Soil carbon sequestration in the Netherlands: Inventory of long term experiments to validate effectiveness of soil carbon management in agriculture and land use change

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Soil carbon sequestration in the Netherlands: Inventory of long term experiments to validate effectiveness of soil carbon management in agriculture and land use change

L. Kooistra
P.J. Kuikman

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ABSTRACT

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Carbon sequestration in agricultural soils is accountable under article 3.4 of the Kyoto protocol. In this report we present an inventory of relevant long-term experiments that can provide estimates of carbon sequestration in soils for activities in the Netherlands. Two main sources relevant to Dutch conditions were identified: archived information on several 10's of concluded experiments (TAGA) and a series of some 30 ongoing experiments run by different research groups. The information of this inventory is stored in an accessible data base (www.carboninsoil.alterra.nl). A strategy is proposed to make the information in TAGA that is available on paper forms only accessible in digital form for easy use and renewed analyses. This will provide an assessment of the carbon sequestration potential, an upper limit (carrying capacity) of soil carbon and estimate of uncertainty and variability in space and time without having to set-up long lasting, new and costly experiments.

Keywords: carbon, sequestration, soil, long term experiments, TAGA, Kyoto protocol

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Summary

Carbon sequestration in agricultural soils is accountable under article 3.4 of the Kyoto protocol. In view of the upcoming first evaluation period from 2008 to 2012, it is relevant to gain insight in the options of carbon sequestration in the Dutch soils for activities as defined in article 3.4 of that Protocol. However, changes in soil carbon are generally slow and may thus require measurements over longer time periods than the 5 year in the first commitment period.

In this report we present an inventory of relevant long-term experiments that can provide such estimates or measures of carbon sequestration in soils for activities in the Netherlands. Such information is required to identify additional carbon sequestration in the soil due to human induced activities.

Two main sources of long term experiments relevant to Dutch conditions were identified by a group of expert of Alterra and Plant Research International (PRI): archived information on several 10's of concluded experiments (TAGA) and a series of some 30 ongoing experiments run by different research groups. The information of this inventory is stored in an accessible data base (appendix 2 or www.carboninsoil.alterra.nl).

Few of these experiments specifically focus on activities that are proposed under article 3.4. Most information relates to cropland management. Rather limited information is available on grassland and wetland management. In many experiments, no actual measurements of total carbon but more often only measures of soil organic matter content are available; for a large part of experiments soil samples are still available for repeated or renewed analyses.

Sofar the TAGA soils archive with information on a large number of potentially interesting experiments is only available on paper forms. A strategy is proposed to efficiently select relevant information from TAGA and make the data-sets available in digital form for easy access, use and analyses.

The advantage of using archived information on concluded experiments is that estimates on soil carbon changes are readily available that normally would take years to decades to observe and monitor. However, data from concluded experiments may not fully reflect current agricultural practices and may not account for effects due to variation in farmers skills and motivation. By combining results from TAGA with modeling results, current management activities can be evaluated (i.e. SOMNET). This would allow for an assessment of the carbon sequestration potential, an upper limit (carrying capacity) of soil carbon, uncertainty and variability in space and time.

1 Introduction

1.1 Background

Carbon sequestration in agricultural soils is accountable under article 3.4 of the Kyoto protocol[1]. Principal challenges associated with the identification and quantification of accountable activities still remain unanswered and require political decisions (Freibauer et al., 2002). These challenges include a quantitative estimation of the carbon absorption potential per hectare and the area of agricultural land that is suitable and available for the proposed agricultural activities under article 3.4. In addition, insight is required in the ancillary environmental effects of these activities as well as the effects on farm income.

Also for the Netherlands it seems wise to gain insight in the options of carbon sequestration in the Dutch soils for activities as defined in article 3.4 of the Kyoto Protocol. Currently, the upcoming and first evaluation period of the Kyoto protocol on this article is between 2008 and 2012. However, changes in soil carbon are generally slow and may thus require measurements over longer time periods than the 5 year in the first commitment period. If so, what length of measurement and activity period will indeed provide significant trends in carbon sequestration? And if emissions have to be reduced to the level of 1990, what were these levels then?

Changes in carbon stocks and net greenhouse emissions over time can be estimated using a combination of direct measurements, activity data and models based on accepted principles of statistical analysis, forest inventory, remote-sensing techniques, flux measurements, soil sampling and ecological surveys. These methods vary in accuracy, precision, verifiability, cost and scale of application (IPCC, 2000). Long term experiments that include direct measures of soil carbon can provide qualitative and quantitative information on the effects that can be expected as a result of particular land use, land use activities and land use change. Such experiments may be used to validate options for carbon sequestration through specified land management. During the last century several institutes and research groups in the Netherlands have carried out long term experiments on agricultural activities and these were mostly related to fertilization and crop production. Is it likely that the results from these experiments are useful to underpin decisions that are expected on options to be implemented within the framework of article 3.4. In addition, new

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[1] **Kyoto Protocol Article 3.4**: Prior to the first session of the Conference of the Parties ……., each Party included in Annex I shall provide …… data to establish its **level of carbon stocks in 1990** and to enable an estimate to be made of **its changes in carbon stocks in subsequent years**. The Conference of Parties …… shall ….. decide upon modalities, rules and guidelines as to how, and which, **additional human-induced activities** related to changes in greenhouse gas emissions by **sources and removals by sinks in the agricultural soils and the land-use change and dorestrey** categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I ……. A Party may choose to apply such a decision on these additional human-induced activities for its first commitment period, provided that these **activities have taken place since 1990**.

experiments are being set up or have recently started that are typically focusing on the measurement of changes in soil carbon stocks in agricultural soils. A major limitation is that the most relevant information from past experiments is published in research reports only and relatively few data are available in international literature. This is a major limitation as such research reports are cataloged rather scattered and this limits the use of possibly highly relevant information from these experiments. In this report, we provide an overview of available historic and recent long term experiments in the Netherlands.

1.2 Objective and research questions

In this report we present an inventory of relevant long-term experiments that can provide an estimate or measure of carbon sequestration in soil for activities in the Netherlands that are defined under article 3.4 of the Kyoto protocol. In addition, relevant parameters that are required to make verifiable estimates of carbon stocks in soils and carbon fluxes following agricultural and forest management are identified. This will allow for evaluation of results from historic and often closed experiments and define the criteria that ongoing experiments would have to meet. Such information is also required to distinguish between the autonomous development in a business-as-usual scenario and additional carbon sequestration in the soil due to human induced activities.

The inventory focuses on experiments that are relevant to activities that may actually be implemented in the Netherlands. For the Dutch situation the following questions need to be addressed:

- Which experiments include activities or treatments that are relevant for the Netherlands under article 3.4 and can a (renewed) analyses of these experiments provide a measure of effectiveness of such activities?
- Can long term experiments provide data that can be used to validate the results in activities that have been implemented and should lead to carbon sequestration in the Netherlands?
- Can long term experiments be used to assess any upper limit (carrying capacity) for carbon sequestration in specific ecosystems, land use or soils for agronomic activities in the Netherlands?

Although the inventory focuses on experiments that are representative for the Dutch situation, these may very well be located in countries such as Germany, Flanders in Belgium or UK as long as the environmental conditions and soils can be related to Dutch conditions.

The methodology used in this project can be characterized as an analysis of the requirements (*demand*) and availability (*supply*) of long term experiments on soil carbon sequestration in the Netherlands. A literature review of most recent IPCC documentation and additional material was made to assess the current needs for long term experiments both in general but also specified for the Dutch situation (chapter 2). On the basis of interviews and a brainstorm session with specialists from Alterra and Plant Research International (PRI) (appendix 1), the availability of relevant long term experiments was assessed. The resulting list of experiments is stored in a accessible database and described in chapter 3. In chapter 4, we compare the available experiments with the identified current demands for long term experiments in the light of Kyoto Protocol requirements. This allows us to evaluate the current state of knowledge on carbon sequestration in agricultural soils in the Netherlands, to identify the gaps between requirements and availability of quantitative information and to propose priorities for future research.

2 Assessment of changes in soil carbon stocks

2.1 The Kyoto protocol and Article 3.4

The Kyoto Protocol is an international treaty designed to limit global greenhouse gas emissions. As decided in December 1997, article 3 of the Kyoto Protocol, provides that countries must count both sequestration (storage) and emissions of greenhouse gases from eligible land use change and forestry activities during the commitment period (2008-2012). Under article 3.4, countries need to decide on which additional human-induced activities in the agricultural soils and land use change and forestry categories to include.

The international community is still debating which additional activities can be credited under Article 3.4 of the Kyoto Protocol and decisions have not yet been formalized (IPCC, 2000). Currently the following broad categories are identified (Marrakesh Accords 2001), for every category some relevant activities for the Dutch situation are given:

- Forest management: fertilization, grazing management;
- Cropland management: zero or reduced tillage, organic additions, organic farming;
- Grazing land management: permanent grassland, livestock management;
- Land use change: convert arable to grassland; convert arable to woodland;
- Wetland management: restored wetlands, management of water tables.

For the implementation, it is required that the definitions of the activities are unambiguous, realistic and verifiable. On the long term an increase in carbon stock can be measured but on the short term an evaluation can be made on the management activities that are carried out.

Terrestrial ecosystems are dynamic. Carbon stocks change over the full range of time and space scales for many different reasons. Although carbon stock changes can be measured directly with a variety of techniques, attributing a given change in carbon stocks to a particular cause can be much more challenging (IPCC, 2000). Article 3.4 explicitly stated that activities should be *additional human induced*. The land management activities proposed for Article 3.4 are all human-induced in the sense that they are carried out by people usually in intentional efforts to produce food, fiber, and other goods and services that people need or desire (IPCC, 2000). Separation of natural from direct and indirect human effects can be approximated by model-based interference or by using control-plots where a no-treatment regime is monitored.

Choices need to be made on the accounting rules for Article 3.4, which will affect how the adjustments in carbon sequestration are to be calculated (IPCC, 2000). Currently, it is proposed that for the carbon impacts of the agriculture-related activities in the commitment period the principal of net-net accounting is applied (Figure 1). This means that net emissions or removals of greenhouse gases during the commitment period are compared to the net emissions and removals during the base year (multiplied by five). For most countries the baseline year will be 1990. For this year, the total areas on which each of the activities occurred need to be determined and the change in carbon stocks calculated.

An important consideration in negotiating the Kyoto Protocol article 3.4 was the difference between basing credits or debits for land-use change and forestry on a change in net flows or a change in net stocks. The net-net approach considers a change in net flows. As a result it effectively includes the 1990 sequestration rate into a national baseline for 1990 against which future emissions and removals would be evaluated. This would then mean that counties need to sustain a sequestration rate indefinitely. If not sustained a debit in carbon and emissions are to be reported from this activity.

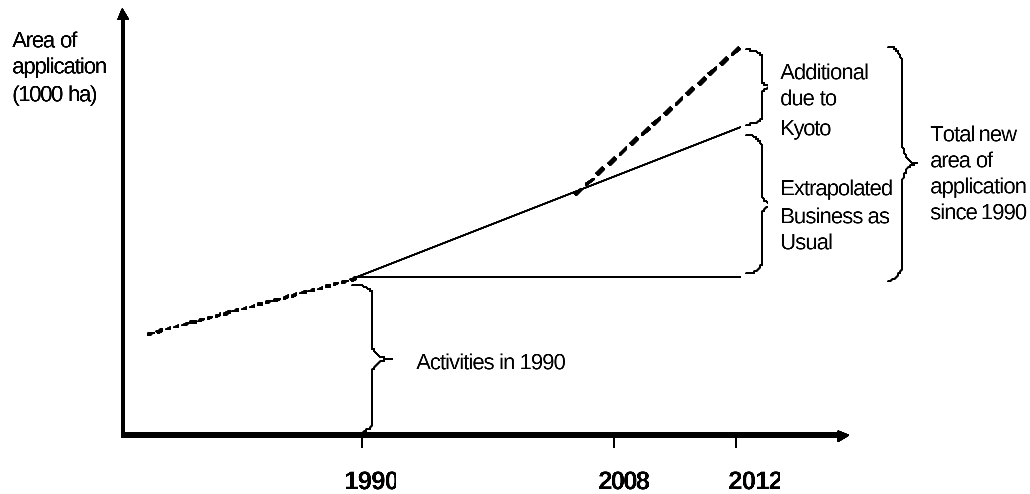

Figure 1: Illustration of the concept of human induced additional carbon sequestration. Only the changes in carbon emissions of carbon stocks that directly result from measures and activities that were developed and implemented under the Kyoto Protocol are expected to be eligible for crediting. This approach excludes specifically any result that is based on activities that were either ongoing or a trend of an increasing carbon store e.g. due to higher temperatures, CO2 concentration or other policies implemented before 1990. The alternative would be a stock based approach in which a record is being made and kept of the overall carbon store in a given (set of) ecosystems and all changes in the stock will be reported and accounted for by a country.

For a proper assessment of the changes in soil carbon stocks several good practice aspects that are currently under review (IPCC guidelines) have to be considered. This means that countries under the Kyoto protocol have to provide verifiable and transparent information for the activities that will be assessed. This will allow independent reviewers to recreate the figures reported. Within the proposed IPCC guidelines three tiers will be distinguished, which correspond to a transition from the use of largely default data in simple equations to the use of country-specific data in complex national models. The choice of a tier will depend on the available information and resources in a country. Moving from lower to higher tiers will require increased resources, and institutional and technical capacity organized in a National Carbon Inventory System.

When default carbon emission/removal factors as defined in tier 1 are replaced by country specific values, adjusted factors should be based on measurements that are conducted frequently enough and over a long time period to reflect variability of the underlying processes, and they should be documented in refereed publications. Furthermore, it requires a complete coverage of all emissions and removals for all identified pools: aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter. If a pool is not accounted for then verifiable information should be provided that the pool has not been a source over the commitment period. Finally, a consistent time series should be developed, and uncertainties need to be quantified and reduced as far as possible. Changes in soil carbon stocks are in some instances small and difficult to assess accurately over the 5-year time period of the commitment period. This problem may be addressed by adoption of appropriate sampling techniques supported by simulation modeling that take into account spatial variability (IPCC, 2000).

2.2 Requirements for long term experiments

The most direct means of determining soil carbon sequestration is to sequentially measure changes in soil carbon over time and relate this to specific management. Such measurements are complicated by the spatial and temporal heterogeneity of soil carbon contents and its relatively slow relative rate of change as compared to the stock size. This problem can be overcome through the use of well-designed sampling and analysis procedures that minimize effects of spatial and temporal variability and standardize sample preparation (IPCC, 2000).

A number of reasons have been identified as to why long term experiments are needed for the assessment of changes in soil carbon stocks (Powlson et al., 1998; IPCC 2000). Firstly, small changes in carbon content are difficult to measure accurately over short periods, because of the year-to-year variation in for example crop growth and spatial variation. Secondly, any changes should be measured against the relatively large background of carbon already present in the soil and methodological variation in chemical analysis for soil carbon may override such small numbers. Thirdly, changes in soil carbon occur slowly and can only be detected in experiments that have run for approximately 20 years or more in temperate climates. But in tropical climates, or where drastic alterations in land-use have occurred, changes may well be measurable over shorter periods. Finally, approaches using soil carbon simulation models in conjunction with regional networks of long term experiments are promising though such model calculations need validation of the model against local data at some point. But both in simulations and measurements (spatial and temporal variability) large uncertainties in results have to be taken into account, e.g., > 50 % (Freibauer et al., 2002; Vleeshouwers & Verhagen, 2001).

In addition to the Good Practice Guidance requirements described by IPCC (paragraph 2.1) some specific characteristics of long term experiments are important. Ideally a long term experiment should have accurate recording of all activities and analyses, archived samples and continuity of treatments, as long as the treatments remain relevant and do not cause soil damage or crop failure. Whether or not a long term experiment is representative is another important issue (What factors might affect the outcome of the experiment? How can you design the experiment to account for this?) as this gives information about the variability and the reproducibility of an experiment (Figure 2). In order to separate natural from direct and indirect human effects it is essential to include control plots in the experiment. Different activities as described in Article 3.4 could be applied next to a control plot where the activity was not applied. The carbon stock difference, if any, measured on the two areas would be an indication of the effect of the activity (IPCC, 2000).

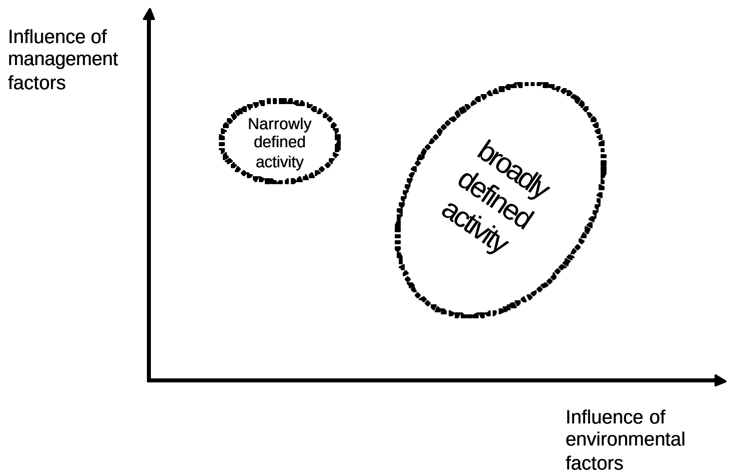

Figure 2: Illustration of the representivity of a long term experiment. To evaluate the representivity of an experiment two types of factors have to be taken into account: environmental factors (season, soil, climate, etc.) and management factors (technique, farmer etc.). On the basis of this distinction it is possible to categorize activities as narrowly or broadly defined.

2.3 Requirements for the Dutch situation

For the Netherlands it is useful to gain insight in the options for carbon sequestration in the Dutch soils for the activities that are eligible under article 3.4. For a first evaluation of the effectiveness of such options one could refer to studies that have been carried out at an European scale (Freibauer et al., 2002; Vleeshouwers and Verhagen, 2001; Smith et al., 2000). The results from these studies show that there is a realistic potential to sequester up to 60-70 Mton CO_2 in agricultural soils of the European Union during the first commitment period. Promising activities are to increase carbon inputs from organic amendments, and organic farming on cropland, to maintain a more shallow water table for grassland, and rewet grasslands on peat soils, and apply permanent revegetation of set-aside areas with perennial grasses or woody bioenergy crops. Although these results give directions for carbon sequestration in the Netherlands, it may very well be necessary to supply country specific data in order to meet the conditions described in Article 3.4.

The first choice to be made is related to which activities will be implemented in the Netherlands. In order to decide on this issue, well informed results from historic and ongoing long term experiments can be used to provide information on the anticipated effectiveness of a specific (group of or combination of) measure in Dutch conditions. Not only effectiveness but also the expected life time of the carbon sequestration (what is the maximum and will the carbon stay where it is?) can be assessed on the basis of existing or ongoing long term experiments. The final choice on which activities will be implemented needs to be integral as also other effects need to be accounted for such as economic feasibility, biodiversity and other greenhouse gases such as methane and nitrous oxide. An optimal trade-off has to be achieved (CCB, 2000).

Information on changes in carbon stocks in the Netherlands is required for both the base year 1990 and the commitment period of 2008-20012. Kuikman *et al.* (2002) examined four options for monitoring carbon stocks at a national level and made an estimation of the total carbon stock in the top layer (0 – 30 cm) of the Dutch soils on the basis of the Soil Map of The Netherlands: 286 Tg. But the best option had an accuracy of maximal 80 percent. Although these figures could serve as an estimate for the baseline situation, long-term information on the specific effects of certain management activities will be required. Currently, the availability of information from long term experiments in the Netherlands is limiting as results are published and cataloged rather scattered. Therefore, a first requirement is to make an inventory of relevant experiments. Next, the results have to be evaluated on their representivity for the current situation. On the basis of this information recommendations for additional data acquisition can be made. The final goal would be to set up a National Carbon Inventory System for the Netherlands that provides location specific information on soil carbon sequestration for different management activities.

3 Inventory of long term experiments

During the last century, several (former) DLO research institutes and departments at Wageningen University have carried out long term experiments with the objective to evaluate the effect of common agricultural management activities (e.g. fertilization, liming) on soil, groundwater and crop yield. Although not directly linked with the issue of carbon sequestration, the results from these experiments likely can be used to evaluate soil carbon stock changes. Results and original soil samples for a large set of these experiments are stored in the *Technisch Archief en Grondmonster Archief* (TAGA). In paragraph 3.1 the structure and type of information within TAGA is described, and a strategy for exploration of information within TAGA is proposed.

In addition new experiments are being set up or already running for some time that in some cases explicitly focus on the measurements of changes in soil carbon stocks under management activities as proposed in Kyoto article 3.4. In a brainstorm session with 7 specialists from Alterra and Plant Research International, an inventory was made of these long term experiments that are relevant for the estimation carbon sequestration in the soil in the Netherlands. For every experiment the relevant characteristics were summarized and the whole set of experiments was stored in a data base. Paragraph 3.2 summarizes the results from the data base and three examples are given that illustrate how measurements from long term experiments can be used to estimate changes in soil carbon sequestration. The data base with long term experiments is presented in appendix 2.

3.1 Long term experiments in TAGA

TAGA is an archive containing the results of more than a hundred years of soil research, and includes soil samples, but also samples of crop, fertilizer and soil amendments (manures) (Ehlert et al., 2002; Willigen et al., 2001). Currently TAGA contains the results of 20,000 field experiments (both short and long term), 300,000 soil samples, 35,000 crop samples and 7,000 samples of fertilizers and soil amendments. The first experiment originates from 1879, while currently still samples are added. The samples are from experiments located over the whole of the Netherlands. The structure of TAGA with three main components is illustrated in Figure 3 (Ehlert et al, 2002). The data in the Search System (former card index) are since 1999 digitally available. It should be explicitly stated that these digital data are not the actual results of experiments but contain information on the experiments: location, soil type, year of construction, type of experiment, investigated factors, crops etc. This information is stored in an EXCEL sheet. A selection of this sheet is shown in Figure 3. On the basis of the code of an experiment, actual data of measurements and analytical data can be looked up in the second component of TAGA, the Technical Archive. This consists of all documents of the archived experiments that give a full description of the experiment: experimental design and journals, measurements on crop and soil including analytical data and sample numbers. The actual samples can then be found in the Sample Archive in Wageningen. In addition to TAGA, long term experiments on forest management might be found in the Dorschkamp archive (Ehlert et al., 2002). This archive is stored at Alterra but very little digital information is available and therefore may require a larger effort to use these experiments.

Grond	Proef	Beginjaar	Eindjaar	N	P	K	Na	Mg	Ca	Cu	Anorg	stalmest	gier	groen	org	compost
5	9831	1881	1934	8	0	0	0	0	0	0	0	16	0	0	0	0
5	9830	1881	1960	8	0	0	0	0	0	0	0	16	0	0	0	0
2	14159	1900	1948	8	0	0	0	13	0	0	0	16	0	0	0	0
2	14158	1906	1948	8	0	10	0	13	0	0	0	16	0	0	0	0
2	14750	1911	1941	0	0	10	0	0	0	0	0	16	0	0	0	0
2	10458	1913	1967	8	0	10	0	0	0	0	0	0	0	0	20	0
2	9832	1915	1963	8	9	0	0	0	12	0	0	16	0	0	0	0
5	9827	1915	1949	8	0	0	0	13	0	14	0	16	0	0	0	0
2	9828	1916	1954	0	0	0	0	0	12	14	0	16	0	0	0	0

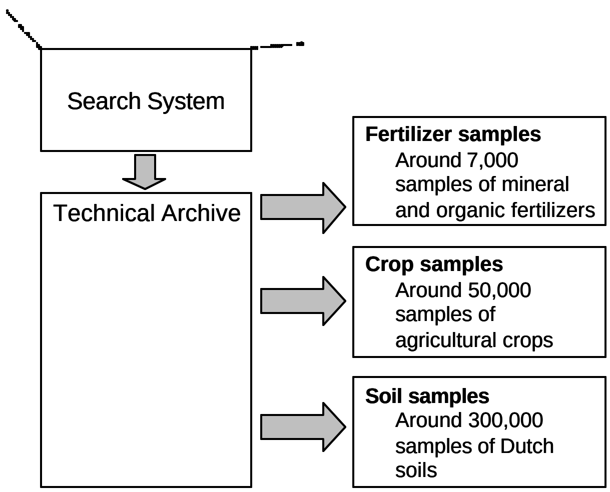

Figure 3: Structure of the TAGA-archive (Ehlert et al., 2002) with an example of the available meta-data for the selected experiments of Figure 4. Within the first column 6 soil types are distinguished (1=marine clay, 2=sand, 3=river clay, 4=loess, 5=excavated peat, 6=peat). The second column gives the experimental number that is used to look up the available paper documentation in the Technical Archive. The other columns give information on the start and end year of the experiment and the factors that were investigated in the experiment.

3.1.1 Activities and measured soil parameters

Most experiments in TAGA were carried out on arable land, also a collection for grassland and for land use change (arable to grassland, grassland to arable) is available. For the availability of long term experiments for a certain agricultural activity the following order can be given: crop residues/organic additions > land use change > tillage > water management (pers. comm. Phillip Ehlert). For example the number of available long term experiments with a minimum duration of at least 15 years in which the factor organic soil amendment was taken into account is 52 (Figure 4). For a large part of the experiments focus was on the measurement of N and P, these factors can directly be looked up in the digital Search System of TAGA (Figure 3). The Search System does not provide information on the actual measurements and analytical data. This information can be found in the archived data file of the technical archive. Carbon content is a regularly measured soil parameter at the start of each experiment, but values on trends in the organic matter content caused by different treatments are less frequently reported. However as soils samples for a large part of the experiments are still available in the sample archive[2], trends can be established by re-analysing the samples for carbon content. The methods for the determination of organic and inorganic carbon have changed in the last decades. Different methods based on wet oxidation have been abandoned and nowadays mostly loss-on-ignition is used (pers. comm. Phillip Ehlert). In case that long term soil carbon time series are available one should take into account the specific method of carbon analysis as this could explain differences in the time series.

3.1.2 Spatial and temporal variability

In order to construct a time series, three types of experiments within TAGA could be relevant:

1. Long term experiments at one plot or field; often these experiments also include a plot or field with no treatment to assess the autonomous development (Table 1);
2. One location that is sampled at different moments in time within different projects;
3. Possibly, short term experiments with different treatments and a clear statistically set up sampling scheme.

For all three options, in principle it is possible to return to the original locations and do an additional sampling and analysis for the current situation. But this is only relevant in the case current land use and treatment is comparable to the original experimental set-up or land use change since abandonment of the experiment has been documented. Figure 4 shows that for a certain treatment the experiments vary both in year of construction and duration. Furthermore, as the experiments are located in different parts of the Netherlands on different soil types also the spatial representivity could be assessed. A major drawback of information in TAGA is that experimental conditions are fixed and management practices are dated. However, available data make analyses often cheaper than the construction of new experiments. By combining results from TAGA with soil carbon models, current management activities can be evaluated (e.g. SOMNET).

[2] For some experiments all samples are available, while for other (e.g. one year experiments) no samples are present. For series of one year experiments and long term experiments that focus on organic matter, P, K, Mg, and Ph, soil material is often available (sometimes as a selection of all years). Remarkably, soils samples that were analyzed for N are often not available (pers. Comm. Phillip Ehlert).

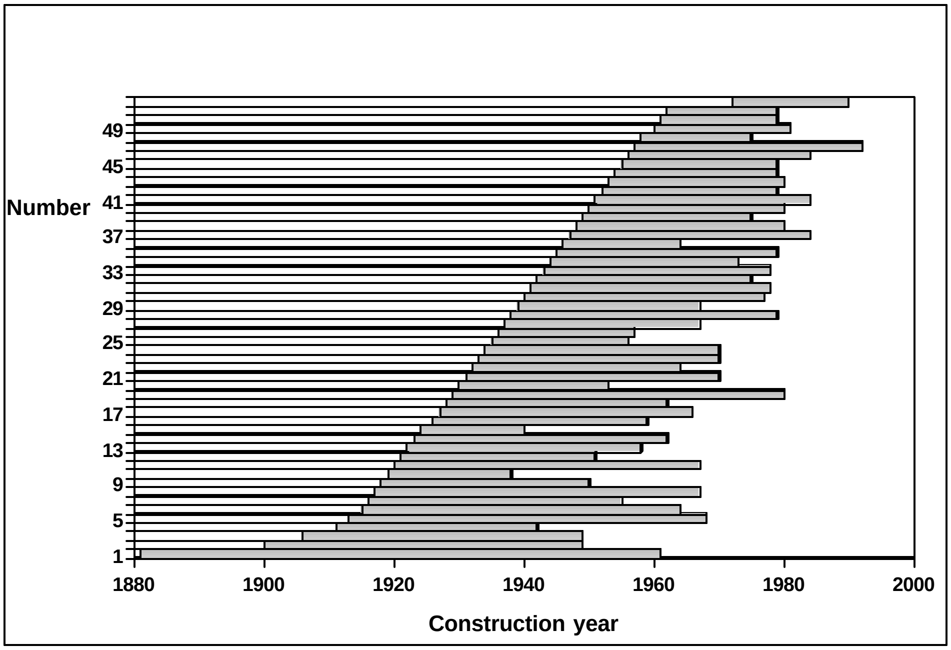

Figure 4: Number of long term experiments of TAGA on organic amendments with a minimal duration of 15 years available within TAGA. The width of the bars shows the duration of the experiments. Experiments are located in different locations in the Netherlands on six different soil types.

Table 1: Example of the results of an experiment stored in TAGA (experimental code: IB1694). The experiment was conducted between 1970 and 1980 and investigated the effect of different fertilizers and organic additions on grassland production. Koopmans et al. (2003) used the results to calculate a phosphorus balance for this system. The organic matter content was measured annually but for this study these values have not been stored digitally from the TAGA documentation. Additional look-up of these values would take 2-3 days (pers. comm. Gerwin Koopmans). With this information an analysis of the trend of the carbon storage in the soil for the different treatments could be performed. Because a control plot was included in the field experiment, the storage of carbon can be determined without interference of the treatments. Furthermore, as the amount of organic matter in the animal manure has been measured, the autonomous storage of carbon can be deduced from the treated plots as well.

Treatment	Application	P Balance†	pH (KCl)	Organic matter	P_w‡	Total P	Organic P§	$[Al+Fe]_{ox}$§	DPS¶
		kg P ha^{-1}		%	mg P kg^{-1}	mg P kg^{-1}	mg P kg^{-1} (%)#	mmol kg^{-1}	%
Initial soil			4.4	5.4	2.1	393	240 (61)	56	34
No fertilizer (control)		-158	4.0	5.9	3.0	436	269 (62)	54	39
N fertilizer	200 kg N ha^{-1}	-219	4.0	6.8	1.4	349	286 (82)	45	35
N-P-K fertilizer	200 kg N, 52 kg P and 199 kg K ha^{-1}	236	4.1	6.3	13.8	742	288 (39)	56	66
Solid poultry manure	25 Mg ha^{-1}	2486	6.5	6.5	29.0	2400	529 (22)	57	194
Idem mixed with litter	25 Mg ha^{-1}	3542	6.3	6.8	39.8	2007	470 (23)	53	208
Poultry slurry	30 Mg ha^{-1}	1690	6.3	6.0	22.7	1658	477 (29)	50	155
Calf slurry	25 Mg ha^{-1}	1066	5.7	5.7	26.5	1134	328 (29)	56	111
Pig slurry	25 Mg ha^{-1}	1000	5.4	6.7	22.0	1222	441 (36)	60	107

†The cumulative P balance was calculated as the difference between the P applied and P removed with the harvestedgrass.

‡Water-extractable P at a soil to solution ratio of 1:60 (v/v) (Sissingh, 1971).

§Organic soil P and $[Al+Fe]_{ox}$ were determined in this study; other data were taken from van der Veen (1985).

¶Degree of phosphorus saturation (DPS) was calculated according to Eq. [1].

#Organic P as a fraction of total P is shown in parentheses.

3.1.3 Exploration of TAGA

As the data on soil parameters in TAGA are not digitally available yet, a clearly defined search profile is required to efficiently explore the information within TAGA. To extract data from TAGA at least 5 steps and preferably 7 steps have to be undertaken (box 1). To evaluate the potential results of experiments within TAGA so-called gray literature (none digitalized research report) can be explored whether the available data can meet new research topics and questions. For step 4 that links concluded past experiments to their associated investigators[3] and step 5, specialist knowledge is required as no standard digital coupling exist between primary data and soil samples and published report including analyses of results. Steps 4 and 5 can be conducted independent of the other steps. These steps increase the efficiency of the query. Steps 6 and 7 are the most time consuming steps and to increase the efficiency of data mining, an efficient and well conditioned query to select the most important experiments is required. If a required soil parameter is not determined then the availability of soil sample material can be assessed through a separate data base. For this the individual sample code needs to be known and thus the paper documents need to be evaluated.

The time required to look up the actual values in the paper documents, step 7 in box 1, depends on several factors: experience of the researcher, the number of parameters that need to be assessed, and detail level of the experiment. On average it will take an experienced researcher 5-8 days to get the values for 20 parameters for one experiment with a duration of 20 years (pers. comm. Phillip Ehlert).

Box 1: Strategy for exploration of information in TAGA

1. Define a clear and conditioned **research question**: which methods or models will be used
2. Define **information question**: which parameters are required (soil/vegetation characteristics but also analysis method, land management, location, soil type)
3. Define a **search profile** for search in meta data base of TAGA (excel): use agricultural terminology
4. **Quick-scan** on relevant experiments in meta data base of TAGA: link name and additional parameters with investigators
5. **Literature search** on these experiments to select most relevant experiments and to get idea of relevancy of results
6. **Retrieval of documents from TAGA.** For the selected experiments retrieve documentation from TAGA and check availability of actual measurements and check suitability of the recorded analytical methods and sample numbers
7. **Retrieval of data from TAGA for further statistical analysis of actual measurements.** The documentation is mined for suitable data which are digitally stored.

[3] For example searches for so-called gray literature on soil carbon related research in agricultural soils in the Netherlands can be found in the reports from Verslagen Landbouwkundig Onderzoek from authors like Groothuis, Kolenbrander, Kortleven, Janssen, Castenmiller, Sluismans (pers. comm. Phillip Ehlert). These reports have been reviewed internally by expert co-workers and are currently available in the library of WAG-UR and can be assessed by AGRALIN or through a specific database available within Alterra.

3.2 Long term experiments not archived in TAGA

In addition to the experiments available in TAGA, an inventory of other relevant long term experiments was made during a brainstorm session with 7 specialists of Alterra and Plant Research International (PRI). Participants and questions that were asked during this meeting are presented in appendix 1. The resulting set of experiments is stored in a simple database and presented in appendix 2. On the basis of a questionnaire most important characteristics of these experiments were acquired. A total number of 37 experiments were identified. For 19 experiments detailed meta data are available (appendix 2); from 8 experiments no additional meta data could be retrieved[4]; 5 experiments were appointed national monitoring networks and are treated in a separate paragraph; 2 experiments were already described in the SOMNET database (Powlson et al., 1998); and 3 experiments were appointed as not relevant after return of the questionnaire.

3.2.1 Activities and measured soil parameters

An evaluation of the resulting set of 19 available long term experiments shows that most experiments are available for cropland management (manure and organic additions) and land-use change (arable land to forest, and rotation grassland and arable land) (Table 2). For grassland management (manure and grazing) and forest management (grazing) only a few experiments are available. For the activity tillage no experiments were identified.

A crucial point here is the applied method for the determination of the soil carbon content. In 10 experiments the soil organic matter content based on loss-on-ignition was available, while for 9 experiments the total carbon content was determined. However, for several experiments sampled soil material is stored and still available for renewed analyses of soil characteristics. Additional parameters that are important for calculating soil carbon stocks such as sampling depth is well described for most experiments though soil bulk density is only determined in a few experiments.

3.2.2 Spatial and temporal variability

Several ongoing experiments are available in the category *land-use change*. Three of these focus on change from arable land to forest and include evaluation of forest biomass. Much of the (current) research on cropland and grassland is carried out on a project basis that is often too short to significantly assess carbon stock changes induced by a specific management practice or activity. Results from long term experiments show that measurement series longer than the commitment period of 5

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[4] Information for these experiments is available within other institutes or could not be retrieved within the duration of this project. The following potential experiments were identified: experiments at experimental farms Schothorst, Wijnandsrade, Minderhoutshoeve (tearing grassland), and OBS in Nagele, and work of Hassink and co-workers (Lune et al., 1993), work of Römkens and co-workers (addition of sludge; Römkens et al., 1999), monitoring forest plots (available in Dorschkamp Archive).

year are required to evaluate temporal variability and to reach equilibrium in a soil carbon pool (Figure 5). Although the required time period will differ per activity, for most activities long term (>10 years) measurements are necessary as inter-annual and spatial variability might interfere with measured trends resulting in uncertainty (Figure 6 and 7). Experimental research with different plots in a well-defined experimental design may already provide verifiable results over shorter time periods. Yet, these not necessarily reflect field conditions where often complicating factors have to be accounted for. In case the location of a closed experiment is well defined and the agricultural activities are still comparable it would be possible to return to the site for additional sampling and analysis.

Table 2: Summary of the number of experiments[5] *available within the institutes of Alterra and Plant Research International (PRI) for the broad land-use categories defined in article 3.4 of the Kyoto protocol. Only the results for the 19 experiments with detailed meta data are presented (see appendix 2).*

	Long term experiment		**Other experiments**	
	closed	**ongoing**	**closed**	**ongoing**
Cropland management	5	1	2	1
Grassland management	1		1	
Forest management		2	1	
Land-use change		4		1
Wetland management				

3.2.3 Monitoring Networks

Within the Netherlands several monitoring networks are run that could provide information on soil carbon stocks. The following were identified:

- On European scale monitoring of forests ecosystems is performed (www.icp-forests.org/): 14 plots in the Netherlands with detailed soil analysis (total carbon) (Dobben and de Vries, 2002; de Vries et al., 2002)
- *Network Bosreservaten*: monitoring of newly established forest reserves every 10 years with analysis of humus profiles (Broekmeyer 1995; Kemmers et al., 2000);
- *Network Functievervulling Bos*: monitoring every 5 years of forest biomass parameters (http://www.sbh.nl/over_sbh.htm)
- Information available in Bodemkundig Informatie Systeem (BIS) available within Alterra (Ehlert et al., 2002) for which online availability is foreseen
- *Monitoring network Bodemkwaliteit* (RIVM): since 1997, soil parameters (e.g. organic matter, DOC) in 40 locations on different soil types in the Netherlands (http://www.rivm.nl/milieu/bwlg/meetnetten/lmb/)are measured every 5 years.

[5] For this inventory we separated experiments with a duration of longer than 10 years that were named long term experiments from other experiments with a duration between 3 and 10 years. In addition it was required that measurements were made on a regular basis and a carbon related soil parameter was measured.

3.2.4 Representative experiments in other countries

In addition to experiments in the Netherlands, experiments in other countries could be relevant as long as they are representative for the Dutch conditions. In 1995, an inventory of long term experiments from around the world has been made (Powlson et al., 1998). The experiments are collected in the GTCE SOMNET database that is online available (http://saffron.res.bbsrc.ac.uk/cgi-bin/somnet-expts). Currently a total number of 69 long term experiments are described in the SOMNET database. A rough selection of experiments that could be representative for the Netherlands on the basis of their location in Europe and a cool temperate climate resulted in a search result of 43 SOMNET experiments (arable 35, forest 3 and grassland 5). These experiments are mainly located in Germany (12, e.g. Bad Lauchstädt Static Fertilizer Experiment (Körschens and Müller, 1996; Körschens, 1996), the UK (10, e.g. Rothamsted) and Hungary (9). Recently, a literature review has been made within the framework of the EU-project AFFOREST on building knowledge and capacity to provide support for decisions regarding afforestation in respect to changes in C, N and H2O pools and fluxes (Hansen, 2002). This report provides insight and figures on the effect of forest management on soil carbon sequestration in several European countries.

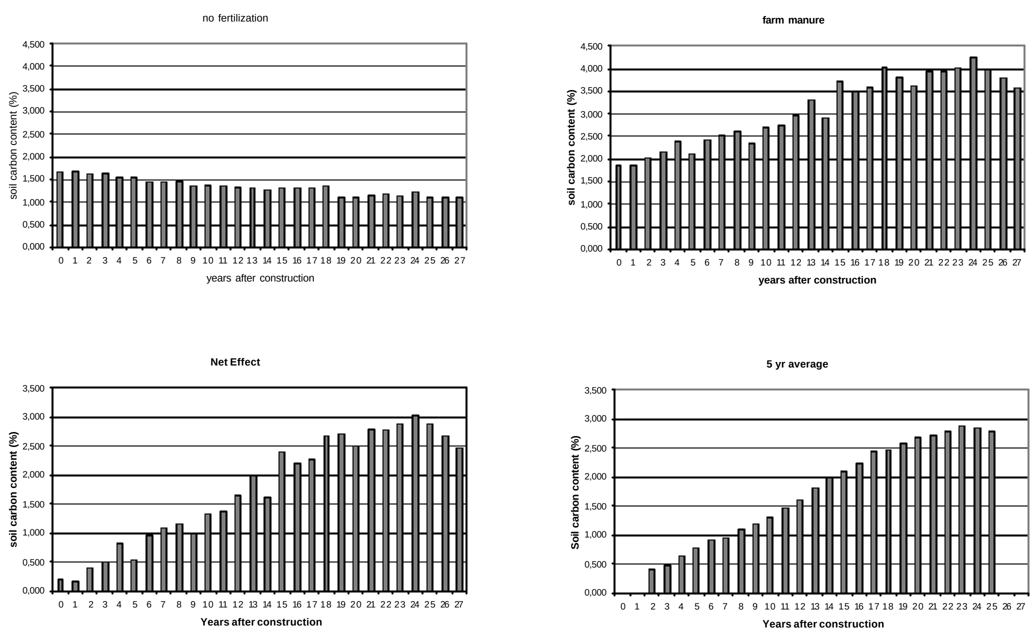

Figure 5: Result of long term field experiment showing the effect of the addition of farm manure on the soil carbon content. During the experiment the soil was kept bare. The results illustrate the variation between years. When the average effect over 5 years is calculated then variation between years is removed. The figure also shows that after a period of approximately 20 years equilibrium is reached for the soil carbon content.

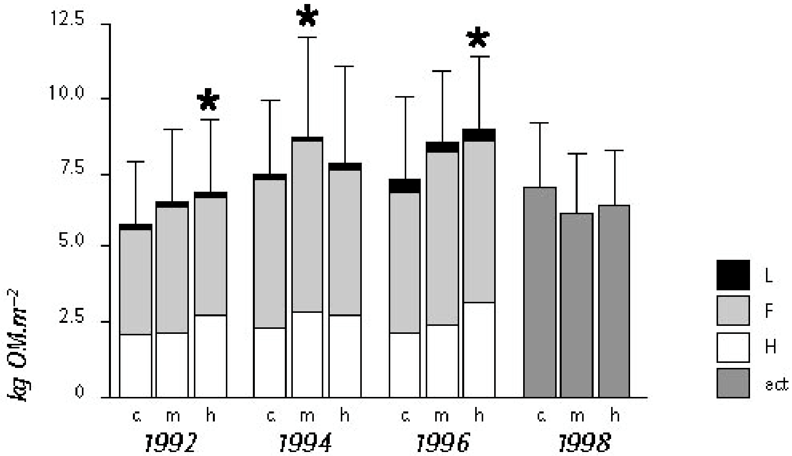

*Figure 6: Average and standard deviations of measured soil organic matter stocks in the ectorganic horizons of the control field © and the moderately (m) and heavily (h) grazed fields in 1992, 1994, 1996 (all n=50) and 1998 (n=25, L, F and H horizons combined). Significant differences (p<0.05) are indicated by an *. In spite of a decrease in organic matter input to the soil in the grazed field, the carbon stocks did not decrease. Based on measurements and literature we concluded that grazing directly and indirectly changes the quality of the organic matter input, which resulted in a decrease of decomposition rates. However, the experimental period was to short to measure significant differences between the fields (Smit, 2000).*

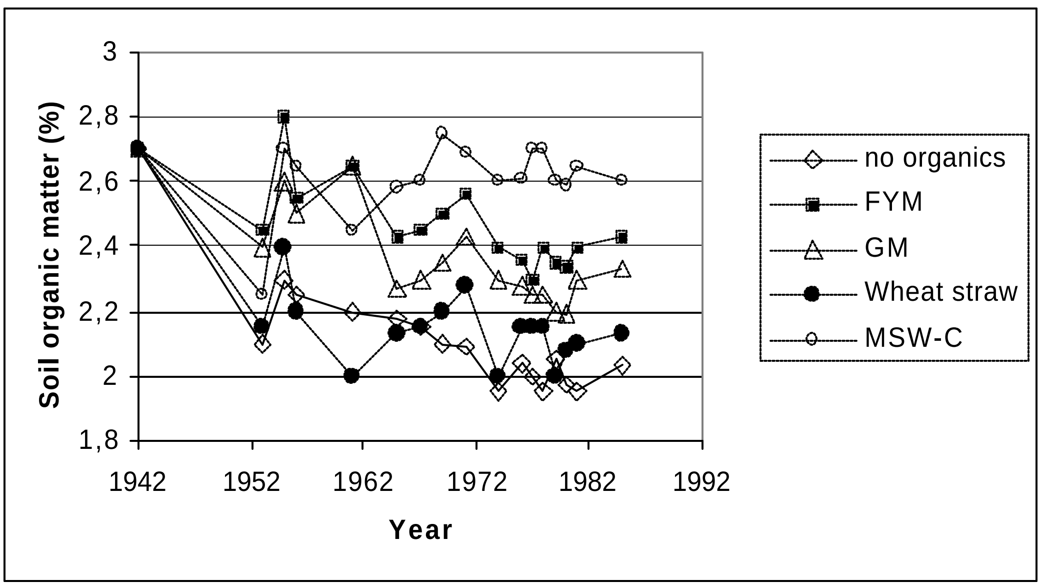

Figure 7: Results from long term field experiment investigating the effect of different organic matter amendments to a Dutch loamy soil in an arable crop rotation. After the start of the experiment, all treatments show a large variation until 1965; after this point soil organic matter in most treatments remains more or less constant. Additional information on environmental and management factors is required to explain this variation. FYM = farm yard manure; GM = green manure (clover or grass); MSW-C = municipal waste compost.For details see appendix 2, LTE_cropland_closed2

4 A comparison of needs and supplies

4.1 Possibilities for soil carbon sequestration in the Netherlands

In an inventory, this study identified available long term experiments for all article 3.4 land use categories identified by the IPCC (par. 2.1). Except for wetland management long term experiments are available for all categories (Table 2). The number of experiments range from 2 for grassland management, 9 for cropland management , 3 for forest management and 5 for land-use change. All experiments of the latter two categories are still ongoing. Most of the experiments available within TAGA relate to cropland management though a small set of experiments is available for grassland management. For other categories very few if any experiments are available. The Dorschkamp archive could provide additional experiments on forest management.

A prioritization for those activities that are considered relevant for the Netherlands resulted in the following order of activities: land-use change > organic additions/crop residues > wetland management > forest management > other activities like productivity increase (fertilizer). Tillage was not considered to be a relevant option in the Netherlands given the extensive use of crop rotations. For the activities land-use change and organic additions/crop residues (both on cropland and grassland) long term experiments are available but for the category wetland management additional effort would be required.

The main focus of this study was on an inventory of available long term experiments on soil carbon sequestration in the Netherlands. No detailed assessment of the actual carbon sequestration potential in the Dutch situation that can be deduced from these experiments has been made yet. Hence, in this report some examples are provided to highlight the potential use of long term experiments to make such calculations. The following types of analysis could be adopted using the long term experiments:

1. Determine historic carbon pools before certain management activities were carried out by backtracking changes (Kuikman et al., 1999). These values give an indication of the potential (maximum) soil carbon levels that can be achieved under different treatments and for different soils (see figure 6);
2. Determine the required time and efficiency of soil carbon pools to reach new equilibrium levels after a management change and evaluate factors like: (1) shortest time required to equilibrium; (2) shortest time required to equilibrium in combination with a higher equilibrium level; (3) higher equilibrium level but on same time scale (figure 8). The possibility to evaluate these trends will generally depend on the duration of the experiments that are carried out (see figure 6).
3. Evaluate the source and magnitude of uncertainty in the estimation of carbon sequestration (see figure 7) and estimate the associated risks that equilibriums will be disturbed: what will be the effect of a management error or events related to weather (annual) and climate change (long term).

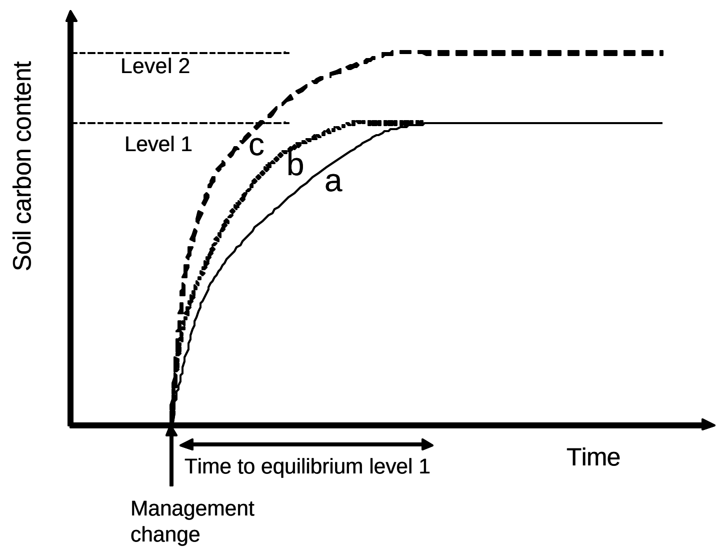

Figure 8: Illustration of possible scenarios of the effect of a management change on the soil carbon content. The three presented scenarios show a difference the required time to reach equilibrium (scenario a vs b) and in efficiency concerning the equilibrium level that can be achieved (scenario a vs c). Differences can be explained by factors like treatment, soil type, or climate.

4.2 Verifiability and representivity of long term experiments

An important requirement for long term experiments is that information needs to be verifiable and transparent. For experiments available in TAGA and other experiments (as presented in appendix 2) accurate documentation of management, duration, analysis techniques, treatment is available in Dutch. In most experiments only the soil organic matter content (loss-on-ignition) is measured and not the total carbon content. In some cases soil material is still available and additional or repeated analysis can be done. Data from long term experiments need not only be accessible and documented but also of good quality according to IPCC. Many though not all experiments have a statistically sound design. Unfortunately, many results have only been published in so-called grey literature and some have never been published.
In addition long term experiments will have to be representative for :

1. Dutch environmental conditions (soil, climate, weather)
2. current (or near future) agricultural management practices
3. reflect management as it is done by a typical (mean) Dutch farmer and not reflect only management on a experimental farm by well trained and supervised farmers.

For many of the ongoing experiments these requirements are fulfilled as they are typically focusing on the assessment of soil carbon sequestration. Drawback of the available closed experiments in TAGA is that experimental conditions are fixed and thus their representivity may sometimes be of limited value. Yet, often it is cheaper and quicker indeed to use results from concluded experiments than start new experiments. By combining results from TAGA with soil carbon models, we expect that current management activities can be properly evaluated (see SOMNET).

4.3 Future developments and requirements

The long term experiments within TAGA could indeed provide relevant information on soil carbon sequestration options in the Netherlands. Unfortunately, the information on soil analyses within TAGA is not digitally available yet. Any effort to make TAGA digitally available needs to be well considered in an integral way as TAGA may also provide relevant information on N, P and other soil parameters. The first step would be to make an inventory of the data sets from TAGA that are already digitally available. Next, the strategy presented in paragraph 3.1 could be used to select the most relevant experiments that have first priority to digitize. Recommendations to make the information within TAGA available are also given in the report by Ehlert et al. (2002, p. 39). Innovative scanning opportunities and automated text assessment may indeed only now make digitization feasible and affordable. A proper manual assessment of the values for one experiment from paper documentation in TAGA (experimental characteristics: duration 20 years, 20 parameters) will take an experienced researcher between 5 and 8 days.

Last but not least, requirements from today's perspective with respect to ongoing and to new long term experiments were identified during the brainstorm session:

- Use of proper experimental design: duration experiment minimum 15 years, include plot without treatment, clear description and analysis of initial situation, use 'extreme' treatments;
- Use of state-of-the-art analysis techniques: which carbon analysis technique, include root separation, determine bulk density, quality of carbon (stable and unstable fractions);
- Combination with proper models that include process knowledge, integral multi-gas approach and take into account differences caused by spatial variation.

Finally, these experiments should not only focus on soil carbon but also include trade-offs with other greenhouse gases (such as N_2O and in wetter soils CH_4) and other environmental parameters should be accounted for.

5 Conclusions and recommendations

In this report we present an inventory of available long term experiments that could provide representative information on possible soil carbon sequestration in the Netherlands for agricultural activities defined under article 3.4 of the Kyoto protocol. In addition, we have presented illustrations of this potential.

The following conclusions can be drawn from this report:

- Two main sources of long term experiments relevant to Dutch conditions exist: archived information on several 10's of concluded experiments (TAGA) and a series of some 30 ongoing experiments run by different research groups. The information of this inventory is stored in an accessible data base (appendix 2 or www.carboninsoil.alterra.nl).
- The TAGA soils archive stores information on a large number of potentially interesting experiments but the relevant information on soil parameters and (experimental) conditions is only available on paper forms; it may be costly to select relevant data-sets and make actual figures available; current scanning and image processing IT may render digitizing less time consuming than so far.
- A strategy is required to efficiently select relevant TAGA information and make the data-sets available for use and analyses.
- The advantage of using archived information on concluded experiments is that estimates on soil carbon changes are readily available that normally would take years to decades to observe and monitor. However, data from concluded experiments may not fully reflect current agricultural practices and may not account for effects due to variation in farmers skills and motivation. Also, experimental conditions from these concluded experiments are by definition fixed.
- Data sets from concluded experiments in TAGA may be used to estimate an indication of carbon sequestration potential and upper limit (carrying capacity) on the basis of original carbon pool, uncertainty, variability in space and time. By combining results from TAGA with modeling efforts, current management activities and conditions can be evaluated (i.e. SOMNET) for carbon sequestration.
- Experts in a brainstorm session agreed that a limited number of additional and often ongoing relevant experiments are available in the Netherlands. Few of these experiments specifically focus on activities that are proposed under article 3.4 and thus give the most representative and verifiable information
- Rather limited information and experiments are available for the land use categories grassland management and wetland management
- In many experiments, no actual measurements of total carbon but more often only measures of soil organic matter content are available; for a large part of experiments soil samples are still available for repeated or renewed analyses.

To make data in TAGA and other concluded long term experiments accessible for renewed analyses on carbon dynamics and sequestration options relevant to the Netherlands under the Kyoto Protocol article 3.4, it is recommended to set up a project that will select and make information in TAGA available. State of the art technology may be used to digitize information. A strategy to achieve this is proposed in this report.

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Appendix 1 Contributors to the inventory of long term experiments

To make an inventory of long term experiments additional to those in TAGA, a brainstorm session was organized with specialists from Alterra and Plant Research International:

- Annemiek Smit
- Kor Zwart
- Jan Verhagen
- Gerwin Koopmans
- Jan Willem van Groenigen

The following questions were addressed during this meeting:

- Make a prioritization for the Dutch situation of the following activities: tillage, crop residues, organic additions, forest management, water management, and land use change
- Make a list of long term experiments that are known to you and that could provide information on soil carbon sequestration
- Provide the following information for these experiments: name, contact person, land use, location, soil type, duration, measured carbon parameter
- Make a list of requirements that should be taken into accounted for the definition of ongoing or new experiments on soil carbon sequestration.

As a follow up of this meeting the participants were asked to fill in a detailed questionnaire for the experiments they had provided.

In addition other specialists were consulted to provide specific and detailed information on TAGA or additional experiments:

- Philip Ehlert
- Gert Jan Nabuurs
- Gerard Velthof
- Carolien van der Salm
- Jaap Schröder

Appendix 2 Overview of long term experiments on carbon sequestration in the Netherlands