw + 60 g additional nitrogen, and
(5) 9645 g FYM.

The average values for soil treatments and organic matter characterization are summarized in Table 3. Over the treatment years, carbon and nitrogen contents of the organic material varied and resulted in different carbon and nitrogen application rates each year (Appendix IV). Organic matter applications were mixed with the upper 25 cm of the soil. A control without any organic applications was included for both soil types. Furthermore, one part of the experiment received the organic applications only once, in November 1961 (Method A), whereas the other applications took place each year in November, starting in 1961 (Method B). All 5 treatments and the control treatment were replicated 4 times for methods A and B and for both soil types. For this study, Method A was not analyzed.

*Table 3. Average values for soil treatments with organic matter characterizations and resulting application rates per hectare for carbon and nitrogen. Exact values for each treatment per year can be found in Appendix IV.I.*

| No. | Treatment[a)b)] | Rates (t $ha^{-1}$) | C/N (-) | C (g $g^{-1}$) | N (g $g^{-1}$) | C (t $ha^{-1}$) | N (t $ha^{-1}$) | Add N (t $ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 0 | Control | - | - | - | - | - | - | - |
| 1 | GW *Lucerne* | 25.00 | 16.3 | 0.442 | 0.027 | 11.1 | 0.675 | - |
| 2 | Chaff/Straw[c)] | 26.50 | 50.8 | 0.385 | 0.008 | 10.2 | 0.212 | - |
| 3 | Chaff/Straw + GW *Lucerne* | 25.75 | 23.0 | 0.391 | 0.017 | 10.1 | 0.438 | - |
| 4 | Chaff/Straw + N | 26.50 | 50.8 | 0.385 | 0.008 | 10.2 | 0.212 | 1.000 |
| 5 | FYM | 160.75 | 14.0 | 0.082 | 0.006 | 13.2 | 0.965 | - |

a) *Method A received treatments only once (November 1961)*

b) *Method B received treatments each year in November (1961-2003)*

c) *Triticale*

## Climate data

Daily temperatures and daily precipitation rates affect the soil environment and thereby the environment of the various organic matter pools. These environmental changes affect decomposition rates and mineralization or immobilization rates. High precipitation rates and high temperatures increase mineralization and may invoke nitrate leaching, whereas dry periods and low temperatures reduce decomposition rates.
Daily climate data came from various weather stations nearby the experiment: Eelde, Twente, Valtermond and Wageningen (Table 4). Various sources were used, as not all climatic data were recorded at the experiment sites. Data were put in the CABO/TPE weather system format (Van Kraalingen *et al.*, 1991).

*Table 4. Climate stations (number) and years where daily values for radiation (kJ $m^{-2}$ $d^{-1}$), minimum and maximum temperatures (Tmin, Tmax; ºC), vapour pressure (VP; kPa), average wind speed (m $s^{-1}$) and precipitation (mm $d^{-1}$) were obtained.*

| | Climate station (number) and location (Longitude/Latitude) | | | | | |
|---|---|---|---|---|---|---|
| Year(s) | Radiation, Tmin, Tmax | | | VP, Wind speed, Precipitation | | |
| 1961-1987 | Eelde | (6) | 6.58/53.13 | Twente | (14) | 6.90/52.27 |
| 1988 | Eelde | (6) | 6.58/53.13 | Valthermond | (8) | 6.00/53.00 |
| 1989-1992 | Eelde | (6) | 6.58/53.13 | Wageningen | (1) | 5.67/51.97 |
| 1993-2004 | Wageningen | (1) | 5.67/51.97 | Wageningen | (1) | 5.67/51.97 |

Variation in daily precipitation rates and cumulative yearly precipitation rates during the experiment are presented in Figure 1. As an example, daily minimum and maximum temperatures for the experiment in 1961 are presented in Figure 2 to point out its variation throughout the year. Figure 3 shows average yearly values for minimum, maximum and resulting topsoil temperatures for the experiment (1961-2003).

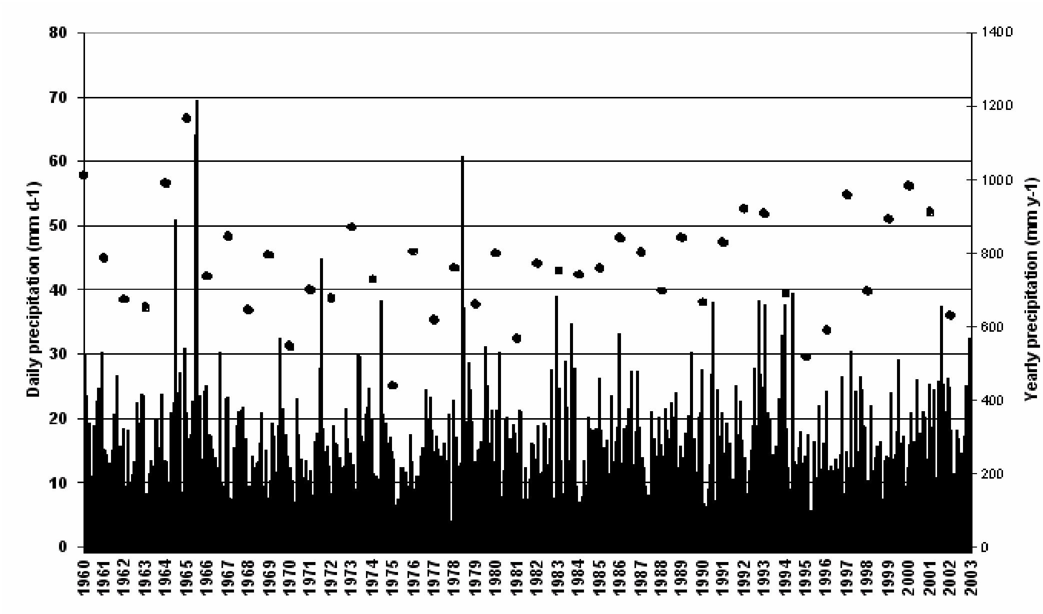



*Figure 1.* *Daily values for precipitation rates (bars; mm d[1]) and cumulative precipitation per year (●; mm y[1]) for De la Lande Cremer experiment 1961-2003.*

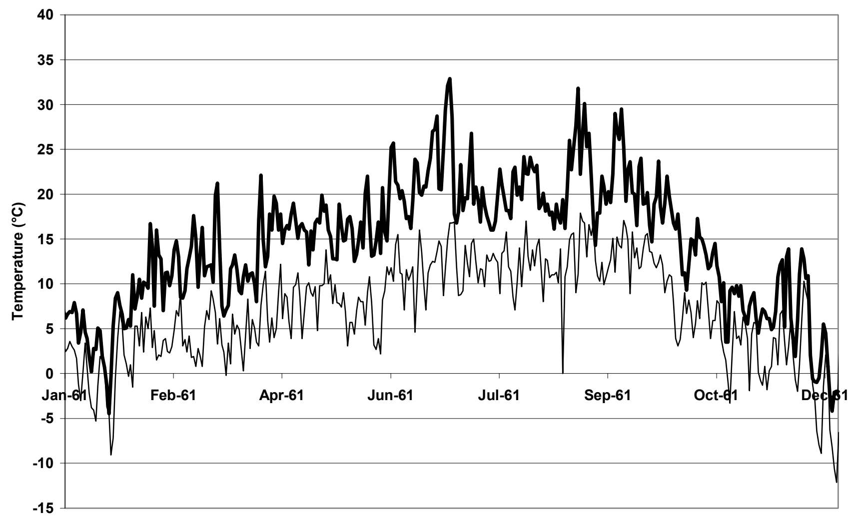



*Figure 2.* *Daily maximum and minimum temperature values for De la Lande Cremer experiments: example for 1961.*

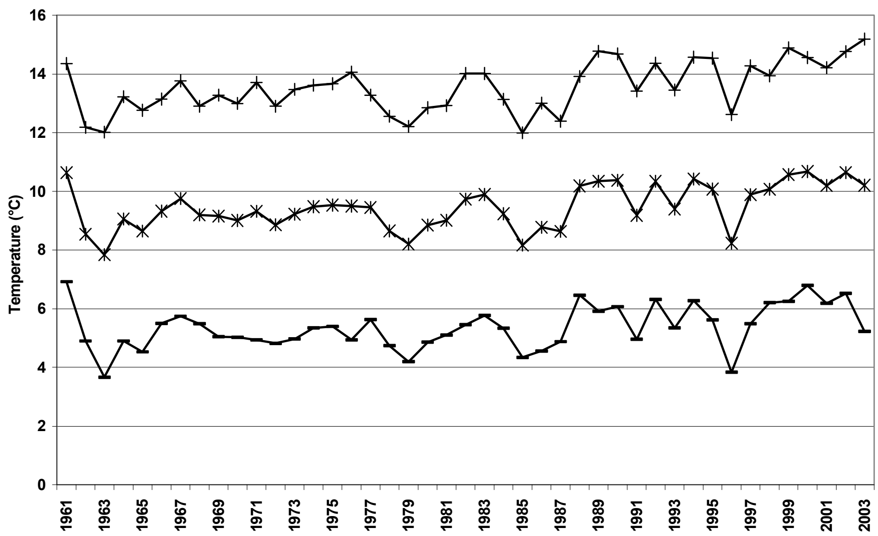



*Figure 3. Yearly average minimum (– ), maximum (+) and resulting topsoil ( *) temperature (°C) for De la Lande Cremer experiment 1961-2003.*

## Model validation

The model is validated against organic matter observations from 1961-1988, for the treatments Control, Chaff/Straw and farm yard manure (FYM) for Soil A (clay) and Soil B (loam).

## Simulations

The simulations that are performed in this study are:

a) *De la Lande Cremer* experiment method B: Yearly applications of 5 organic fertilization types
b) Calibrated runs with adaptations based on comparison with observed values for Chaff/Straw, FYM and control treatment 1961-1988
c) Simulation experiment with yearly applications of Chaff/Straw and FYM with increasing application rates and stable carbon and nitrogen contents

# Results and discussion

## Discussion of the input data

The application rates of the organic materials (Table 3) are very high and do not reflect actual farm management practices. Chemical analyses of the organic material that was applied in the experiment (Appendix IV) showed more than once extremely deviating values over the experimental years. If this was the case, these extreme values were replaced by average values (see comments in Appendix IV). Some deviating values were retained, such as the 1999 observations for FYM.

The variation in carbon and nitrogen contents of the organic materials is large, which leads to large differences in carbon and nitrogen application rates (t $ha^{-1}$ $y^{-1}$). In combination with climatic variation (temperature, wind speed and precipitation), soil type (infiltration rate, water holding capacity), decomposition rates may either increase or decrease. Although interaction between climate and (self-produced) plant organic fertilizers can be expected, it is assumed that this interaction between carbon and nitrogen organic matter content and climate is not present in this study, because of the use of plant organic matter stocks (plant organic material). This assumption was not analyzed.

# Discussion of the validation data

The validation data that were observed come across as unrealistic for various reasons. The high input rates of the organic matter treatments are expected to lift the organic matter contents in both soil types more than was observed (Figure 4). The fact that FYM (*) treatments with C/N ≈ 14 result in higher organic matter contents than Chaff/Straw (■) treatments with C/N ≈ 51, Appendix IV) is remarkable as well.

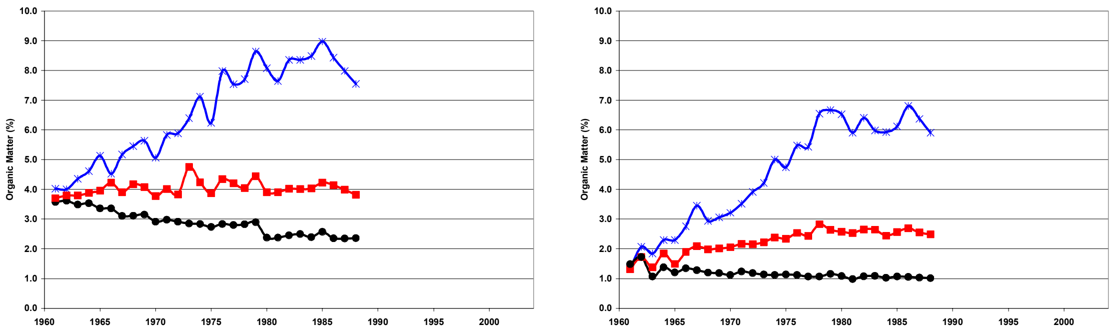



*Figure 4.* *Observed organic matter values (%) for clay soil (Soil A; left) and loam soil (Soil B; right) for 1961-1988 experiment years (Zwart, unpubl.). Treatments are given by: ● Control (no organic matter application); ■ Chaff/Straw and * FYM.*

Reasons for the relatively high decomposition rates of Chaff/Straw applications can be sought in the mixing procedure at application dates; the 25-cm topsoil was removed from the containers and thoroughly mixed with the organic material. This may have resulted in higher activity of the microbial biomass because of increased aeration and less protection of the organic material by soil texture. As a reason for the relatively high soil organic matter increase of the FYM application, Zwart (unpubl.) mentions that FYM might have been pre-composted. However, this is not supported by the FYM C/N values (Appendix I).

The control treatments (●) in Figure 4 show a decrease in soil organic matter contents of about 0.05% $y^{-1}$ for clay soils and about 0.02% $y^{-1}$ for loamy soils. Initially, the clay soil type had higher soil organic matter contents than the loam soil type. As the loamy soil type (B) has lower soil water holding capacity than the clay soil type (A), it is relatively drier, which results in an increased build-up of soil organic matter contents compared to the clay soil type (A).

# Discussion of the simulation results

## De la Lande Cremer experiment

The simulation results for organic matter contents of soil type A (clay) and B (loam) show similar patterns for different initial states. The decomposition rates (Table 1) seem to be underestimated, as organic matter increase is larger in the simulation set, with respect to the observed organic matter dynamics, with the exception of FYM (*) (Figure 4).
The simulation results follow the theoretical patterns: organic applications with higher C/N values tend to show the strongest increase in soil organic matter content. Additional nitrogen applications increase decomposition processes lowering C/N in the organic pools. The extremely high application rates of 1000 kg N $ha^{-1}$ are largely leached to the groundwater. Leaching is even more pronounced in the loamy soil B with lower soil moisture holding capacity and higher drainage rates. This results in a reduced effect of the additional nitrogen applications.

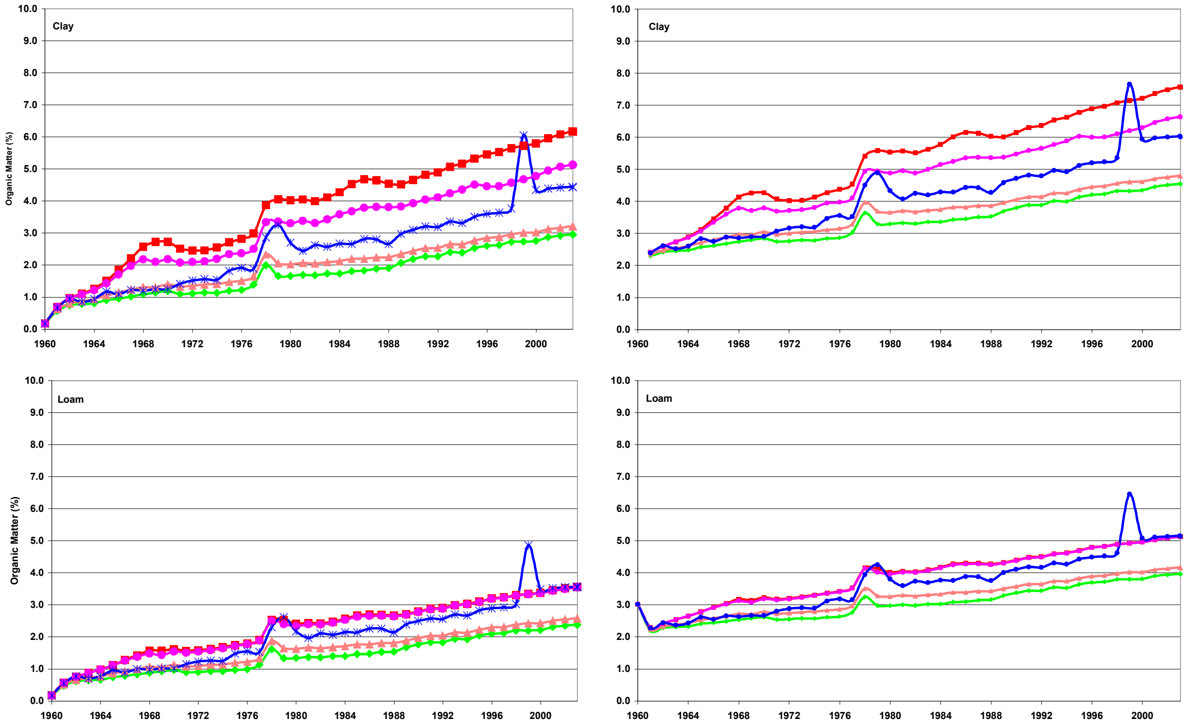



*Figure 5.* *Simulation results of changes in soil organic matter for clay soil type (Soil A, top) and loamy soil type (Soil B, bottom) at low initial organic matter content content (left) and high initial organic matter content (right). Treatments are represented by ♦ GW Lucerne; ■ Chaff/Straw; ▲ GW Lucerne + Chaff/Straw; ● Chaff/Straw + N and * FYM.*

The differences between the treatments for soil organic matter contents are more pronounced in the clay soil (A) than in the relatively drier loam soil (B). A remarkable section is the dip occurring in the years 1969-1977 and the relatively quick increase in organic matter in the years that follow: 1978 and 1979. According to the climate data (Figures 1 and 3), the period 1969-1977 was below average as regards rainfall and temperature. The same is true for the year 1988.
Careful analysis of the yearly data (Appendix IV) shows that the application rates of carbon are doubled in 1978 by high C/N of Lucerne and Chaff/Straw. It is clear that this adds more significantly to the organic matter increase than the climatic effects. This was further explored by simulating 2 additional simulation scenarios with the same values for soil and climate input parameters (see 'model explorations' below).

## Model calibration

The results of the 1$^{st}$ simulations led to the following adaptations with respect to the *De la Lande Cremer* experiments to better fit the observed values:

- Initial carbon and nitrogen fractions were changed
- The decomposition rate for Stable Organic Matter was increased by a factor 10
- The deviating FYM (*) value for carbon and nitrogen of 1999 were replaced by average values for FYM

Simulation results for the calibration runs (Figure 6) show that soil organic matter increase is less than the unadjusted results and fit better to the observed values (Figure 4). This is perceived by the increased decomposition rates of the stable organic matter fraction. The model behaves the same with respect to the C/N values of organic matter applications: material with higher C/N values decomposes less than organic materials with lower C/N values.

The effect of additional N applications (▲) is less pronounced or absent in the calibrated runs. The effect of management factors (like application rate and C/N of the organic material) is still visible and shown by the variation in soil organic matter contents (%).

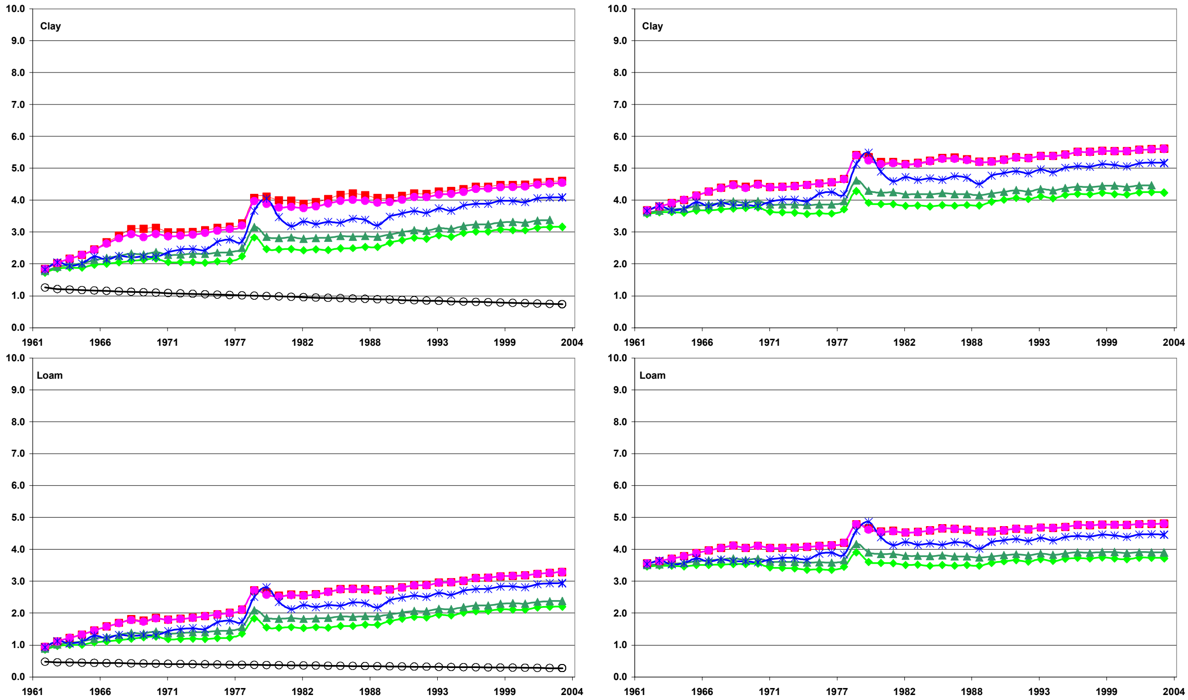



*Figure 6.* *Calibration runs: soil organic matter (%) simulation results for clay soil type (Soil A, top) and loamy soil type (Soil B, bottom) at low initial organic matter content (left) and high initial organic matter content (right). Treatments are represented by ○ Control; ♦ GW Lucerne; ■ Chaff/Straw; ▲ GW Lucerne + Chaff/Straw; ● Chaff/Straw + N and * FYM.*

The simulated control values (○) in Figure 6 show a decrease in soil organic matter contents of 0.02% $y^{-1}$ for low, and 0.04% $y^{-1}$ for high initial organic matter contents for the situations with high initial organic matter contents. These values are in agreement with the observed values (Figure 4).

## Model explorations

The calibrated model was used to explore the fate of more realistic application rates of soil organic matter applications. The model exploration included the following points:

- Application rates were reduced and varied over 15, 30, 45 and 60 t $ha^{-1}$
- Fixed quantity (application rates) and quality (carbon and nitrogen contents) of organic materials
- Average C/N ratios (Table 3) were taken for Chaff/Straw and FYM applications

Results of the model explorations demonstrate that fixed application rates with fixed C/N ratios show much less variation in soil organic matter contents than the *De la Lande Cremer* experiments (Figures 7 and 8). With regard to FYM applications (Figure 8), yearly application of Chaff/Straw (Figure 7) resulted in a higher increase in soil organic matter for both soil types, reaching stable situations eventually.

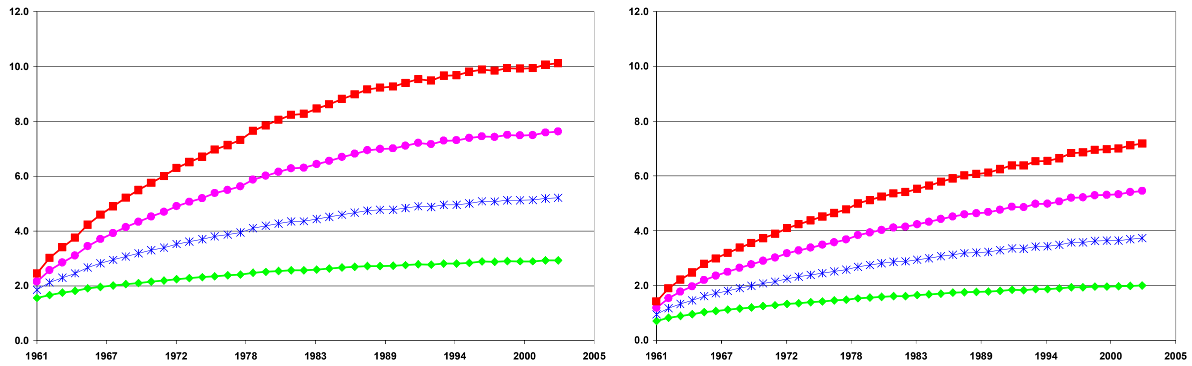



*Figure 7.* *Soil organic matter (%) simulation results of varying application rates (♦15; * 30; ● 45 and ■ 60 t ha-1) with average but fixed C/N values for Chaff/Straw in clay soil (A; left) and in loamy soil (B; right).*

For FYM applications (Figure 8), application rates higher than 30 t ha $y^{-1}$ resulted in a small increase in soil organic matter contents in the clay soil type (A), whereas for the loamy soil type (B), lower FYM application rates resulted in increased soil organic matter contents. This can be explained by the fact that loamy soil types are relatively dryer, resulting in reduced decomposition rates.

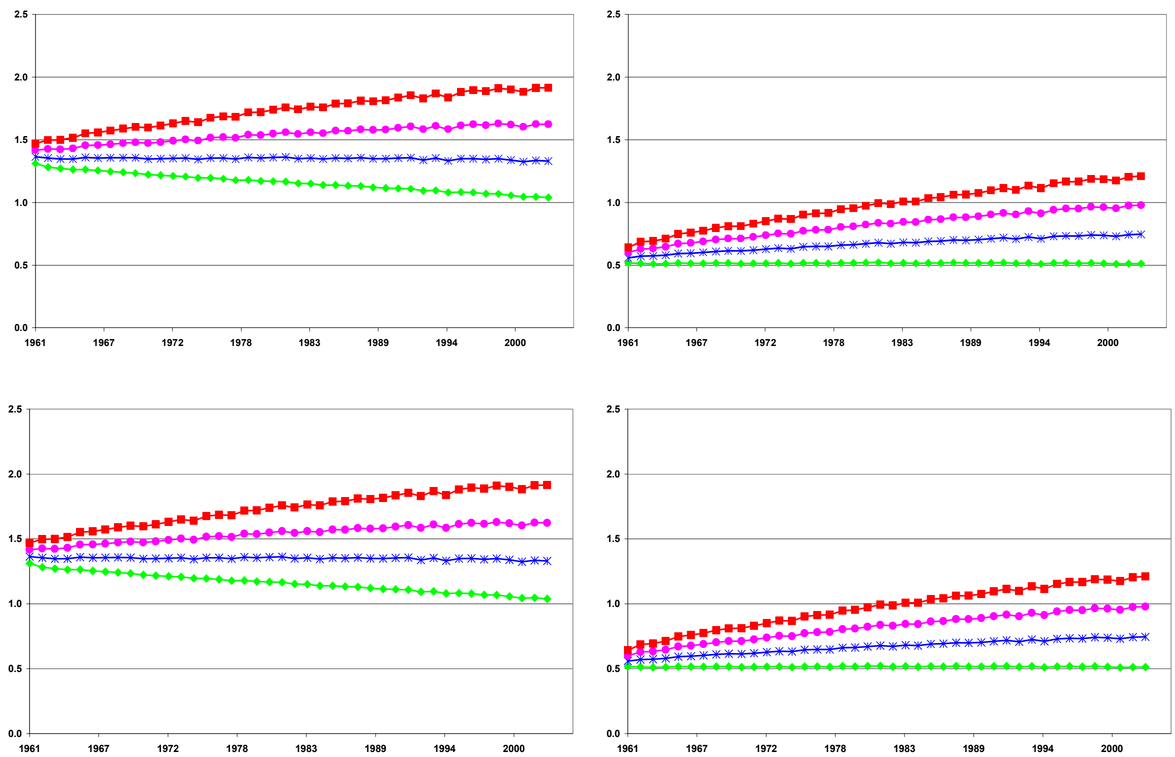



*Figure 8.* *Soil organic matter (%) simulation results of varying application rates (♦15; * 30; ● 45 and ■ 60 t ha-1) with average but fixed C/N values for FYM in clay soil (A; left) and in loamy soil (B; right).*

# Conclusions

Although soil types and climate set the obtainable levels for soil organic matter contents, management factors (like application rates and C/N of the organic material) are the main source of variation. Temperature and precipitation are of minor importance.

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| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1961 | 1 | GW Lucerne | 16.53 | 44.22 | 2.68 | 1500 | 25.00 | 11.06 | 668.90 | | Average value for all GW Lucerne |
| | 2 | Chaff/Straw | 59.72 | 42.40 | 0.71 | 1590 | 26.50 | 11.24 | 188.15 | | Stock 1961 |
| | 3 | Chaff/Straw+Lucerne | 26.01 | 43.29 | 1.66 | 1545 | 25.75 | 11.15 | 428.52 | | From stock 1961 |
| | 4 | Chaff/Straw+N | 59.72 | 42.40 | 0.71 | 1590 | 26.50 | 11.24 | 188.15 | 1000 | From stock 1961 |
| | 5 | FYM | 15.00 | 8.40 | 0.56 | 9645 | 160.75 | 13.50 | 900.20 | | From stock 1961 |
| 1962 | 1 | GW Lucerne | 16.53 | 44.22 | 2.68 | 1500 | 25.00 | 11.06 | 668.90 | | Average value for all GW Lucerne |
| | 2 | Chaff/Straw | 45.12 | 37.00 | 0.82 | 1590 | 26.50 | 9.81 | 217.30 | | From stock 1962 |
| | 3 | Chaff/Straw+Lucerne | 23.54 | 40.51 | 1.72 | 1545 | 25.75 | 10.43 | 443.10 | | From stock 1961 + 1962 |
| | 4 | Chaff/Straw+N | 59.72 | 42.40 | 0.71 | 1590 | 26.50 | 11.24 | 188.15 | 1000 | From stock 1961 |
| | 5 | FYM | 8.17 | 7.28 | 0.89 | 9645 | 160.75 | 11.70 | 1431.91 | | Average value for all FYM |
| 1963 | 1 | GW Lucerne | 16.53 | 44.22 | 2.68 | 1500 | 25.00 | 11.06 | 668.90 | | Average value for all GW Lucerne |
| | 2 | Chaff/Straw | 46.75 | 37.40 | 0.80 | 1590 | 26.50 | 9.91 | 212.00 | | From stock 1963 |
| | 3 | Chaff/Straw+Lucerne | 23.80 | 40.71 | 1.71 | 1545 | 25.75 | 10.48 | 440.45 | | New stock |
| | 4 | Chaff/Straw+N | 46.75 | 37.40 | 0.80 | 1590 | 26.50 | 9.91 | 212.00 | 1000 | New stock |
| | 5 | FYM | 14.60 | 7.30 | 0.50 | 9645 | 160.75 | 11.73 | 803.75 | | New stock |
| 1964 | 1 | GW Lucerne | 17.95 | 38.60 | 2.15 | 1500 | 25.00 | 9.65 | 537.50 | | From stock 1964 |
| | 2 | Chaff/Straw | 54.20 | 37.40 | 0.69 | 1590 | 26.50 | 9.91 | 182.85 | | From stock 1964 |
| | 3 | Chaff/Straw+Lucerne | 27.15 | 37.98 | 1.40 | 1545 | 25.75 | 9.78 | 360.18 | | From stock 1964 |
| | 4 | Chaff/Straw+N | 54.20 | 37.40 | 0.69 | 1590 | 26.50 | 9.91 | 182.85 | 1000 | From stock 1964 |
| | 5 | FYM | 13.00 | 7.80 | 0.60 | 9645 | 160.75 | 12.54 | 964.50 | | New stock |
| 1965 | 1 | GW Lucerne | 17.95 | 38.60 | 2.15 | 1500 | 25.00 | 9.65 | 537.50 | | From stock 1964 |
| | 2 | Chaff/Straw | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | | From stock 1965 |
| | 3 | Chaff/Straw+Lucerne | 29.58 | 37.26 | 1.26 | 1545 | 25.75 | 9.60 | 324.40 | | From stock 1964 + 1965 |
| | 4 | Chaff/Straw+N | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | 1000 | From stock 1965 |
| | 5 | FYM | 8.17 | 7.28 | 0.89 | 9645 | 160.75 | 11.70 | 1431.91 | | New stock, but C value is wrong! Average value all FYM taken |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1966 | 1 | GW Lucerne | 17.95 | 38.60 | 2.15 | 1500 | 25.00 | 9.65 | 537.50 | | From stock 1964 |
| | 2 | Chaff/Straw | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | | From stock 1965 |
| | 3 | Chaff/Straw+Lucerne | 29.58 | 37.26 | 1.26 | 1545 | 25.75 | 9.60 | 324.40 | | From stock 1964 + 1965 |
| | 4 | Chaff/Straw+N | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | 1000 | From stock 1965 |
| | 5 | FYM | 14.10 | 7.05 | 0.50 | 9645 | 160.75 | 11.33 | 803.75 | | From stock 1966 |
| 1967 | 1 | GW Lucerne | 17.95 | 38.60 | 2.15 | 1500 | 25.00 | 9.65 | 537.50 | | From stock 1964 |
| | 2 | Chaff/Straw | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | | From stock 1965 |
| | 3 | Chaff/Straw+Lucerne | 29.58 | 37.26 | 1.26 | 1545 | 25.75 | 9.60 | 324.40 | | From stock 1964 + 1965 |
| | 4 | Chaff/Straw+N | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | 1000 | From stock 1965 |
| | 5 | FYM | 14.91 | 8.20 | 0.55 | 9645 | 160.75 | 13.18 | 884.13 | | From stock 1967 |
| 1968 | 1 | GW Lucerne | 17.95 | 38.60 | 2.15 | 1500 | 25.00 | 9.65 | 537.50 | | From stock 1964 |
| | 2 | Chaff/Straw | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | | From stock 1965 |
| | 3 | Chaff/Straw+Lucerne | 29.58 | 37.26 | 1.26 | 1545 | 25.75 | 9.60 | 324.40 | | From stock 1964 + 1965 |
| | 4 | Chaff/Straw+N | 85.71 | 36.00 | 0.42 | 1590 | 26.50 | 9.54 | 111.30 | 1000 | From stock 1965 |
| | 5 | FYM | 13.47 | 6.60 | 0.49 | 9645 | 160.75 | 10.61 | 787.68 | | From stock 1968 |
| 1969 | 1 | GW Lucerne | 17.95 | 38.60 | 2.15 | 1500 | 25.00 | 9.65 | 537.50 | | From stock 1964 |
| | 2 | Chaff/Straw | 31.34 | 25.70 | 0.82 | 1590 | 26.50 | 6.81 | 217.30 | | From stock 1969 |
| | 3 | Chaff/Straw+Lucerne | 21.81 | 31.96 | 1.47 | 1545 | 25.75 | 8.23 | 377.40 | | From stock 1964 + 1969 |
| | 4 | Chaff/Straw+N | 31.34 | 25.70 | 0.82 | 1590 | 26.50 | 6.81 | 217.30 | 1000 | From stock 1969 |
| | 5 | FYM | 13.47 | 6.60 | 0.49 | 9645 | 160.75 | 10.61 | 787.68 | | From stock 1968 |
| 1970 | 1 | GW Lucerne | 17.71 | 40.56 | 2.29 | 1500 | 25.00 | 10.14 | 572.50 | | From stock 1970 |
| | 2 | Chaff/Straw | 30.79 | 37.87 | 1.23 | 1590 | 26.50 | 10.04 | 325.95 | | From stock 1970 |
| | 3 | Chaff/Straw+Lucerne | 22.46 | 39.18 | 1.74 | 1545 | 25.75 | 10.09 | 449.23 | | From stock 1970 |
| | 4 | Chaff/Straw+N | 30.79 | 37.87 | 1.23 | 1590 | 26.50 | 10.04 | 325.95 | 1000 | From stock 1970 |
| | 5 | FYM | 14.81 | 6.37 | 0.43 | 9645 | 160.75 | 10.24 | 691.23 | | From stock 1970 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1971 | 1 | GW Lucerne | 12.49 | 27.60 | 2.21 | 1500 | 25.00 | 6.90 | 552.50 | | From stock 1971 |
| | 2 | Chaff/Straw | 28.79 | 30.80 | 1.07 | 1590 | 26.50 | 8.16 | 283.55 | | From stock 1971 |
| | 3 | Chaff/Straw+Lucerne | 18.02 | 29.25 | 1.62 | 1545 | 25.75 | 7.53 | 418.03 | | From stock 1971 |
| | 4 | Chaff/Straw+N | 28.79 | 30.80 | 1.07 | 1590 | 26.50 | 8.16 | 283.55 | 1000 | From stock 1971 |
| | 5 | FYM | 13.34 | 8.14 | 0.61 | 9645 | 160.75 | 13.09 | 980.58 | | From stock 1971 |
| 1972 | 1 | GW Lucerne | 12.49 | 27.60 | 2.21 | 1500 | 25.00 | 6.90 | 552.50 | | From stock 1971 |
| | 2 | Chaff/Straw | 30.66 | 32.50 | 1.06 | 1590 | 26.50 | 8.61 | 280.90 | | From stock 1972 |
| | 3 | Chaff/Straw+Lucerne | 18.61 | 30.12 | 1.62 | 1545 | 25.75 | 7.76 | 416.70 | | From stock 1971 + 1972 |
| | 4 | Chaff/Straw+N | 30.66 | 32.50 | 1.06 | 1590 | 26.50 | 8.61 | 280.90 | 1000 | From stock 1972 |
| | 5 | FYM | 12.25 | 8.45 | 0.69 | 9645 | 160.75 | 13.58 | 1109.18 | | From stock 1972 |
| 1973 | 1 | GW Lucerne | 12.49 | 27.60 | 2.21 | 1500 | 25.00 | 6.90 | 552.50 | | From stock 1971 |
| | 2 | Chaff/Straw | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | | From stock 1973 |
| | 3 | Chaff/Straw+Lucerne | 21.44 | 30.83 | 1.44 | 1545 | 25.75 | 7.94 | 370.33 | | From stock 1971 + 1973 |
| | 4 | Chaff/Straw+N | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | 1000 | From stock 1973 |
| | 5 | FYM | 12.62 | 7.70 | 0.61 | 9645 | 160.75 | 12.38 | 980.58 | | From stock 1973 |
| 1974 | 1 | GW Lucerne | 12.49 | 27.60 | 2.21 | 1500 | 25.00 | 6.90 | 552.50 | | From stock 1971 |
| | 2 | Chaff/Straw | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | | From stock 1973 |
| | 3 | Chaff/Straw+Lucerne | 21.44 | 30.83 | 1.44 | 1545 | 25.75 | 7.94 | 370.33 | | From stock 1971 + 1973 |
| | 4 | Chaff/Straw+N | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | 1000 | From stock 1973 |
| | 5 | FYM | 15.11 | 7.10 | 0.47 | 9645 | 160.75 | 11.41 | 755.53 | | From stock 1974 |
| 1975 | 1 | GW Lucerne | 12.49 | 27.60 | 2.21 | 1500 | 25.00 | 6.90 | 552.50 | | From stock 1971 |
| | 2 | Chaff/Straw | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | | From stock 1973 |
| | 3 | Chaff/Straw+Lucerne | 21.44 | 30.83 | 1.44 | 1545 | 25.75 | 7.94 | 370.33 | | From stock 1971 + 1973 |
| | 4 | Chaff/Straw+N | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | 1000 | From stock 1973 |
| | 5 | FYM | 8.17 | 7.28 | 0.89 | 9645 | 160.75 | 11.70 | 1431.91 | | No data: average value for FYM taken |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1976 | 1 | GW Lucerne | 12.49 | 27.60 | 2.21 | 1500 | 25.00 | 6.90 | 552.50 | | From stock 1971 |
| | 2 | Chaff/Straw | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | | From stock 1973 |
| | 3 | Chaff/Straw+Lucerne | 21.44 | 30.83 | 1.44 | 1545 | 25.75 | 7.94 | 370.33 | | From stock 1971 + 1973 |
| | 4 | Chaff/Straw+N | 47.72 | 33.88 | 0.71 | 1590 | 26.50 | 8.98 | 188.15 | 1000 | From stock 1973 |
| | 5 | FYM | 8.17 | 7.28 | 0.89 | 9645 | 160.75 | 11.70 | 1431.91 | | No data: average value for FYM taken |
| 1977 | 1 | GW Lucerne | 14.56 | 43.24 | 2.97 | 1500 | 25.00 | 10.81 | 742.50 | | From stock 1977 |
| | 2 | Chaff/Straw | 51.72 | 38.27 | 0.74 | 1590 | 26.50 | 10.14 | 196.10 | | From stock 1977 |
| | 3 | Chaff/Straw+Lucerne | 22.32 | 40.68 | 1.82 | 1545 | 25.75 | 10.48 | 469.30 | | From stock 1977 |
| | 4 | Chaff/Straw+N | 51.72 | 38.27 | 0.74 | 1590 | 26.50 | 10.14 | 196.10 | 1000 | From stock 1977 |
| | 5 | FYM | 13.83 | 8.30 | 0.60 | 9645 | 160.75 | 13.34 | 964.50 | | From stock 1977 |
| 1978 | 1 | GW Lucerne | 23.16 | 82.00 | 3.54 | 1500 | 25.00 | 20.50 | 885.00 | | From stock 1978 |
| | 2 | Chaff/Straw | 103.64 | 79.80 | 0.77 | 1590 | 26.50 | 21.15 | 204.05 | | From stock 1978 |
| | 3 | Chaff/Straw+Lucerne | 38.24 | 80.87 | 2.11 | 1545 | 25.75 | 20.82 | 544.53 | | From stock 1978 |
| | 4 | Chaff/Straw+N | 103.64 | 79.80 | 0.77 | 1590 | 26.50 | 21.15 | 204.05 | 1000 | From stock 1978 |
| | 5 | FYM | 26.71 | 18.70 | 0.70 | 9645 | 160.75 | 30.06 | 1125.25 | | From stock 1978 |
| 1979 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 38.30 | 34.85 | 0.91 | 1590 | 26.50 | 9.24 | 241.15 | | From stock 1979 |
| | 3 | Chaff/Straw+Lucerne | 18.33 | 35.09 | 1.91 | 1545 | 25.75 | 9.04 | 493.08 | | From stock 1979 |
| | 4 | Chaff/Straw+N | 38.30 | 34.85 | 0.91 | 1590 | 26.50 | 9.24 | 241.15 | 1000 | From stock 1979 |
| | 5 | FYM | 14.10 | 7.19 | 0.51 | 9645 | 160.75 | 11.56 | 819.83 | | From stock 1979 |
| 1980 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 38.30 | 34.85 | 0.91 | 1590 | 26.50 | 9.24 | 241.15 | | From stock 1979 |
| | 3 | Chaff/Straw+Lucerne | 18.33 | 35.09 | 1.91 | 1545 | 25.75 | 9.04 | 493.08 | | From stock 1979 |
| | 4 | Chaff/Straw+N | 38.30 | 34.85 | 0.91 | 1590 | 26.50 | 9.24 | 241.15 | 1000 | From stock 1979 |
| | 5 | FYM | 14.10 | 7.19 | 0.51 | 9645 | 160.75 | 11.56 | 819.83 | | From stock 1979 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1981 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 42.58 | 39.60 | 0.93 | 1590 | 26.50 | 10.49 | 246.45 | | From stock 1981 |
| | 3 | Chaff/Straw+Lucerne | 19.50 | 37.54 | 1.93 | 1545 | 25.75 | 9.67 | 495.73 | | From stock 1979 + 1981 |
| | 4 | Chaff/Straw+N | 42.58 | 39.60 | 0.93 | 1590 | 26.50 | 10.49 | 246.45 | 1000 | From stock 1981 |
| | 5 | FYM | 8.20 | 5.00 | 0.61 | 9645 | 160.75 | 8.04 | 980.58 | | From stock 1981 |
| 1982 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 52.50 | 36.75 | 0.70 | 1590 | 26.50 | 9.74 | 185.50 | | From stock 1982 |
| | 3 | Chaff/Straw+Lucerne | 19.96 | 36.07 | 1.81 | 1545 | 25.75 | 9.29 | 465.25 | | From stock 1979 + 1982 |
| | 4 | Chaff/Straw+N | 52.50 | 36.75 | 0.70 | 1590 | 26.50 | 9.74 | 185.50 | 1000 | From stock 1971 |
| | 5 | FYM | 10.64 | 9.04 | 0.85 | 9645 | 160.75 | 14.53 | 1366.38 | | From stock 1982 |
| 1983 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 52.50 | 36.75 | 0.70 | 1590 | 26.50 | 9.74 | 185.50 | | From stock 1982 |
| | 3 | Chaff/Straw+Lucerne | 19.96 | 36.07 | 1.81 | 1545 | 25.75 | 9.29 | 465.25 | | From stock 1979 + 1982 |
| | 4 | Chaff/Straw+N | 52.50 | 36.75 | 0.70 | 1590 | 26.50 | 9.74 | 185.50 | 1000 | From stock 1971 |
| | 5 | FYM | 13.28 | 6.64 | 0.50 | 9645 | 160.75 | 10.67 | 803.75 | | From stock 1983 |
| 1984 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 66.57 | 38.61 | 0.58 | 1590 | 26.50 | 10.23 | 153.70 | | From stock 1984 |
| | 3 | Chaff/Straw+Lucerne | 21.22 | 37.03 | 1.75 | 1545 | 25.75 | 9.53 | 449.35 | | From stock 1979 + 1984 |
| | 4 | Chaff/Straw+N | 66.57 | 38.61 | 0.58 | 1590 | 26.50 | 10.23 | 153.70 | 1000 | From stock 1984 |
| | 5 | FYM | 13.22 | 8.46 | 0.64 | 9645 | 160.75 | 13.60 | 1028.80 | | From stock 1974 |
| 1985 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 66.57 | 38.61 | 0.58 | 1590 | 26.50 | 10.23 | 153.70 | | From stock 1984 |
| | 3 | Chaff/Straw+Lucerne | 21.22 | 37.03 | 1.75 | 1545 | 25.75 | 9.53 | 449.35 | | From stock 1979 + 1984 |
| | 4 | Chaff/Straw+N | 66.57 | 38.61 | 0.58 | 1590 | 26.50 | 10.23 | 153.70 | 1000 | From stock 1984 |
| | 5 | FYM | 12.25 | 6.98 | 0.57 | 9645 | 160.75 | 11.22 | 916.28 | | From stock 1985 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1986 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 31.71 | 35.20 | 1.11 | 1590 | 26.50 | 9.33 | 294.15 | | From stock 1986 |
| | 3 | Chaff/Straw+Lucerne | 17.48 | 35.27 | 2.02 | 1545 | 25.75 | 9.08 | 519.58 | | From stock 1979 + 1986 |
| | 4 | Chaff/Straw+N | 31.71 | 35.20 | 1.11 | 1590 | 26.50 | 9.33 | 294.15 | 1000 | From stock 1986 |
| | 5 | FYM | 19.77 | 8.50 | 0.43 | 9645 | 160.75 | 13.66 | 691.23 | | From stock 1986 |
| 1987 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 31.71 | 35.20 | 1.11 | 1590 | 26.50 | 9.33 | 294.15 | | From stock 1986 |
| | 3 | Chaff/Straw+Lucerne | 17.48 | 35.27 | 2.02 | 1545 | 25.75 | 9.08 | 519.58 | | From stock 1979 + 1986 |
| | 4 | Chaff/Straw+N | 31.71 | 35.20 | 1.11 | 1590 | 26.50 | 9.33 | 294.15 | 1000 | From stock 1986 |
| | 5 | FYM | 14.00 | 7.00 | 0.50 | 9645 | 160.75 | 11.25 | 803.75 | | From stock 1987 |
| 1988 | 1 | GW Lucerne | 11.86 | 35.35 | 2.98 | 1500 | 25.00 | 8.84 | 745.00 | | From stock 1979 |
| | 2 | Chaff/Straw | 31.71 | 35.20 | 1.11 | 1590 | 26.50 | 9.33 | 294.15 | | From stock 1986 |
| | 3 | Chaff/Straw+Lucerne | 17.48 | 35.27 | 2.02 | 1545 | 25.75 | 9.08 | 519.58 | | From stock 1979 + 1986 |
| | 4 | Chaff/Straw+N | 31.71 | 35.20 | 1.11 | 1590 | 26.50 | 9.33 | 294.15 | 1000 | From stock 1986 |
| | 5 | FYM | 8.31 | 5.40 | 0.65 | 9645 | 160.75 | 8.68 | 1044.88 | | From stock 1988 |
| 1999 | 1 | GW Lucerne | 16.30 | 42.21 | 2.59 | 1500 | 25.00 | 10.55 | 647.28 | | From stock 1999 |
| | 2 | Chaff/Straw | 46.87 | 39.48 | 0.84 | 1590 | 26.50 | 10.46 | 223.19 | | From stock 1999 |
| | 3 | Chaff/Straw+Lucerne | 24.14 | 40.81 | 1.69 | 1545 | 25.75 | 10.51 | 435.24 | | From stock 1999 |
| | 4 | Chaff/Straw+N | 46.87 | 39.48 | 0.84 | 1590 | 26.50 | 10.46 | 223.19 | 1000 | From stock 1999 |
| | 5 | FYM | 16.30 | 42.21 | 2.59 | 9645 | 160.75 | 67.86 | 4162.04 | | From stock 1999 |

# Appendix V.

# Combining flux data and a process-based model to separate direct and indirect effects

Isabel van den Wyngaert and Bart Kruyt

## The use of soil respiration measurements in separation of direct and indirect effects

One way of separating the directly human-induced effects from the indirect effects and other changes in carbon uptake is to use well-calibrated models of the carbon cycling in ecosystems of interest. Such a model, like CENTURY, given that human-induced processes are represented adequately, can be run to represent situations with and without human actions, and the effects of different processes can be calculated. So far, confidence in such models is not sufficient, unfortunately, to allow reliable and economically feasible quantification. One of the reasons for this is a lack of a sound basis in measured data, where data often are not available or not congruent with model-predicted phenomena. It may be necessary to add to models processes that are not of direct interest to the overall carbon cycle but that represent the phenomena that are measured more directly, such as modelling the effects of in-canopy mixing or $CO_2$ dynamics inside the soil profile (Figure 1). We have explored some possibilities where CENTURY was constrained on components, such as the overall carbon balance or the net emission from the soil. This section focuses on the use of soil respiration data to constrain models of carbon cycling. Soil respiration is the emission of $CO_2$ from soils that arises from the decomposition of organic material ('heterotrophic' respiration) and from the maintenance and growth metabolisms of roots ('autotrophic' respiration).

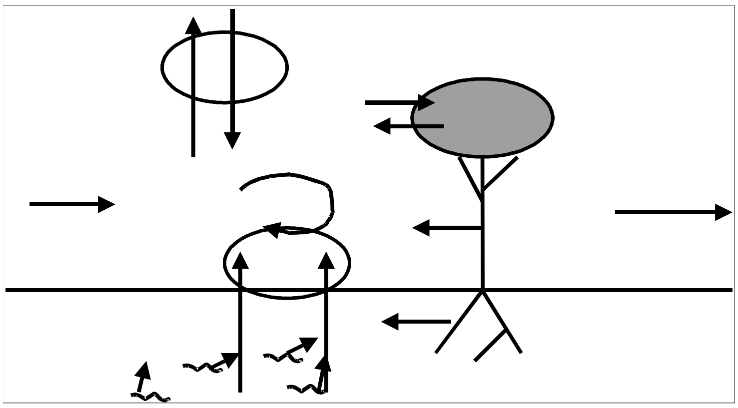

*Figure 1.* *Diagram representing fluxes of carbon dioxide into and out of an ecosystem (arrows). Routine direct flux measurements usually only address those encircled in the diagram. Ecosystem flux measurements represent the exchange across an upper limit of the ecosystem-air space without accounting for delays from fluxes from plants and soil due to poor mixing, or for lateral fluxes. Soil respiration fluxes measure the bulk soil flux, without separating autotrophic and heterotrophic respiration and, again, storage in the soil pore space.*

## Measurement of soil respiration: principles and limitations

Measurements of soil respiration can be made using chambers. The basic principle is that after a closed chamber is placed on the soil, the $CO_2$ concentration inside starts to rise at a rate proportional to the soil $CO_2$ emission rate. To enable measurement of this concentration over time, the air inside is sampled continuously and led to an infrared gas analyzer (IRGA), and then brought back to the chamber to minimize pressure differences between the inside of the chamber and the outside. An alternative method uses chambers that have a small opening to the outside air to transmit the small atmospheric pressure fluctuations to the soil surface observed. In this case, air is pumped through the chamber with known rates and a steady-state concentration builds up inside the chamber, of which the difference with the outside concentration is continuously recorded. Either the increase in the first method or the difference in the second method can be converted to a soil flux rate. Although simple in principle, the methods are frought with difficulties. For example, it is essential that air is mixed well enough inside a chamber, but pressure differences should be avoided as these will lead to leakage flows. The soil surface should not be disturbed but at the same time the chamber should be placed on the soil firmly enough to seal the bottom of the chamber from the outside air. The disturbance of the environment (temperature, rainfall, pressure) inside should be minimal. Finally the spatial variability of soil respiration is usually very high, requiring measurements at many points.

To address some of the above issues as well as possible, measurements have been made either with 1) a portable system of the first, closed type, which was moved from point to point along a pre-set transect in pine forest (in Loobos, Veluwe), only covering the soil for short periods, and 2) a continuously measuring, automatic system consisting of four chambers with a lid that is normally open, and only closes for short periods when a measurement is made in tropical rain forest (Rondonia, Amazon) and 3) an open system (the second type) of several chambers placed in an open parkland-type forest (Dehesa, Estremadura, Spain). The two latter experiments are also associated with experimental manipulation of the amount of rainfall reaching the ground (shielding and irrigation), so that the (indirect!) effects of climate change can be experimentally investigated.

## Available data sets and analysis of soil respiration parameters

The availability of data in the FLUXNET community is now rapidly increasing. Usually these are time series of manual chamber measurements made at a large number of points inside an ecosystem, at intervals of one to several weeks. Although not many have been published yet, several research groups are now working on a synthesis of such data sets to derive basic parameters of soil temperature and soil moisture sensitivity.

## The use of soil respiration parameters in models of the carbon cycle

The two most obvious relationships to explore from soil respiration data are the dependences on soil temperature and on soil humidity. Figure 2 shows such relationships for one season's data collected with a closed automatic system in a rain forest fragment in Rondonia, by a Brazilian MSc student (Fabricio Zanchi) linked to the University of Sao Paulo and Alterra. These data were collected during the dry season of 2003. The data show broad scatter, but also a consistent increase with both temperature and soil water content. During the wet season (data not shown) the relationships were not as clear, probably because frequent water logging inhibited respiration (causing an negative dependence of respiration on soil humidity). Directly following rain, respiration often peaked, while air temperatures were relatively cool, againg leading to apparently negative sensitivity of respiration on soil temperature.

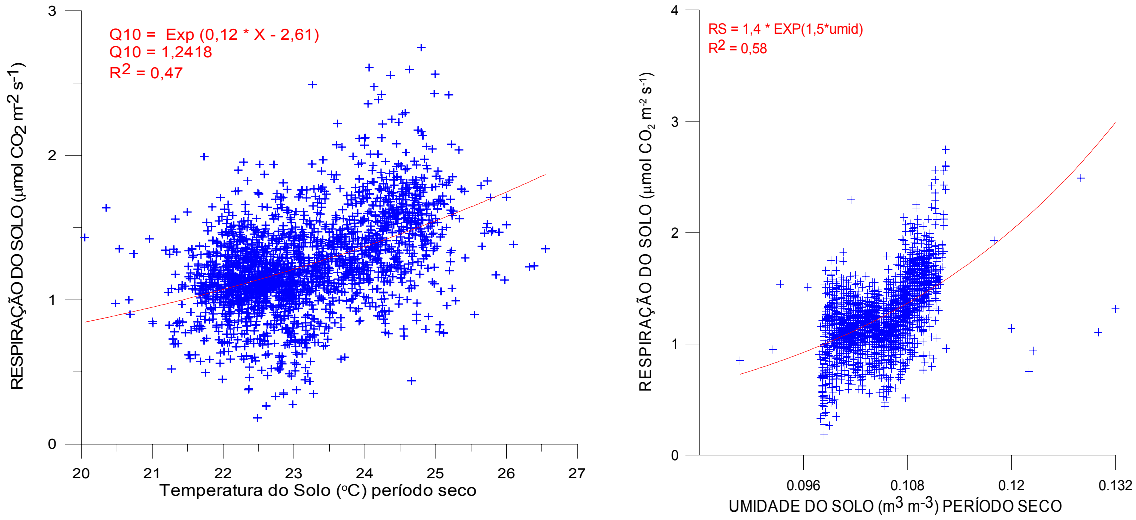


*Figure 2.* *Results of wet-season continuous soil respiration measurements in Rondonia, Amazonia.*

The soil respiration measurements made in Spanish Dehesa landscape do not show very clear dependences on soil temperature, but there are vigorous responses to rainfall after a long dry period, which are much quicker than the rewetting of the soil surface (Figure 3). In order to interpret such phenomena and derive an underlying dependence of soil organic carbon decomposition on temperature, the rapid response effects, probably related to displacement of soil air by rain water, need not be filtered out. A study is under way at Alterra to incorporate such rapid effects in a soil carbon exchange model (SWAPS-C), allowing its interpretation ( Braakhekke, in prep.).

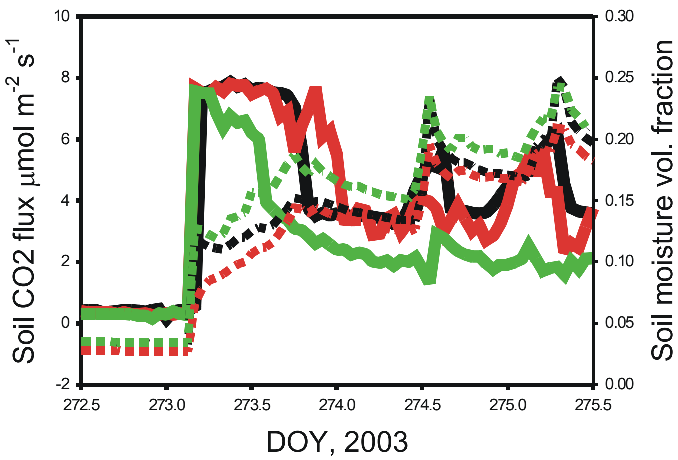


*Figure 3.* *Measurements of soil respiration (solid lines) and soil moisture (dashed lines) in three chambers (colors), during the transition from a very dry summer to a more rainy autumn. First rain exactly coincided with the sharp increase at day 273.*

Finally, we show an analysis of soil respiration data collected over 18 months on a bi-weekly basis along a transect in the Loobos Scots pine forest, Netherlands. Figure 4 shows the relationship of measured average flux with the measured average air temperature near the ground, together with the soil *heterotrophic flux* (only) simulated by Century, again as a function of air temperature (but this time the above-canopy air temperature input to the model). These relationships are not exactly comparable because the measurements also include root respiration and air temperature near the ground in a forest is usually warmer during nights and cooler during daytime. We would expect the model to give lower respiration values but also that the modeled relationship would be less steep than the measured one because of the wider temperature range. It is useful to note that the modeled and the measured relationships are completely independent, i.e., no calibration of the model whatsoever has been performed using these data. The resemblance of the relationships is striking. If we account for the expected reduction in slope in the modeled relationship, the comparison even improves more. The few low outliers in the model at higher temperatures are likely to be related to simulated very dry soils, whilst in the measurements dryness is averaged over the transect. But of course, if we take into account that the model is not showing the root respiration, we have to conclude that the model *over*estimates total soil respiration by an unspecified amount.

This is only an example of comparing data with models, but it illustrates the general principle that even long-term predictive models such as Century can be calibrated and validated against short-term field data representing only a component of the total carbon exchange, and can therefore contribute to the use of such models in separating direct and indirect effects.

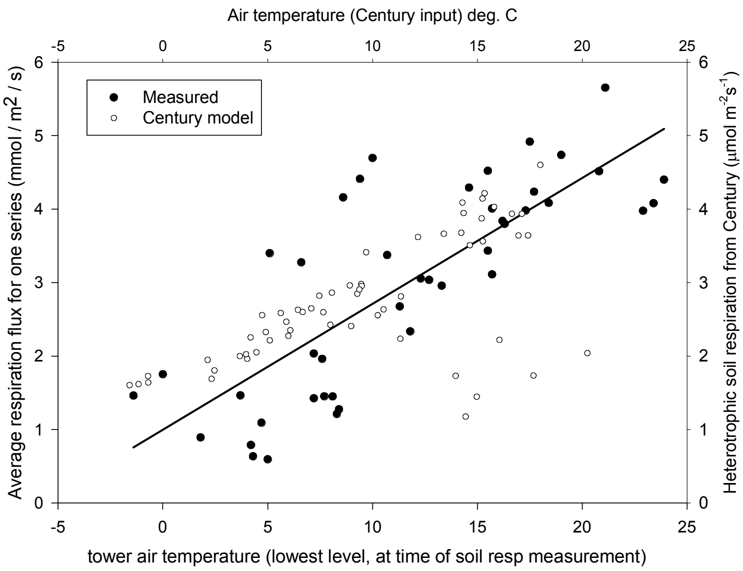


*Figure 4. Comparison of soil respiration-temperature relationships from measurements and the CENTURY model.*

# Effects of N deposition and thinning on C sequestration: analysis using Century

Process-based ecosystem models may act as a useful tool to separate between direct and indirect impacts of human activity on ecosystem carbon cycling. Within the limitations posed by the modelling concepts used, simulation of different scenarios provides not only an estimate of the magnitude of a specific impact (run with/without) but may contribute to better understanding of interactions between different – direct and/or indirect – impacts on ecosystems (e.g. van Oene *et al.*, 1999; Ollinger *et al.*, 2002).

This approach assumes a well-calibrated and validated model with a good representation for the impact(s) of interest. Though this may not be available for all impacts, the simulation of nitrogen enrichment can build on a wide experience with nitrogen cycling and fertilization in agriculture and grazing systems.

The strong increase in atmospheric nitrogen deposition is on of the most obvious indirect human impacts on all ecosystems over the last century. Nitrogen emissions have steadily increased since the 1940s with current atmospheric N deposition rates between 2-6 g N $m^{-2}$ $year^{-1}$ for non-forest ecosystems and even higher values for forests in Europe and the USA. This contrasts sharply with estimated background inputs of about 0.1-0.3 g N $m^{-2}$ $year^{-1}$ around 1900 (e.g. Galloway, 1995; Asman *et al.*, 1998; Fowler, 2002). Though nitrogen is the limiting nutrient for plant growth in many natural and semi-natural ecosystems, the extent to which nitrogen deposition contributes to increases in carbon accumulation in forests is still a topic of discussion (e.g. Nadelhoffer *et al.*, 1998; Groenenberg *et al.*, 1998).

CENTURY, an operational ecosystem model that was developed to simulate long-term carbon-nitrogen cycling in soil and vegetation, was calibrated on a high- and a low- productive *Pinus sylvestris* stand to ensure a realistic response to nitrogen. Soil and vegetation carbon stocks were used for calibration and a comparison was made with carbon fluxes measured using the eddy-covariance method on the low-productive site. This parameter-set for *Pinus sylvestris* was used to explore the effects of a range of atmospheric nitrogen deposition values on carbon accumulation in the vegetation and soil compartment. The model was run to equilibrium over thousands of years starting from a fictional 'zero' situation (e.g. as occurred on Dutch inland dunes during the last century) for 'unmanaged' forest as well as for thinning intensities ranging from 1-20%.

## Model description

CENTURY is a dynamic terrestrial ecosystem model, which has been developed, tested and used over the past fifteen years to simulate the major pathways of carbon and nitrogen cycling (Parton *et al.*, 1987, Parton *et al.*, 1988, Parton *et al.*, 1994; Kelly *et al.*, 1997). CENTURY includes the effects of climate, human management and soil properties on plant productivity and decomposition processes with a monthly time step. Different plant production submodels exist for grasslands/crops, forests, and savannas. Plant production submodels are linked to a common multiple compartment organic matter sub-model. Both are described in more detail below. Water availability and flow through the system is simulated using a simplified water budget model which is mostly determined by soil texture and depth.

### Plant production sub-model

In this study only the forest sub-model has been used for the scenario studies. The combination of trees and grasses in the savanna sub-model gives the opportunity to explicitly simulate undergrowth in a forest along with the tree compartment. and this was used for the Loobos simulation. Monthly net production in a forest system is the product of a fixed/genetically determined maximum (gross) production rate and factors (0-1) describing the effect of moisture, soil temperature, nutrient availability and live LAI. Net production is allocated to leaves, fine branches, stem wood, coarse and fine roots according to a fixed pattern, which may differ between young and old forests but shows no annual course. However, in deciduous trees, 80% of all assimilates in the first month of growth is allocated to leaves.
The grass/crop sub-model is not described in detail here but simulates monthly net production analogous to the forest sub-model.

Both in coniferous and deciduous trees leaf mortality rate is set per month, while in deciduous trees an additional leaf mortality rate is specified for the senescence month. Death rates of all other tree compartments are specified as fixed fractions of live pools. Nutrient concentrations of tree components may be set as fixed or allowed to float between maximum and minimum values. During leaf senescence, a fixed percentage of nutrients is retranslocated to other tree parts.

### Organic matter production sub-model

The soil organic matter sub-model is based on multiple compartments of SOM describing different SOM fractions. The model receives organic matter as above- and belowground dead material from the forest production sub-model, and partitions these into above- and belowground structural and metabolic litter pools as a function of the lignin to N ratio of the material. The structural pool contains all lignin. Further pools are above- and below-ground active SOM, equivalent to the microbial biomass and its product (Metherell, 1993), and slow and passive SOM. Microbial decomposition processes determine flows between different pools with associated $CO_2$ loss as a result of respiration. $CO_2$ loss associated with decomposition of the active pool increases with increasing soil sand content (Metherell, 1993; Parton *et al.*, 2001). Effects of temperature, soil moisture (drought as well as anaerobic conditions), soil texture, and carbon reduce maximum potential decomposition rates to nutrient ratios. Nutrient pools in soil organic matter are analogous to carbon pools. Carbon to nitrogen ratios can float within more or less narrow ranges for different pools. The flows of nitrogen between pools follow the flows of carbon. Mineralization to or immobilization from the inorganic nitrogen pool occurs as necessary to maintain the carbon to nitrogen ratios of the different pools. If the immobilization demand for nitrogen cannot be met, the decomposition rate is reduced.

## Model calibration and performance

The model was calibrated for *Pinus sylvestris* stands using growth and yield plot data from Sprielderbosch (52 14 N 5 38 W) and soil and vegetation data from a 90-year old *Pinus sylvestris* stand planted on inland dunes at Loobos (52 10 N 5 44 W).

Sprielderbosch is one of the few Dutch sites that have not been used as agricultural or grazing land during the past centuries, but has retained a forest cover (Nabuurs, pers. comm.). CENTURY was run to equilibrium with an initial parameter set of *Pinus sylvestris* to obtain initial soil conditions for this site. Parameters for *Pinus sylvestris* were derived from literature or were estimated using site-specific data (Smit, 2000; unpublished data) and no management was simulated. Soil texture was derived from the 'bodemkaart' (soil map). Planting date was assumed to coincide with the first yield recording (no thinning carried out) in 1968 and 7-year old trees were used. From then on the management as recorded in the growth and yield plots was simulated untill 1985, when the last yield record was dated. Standing and harvested stem carbon stocks were calculated from standing and harvested stem volumes using *Pinus sylvestris* wood density. Nitrogen deposition was assumed to be similar to the Loobos site.

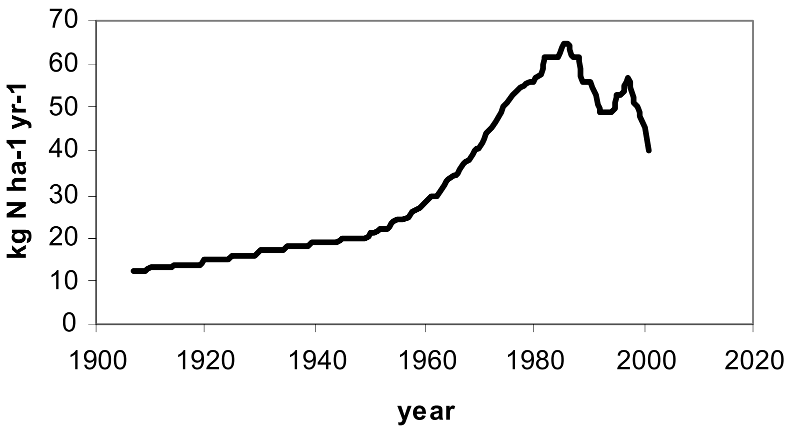


*Figure 5.* *Estimated atmospheric nitrogen deposition trend for a* Pinus sylvestris *forest near Kootwijk, the Netherlands.*

The tower site at Loobos is one of the areas in the Netherlands where drifting inland dunes, sandy soils almost without any organic matter, were planted with *Pinus sylvestris* to stabilize the sand and, on the other hand, to provide wood for the mining industry. Early records from forest managers at Kootwijk provide evidence for the extremely poor initial growth conditions of these stands. Tree and grass (*Deschampsia flexuosa*) growth was simulated between 1907, when the site was planted, and 2001. Actual weather values for the Netherlands were used between 1907 and 1996 and site values were used from then on. The nitrogen deposition values used are shown in Figure 5. (Bobbink, pers. comm.; RIVM, pers. comm.). Thinning was simulated in 1932, 1937, 1942, 1947, 1952, 1962, 1974, 1982 and storm damage occurred in 1990. Forest biomass was estimated in 1997 and soil organic carbon and nitrogen were measured at the end of 2000 (Persson, unpublished data). For 1997 to 2000, annual NEE as measured using eddy correlation was compared with the simulated NEE in Century (CARBODATA, 2002).

*Table 1. Comparison between simulated and measured tree and soil carbon stocks at Loobos.*

| Variable | Unit | Model | Measurement |
|---|---|---|---|
| Leaf Biomass | g DM $m^{-2}$ | 488 | 302 ± 95 |
| Branch Biomass | g DM $m^{-2}$ | 927 | 815 ± 287 |
| Stem Biomass | g DM $m^{-2}$ | 7088 | 7312 ± 1598 |
| Soil Organic C | g C $m^{-2}$ | 7455 | 7761 ± 248 |

Figure 6 shows simulated and measured stem carbon over time at Sprielderbosch after calibration of the dataset on both sites. Table 1 shows simulated and measured carbon stocks for Loobos and Figure 6 shows growth of stem carbon over a 93-year period. The difference in growth rate between Sprielderbosch and Loobos can be attributed to a small difference in soil texture and a large difference in carbon and nitrogen stocks in the soil at the start of the simulation and the resulting difference in nitrogen availability. In Sprielderbosch, growth was not or only marginally limited by nitrogen, while there was strong nitrogen limitation over the whole period in Loobos.

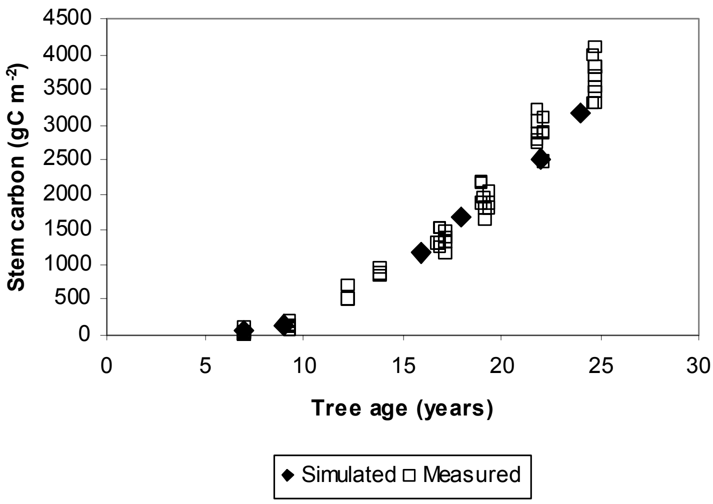


*Figure 6. Simulated and measured accumulation of carbon in stems of a Pinus sylvestris stand (Sprielderbosch).*

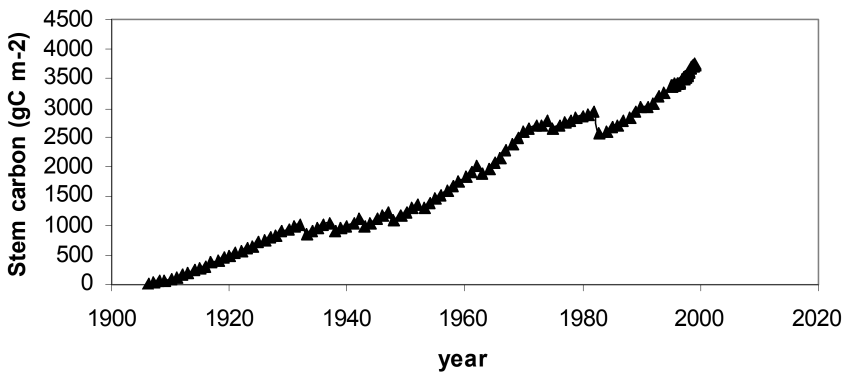


*Figure 7. Simulated accumulation of carbon in stems of a* Pinus sylvestris *stand (Loobos).*

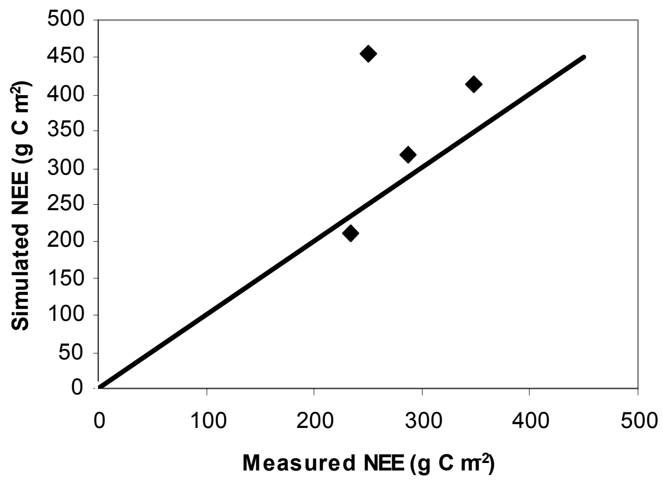


*Figure 8.* *Simulated and measured carbon fluxes from a* Pinus sylvestris *stand at Loobos.*

Though soil and vegetation carbon stocks at Loobos were used for model calibration, flux data of this site had been measured independently from carbon stocks and had not been used for calibration. Comparing annual carbon fluxes between 1997 and 2001 at Loobos showed a reasonable to good correspondence for 3 out of 4 years (< 20% difference between measured and simulated). In 1998, simulated NEE was almost twice as high as measured (Figure 8).

## Model application and scenario analysis

Accumulation of carbon in soil and vegetation was simulated using the vegetation parameters of *Pinus sylvestris* and initial soil conditions reflecting sand without organic material. Atmospheric nitrogen deposition was the only nitrogen input into the system and ranged between 0.2 g N $m^{-2}$ $year^{-1}$, reflecting 'undisturbed' background values, to 8 g N $m^{-2}$ $year^{-1}$, representing high but realistic atmospheric nitrogen deposition values in forests in the 80s and 90s of the last century. Management was carried out every 10 years and varied from no management to 20% thinning. The model was run until changes in carbon stock were negligible and it was assumed that equilibrium was reached.

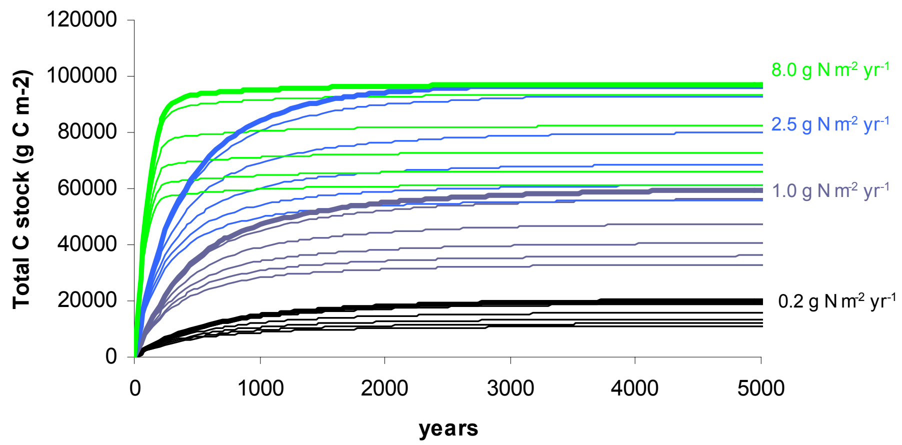


*Figure 9.* *Simulated accumulation of carbon in* Pinus sylvestris *stands on sand under different values of atmospheric nitrogen deposition and thinning (no thinning: thick lines, thinning management: thin lines).*

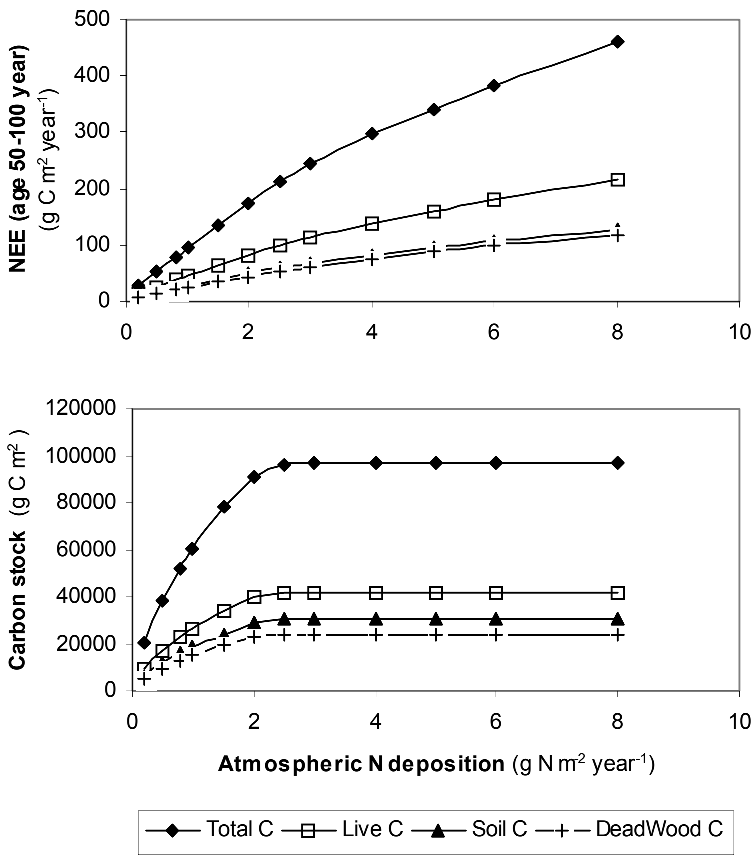


*Figure 10.* *Simulated accumulation of carbon in* Pinus sylvestris *stands on sand under different values of atmospheric nitrogen deposition (no management).*

Equilibrium was reached much sooner with high nitrogen input than with low nitrogen input values. The initial rate of carbon accumulation increased almost linearly with nitrogen input (Figure 10 (top)), and the total amount of carbon stored in the simulated *Pinus sylvestris* stands increased with increasing nitrogen input until a nitrogen input of about 3 g N $m^{-2}$ year (Figure 9, Figure 10 (bottom)). Thinning decreased the total amount of carbon stored in the system (Figure 9). Thinning 20% every 10 years decreased equilibrium carbon stocks with 45% (0.2 g N $m^{-2}$ $year^{-1}$) to 37% (5-8 g N $m^{-2}$ $year^{-1}$ ). The effect of thinning frequency was tested by simulating a thinning of 10% every then years, 5% every 5 years of a yearly thinning of 1%. There was no difference in carbon stock nor in accumulation rate between these simulations (data not shown).

# Discussion and conclusions

The CENTURY model was able to simulate the difference between a forest site which was known to be of high quality and a very poor site by adapting only initial conditions and atmospheric nitrogen deposition. The model which was calibrated on tree and soil carbon stocks, predicted annual net ecosystem exchange for Loobos within 20% of measured values for 3 out of 4 years. However, estimates of atmospheric nitrogen deposition were made using regional values, as no actual measurements are carried out at the site. As atmospheric deposition depends on stand structure (Draaijers *et al.*, 1992) and especially deposition of ammonia is strongly influenced by local sources, regional values may deviate from actual values at Loobos. The accurate response of the model to decreased nitrogen availability in case of the *Pinus sylvestris* stand planted on former drift sand dunes allowed us to investigate the effect of different nitrogen deposition scenario's on carbon accumulation. Overall, there was a strong effect of initial rate of carbon accumulation with increased nitrogen deposition both in the vegetation and in the soil. Higher rates of carbon accumulation resulted in higher carbon stocks for nitrogen deposition values up to 2.5 g N $m^{-2}$ $year^{-1}$.

A strong increase in carbon accumulation with increased nitrogen availability in these ranges was also found for boreal *Pinus sylvestris* forests by Makipaa *et al.*(1998). They used data from a long-term forest fertilization experiment to validate a gap-type forest simulation model with both carbon and nitrogen (78-79 g N $m^{-2}$ added over 32-35 years; background nitrogen deposition 0.5-0.7 g N $m^{-2}$ $year^{-1}$), and found that their model accurately predicted an increase in tree production of about 30-60% and increased carbon accumulation in the soil. As in their model, any negative effect of nitrogen on microbial activity is not included in the CENTURY model and therefore the increase in soil carbon with increasing nitrogen can be attributed to an increase in litter fall.
In the CENTURYruns used in this paper, nitrogen input higher than 2.5 g N $m^{-2}$ $year^{-1}$ does not increase the final amount of carbon that is accumulated in the system, but the higher initial rates of production lead to a faster accumulation and the 'equilibrium value' is reached sooner. Though a very wide range of nitrogen deposition values was used, average simulated soil C/N ratios decreased from 30 to 18 with increasing carbon accumulation between 0.2 and 2.5 g N $m^{-2}$ $year^{-1}$ but remained between 18 and 20 for any higher rates of nitrogen deposition. Nitrogen was clearly not limiting anymore to either vegetation or soil micro-organisms.
For nitrogen input higher than 3 g N $m^{-2}$ $year^{-1}$ the amount of nitrogen leaching from the system in equilibrium to deeper ground water increased linearly with the nitrogen input (Figure 11). This is a slightly higher threshold than was found in data from ICP forests where increased leaching was found for coniferous forests above about 2 g N $m^{-2}$ $year^{-1}$ (De Vries *et al.*, 2003).

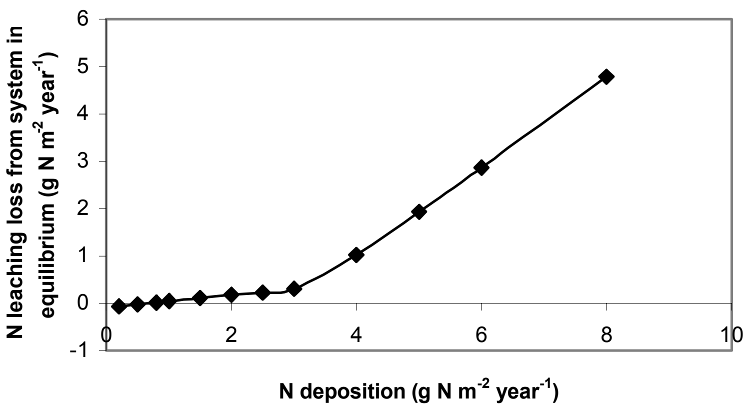


*Figure 11. Simulated leaching of nitrogen for a series of atmospheric nitrogen deposition scenarios.*

Thinning reduces the storage of carbon in the system, and as these reductions are larger than the relative amounts removed, this is not only the direct result of removing some of the carbon from the system. In CENTURY, which was originally developed for grasslands, biomass production is calculated as a genetically fixed maximal growth rate reduced by environmental variables (water, temperature), nutrients and live LAI. As radiation is not included in the model, removing some of the biomass does not lead to a better environment for the remaining trees, as in real-world forest stands, but only decreases LAI and thus production. This conflicts with common forest management practice that uses thinning to increase wood production from stands. A comparison between CENTURY and FORSPACE, a spatially explicit gap-type model, revealed that the simulation of management practices was the weaker point of CENTURY and the strength of FORSPACE, whereas the well-validated soil module is the strength of CENTURY (Kruijt *et al.*, 2004).
The effect of thinning increased with decreasing nitrogen input, and this most probably reflects the loss of nutrients from the system in increasingly nutrient-limited conditions.

The process-based biogeochemical model CENTURY adequately simulated ecosystem response to varying levels of nitrogen deposition, an example of an indirect effect. The simulations showed a strong effect of nitrogen on the carbon accumulation rate in young, nutrient-poor systems on sand. Eventual (theoretical ) equilibrium carbon stocks were also strongly determined by nitrogen input for levels of nitrogen deposition below and up to currently occurring values (regions with low nitrogen deposition in the Netherlands). From about 3 g N $m^{-2}$ $year^{-1}$ carbon stocks did not increase further with increasing nitrogen deposition, but there was a strong increase in leaching from the system. Thinning strongly affected carbon stocks and a 20% thinning every 10 years could almost halve eventual equilibrium carbon stocks for nitrogen limited conditions. The loss of production through increased nitrogen limitation was smaller, however, than the loss of production through loss of leaf area, and even in situations with ample nitrogen supply thinning lead to large (up to 37%) reductions in carbon stocks. For a more accurate representation of management practices, a spatially explicit or gap-type forest model would be needed. However, this would probably lead to much longer calculation times.

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