climate changes spatial planning

Mitigation

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Contents

Summary

Summary in Dutch

Landgebruik en -beheer leidt tot zowel emissie als opname van de broeikasgassen koolzuurgas (CO_2), methaan (CH_4) en lachgas (N_2O). Daarmee onderscheidt landgebruik zich van andere bronnen zoals transport en verbranding van fossiele brandstoffen voor de energievoorziening. In Nederland komt ongeveer 10% van alle emissies van de broeikasgassen uit land-gebonden bronnen en nog eens 5% uit aan het landgebruik verbonden activiteiten.

Onder het VN-klimaatverdrag zijn landen verplicht om te rapporteren over de omvang van hun broeikasgasemissies. Kenmerkend voor de emissies van land-gebonden bronnen zijn de relatief grote onzekerheid over de omvang daarvan en de generieke benaderingswijze die weinig of geen rekening houdt met regionale en lokale omstandigheden. Onder het klimaatverdrag worden landen voortdurend uitgedaagd om hun emissieberekening te verbeteren en de onzekerheid terug te dringen. Deze acties maken een realistischer en gerichter aanpak van emissievermindering mogelijk en vergroten de zichtbaarheid van lokale en regionale initiatieven om hetzelfde te doen.

Nederlandse onderzoekers hebben binnen het Bsik-onderzoeksprogramma Klimaat voor Ruimte (KvR) gewerkt aan het verbeteren en verfijnen van de emissieschattingen in tijd en ruimte, aan het terugdringen van de onzekerheid in de emissiedata, het ontwerpen van maatregelen om de emissies van het landgebruik te reduceren en innovatieve methoden om N_2O en CH_4 emissies te bepalen toegepast en verder ontwikkeld.

Land-gebonden CO_2 emissies vertonen een regelmatige en redelijk voorspelbare variabiliteit op dag- en seizoens-basis. Die variabiliteit is vooral gerelateerd aan de hoeveelheid zonlicht en de temperatuur. De temporele variabiliteit van N_2O emissies kenmerkt zich door periodes met een lage achtergrondemissie die onderbroken worden door relatief zeldzame, maar extreem hoge piekemissies. Zulke piekemissies worden getriggerd door neerslag en bemesting. Temporele variabiliteit van CH_4 emissies is eveneens groot, maar de oorzaken hiervan zijn minder duidelijk. Ruimtelijke variabiliteit van N_2O en CH_4 emissies worden deels veroorzaakt door verschillen in grondwaterstand en intensiteit van het land- en bodemmanagement.

Emissies en opnames van CO_2 en N_2O zijn vertaald van de landschapsschaal naar de nationale schaal. Voor CH_4 is dit niet gelukt omdat hiervoor betere gegevens over het waterniveau nodig zijn. Voor alle drie de gassen zullen de schattingen op nationale schaal verbeteren als actuele informatie over de snelle veranderingen in de Nederlandse veengebieden gebruikt kan worden.

Vernatting van agrarische veengronden kan zulke gebieden van een bron doen omslaan in een put voor broeikasgassen. In de zomer zijn emissies van grote ondiepe meren hoger dan die van gemanagde polders, maar ze zijn lager dan die van de drainagesloten in de polders.

De binnen dit onderzoek gebruikte innovatieve meetmethodes om broeikasgasopnames en -emissies te bepalen (EC, REA en DEC) blijken voor N_2O en CH_4 weliswaar nauwkeurig te zijn, maar nog niet efficiënt in economische zin. Voor CO_2 zijn dergelijke accurate en betaalbare methodes wel beschikbaar.

Summary

Within the framework of the Bsik research program Climate Changes Spatial Planning (CCSP), research has been carried out to improve estimates of greenhouse gas (GHG) emissions (GHG) from land-use and land management in space and time, to reduce the uncertainty in such GHG emission estimates, to identify measures to reduce GHG emissions from land-use and to apply and further develop innovative methods to measure the emissions of N_2O and CH_4 in particular.

CO_2 emissions show a quite regular and predictable seasonal and daily variability mainly related to light and temperature. Temporal variability of N_2O emission is characterized by low background emissions interspersed with rather rare but extremely high emission peaks mainly triggered by precipitation and application of fertilizer. Temporal variability of CH_4 emission is very large as well, but the causes of this variability are less clear. Spatial variability of N_2O and CH_4 emissions is to some extent caused by differences in groundwater level and land and soil management intensity.

The objective to upscale flux estimates from the landscape level to country-wide level was achieved for CO_2 and N_2O but not for CH_4. In particular improvement of water table information is important for upscaling of CH_4 fluxes, while all models will profit from updated information on the rapidly changing peat soils in the Netherlands.

We have found that the rewetting of agricultural peatland can turn areas from a GHG source into a sink. Summer emissions from large shallow lakes are higher than those from intensively and extensively managed polders but lower than those from drainage ditches within the polders.

The current innovative measurement methods (EC, REA and DEC) for N_2O and CH_4 fluxes are accurate but not yet economically efficient. For CO_2 there are accurate and economically efficient methods in place.

Extended summary

Our global climate is changing and this is most likely due to higher greenhouse gas emissions and related rising greenhouse gas concentrations in the atmosphere. Policymakers have concerns on serious negative socio-economic and environmental consequences from global warming and agreed that the global average air temperature should not increase by more than 2 degrees in the coming 100 years [Kabat et al, 2005]. This principle is guiding the on-going climate negotiations where countries aim for a reduction of GHG emission of 60 to 80% compared to the year 1990 in the decades to come. Europe and the Netherlands formulated a reduction target of 20% in 2020 relative to 1990. Such a reduction requires fundamental changes in the energy-, industry-, transport and agricultural sector.

Agricultural practices and land-use and management largely determine the emission of the greenhouse gases (GHGs) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from Dutch (agro)ecosystems. Specific forms of land-use and land-management can turn an area either into a source or a sink of GHGs. This sink and source option for soils is one of the main differences with other GHG sources such as transport and anthropogenic energy consumption. About 10% of all emissions in the Netherlands is derived from terrestrial sources and 5% is directly linked to activities connected to land-use and land-use change.

Key sources and sinks

The key sources and sinks for land use related GHG emissions in the Netherlands are forest, grassland, agriculture and peat-land. Forests are generally expected to be a sink [e.g. Dolman et al., 2002], grasslands a minor sink [Soussana et al., 2004], agriculture a source [Moors et al., 2010] and peat-land a source if drained substantially, and a sink if not [Jacobs et al., 2003]. Due to past and continued water level reductions, Dutch fen meadow ecosystems on peat have been a strong net source of carbon dioxide as a result of increased peat oxidation over a long period of time. The source strength is in the order of 10-25 tonne CO_2 equivalent ha^{-1} yr^{-1} [Dirks & Goudriaan 1994; Langeveld et al. 1997; Kuikman et al., 2005; Wyngaert, 2009]. This source of CO_2 is twice as large as the sink for CO_2 in Dutch forest ecosystems [Nabuurs et al., 2005].

Emission reduction

Emission reductions related to land-use and spatial planning require additional policies and policy instruments. The agricultural sector will have to realize emission reductions under the rules laid out in the EU Effort Sharing Decisions (ESD). Accounting options for the land-use related emissions in the emission reduction settings from the 27 EU countries are considered and investigated at this time. The outcome of this process is expected to have an immediate and considerable effect on the management and use of the land in the Netherlands.

Monitoring, reporting and verification of emissions

Under the UN-climate convention most of the countries are obliged to report the full extent of their GHG emissions. In these reports the emissions from industry and transport, but also the emissions from agricultural- and natural ecosystems (forests) are calculated in accordance with international standards such as can be found in the IPCC guidelines [IPCC leaflet]. Estimates of GHG emissions from terrestrial sources are generally characterized by a relatively large uncertainty and a generic (Tier-1) approach that does not take into account specific regional and local conditions. Countries within the climate convention are thus continuously challenged to improve their emission calculations and to reduce the uncertainty and use country specific methodologies (Tier-2 or -3). These efforts will then hopefully lead to a more realistic and direct calculation of emission reductions. The involvement of local and regional government will also increase, since they may be required to act similarly and explicitly report emission reductions in their region. New scientific questions arise from the desire to better quantify and reduce the emissions of GHGs arising from a land-use and land management.

Objectives

Dutch researchers from institutes in this field worked within this Bsik-research program “Climate Changes Spatial Planning” (CCSP) to improve and refine estimates of GHG emissions in time and space and reduce uncertainties in emission data and to further identify potential actions to reduce the land-use emissions (mitigation). This report is the outcome of that project and discusses the following objectives:

1. To develop an accurate and yet economically efficient system to monitor coupled GHG emissions for the most relevant Dutch natural and agricultural ecosystems.
2. To determine the size and variability of coupled GHG (CO_2, N_2O and CH_4) emissions related to land use management and land use change in the Netherlands.
3. To develop simple, yet physically based parameterisations to link small-scale field studies to regional and national-scale GHG flux estimates and to construct land use related emission factors for Dutch natural and agricultural ecosystems.

4. To assess the sensitivity of the coupled GHG fluxes and budgets to land-use change and land-management practice and to identify possibilities for emission reductions by changing land use and land-management practice.

Dual constraints approach

There is currently no single technique available that allows accurate determination of the GHG balance of the land surface for large regions, up to the size of nations. Therefore the international research community [Global Carbon Project, 2003] has further developed the "multiple constraints" approach that was pioneered by the CarboEurope cluster [e.g., Janssens et al., 2003]. The present research contributed to this approach by developing and building a system that allows the best possible "bottom up" estimate of the GHG balance of the Netherlands. To achieve this goal a three-pronged approach was used. First, the techniques that measure routinely the fluxes of CO_2, CH_4 and N_2O from the main land use types and management was applied and further developed. Secondly, the main driving variables (climate, soil heterogeneity, past land use) of these fluxes were established. Finally the fluxes and driving variables were integrated into a coherent bottom up modelling system that allowed determination of the magnitude, variability and uncertainty of the fluxes.

Results

Our main results and conclusions on the four objectives are:

1. The current innovative measurement methods (EC, REA and DEC) for N_2O and CH_4 fluxes are accurate but not yet economically efficient. For CO_2 there are accurate and economically efficient methods in place. Notably REA and automatic chamber systems have the potential to be improved such that they become accurate and economically efficient systems for GHG exchange measurements as well.
2. CO_2 emissions show a quite regular and predictable seasonal and daily variability mainly related to light and temperature. Temporal variability of N_2O emission is characterized by low background emissions interspersed with rather rare but extremely high emission peaks mainly triggered by precipitation and application of fertilizer. Temporal variability of CH_4 emission is very large as well, but the causes of this variability are less clear. Spatial variability of N_2O and CH_4 emissions is to some extent caused by differences in groundwater level and land and soil management intensity.
3. The objective to upscale flux estimates from the landscape level to country-wide level was achieved for CO_2 and N_2O but not for CH_4. In particular improvement of water table information is important for up-scaling of CH_4 fluxes, while all models will profit from updated information on the rapidly changing peat soils in the Netherlands.
4. We have found that the rewetting of agricultural peat-land can turn areas from a GHG source into a sink. Summer emissions from large shallow lakes are higher than those from intensively and extensively managed polders but lower than those from drainage ditches within the polders.

Recommendations and perspectives

We recommend performing continuous micrometeorological measurements at field scale on multiple locations both nationally and internationally for all relevant greenhouse gases (CO_2, CH_4 and N_2O). Such measurements would be useful to reduce uncertainties in emission estimates and to quantify and verify impacts of mitigation actions. These measurements could be performed using EC flux technique and by application of cheaper alternatives such as REA and DEC. The field scale measurements should be performed in combination with traditional chamber measurements to provide a link to previous and default values for GHG emission estimates.

This study shows that the N_2O emission is strongly related to groundwater level and can be estimated with reasonable accuracy using mean annual groundwater levels. We identified variations in emissions for wet and dry peat soils and argue to implement for peat areas a variable-value emission factor in the official estimation methodologies.

In general, the interpretation of the variability of GHG emissions is extremely difficult because of interactions with management effects. There is as yet no universally accepted method to take effects of management at the plot or farm scale into account [Cescia et al., 2010]. Farm-scale full GHG accounting also requires extensive observation strategies on management and other activities [Smith et al., 2010].

We did not study farm-based emissions separately. The determination of these emissions is feasible yet requires further studies addressing specific farm-based emissions. These should include measurements for on-farm manure storage and application technologies. It was found that lowering the storage temperatures reduced GHG emissions from manure by 0-40%. Significant GHG emission reductions were obtained when slurry was separated into a solid, organic component and a liquid component that was applied to the fields before applying the solid fraction.

Until now, the national reporting takes place on the basis of relative simple, but in UNFCCC context, internationally widely accepted calculation procedures. Our measurements and modeling efforts have shown that in principle it is possible to develop a cost effective observation scheme for GHG flux measurements. By taking key observations at representative landscapes it is possible to improve upon the simple schemes by adding more detail. Such information would be necessary to verify changes and mitigation of emissions.

The uncertainty in the natural sinks in the carbon cycle is a major contributor to the uncertainty in climate predictions. The feedbacks between climate change and the carbon reservoirs are not well known or understood. The spatial and temporal distribution of natural sinks over land and oceans remains elusive, which precludes better quantification of their underlying mechanisms and drivers. In addition to natural sinks, anthropogenic emissions from fossil fuel burning and land use change need to be known at regional level and with better accuracy. These uncertainties must be reduced to underpin well-informed, evidence-based policy action.

A key reason for limited understanding of the global carbon cycle is the dearth of global observations. An increased effort to implement and use an improved and coordinated observing system for quantifying the regional and global carbon cycle is a prerequisite to gaining that understanding. Bsik ME01 has contributed some important steps towards this goal by developing key elements for such a monitoring system for the Netherlands.

1. Introduction

Our global climate is changing and this is most likely due to higher GHG emissions and build up of greenhouse gas concentrations in the atmosphere. There is agreement among policymakers that in order to avoid serious negative socio-economic and environmental consequences, the global average air temperature should not increase by more than 2 degrees in the coming 100 years [Kabat et al, 2005]. This principle was the starting point for the climate negotiations in December 2009 in Copenhagen and demands for a reduction of GHG emission of 60 to 80% compared to the year 1990. Europe and the Netherlands formulated a reduction target of 20% (possibly higher to 30% upon an international agreement extending beyond the Kyoto Protocol commitment period 2008-2012) in 2020 compared to 1990. To realise this, fundamental changes are necessary in the energy-, industry-, transport and agricultural sector. Some of the reductions in these sectors can be realized by means of the so called European Emission Trade System (EU-ETS) and others through the European Effort Sharing Decisions (EU-ESD). Specific emissions from land use (so called sector LULUCF have not been included in any European commitment or reduction scheme yet).

Agricultural practices and land-use and management largely determine the emission of the greenhouse gases (GHGs) carbon dioxide (CO_2) methane (CH_4) and nitrogen oxide (N_2O) from the Dutch ecosystems. However, specific forms of land-use and land use management can turn an area either into a source or into a sink of GHG's. This sink and source option for soils is one of the main differences with other GHG sources such as transport and anthropogenic energy consumption. About 10% of all emissions in the Netherlands is derived from terrestrial sources, 3% is directly linked to activities connected to land-use and land-use change.

Emission reductions related to land-use and spatial planning require additional policy instruments. The agricultural sector has to realize objectives for emission reductions under the rules laid out in the EU Effort Sharing Decisions (ESD). Accounting options for the land-use related emissions in the emission reduction settings from the 27 EU countries are being investigated at this time. The outcome of this process is expected to have an immediate and considerable effect on the management and use of the land in the Netherlands.

Under the UN-climate convention most of the countries are obliged to report the full extent of their GHG emissions. In these reports the emissions from industry and transport, but also the emissions from agricultural- and natural ecosystems (forests) are calculated in according to international standard such as can be found in the IPCC guidelines [IPCC leaflet] Estimates of GHG emissions from terrestrial sources are generally characterized by a relatively large uncertainty and a generic (Tier-1) approach that does not take into account specific regional and local conditions. Countries within the climate convention are thus continuously challenged to improve their emission calculations and to reduce the uncertainty and use country specific methodologies (Tier-2 or -3). These efforts will then hopefully lead to a more realistic and direct calculation of emission reductions. The involvement of local and regional government will also increase, since they may be required to act similarly and explicitly report emission reductions in their region.

New scientific questions arise from the wish to better quantify and reduce the emissions of GHGs from a landscape. A multidisciplinary consortium of Dutch researchers from institutes in this field worked within the Bsik-research program "Climate Changes Spatial Planning" (CCSP) to improve and refine estimates of GHG emissions in time and space. The overall aim was to reduce the uncertainties in emission data and to formulate the potential for actions to reduce the land-use emissions. More information on the CCSP program can be found at: [Mitigation].

This report is the outcome of that project and discusses the following questions:

- How adequately can GHG emissions in terrestrial ecosystems currently be measured?
- How large is the variability in emissions within and between different types of land-use and what is the influence of land-use changes on these emissions?
- How can the Dutch terrestrial GHG emission budget be determined from these observations?
- How do changes in land- and water management or spatial planning change the amount of GHG emissions?

2. Objectives

The key sources and sinks for land use related GHG emissions in the Netherlands are forest, grassland, agriculture and peatland. Forests are generally expected to be a sink [e.g. Dolman et al., 2002], grasslands a minor sink [Soussana et al., 2004], agriculture a source [Moors et al., 2010] and peatland a source if drained substantially, and a sink if not [Jacobs et al., 2003]. Due to past and continued water level reductions, Dutch fen meadow ecosystems on peat have been and still are a strong net source of carbon dioxide as a result of increased peat oxidation over a long period in the order of 10-25 tonne CO_2 equivalent ha^{-1} yr^{-1} [Dirks & Goudriaan 1994; Langeveld et al. 1997; Kuikman et al., 2005; Wyngaert, 2009]. This source of CO_2 is twice as large as the sink for CO_2 in Dutch forest ecosystems [Nabuurs et al., 2005]. Peat oxidation can be slowed down and reduced and fen meadows even be turned from sources into sinks of CO_2 provided that water levels are increased as suggested from a host of literature from mostly more natural (i.e. less exploited) fen ecosystems [Burgerhart, 2001]. The total GHG emission reduction through the increase of water levels is estimated to be considerable (5 – 15 tonne CO_2 equivalent ha^{-1} yr^{-1}). This is similar to the carbon gain that potentially could be achieved in mature temperate forests (4 – 11 tonne equivalent CO_2 ha^{-1} yr^{-1}, [Dolman et al., 2002]).

Assessing the integral effect of ecosystems on the GHG balance of the atmosphere requires determining the full GHG balance of these systems. Only then can we adequately determine trade offs between, for example, reduced peat oxidation versus enhanced CH_4 production. For CO_2 only full carbon accounting appears a viable option for future commitment periods [e.g. Field and Raupach, 2004]. We aimed in this project to contribute firstly to the observations supporting such accounting systems by establishing a close link with the regional GHG monitoring project (Bsik ME02) and secondly to the discussions in the Conference of the Parties and SBSTA (Subsidiary Body for Scientific and Technological Advice) meetings preparing schemes for future commitment periods. Thirdly, the project also aimed to develop and advance the technical capability to measure GHG emissions, fourthly to validate and integrate these measurements and finally to develop a sound and Tier 3 compatible monitoring system of GHG emissions.

Our specific objectives were thus:

1. To develop an accurate and yet economically efficient system to monitor coupled GHG emissions for the most relevant Dutch natural and agricultural ecosystems.
2. To determine the size and variability of coupled GHG gas (CO_2, N_2O and CH_4) emissions related to land use management and land use change in the Netherlands.

3. To develop simple, yet physically based parameterisations to link small-scale field studies to regional and national-scale GHG flux estimates and to construct land use related emission factors for Dutch natural and agricultural ecosystems.
4. To assess the sensitivity of the coupled GHG fluxes and budgets to land-use change and land-management practice and to identify possibilities for emission reductions by changing land use and land-management practice.

3. Methods

3.1 Introduction

Dual constraints approach

There is currently no single technique available that allows accurate determination of the GHG balance of the land surface for large regions, the size of nations. Therefore the international research community [Global Carbon Project, 2003] has further developed the "multiple constraints" approach that was pioneered by the CarboEurope cluster [e.g., Janssens et al., 2003]. The present research contributed to this approach by developing and building a system that allows the best possible "bottom up" estimate of the GHG balance of the Netherlands. To achieve this goal a three-pronged approach was used. First, the techniques that measure routinely the fluxes of CO_2, CH_4 and N_2O from the main land use types and management was applied and further developed. Secondly, the main driving variables (climate, soil heterogeneity, past land use) of these fluxes were established. Finally the fluxes and driving variables were integrated into a coherent bottom up modelling system that allowed determination of the magnitude, variability and uncertainty of the fluxes (Figure 1).

Observations

Ecosystem-atmosphere CO_2 exchange at short time-scales, i.e. 30 minuets can be measured [e.g. Dolman et al., 2002] using micrometeorological techniques such as eddy covariance (EC), which relies on rapidly responding sensors mounted on towers to resolve the net flux of CO_2 between a patch of land and the atmosphere. The net flux measurement implies that when fluxes with opposing sign occur, such as respiration and assimilation, flux separation techniques need to be applied. The flux measurement innovation has led to the establishment of a rapidly expanding network of long-term monitoring sites [FLUXNET]. Current flux measurement techniques typically integrate processes at a scale of about 1 km^2. A particular problem that arises here is the spatial and temporal variability within a 1 km^2 patch. Assessing this variability is essential to understand the key driving mechanisms behind the emission, particularly of CH_4 and N_2O emissions. Chamber based methods are an appropriate tool for point measurements, at a scale of less than 1 m^2 [e.g. Velthof, 1997; Velthof et al., 2002]. In addition to the spatial flux variability revealed by such measurements, N_2O fluxes exhibit an extreme temporal variability with 80% of the emissions arising immediately after a few rainfall events. Past and current fertilization practices determine to a large extent when such "jump" releases occur. Furthermore fluxes of GHGs should be measured over several years to address source and sink variability created by inter-annual variability in climate, amount and timing of rainfall, soil moisture, biomass development, groundwater level fluctuations, hydrochemistry and other controlling factors.

Representative landforms that could accommodate the constraints of the above measurement techniques were selected as potential sites. In addition new measurement techniques were tested to among others complement the existing micrometeorological techniques for CO_2 and to improve the chamber measurements.

Sites

The final site selection took into account the potential contribution to GHG flux balances in the Netherlands, based on surface area, size of the carbon pool, and contribution to the GHG budget and sensitivity to changes in the environment. Also logistical issues, such as available power supply, played a role in the site selection.

Based on these selection criteria a network of micrometeorological sites was established to cover as many as possible relevant ecosystems and land use systems in the Netherlands. Three sites that have been operational since the start of the project provided the central framework for our research efforts. In addition to these sites GHG fluxes were also observed at a number of locations using quasi-mobile equipment. During the lifetime of the project about 42 site-years of data have been collected at 12 different locations (see Table 1).

3.2 How to measure GHG gas emissions

Measurement methods

Accurate GHG emission measurements are required at point (about 0.5 m^2) and field (hectare) scale from different landscapes. Point scale measurements are primarily needed in order to understand the processes that cause the emissions. Field scale emissions are not only needed to understand the processes at a larger scale, but also for among others the national inventory reports. The GHGs CO_2, CH_4 and N_2O were determined at both scales at different ecosystems.

There are different measurement methods and instruments available. The most common methods are chamber and eddy covariance (EC) flux method. Chamber measurements are point or plot scale measurements which can be made manually and automatically. EC flux technique is a micrometeorological technique with which emission estimates can be derived at field or hectare scale.

Chambers

Chambers were used in different shapes varying in size from 15 cm [Schrier-uijl et al., 2010b; Van Beek et al., 2010] to large chambers of nearly 1 x 1 m [Stolk et al., 2011a; Kroon et al., 2008]. Chambers were also used in continues monitoring exercises [Hendriks et al., 2009; Stolk et al., 2009; Kroon et al., 2008] or in campaigns. Usually emissions on a time scale of hours could be derived from these measurements. For wetland CH_4, measurements with chambers have the disadvantage that they are very sensitive to mechanical disturbance of soils. In many cases the chambers were used continuously for periods of more than a year. A special fast chamber (for hit and run actions) was used by [Kroon et al., 2008].

Eddy covariance methodology

Eddy covariance fluxes, meteorological parameters and soil parameters were continuously monitored with EC flux systems and meteorological systems according to the CarboEurope protocol [Aubinet et al., 2000] whereas other parameters were determined only a few times during the whole study period (soil nitrogen content, organic matter content, leaf area index and others). An EC processing software intercomparison was performed to assess the uncertainty of GHG flux estimates due to differences in post processing [Mauder et al., 2008]. We applied a site evaluation approach combining Lagrangian Stochastic footprint modelling with a quality assessment approach for eddy-covariance data to address the spatial representativeness of the flux measurements, instrumental effects on data quality, spatial patterns in the data quality, and the performance of the coordinate rotation method [Göckede, 2008].

Measurement set-up

In the interpretation of the results relevant parameters could be confronted with emissions in an attempt to derive parameterizations. This is mostly done on the scale of the chambers. It is assumed implicitly that relevant parameters are more or less constant on these scales of less than 1 m^2. In addition, parameterisations at field scale are derived using EC flux measurements. In this project, different parameterisations based on several measurements techniques are compared [Kroon et al., 2010d].

Micrometeorological methods such as the EC flux method provide measurements of fluxes on the next scale i.e. the field scale. Attempts to measure on the landscape scale using tall towers or aircraft have been carried out in ME02 and will not be discussed here. On the field scale the advantage is clearly that the small scale variation visible in the chamber measurements is averaged out. At the same time this makes simple parameterizations more difficult.

Therefore, net ecosystem exchange was measured using a combination of EC flux and chamber method since accurate and process information could be better obtained by a combination of both methods. Specially designed experiments have been carried out to proof the equivalence of chamber and aerodynamic methods such as the EC flux methods [Schrier-Uijl, 2010a]. These will be discussed below.

At all sites, continuous micrometeorological CO_2 flux measurements were performed. At six sites N_2O and/or CH_4 flux measurements were carried out, using novel micrometeorological instrumentation and techniques (see Figure 2 and 3 and Table 1) as well as advanced automated flux chamber observations.

In all cases, flux measurements were accompanied by a suite of meteorological and soil hydrological observations. Furthermore, soil and vegetations characteristics were determined. At most sites, soil properties have been described in the main footprint area of the flux towers. Vegetation characteristics such as leaf area and development stage were observed during servicing. Management information has been collected using questionnaires.

See [Hensen et al., 2010; Hendriks, 2008; Schrier-Uijl et al., 2010a; Kroon et al., 2010d; Stolk et al., 2009 and Veenendaal et al., 2007] for an overview of used measurements methods.

New techniques

At the start of the project, chamber flux techniques were available for all three GHGs. Thus far, EC flux measurements were only performed for CO_2 because of a lack of suitable instruments for CH_4 and N_2O. Possible instrumentation for the non-CO_2 GHGs came available at the beginning of the project. One of the tasks was therefore devoted to check the suitability of some instruments for CH_4 and/or N_2O EC flux measurements. The suitability of a quantum cascade laser (QCL, Figure 4) and a Los Gatos cavity ring down (CRD) laser system was investigated in detail using laboratory and field tests.

At the moment, with the current costs of the non-CO_2 EC systems, it is still not a serious option to install the instrumentation at many sites. Therefore, the possibility of using other measurement methods and cheaper instrumentation were also checked within this project. In addition a new technique which would allow for a low power consumption measurement set-up was tested.

The plot scale measurements were also developed further within our project. Chambers were made suitable for measuring above lakes and ditches. The quality of the chambers was checked carefully using literature studies and additional tests. In addition, the use of automatic chamber systems was checked. Next to the N_2O chamber measurements, an isotope technique was co-developed in this project for investigating the processes of N_2O production.

3.3 Up-scaling techniques

At the landscape scale the interaction between man and the environment is most strongly felt. Also manipulation of the groundwater level may lead to changes in emissions of GHG. However the GHG emissions can vary enormously across the landscape because important parameters such as soil conditions and texture, groundwater level, fertilization, vegetation may vary strongly at this scale. In order to predict the effect of mitigation options accurate emission estimates on the landscape scale are needed. In a bottom up approach these maybe based upon estimates of fluxes on the field scale. Research in the last decades has shown that even within this scale large variations in emissions may exist. On the point scale (about 1 m^2) fluxes may differ orders of magnitude because of small scale variations of soil texture, fertilizer input, groundwater level and the presence of bacteria.

Emission factors are the basis for the TIER1 and TIER2 reporting of the national GHG emissions. For the agricultural sector emissions of N_2O are in the Netherlands the most important GHG presently reported. As a starting point for our project we assessed the emissions of N_2O and emissions factors in the Netherlands from measurements in the period 1993 – 2003. The overall averaged emission factor extracted from over 86 series of one year measurements on nitrous oxide emission from agricultural fields in the Netherlands is 1.1% and a weighed average for soil types is 1.01%. The average for mineral soils is 0.88%. The calculated emission factors are lower than the value suggested by the IPCC for EF1 for fertilizer and animal manure of 1.25%. We recommend to use a value of 1.0% for EF1 and to use corrections of EF1 in reporting the use of fertilizers without nitrate (0.5%), for subsurface application of manure (1.5%) and for fertilizer, manure and urine on organic soils (2.0%) [Kuikman et al., 2006].

To scale up observed fluxes from the point to the field scale as well as from the field to the regional or national scale models are required. Besides for this spatial up-scaling to arrive at a TIER3 national reporting of the GHG emissions, models were also applied to scale up in time and for scenario analysis. For all these purposes we aimed at developing a system that uses several specialized models instead of producing a single modular model that deals with all ecosystems. Specialized models often better represent crucial elements for a specific land use type that would be lost in a more general model.

Models

The following models were applied in support of the present research:

1) SWAP-ANIMO (Soil-Water-Atmosphere-Plant – Agricultural Nutrient Model) has been applied to model and interpret N_2O emissions at the plot scale, notably those of the managed grassland sites *Oukoop, Stein* and *Zegveld*.(e.g. [Stolk et al., 2011]).

2) DNDC (Denitrification – Decomposition) was used to study the effect of temporal resolution on estimates of annual N_2O emission from the Dutch fen meadow area [Nol et al., 2009].

3) SiB (Simple Biosphere Model) was used for upscaling of net ecosystem exchange and CO_2 fluxes. It has been calibrated using EC flux data, covering the main land use types in the Netherlands [Garcia-Quijano et al., submitted].

4) PEATLAND (Wetland CH_4 and CO_2) PEATLAND has been used to model CH_4 and CO_2 emissions at *Horstermeer* and for upscaling of regional CH_4 emissions from natural wetlands in the Drenthe province. For country-wide upscaling, the lack of reliable groundwater table data is still a problem [Petrescu et al., 2009].

5) INIATATOR (Integrated Nitrogen Impact Assessment Tool on a Regional scale) was applied in uncertainty assessments N_2O inventories, including an N_2O emission scenario study for the Dutch fen meadow area [Nol, 2010].

The upscaling of net ecosystem exchange and CO_2 fluxes was done with SiB (Simple Biosphere Model – from Colorado State University). The model includes soil respiration and net primary production and is driven by meteorological data, and has modest parameter requirements [Garcia-Quijano et al., in prep.]. However, the model proved to be insufficiently accurate in modelling of agricultural systems, which dominate land use in the Netherlands. Within short, an improved version will be available and new model results will be produced, after which a final publication will be submitted.

For CH_4 (PEATLAND model) accurate groundwater table and vegetation information is crucial, as has been shown in a regional study for the province of Drenthe by [Petrescu et al., 2009]. For N_2O uncertainty due to model inputs is substantial (52-78%). With upscaling to a landscape scale uncertainty due to land cover data input becomes important. The model studies have been applied in future scenario studies for peat areas on a regional scale in the province of Drenthe (Internal report Alterra) and will be applicable for future scenario studies.

The model combination SWAP-ANIMO was used to analyse and model the temporal variability of N_2O fluxes at the plot scale. SWAP [Van Dam, 2000; Kroes et al., 2008; Van Dam et al., 2008] is a multi-layered simulation model with output of soil moisture fluxes and content and soil temperature on a daily basis or shorter. The output of SWAP is utilized to drive the ANIMO model, which is a dynamic process-based simulation model with a daily time step for nutrients (N and P) and organic matter dynamics in the soil [Rijtema et al., 1999; Groenendijk et al., 2005; Renaud et al., 2005; Hendriks et al., 2010]. Recently, the ANIMO model has been extended with routine to simulate GHG emissions (CH_4, N_2O) from the soil surface [Stolk et al., 2009a; Hendriks et al., 2010; Stolk et al., 2011a]. Furthermore, a new concept to account for the effect of soil aggregates on N_2O emissions has been implemented. This leads to considerable improvement of the simulation of peak emissions [Stolk et al., 2011b] and therefore to improvement of annual N_2O emission estimates, while offering opportunities to construct detailed emission scenarios [Stolk, 2011].

Determination of model uncertainty is critical; model outcomes are highly dependent on quality of the input and parameterization, and structural differences in models may result in largely different upscaling results. This is for example shown in the thesis of [Nol, 2010] where the uncertainty of N_2O emission related to model formulation between two different models (INITATOR and DNDC) is estimated at 32%. To determine model uncertainty, the performance of the individual models has been tested against observations at landscape scale from the chamber and micrometeorological flux measurements. Monte Carlo analysis and sophisticated error propagation methods were the main tools to determine parameter uncertainty. Special attention was paid to land use information, and variability in vegetation, soil physical and chemical parameters as these are related to land use history and previous management. For soil and land use information we also exchange knowledge with Bsik ME02 (Regional experiment) and ME03 (Soils and biomass information).

4. Results and discussion

4.1 Innovations in measurement techniques; objective 1

Eddy covariance instrumentation

Two instruments were tested for their suitability to perform EC flux measurements for non-CO_2 trace gasses. A thorough quality check was performed for a Quantum Cascade Laser spectrometer (Aerodyne Research Inc.) for CH_4 and N_2O, and Cavity Ring Down spectrometer CRD (Los Gatos) for CH_4 [Hendriks et al., 2008; Kroon et al., 2007, 2010a, b, c, e, g]. The QCL was shown to be suitable for performing EC flux measurements of CH_4 and N_2O. The required criteria for EC flux observations including continuity, sampling frequency, precision and stationarity were met. Both CH_4 and N_2O could be successfully detected for emissions larger than 40 ng C m^{-2} s^{-1} for CH_4 and 10 ng N m^{-2} s^{-1} for N_2O [Kroon et al., 2007]. The (CDR) system was also proven to be suitable for EC CH_4 flux measurements [Hendriks et al., 2008].

A comparison between both instruments reveals that both have some advantages and disadvantages. An advantage of CDR system is that there is no need for liquid nitrogen to cool the detector; the system is relatively low costs and compact. Advantages of QCL are the possibility to measure several GHGs simultaneously and the fact that this instrument is less sensitive to contamination of the mirrors. Contamination of mirrors is likely to be a serious problem in relatively polluted environments (e.g. *Horstermeer*).

Continuous EC flux measurements were performed using the QCL at a managed peat area (*Oukoop* site) and at a restored peat area (*Horstermeer* site) using the CRD. We thoroughly checked whether the measured EC fluxes represent the real emissions of both areas well. Corrections were made for some systematic errors due to the measurement method and instruments [e.g. Hendriks et al., 2008; Kroon et al., 2010b, c].

Comparison of EC flux measurements with chamber flux measurements

It is interesting to see how well the estimates of emissions derived from Eddy Covariance techniques compare with those using chambers or boxes on the field scale, in this project a few attempts were made to compare estimates of these fluxes. In an experiment carried out in a fen meadow [Kroon et al., 2010d] fluxes of methane were compared by various methods. Method 2 and 4 in Table 7 can be considered as a comparison between estimates by EC flux methods (2) and chamber measurements (4). The comparison is very good although it should be noted that the emissions are calculated from a regression model which took temperature into account (among others). However, the regression models are independently derived by means of the chamber or EC flux data.
Similar comparisons between EC flux and chamber measurements were made by [Hendriks et al., 2009]. Their analysis includes footprint analysis of EC measurements. In that case the daily emissions of CH_4 were overestimated by the chamber measurements by nearly 40%.This could be

related to the chamber measurements being made in the daytime only when emissions could be relatively high. It was found that the emission estimates based on EC flux and chamber compared very well at *Oukoop* and *Horstermeer* [Hendriks et al., 2008, 2010; Kroon et al., 2010d; Schrier-Uijl et al., 2010a].

In addition, the uncertainty in emission estimates based on EC fluxes were compared with the uncertainty in emission estimates based on chambers. It is known that annual CH_4 and N_2O emissions from ecosystems based on chambers have significant uncertainties which can be larger than 50% of the mean. These large uncertainties are mainly due to the complexity of the sources and sinks (i.e. spatial and temporal variation, the limitations in the measurement equipment and methodology of the chamber method). It was shown that the uncertainty in annual numbers can be significantly decreased by means of EC flux measurements [Kroon et al., 2010c, d, e, g]. This means that the use of EC flux measurements can seriously contribute to more accurate estimates of net ecosystem exchange of both gases. It was stated that an uncertainty even smaller than 10% can be reached in the annual estimates of both gases at field scale.

Alternative EC flux measurement techniques

Consequently, the main uncertainties in the national inventory report of 2008 [Maas et al., 2008] can possibly be decreased using these innovative measurement method for CH_4 and N_2O. Unfortunately, the required instruments (like QCL and CRD) are still too expensive to install them at tens of measurement locations. Therefore, low costs field scale measurements were also investigated. Two alternative techniques were investigated for performing direct field scale measurements: Relaxed eddy accumulation (REA) and Disjunct eddy correlation (DEC). No fast concentration-sampling instrument is needed for both techniques. But the precision of the concentration measurements should be very high, at the front end of the possibility with high precision optical (QCL) or GC techniques. Therefore, we have tried to develop a low maintenance system for routine measurement of fluxes of N_2O and CH_4 during this project. An innovative H2O sensor (SIOS, sensitive integrated optical sensor) from Optisense was tested in the laboratory however it proved impossible to develop similar sensors for CH_4 and N_2O at short notice.

We have checked the option of developing the REA measurements for CH_4 and N_2O. In case of REA, gas samples are collected and these are analyzed in the laboratory. One of the challenges of REA measurements is the precision of the instruments for detecting the small concentration difference between up and down draft air parcels. Simulations based on EC flux measurements were made for deriving the required precision for measuring CH_4 and N_2O fluxes from managed peat areas. It was found that high precisions should be achieved. In fact the required precision to resolve concentration differences between up and down going airflow sampled with the REA technique are at the edge of what currently can be obtained using high precision QCL or GC techniques [Ouwersloot, 2008]. Some first test measurements were performed which gave promising results. But more improvements are needed before REA can be implemented at a large scale.

Improvements in chamber flux measurement techniques

In our project, we have also worked on improvements of the automatic chambers. Automatic chambers are a good option for decreasing the uncertainty in estimates by manual chambers due to the large temporal variation of the fluxes. We have checked in detail the quality of the different calculation methods. It was found that the flux estimates could be drastically underestimated (even more than 40%) when a linear increase in the concentration in the chamber was assumed [e.g. Kroon et al., 2008; Stolk et al., 2009]. It was shown that the underestimations could be minimized when an appropriate non-linear model is used. Next to the calculation problem, chamber measurements could suffer from leakage which could also lead to a serious underestimation. We have shown using automatic chamber measurements at *Cabauw* that a C2H6 tracer could be used to correct for leakage.

The automatic chamber measurements have been successfully applied at several sites. The most challenging experiments were made above ditches. CH_4 fluxes were continuously measured during several months above a ditch located at the managed dairy farm site at *Oukoop* (Figure 5). Large CH_4 emissions were detected which were investigated in detail using intensive measurement campaigns. During these campaigns CH_4, CO_2 and N_2O fluxes were measured above ditches and lakes. N_2O emissions were often too low to detect with the used chambers. N_2O production processes were also evaluated using an innovative N isotope method which was co-developed in these projects. This isotope sampling technique was tested at the peat site *Zegveld*. It was shown that the concept of this innovative method works well. Very small fluxes were observed at *Zegveld* which is in agreement with the results of the floating chambers in *Oukoop*.

4.2 Size and variability of GHG emissions at the field scale; objective 2

CO_2

The variability of the CO_2 emissions of Dutch *grasslands* was further studied, using datasets obtained at eight different sites. For reporting purposes, it is assumed that grassland at the national scale is homogeneous, that is, variability can be ignored. However, the CO_2 emission variability of grasslands in The Netherlands appeared to be considerable. A clear distinction could be made between grasslands on organic soils and on mineral soils. Other important sources of variability were found to be differences in eco-physiological conditions and differing weather conditions [Jacobs et al., 2007]. The total variability was similar to the one found at a European scale [Gilmanov et al., 2006].

[Schrier-Uijl et al., 2010a] and [Kroon et al., 2010d] carried out experiments aimed at comparing flux measurements on the field scale. The measurements were performed at a dairy farm site in *Oukoop*, a flat and heterogeneous area. In this landscape three main elements were identified ditches, ditch edges and field plots. These landscape elements were taken into account in the calculation of landscape scale estimates based on chamber flux measurements. The cumulative CO_2 respiration was estimated over one year (2006) for both methods. The EC and chamber based estimates agreed very well when the three landscape elements (ditches, ditch edges and field plots) were taken into account. However, both methods differed significantly when only field plot emissions were taken into account when up-scaling chamber measurements to field or landscape scale. Figure 6 shows the good comparison between the chamber based emission estimates and EC flux estimates.

The CO_2 emission variability of *croplands* was studied by [Moors et al., 2010], taking lateral flows of carbon into account. Again, considerable variability was found which was caused in the first place by crop choice, second by location and third by climatic differences. Attribution of the variability appeared to be extremely difficult, partly because of management effects [e.g., Eugster et al., 2010; Jans et al., 2010]. Also, from the climate point of view full GHG accounting at the scale of the farm should probably be attempted, but is quite difficult as yet [Ceschia et al., 2010].

The site with the pine forest at the *Loobos* site has the longest record, allowing to investigate the interannual variability [Moors et al., 2011 in prep]. The maximum difference in NEP measured at *Loobos* over this 14 year period is close to 400 g C m^{-2} y^{-1}. In Figure 7 the total annual NEP, GPP and R_{eco} are depicted. The average annual NEP = 433 (S.D. ± 127) g C m^{-2} y^{-1}, GPP = 1286 (S.D. ± 62) g C m^{-2} y^{-1} and Reco = 854 (S.D. ± 106) g C m^{-2} y^{-1}.

The yearly numbers show no clear trend in NEP, Reco or GPP. For a number of years NEP follows changes in GPP, see for example the years 2006 to 2009. However, this pattern is not always followed. Comparing years with comparable GPP, such as 2000 and 2009, show a completely different NEP resulting from differences in Reco. These differences clearly show that based on annual totals, the interannual variability in NEP is the result of variations in both Reco and GPP. NEP is the result of two different processes, i.e. photosynthesis and respiration with as main drivers radiation and temperature. A part of the interannual variation in NEP can be explained using simple non-linear relations of radiation and temperature on a monthly time step. However, these relations cannot explain all variations in NEP in Figure 7. To explain the remaining interannual variability models will have to be developed that are capable to combine the effect on NEP of a number of drivers, such as changes in the response functions, frost damage, prolonged dry periods combined with a relatively low groundwater table and nitrogen deposition.

CH_4

[Schrier-Uijl et al., 2008] as well as [Hendriks et al., 2007] carried out experiments investigating the CH_4 emissions of the peat land area in the western part of The Netherlands. [Hendriks et al., 2009] carried out measurements in a fen meadow and distinguished four areas with different methane fluxes. Highest fluxes were observed from the saturated land near ditches (23 mg m^{-2} hr^{-1}) and lowest fluxes from the dry, middle part of the area (1.2 mg m^{-2} hr^{-1}). Ditch water surface as well as sites with intermediate groundwater level showed intermediate fluxes of 8 and 4 mg m^{-2} hr^{-1} respectively. [Schrier-Uijl et al., 2010c] observed also differences between different areas in the field and indicated ditches and their borders as hotspots of methane. They also derived flux estimates relevant categories, Table 5 shows the emissions that were derived in this study. Ditches and borders appeared to emit 60% to 70% of the total terrestrial flux.

Methane fluxes in the peat meadow in the *Horstermeer* also showed high temporal variability different scales: CH_4 fluxes showed a clear diurnal cycle during all seasons as well as significant day-to-day variability, and seasonal variations. Continuous eddy covariance measurements showed a clear diurnal cycle of CH_4 fluxes in spring, summer and autumn. During night-time, emissions were similar for all seasons (approximately 0.90 mg m^{-2} h^{-1}), while the amplitude observed during daytime was largest in summer and lower, but comparable in spring and autumn [Hendriks et al., 2010]. These results depend also strongly on specific vegetation type [Hendriks et al., 2009].

Methane emissions were compared for an intensively and extensively managed agricultural area on peat soils in the Netherlands to evaluate the effect of reduced management on the CH_4 balance. Chamber measurements (photo-acoustic methods) for CH_4 were performed for a period of three years in the contributing landscape elements in the research sites. Various factors influencing CH_4 emissions were evaluated and temperature of water and soil was found to be the main driver in both sites. For upscaling of CH_4 fluxes to landscape scale, regression models were used which were specific for each of the contributing landforms. Ditches and bordering edges were emission hotspots and emitted together between 60% and 70% of the total terrestrial CH_4 emissions. Annual terrestrial CH_4 fluxes were estimated to be 203 (±48%), 162 (±60%) and 146 (±60%) kg CH_4 ha^{-1} and 157 (±63%), 180 (±54%) and 163 (±59%) kg CH_4 ha^{-1} in the intensively managed site and extensively managed site, for 2006, 2007 and 2008 respectively. About 70% of the CH_4 was emitted in the summer period. Farm based emissions caused per year an additional 257 kg CH_4 ha^{-1} and 172 kg CH_4 ha^{-1} for the intensively managed site and extensively managed site, respectively.

This shows how fluxes can be estimated to the landscape level by using parameterized results to estimate fluxes. In addition, annual terrestrial CH_4 fluxes were determined by means of EC flux measurements in *Oukoop* for the same period (2006-2009). Annual values of both methods compare very well.

N_2O

The temporal variability of emissions of N_2O can be very large. This variability exists at daily timescales but also annual fluxes can differ strongly. [Schrier-Uijl, 2010] demonstrated strong seasonality and lesser year to year variability in N_2o emissions. This effect may (in the case of N_2O) be so large that up to 25 % of the annual emission may be released in one single event of a few days [Van Beek et al., 2010] and up to 50% on wet fields. This release can sometimes be related to fertilizer application or rainfall. But in a number of cases the magnitude or even the occurrence is difficult to explain.

Whereas the problem of temporal variability can be addressed by long measurement series and used in model tests, spatial variability is more difficult to address and may lead to systematic errors in emission factors. The absence of stable patterns is an important parameter in designing measurement strategies. In an experiment carried out on an intensively managed grassland [Van Beek et al., 2010] observed spatial variability of N_2O fluxes of 40-50 % in a dry field and up to 100 % on a wet field. On the basis of the observed variability [Van Beek et al., 2010] conclude that to make reliable estimates (uncertainty less than 10%) of the annual emission of N_2O of a field of circa 1 ha 40 replicates are needed. In these experiments small (30cm) chambers were used. In the experiments carried out in *Stein* larger automatic chambers were used. These also showed a spatial variability of 100% [Stolk et al., 2009].

Emissions of nitrous oxide (N_2O) from managed and grazed grasslands on peat soils are amongst the highest emissions in the world per unit of surface of agricultural soil. According to the IPCC methodologies the direct N_2O emissions from organic soils is the sum of N input derived N_2O emissions, including urine and dung of grazing cattle, and a constant agro-climatic zone depended background emission. In this paper we questioned the constant nature of this background emission from peat soils by monitoring N_2O emissions, groundwater levels, N inputs and soil NO3-N contents from 4 grazed and fertilized grassland fields on peat soil. Two fields had a relatively low groundwater level ('dry' fields) and two fields had a relatively high groundwater level ('wet' fields). To measure background N_2O emission unfertilized sub-plots were installed on each field. Measurements were performed monthly and after selected management events for 2 years (2008-2009). On the managed fields average cumulative emission equalled 21 ± 2 kg N $ha^{-1} y^{-1}$ for the 'dry' fields and 14 ± 3 kg N $ha^{-1} y^{-1}$ for the 'wet' fields. On the unfertilized sub-plots emissions equalled 4 ± 0.6 kg N $ha^{-1} y^{-1}$ for the 'dry' fields and 1 ± 0.7 kg N $ha^{-1} y^{-1}$ for the 'wet' fields, but differences between replicated fields were large. Background emissions were closely related to groundwater level (R^2=0.73) and accounted for approximately 22% of the cumulative N_2O emission for the dry fields and for approximately 10% of the cumulative N_2O emissions from the wet fields. These results demonstrate that the accuracy of estimating direct N_2O emission from peat soils can be improved with approximately 20% by applying a groundwater level related background emission.

[Nol et al., 2009] showed that even if good quality flux data are available there are still other problems to overcome. These are related to the resolution in the underlying land use data. Although this error is considerably smaller then the error in emission factors it is a systematic error that could be avoided if good quality land use data is used. In a different study [Nol, 2010] investigated the propagation of errors in N_2O fluxes derived from model calculations. At the point scale the estimated N_2O fluxes suffer from an estimated error of some 80%. This error is due to uncertainties in soil input and estimates of nitrification and denitrification rates. In the framework of these processes, improvement is expected from incorporation of the effects of (peat) pore geometry on soil moisture and consequently on N_2O production, reduction, storage and transport [Stolk et al., 2011a]. At the landscape scale the error is slightly smaller due to averaging and is caused by uncertainties in nitrification and denitrification rates.

An advantage of the variability of the fluxes observed by continuous monitoring is that it allows easy and intensive comparison with models [Kroon et al., 2008; Kroon et al., 2010d; Hendriks, 2009]. The influence of point scale parameters such as temperature, fertilizer input, precipitation and ground water level can be studied really well. [Stolk et al., 2011a] ran the SWAP-ANIMO model for a period of one year to calculate N_2O emission. The emissions were observed on three sites, differing in intensity of management and other parameters such as clay content and drainage. Figure 8 shows the results of the comparison. Some peaks observed (at *Zegveld*) were simulated quite well whereas others were completely missed. At *Stein* many emission peaks were simulated but not observed at all.

It was concluded after a comprehensive sensitivity analyses that the model overestimated diffusion of N_2O from the top soil to the atmosphere, thereby underestimating further reduction of N_2O to N_2. This was probably linked to the complex peat pore geometry and a decoupling between anoxic N_2O production sites (production by denitrification) and the main diffusion streams [Stolk et al., 2011a]. Also the description of the N_2O processes in the model is insufficient to accurately simulate daily N_2O emissions from peat soils, even when the main controlling factors (water content etc.) are accurately simulated. Therefore, a new and innovative concept was implemented in SWAP-ANIMO to account for the effect of soil aggregates on N_2O emission from denitrification. This led to considerable improvement of the simulation of N_2O peak emissions and therefore of annual N_2O emission estimates for the sites that were simulated [Stolk et al., 2011b]. The model could now be used to simulate spatial variation on any scale.

Variability as a result of different crops and lateral flows

Figure 9 shows the Net Ecosystem Exchange (NEE) for the vegetation types studied. All vegetation types, excluding the forest at Loobos and the fen meadow at *Horstermeer* are sources of carbon. Note that these vegetation types are mostly agricultural and thus strongly managed. The forest and fen meadow are not managed. In the case of the fen meadow however, the net exchange flux with the atmosphere is -280±78 g C m^{-2} yr^{-1}. In terms of Global Warming Potential, when taking CH_4 into account, this becomes of -182 g m^{-2} yr^{-1} (based on a 100-year time scale) due to the greater GWP of CH_4. When fluxes through water were added to the balance, the area was a carbon sink of -262±84 g C m^{-2} yr^{-1}, and only a small net GHG sink given as CO_2-equiv. of -86 g m^{-2} $yr^{-1}$when considered in terms of GWP. This change of a sizable net sink into a smaller one is largely due to the inclusion of CH_4 in the budget, but lateral transport to water also plays some role.

4.3 Magnitude and variability of GHG emissions at the regional and national-scale; objective 3

CO_2

The upscaling of net ecosystem exchange and CO_2 fluxes was done with SiB (Simple Biosphere Model – from Colorado State University) [Garcia-Quijano et al., submitted]. The model includes soil respiration and net primary production and is driven by meteorological data (i.e. temperature, wind speed, long and short wave radiation, precipitation, relative humidity). It was calibrated using EC flux data, covering the main land use types in the Netherlands.

Results (Figure 10) show that (1) the growing season has extended with 2 months from the year 2000 to 2007 covering a total period of 8 months in recent years from the month of March to October. Furthermore, the month of February might be changing from an emission to a sink-month. (2) The general shape of the net ecosystem exchange curve has experienced a transformation from a regular triangular shape curve – in line with the energy distribution through the year – to a plateau-like shape curve with a broader base (i.e. longer period of assimilation) and shorter shallow tails (i.e. shorter periods of respiration with lower magnitudes). The annual average net ecosystem exchange per squared km is ca. -100.0 ton C from the year 2000 to 2002. This value has increased to approximately -250 ton C from 2003 to 2007.

CH_4

CH_4 modelling was attempted with the PEATLAND model and the SWAP-ANIMO model combination. SWAP-ANIMO includes a newly developed CH_4 module, of which the first site-level test of CH_4 fluxes proved to be successful. A model comparison between SWAP-ANIMO, and PEATLAND is still in progress.

In the uncertainty analysis, only PEATLAND has been considered [Van Huissteden et al., 2009]. The model includes a version of the Walter-Heimann (2000) model. This model is very sensitive to water table in the top 30 cm of the soil (as are measured fluxes). It requires input of time series of water table at with an accuracy of a few cm to model the effects of temporal water table variations correctly. Therefore water table information on a detailed scale is crucial. This type of information is not available on the desired scale in the Netherlands, because the existing groundwater monitoring networks are based on piëzometers in the topmost aquifer, neglecting water table variations at smaller spatial scale in the topsoil. Figure 11 shows an example of the type of variation that is encountered at the *Horstermeer* site.

[Petrescu et al., 2009] applied the model in a regional study on wetlands in the province of Drenthe, by coupling PEATLAND to a simple bucket-type water table model. This resolved the lack of available data, although it shifts the problem to the quality of the water table model. Uncertainty analysis using the GLUE method [Van Huissteden et al., 2009] demonstrated the model is not very sensitive to soil parameters, except organic horizon thickness for mineral soils with a peat cover. However, the model is very sensitive to parameters relating to transport of CH_4 through vegetation. This can be accommodated using a vegetation classification based on CH_4 emission properties [Petrescu et al., 2009].

A gap in the existing suite of models is the lack of models that simulate fluxes from open water. During the project it became clear that open water fluxes can be large [Schrier-Uijl et al., 2008; Schrier-Uijl et al., 2010b, c; Hendriks et al., 2010], while most of the peatland areas in the Netherlands have a dense network of open water in ditches and lakes. As yet, it appears necessary to restrict to an emission factor approach for open water.

The current generation of models is solely based and tested on chamber flux data. This has affected model structure, which includes only exchange processes that affect fluxes recorded with chambers. During the recent EC flux campaigns it has been shown that other exchange processes operate that cannot be measured with chambers. Transport by plants is strongly driven by photosynthesis rate, resulting in a strong diurnal cycle of CH_4 fluxes [Hendriks et al., 2010]. Furthermore, EC flux data also show exchange driven by air pressure variations.

N_2O

The emission factors for direct N_2O emission of applied slurry are not well quantified. The effect of slurry application technique on N_2O emission was quantified in field experiments in the Netherlands in order to derive N_2O emission factors for (shallow) injected and surface-applied cattle and pig slurries. The average emission factor of all treatments and years (n = 35) was 0.9% of the N applied, which is close to the default IPCC emission factor of 1%. On both grassland and maize land (shallow), injection of slurry increased the average emission factor of N_2O in comparison to surface application. Differentiation of N_2O emission factors which takes specific factors into account, such as N type and rate and application technique, can improve the quantification of N_2O emission from agricultural soils and is needed to derive most efficient options for mitigation [Velthof and Mosquera 2011, Lesschen et al., 2011]. This differentiation of emission factor values was then applied in the Miterra Europe model used in IC2 and ME4 [Velthof G.L. and J. Mosquira, 2011, Lesschen et al., 2011].

Daily N_2O emissions from peatland have been simulated with SWAP-ANIMO [Stolk et al., 2011a]. Although the dynamics of soil moisture, soil temperature and mineral N content are simulated with high accuracy, simulation of daily N_2O emissions is still insufficient. Peak emissions from denitrification in the top soil after rainfall events are overestimated in the simulations. Improvement is expected from incorporation of the effects of (peat) pore geometry in the sense of the presence and connectivity of micro-sites and meso-pores, on soil moisture and consequently on N_2O storage and reduction. Currently, an improvement of pore geometry representation in the model is being developed.

On the national scale upscaling of CH_4 and N_2O fluxes with the detailed model combination SWAP ANIMO in the framework of the national nutrient emission modelling system STONE [Wolf et al. 2003] offers great potential. The detailed hydrological model SWAP provides the required hydrological data for the biogeochemical simulations. Addition of the effects of pore geometry on the N_2O fluxes is needed before upscaling can take place.

[Nol, 2010] presents an extensive uncertainty assessment of N_2O emission inventories at a larger scale, based on two models with different temporal resolution, INITIATOR and DNDC. The uncertainty due to model formulation of these two models is estimated at 32%. On a point scale uncertainty due to model inputs is substantial (52-78%). With upscaling to a landscape scale uncertainty due to land cover data input becomes important (in particular land cover database and soil information). It should be noted here, that most Dutch soil information is roughly 40 years old and that the area of peat soils is rapidly changing. Distribution of rainfall within a year proves important for temporal upscaling while management data on nitrogen application appear less crucial.

Temporal uncertainty of N_2O fluxes is large caused by the high emission peaks, and therefore an evaluation of the effects of these peaks on yearly emission estimates is necessary. [Nol, 2010] concludes that for annual emission estimates at landscape and national extent high temporal resolution models may not always be the best option. Many parameters required at high spatial and temporal scale have negligible effects at the annual scale.

4.4 Sensitivity of the coupled GHG fluxes and budgets to changes in land use- and water-management; objective 4

The total GHG balance of the managed polders as calculated in this study consisted of terrestrial sinks and sources (including fluxes from fields, waterlogged land and drainage ditches, together further referred to as field) and sinks and sources related to the way farm animals exploit the net primary production (NPP). These include emissions from livestock and emissions from manure storage. The latter are referred to as farm emissions. The quantified flows are summarized in Figure 12.

Carbon Balance

Figure 13 summarizes the carbon balance in the three sites based on chamber and EC flux measurements. In addition, for a complete terrestrial C balance (seen from the field point-of-view) manure inputs and biomass removal were included. For *Oukoop* manure input was estimated at 142 g C m^{-2} yr^{-1} and was based on the years 2005-2007. Very little manure is directly deposited by cattle in the field because under this management scenario few days of field grazing by cattle occur in *Stein*, sporadic grazing by deer occurs at *Horstermeer* and no fertilisers were applied at these sites. The total terrestrial C-release in *Oukoop* (intensive) and *Stein* (extensive) were estimated at 3.8 and 5.4 Mg C ha^{-1} yr^{-1}, respectively, while the total C-uptake in the nature development area *Horstermeer* is 4.4 Mg C ha^{-1} yr^{-1}.

GHG balance

All incoming and outgoing GHG fluxes as shown in Figure 13 could be quantified for the three sites for the period 2006 – 2008 (although leaching to groundwater and runoff were not measured in *Oukoop* and *Stein* and release of N_2O through leaching was estimated for *Oukoop* in [Kroon et al., 2010e]. When calculating fluxes on landscape scale both the proportion of each landscape element in the landscape and the farm-based emissions were taken into account. The CH_4 component in the GHG balance in the ecosystems studied consists of outgoing fluxes only and N_2O emission from the intensively managed site consists of emissions originating from fertiliser events and from background emission. Figure 14 shows the total calculated GHG balance of the three sites in terms of warming potential.

The managed peatland acted as terrestrial GHG sources of 1.4 and 1.0 kg CO_2-eq m^{-2} yr^{-1}, respectively for *Oukoop* and *Stein* and the unmanaged site acted as a GHG sink of 0.8 kg CO_2-eq m^{-2} yr^{-1}. Nitrous oxide emissions were dominant in the intensively managed peatland when no farm based emissions were accounted for. Carbon dioxide and CH_4 dominated the terrestrial GHG balance in the extensively managed peatland. In the unmanaged peatland CO_2 was the most contributing GHG. Accounting for the farm-based CH_4 and CO_2 emissions decreased the relative importance of N_2O in the total GHG balance of the intensively managed peatland. The difference in total source strength between the intensively managed peatland and the extensively managed peatland was mainly attributable to the higher N_2O emission and the higher farm-based CH_4 emissions from the intensively managed site.

Currently, 270,000 ha of the Netherlands, mainly in the western part of the country, consist of peatland, but the area is decreasing because of degradation [Kempen et al., 2009]. In the western peat area, 68% is intensively managed grassland, 8% is extensively managed grassland or unmanaged grassland, and the remaining part is road, farm or has other land use. Using the emission values found in this study for intensively and extensively managed peatland and the total area for both of these land uses under the assumption that the sites measured in this study were representative for the western peat area, emissions were estimates for the total intensively managed grassland and extensively managed/unmanaged grasslands in the western peatland (Table 6). The total terrestrial emission, not taking into account farm-based emissions, estimated using a time-horizon of 100 years (GWP CH_4 = 25 and N_2O = 298) from the western peatland is approximately 1210 Gg CO_2-eq (=Ktonne CO_2-eq) yr^{-1}.

5. Conclusions

This project set out with 4 specific objectives:

1. To develop an accurate and yet economically efficient system to monitor coupled GHG emissions for the most relevant Dutch natural and agricultural ecosystems.
2. To determine the size and variability of coupled GHG gas (CO_2, N_2O and CH_4) emissions related to land use management and land use change in the Netherlands.
3. To develop simple, yet physically based parameterisations to link small-scale field studies to regional and national-scale GHG flux estimates and to construct land use related emission factors for Dutch natural and agricultural ecosystems.
4. To assess the sensitivity of the coupled GHG fluxes and budgets to land-use change and land-management practice and to identify possibilities for emission reductions by changing land use and land-management practice.

Our conclusions with respect to each objective are:

1. The current innovative measurement methods (EC, REA and DEC) for N_2O and CH_4 fluxes are accurate but not yet economically efficient. For CO_2 there are accurate and economically efficient methods in place. Notably REA and automatic chamber systems have the potential to be improved such that they become accurate and economically efficient systems for GHG exchange measurements as well.
2. CO_2 emissions show a quite regular and predictable seasonal and daily variability mainly related to light and temperature. Temporal variability of N_2O emission is characterized by low background emissions interspersed with rather rare but extremely high emission peaks mainly triggered by precipitation and application of fertilizer. Temporal variability of CH_4 emission is very large as well, but the causes of this variability are less clear. Spatial variability of N_2O and CH_4 emissions is to some extent caused by differences in groundwater level and land and soil management intensity.
3. The objective to upscale flux estimates from the landscape level to country-wide level was achieved for CO_2 and N_2O but not for CH_4. In particular improvement of water table information is important for upscaling of CH_4 fluxes, while all models will profit from updated information on the rapidly changing peat soils in the Netherlands.
4. We have found that the rewetting of agricultural peatland can turn areas from a GHG source into a sink. Summer emissions from large shallow lakes are higher than those from intensively and extensively managed polders but lower than those from drainage ditches within the polders.

Hereafter our conclusions are discussed in greater detail. Furthermore, Table 8 provides some recommendations on how to reduce GHG emissions and increase carbon sequestration for a given agricultural practice and ecosystem, derived from our results.

5.1 Progress in measurement techniques; objective 1

The quantum cascade laser (QCL, Aerodyne Research Inc.) system was modified to perform EC flux measurements of CH_4 and N_2O. Very accurate emission estimates at field scale could be made for both gases. In addition, field scale measurements were made possible for CH_4 using a cavity ring down (CRD) laser spectrometer (Los Gatos). Low maintenance systems for routine measurements were shown to be feasible using automatic chambers, relaxed eddy accumulation (REA) and disjunct eddy covariance (DEC) systems. Unfortunately, it was not feasible to develop an economically efficient instrument for measuring CH_4 and N_2O concentrations. CH_4 emissions and indirect N_2O emissions from ditches and lakes were determined using automatic and manual chamber systems based on the systems used for emissions from soils. In addition, an innovative N isotope sampling technique was co-developed in this project to determine the indirect emissions of N_2O from deep soils and water. During the project, no application led to commercialization of technologies. However, notably REA and automatic chamber systems have the potential to be improved such that they become accurate and economically efficient systems for GHG exchange.

5.2 Progress in estimating the size and variability of GHG emissions at the field scale; objective 2

GHG emissions are highly variable in space and time and this hampers the accurate measurement of GHG emissions and development of mitigation options based on land use and (soil) management. There is however a considerable difference among the three GHG's regarding the emission variability. While CO_2 emissions show a quite regular and predictable seasonal and daily variability mainly related to light and temperature, temporal variability of N_2O emission is characterized by low background emissions interspersed with rather rare but extremely high emission peaks mainly triggered by precipitation and application of fertilizer alone or in combination with other (soil) management. The temporal variability of CH_4 emission is very large as well, but the causes of this variability are less clear. Spatial variability of CO_2 uptake and release is related to crop type in arable land or tree species in forests. Attribution of the variability in cropland CO_2 emissions appeared to be extremely difficult, partly because of interactions between weather and season with management . Also, from the climate point of view full GHG accounting at the scale of the farm should probably be attempted, but is quite difficult as yet. In the Netherlands, spatial variability of N_2O and CH_4 is to some extent caused by groundwater level and land and soil management intensity. Emissions of N_2O and CO_2 from managed and grazed grasslands on peat and organic soils are amongst the highest emissions in the world per unit of land and surface. In the Netherlands, GHG emissions from peat soils are twice as large as the carbon removal (sequestration) of the Dutch forests, in spite of the fact that the peat area is only half of the forest area. Ditches and open water are another important cause of spatial variability of GHG emissions at the landscape scale. Innovative approaches to measure actual emissions from these water areas were successfully developed and applied.

5.3 Progress in estimating the magnitude and variability of GHG emissions at the regional and national-scale; objective 3

Regional upscaling of N_2O and CH_4 emissions has been successful but is still subject to large uncertainty related to parcel-scale heterogeneity of water table. Reducing uncertainties would require additional modelling of water table dynamics. A full model uncertainty analysis has been successful. It resulted, in particular for CH_4 and N_2O, in identification of the main sources of uncertainty that apply to upscaling. For N_2O it was shown that spatially and temporally detailed modelling does not necessarily improve large scale annual emission inventories. Therefore, a new and innovative concept was implemented in SWAP-ANIMO to account for the effect of soil aggregates on N_2O emission from denitrification. This concept led for peatlands to considerable improvement of the simulation of N_2O peak emissions and therefore of annual N_2O emission estimates for the sites that were simulated. For CH_4 detailed information on water table and vegetation type appears crucial, which is not always available at even regional scale. The detailed hydrological model SWAP may provide the required hydrological data. Next it was shown that the present state-of-the-art CH_4 eddy covariance data include soil atmosphere exchange processes that are not yet captured by existing models. Also, emission of CH_4 from open water is a large source which hitherto has not been included in any modelling effort. In all cases, investment in improving water table information and updating of existing soil information is likely to result in better estimates.

The objective to upscale flux estimates from the landscape level to country-wide level was achieved for CO_2 and N_2O but not for CH_4. The uncertainty analysis has suggested considerable improvements for future upscaling efforts. For N_2O an estimate of uncertainty due to model structure and model data is available, and also the effects of large temporal uncertainty from emission peaks on yearly budgets have been evaluated. In particular improvement of water table information is important for upscaling of CH_4 fluxes, while all models will profit from updated information on the rapidly changing peat soils in the Netherlands. A crucial gap in the models is the absence of adequate models for CH_4 emissions from open water.

5.4 Progress in assessing the sensitivity of the coupled GHG fluxes and budgets to changes in land use- and water-management; objective 4

We have found that the rewetting of agricultural peatland can turn areas that release carbon into areas that sequester or take up carbon and change the regional GHG balance from a source into a sink. Peat soils without top clay layers are extremely vulnerable to oxidation [Schothorst, 1977] and also strongly vulnerable to subsidence. Therefore, on these soils, intensive management practices are not sustainable. With dynamic water tables in extensively managed polders (high water tables in winter and low water tables in summer), only a small reduction in GHG emission is attained. The lower total emission is mainly due to a decrease in farm-based CH_4 emissions and a reduction in N_2O emissions because no fertiliser is applied. High water tables in summer through e.g. inverse drainage systems likely will reduce emissions of CO_2 from extensively managed areas and reduce subsidence although the direct effects (other than reduced intensity of farming) remain uncertain (e.g. [Parmentier et al., 2008]). The removal of biomass remains the greatest source of C exports and loss from the exploited systems. The present sink strength in the unmanaged polder (*Horstermeer*) may decline in the long term (timescale of centuries) due to a decrease in nutrient availability [Limpens et al., 2008] or remain under nutrient rich conditions (e.g. Alder carr forest).

The creation of lakes and larger wetlands is of importance. The summer emissions from large shallow lakes [Schrier-Uijl et al., 2010c] are higher than the emissions from the intensively and extensively managed polders when considering the sum of CO_2 and CH_4 emissions, but lower than the emissions from drainage ditches within the polders. Reducing the inputs of organic material and nutrients from the surroundings will probably reduce emissions from these water bodies [Schrier-Uijl et al., 2010c]. This suggests there is a strong link between emissions from ditches and the intensity of the management in the polders within the catchment area. Recommendations on how to reduce GHG emissions and increase carbon sequestration based on our results from the observations in the field are summarised in table 8.

Perspectives

We recommend performing continuous micrometeorological measurements at field scale on multiple locations both national and international. These measurements could be made using EC flux technique. However, more research should be done on the applicability of the cheaper alternatives REA and DEC. The field scale measurements should be performed in combination with chamber measurements.

At present, official methods to estimate N_2O emission from grazed grasslands on peat soil use a constant background emission rate. This study shows that the background emission is strongly related to groundwater level and can be estimated within reasonable accuracy using mean annual groundwater levels. Considering that the background emission accounted for approximately 22% of the total emission for the dry fields and for approximately 10% of the total emission from the wet fields, we argue to implement a variable background emission in the official estimation methodologies, once our findings are confirmed for other peat soils.

In general, interpretation of the variability of GHG emissions is extremely difficult because of interaction with management effects. There is as yet no universally accepted method to take effects of management at the plot or farm scale into account [Cescia et al., 2010]. Farm-scale full GHG accounting also requires extensive observation strategies on management and activities [Smith et al., 2010]

We did not study farm-based emissions separately but these may be manageable and need further adressing. [Sommer et al., 2009] studied farm-based emissions in Sweden, Denmark, France and Italy and found that shortening the on-farm manure storage and lowering the storage temperatures reduced GHG emissions from manure by 0-40% depending on current management and climatic conditions. Significant GHG reductions were obtained when slurry was separated into a liquid component and a solid, organic component and the liquid fraction was applied to fields before applying the solid fraction.

Until now, the national reporting takes place on the basis of relative simple, but in UNFCCC context, internationally widely accepted calculation procedures. Our measurements and modeling have shown that in principle it is possible to develop a cost effective observation scheme for GHG flux measurement. By taking key observations at representative landscapes it is possible to improve on these simple schemes by adding more detail.

Understanding the global carbon cycle, and predicting its evolution under future climate scenarios is one of the major challenges science is facing today as climate change may have major societal implications. The uncertainty in the natural sinks in the carbon cycle is a major contributor to the uncertainty in climate predictions. The feedbacks between climate change and the carbon reservoirs are not well known or understood. The spatial and temporal distribution of natural sinks over land and oceans remains elusive, which precludes better quantification of their underlying mechanisms and drivers. In addition to natural sinks, anthropogenic emissions from fossil fuel burning and land use change need to be known at regional level and with better accuracy. These uncertainties must be reduced to underpin well-informed, evidence-based policy action.

A key reason for limited understanding of the global carbon cycle is the dearth of global observations. An increased effort to implement and use an improved and coordinated observing system for quantifying the regional and global carbon cycle is a prerequisite to gaining that understanding.

Figure 15 show the progression needed for such a global observing system to achieve its goals in terms of accuracy and resolution. Bsik ME01 has contributed some important steps towards this goal by developing a prototype system for the Netherlands.

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1 ECN
2 KNMI
3 RUG
4 TNO
5 VU
6 WUR

Tables

Table 1.
Site information.

Site	Latitude, Longitude	Site history	Years	Vegetation	Soil preparation	Fertilisation (M=mineral, O=Organic)	Irrigation mm yr^{-1}	NEP Starting Date	Length cropping period (d)	Soil type
Dijkgraaf	51°59'31"N, 5°38'45"E	Cultivated, organic manure > 10 years. Maize and grassland.	2006-2007	maize	ploughing	O	0	1 oct	146	Haplic Gleysol
Langerak	51°57'13"N, 4°54'10"E	Cultivated, organic and mineral fertilizer. Maize and grassland.	2004-2005	maize	ploughing	O	0	1 feb	154	
Lutjewad	53°23'56"N, 6°21'22"E	Not cultivated (fallow) before 2005.	2005-2007	winter wheat	ploughing	M	0	15 oct	289	Calcaric epigleyic Fluvisol
Molenweg	51°39'00"N, 4°38'21"E	Cultivated, organic and mineral fertilizer > 30 years. Agricultural crops and vegetables.	2004-2005	potato	direct	M + O	0	N.a.	165	Calcaric epigleyic Fluvisol

Site	Latitude, Longitude	Site history	Years	Vege-tation	Soil prepa-ration	Fertilisation (M=mineral, O=Organic)	Irrigation mm yr^{-1}	NEP Starting Date	Length cropping period (d)	Soil type
Vredepeel	51°31'54"N, 5°50'39" E	Cultivated, organic and mineral fertilizer > 30 years. Agricultural crops and vegetables.	2005-2006	sugar beet	ploughing	M + O	0	10 apr	210	Anthric entric Podzol
Loobos	52°10'04"N, 5°44'38"E	Scots pine	2004-2010	Scots pine	n.a.	none	0	1 jan	365	Orthidystric rubic Arenosol
Slootdorp	52°49'54"N, 4°54'33"E	Slush depot	2008-2009	willow	n.a.	none	0			
Zeewolde	52°20'3"N, 5°22'24"E	Grass / maize	2008	maize	ploughing	M + O				
Horster-meer	52°14'25"N, 5°4'17"E	Abandoned agriculture (grassland)	2004-2010	grass	none	none	0	1 jan	365	Clayey peat
Cabauw	51°58'13"N, 4°55'34"E	Sheep grazed	2004-2010	grass	none	By sheep	0	1 jan	365	Fairly heavy Clay on peat (below 75 cm)
Reeuwijk Oukoop	52°03'13"N, 4°78'34"E	Intensive dairy farming	2004-2009	grass	none	M + O	0	1 jan	365	Peat
Reeuwijk Stein	51°02'01"N, 4°77'31"E	Extensive dairy farming	2004-2009	grass	none	none or O (rare occasions)	0	1 jan	365	Peat

Table 2.
Site descriptions, land use and management per peat site.

Site	Peat thickness (m)	Landscape elements				Land use	Grazing	Biomass Removal[1] (ton ha^{-1} yr^{-1})	Cow manure applied[1] (kg N ha^{-1} yr^{-1})	Fertiliser applied[1] (kg N ha^{-1} yr^{-1})
		Dry land %	Wet land %	Water logged land %	Water %					
Oukoop	12	79		5	16	intensively managed grassland	2005 and 2006 by some cows	12	300	88
Stein	12	79		5	16	extensively managed hayfield	young cattle few days per year	10	0	0
Horstermeer	2.1	60	25	10	5	former managed area under restoration	None	0	0	0

1 Values related to management are averaged over the years 2006, 2007 and 2008.

Table 3.
Measurement periods, techniques and temporal up-scaling methods per GHG per site.

GHG	Measurement methods						Temporal up-scaling methods	
	Static chamber			Eddy covariance			Static chamber	Eddy covariance
	Oukoop	*Stein*	*Horster-meer*	*Oukoop*	*Stein*	*Horster-meer*	All locations	All locations
CO_2	2006 2007 2008	2006 2007 2008	2005 2006 2007 2008	2005 2006 2007 2008	2005 2006 2007 2008	2005 2006 2007 2008	*T* regression*	night time measurements and multiple regression for data gaps, with monthly E_o and R_{10} values.
CH_4	2006 2007 2008	2006 2007 2008	2005 2006 2007 2008	2006 2007 2008		April 2007	*T* regression*	measured values and multiple regression with *T* (soil temperature and *U* (wind velocity) for data gaps
N_2O	2006 2007 2008	2006 2007 2008	2005 2006 2007 2008	2006 2007 2008		NA**	NA**	The used method separates background emission and event emission due to manure application

* Regression based on temperature.

** not available, the detection limit of the gas analyzer was too low for the used chamber design.

Table 4.
Emission calculation methods per site per GHG.

Site	GHG	Method	Calculations of emissions	Ref.	Abbreviations
Ou, St, Ho[8]	CO_2	Eddy covariance	Annual NEP_{CO_2} =GPP-R_e Annual NEP is calculated from 30 minute night fluxes $R_e = R_{10}\exp^{E_0((1/283.15-T_0)-1/(T-T_0))}$ R_{10} and E_o are estimated per month and 30 minute day fluxes $F_c = \frac{\alpha.\mathrm{PPFD}.\beta}{\alpha.\mathrm{PPFD}+\beta} + \chi$	1, 2, 3	NEP= net ecosystem production GPP= gross primary production R_e= ecosystem respiration R_{10}= respiration at 10 °C T_o= fixed T at 227.13 K E_o= activation energy F_c= ecosystem flux PPFD= Photosynthetic photon flux density
Ou, St, Ho[8]	CO_2	Dark chamber	Annual R_e is calculated from a regression based on three years of chamber measurement given by $R_e = R_{10}\exp^{E_0((1/283.15-T_0)-1/(T-T_0))}$	4	α, β and χ are parameters
Ou, Ho[8]	CH_4	Eddy covariance	$\mathrm{NEE}_{\mathrm{CH4}} = \sum_{i=1}^{N} F_{\mathrm{CH4},i} T_{av}$ with F_{CH4} 30 minute measured eddy covariance flux or the gap filled flux given by $F_{\mathrm{CH}_4} = \exp^{a+bT+cU}$ *a*, *b* and *c* are factors in the regression	5	NE_{ECH4}= annual emissions of CH_4 F_{CH4}= 30 minute flux of CH_4 T_{av}= averaging time *T*= 30 minute soil temperature *U* =30 minute wind velocity
Ou, St, Ho[8]	CH_4	Dark chamber	$\mathrm{NEE}_{\mathrm{CH4}} = \sum_{i=1}^{N} F_{\mathrm{CH4},i} T_{\mathrm{av}}$ with $F_{\mathrm{CH}_4} = \exp^{a+bT}$ *a* and *b* are factors in the regression and are different per site and per landform	6	
Ou[8]	N_2O	Eddy covariance	$\mathrm{NEE}_{\mathrm{N_2O}} = E_{\mathrm{EC}} + E_{\mathrm{l}} + E_{\mathrm{d}}$ with $E_{\mathrm{EC}} = E_{\mathrm{bgnd}} + E_{\mathrm{fert}}$	5	NEE_{N2O}= annual emissions of N_2O E_{EC}= emission measured by eddy covariance E_l= indirect emission due to leaching and run-off E_d= indirect emission due to deposition E_{bgnd}= background emission E_{fert}= direct emission due to fertilizing events

Site	GHG	Method	Calculations of emissions	Ref.	Abbreviations
St[8]	N_2O	Velthof	Fertiliser related: N_2O emission factors based on available data and expressed as g N_2O-N per kg N, assuming a linear relationship between N flow and N_2O production.	7	
Ho[8]	N_2O	Literature	As above		KO

1 [Lloyd and Taylor, 1994], 2 [Veenendaal et al., 2007], 3 [Falge et al., 2001], 4 [Schrier-Uijl et al., 2010b], 5 [Schrier-Uijl et al., 2010a], 6 [Kroon et al., 2010d], 7 [Velthof et al., 1997; Schrier-Uijl 2010d].
8 Ou= *Oukoop*, St= *Stein*, Ho= *Horstermeer*

Table 5.
Methane emissions from a fen meadow.

	Field	Border	Ditch
Eutrophic fen (intensively managed)	0.7-0.8	4.8-6.0	4.5-7.0
Eutrophic fen (extensively managed)	0.8-0.9	2.7-3.4	4.5-5.43

Table 6.
Estimated area and annual GHG release for the area of intensively managed and extensively managed (mown only) or unmanaged grasslands on peat within the total western peatland region of the Netherlands. Farm-based emissions are not included.

Ecosystem type	Area in western peatland		Total N_2O emission	Total CH_4 emission	Total CO_2 emission
	(ha)	(% of total)	103 kg N_2O yr^{-1}	103 kg CH_4 yr^{-1}	103 kg CO_2 yr^{-1}
Intensively managed grassland	78,375	68%	1881	12853	313498
Extensively managed/ unmanaged grassland	8,786	8%	70	1577	35145
Shallow water bodies	87	6%	unknown	unknown	335831

1 An annual emission of 0.5 kg CO_2 m^{-2} yr^{-1} was assumed.

Table 7.

Annual terrestial CH_4 emission in kg CH_4 ha^{-1} in *Oukoop* in the Netherlands. aAverage EC flux is extrapolated, bBased on EC flux measurements: the remaining gaps are filled by a multivariate regression model, cBased on a multivariate regression model derived by EC flux measurements only, d Based on a multivariate linear regression model derived from static chamber measurements only [Schrier-Uijl et al., 2010]. Table is taken from Kroon et al., (2010d).

	2006	2007	2008	Average
Method 1a	194 (±54%)	140 (±63%)	138 (±53%)	157 (±33%)
Method 2b	176 (±30%)	169 (±31%)	149 (±26%)	165 (±17%)
Method 3c	172 (±37%)	166 (±37%)	155 (±37%)	164 (±32%)
Method 4d	203 (±48%)	162 (±60%)	146 (±60%)	170 (±32%)

Table 8.
Recommendations on how to reduce GHG emissions and increase carbon sequestration based on our results from the observations in the field.

Land use	Management	Measure	Remarks
Croplands	Intense	Reduce inputs of manure and fertilizer	
		Change timing of the manure and fertilizer application	For example: apply irrigation after manure or fertilizer application to reduce N_2O peak emissions
		Management of the fallow period by intercropping	The annual emissions of a field are largely determined by the management during the intercropping period
	On-farm manure storage	Lowering storage temperatures	
	Manure application	Separate slurry into a liquid and a solid organic component and apply the liquid fraction to fields before applying the solid fraction	
Grasslands	Agricultural peat-land	Rewet by increasing the groundwater table Reduce management intensity	
	agricultural	Reduce inputs of manure and fertilizer	See also farm management options
	Natural managed peat-land	Maintain a high groundwater table	A negative effect could be CH_4 emissions from the soil and surrounding ditches and lakes.
Water bodies	Natural managed shallow lakes	Reduce inputs of organic material and nutrients	
	Ditches	Reduce inputs of organic material and nutrients	Emissions are correlated with water depth, however possible effect of managing the water depth is unclear
Forests	Natural	Maintain present management practice	Forest sinks in the Netherlands seem reasonably stable under current management
		Increase forest area	

Figures

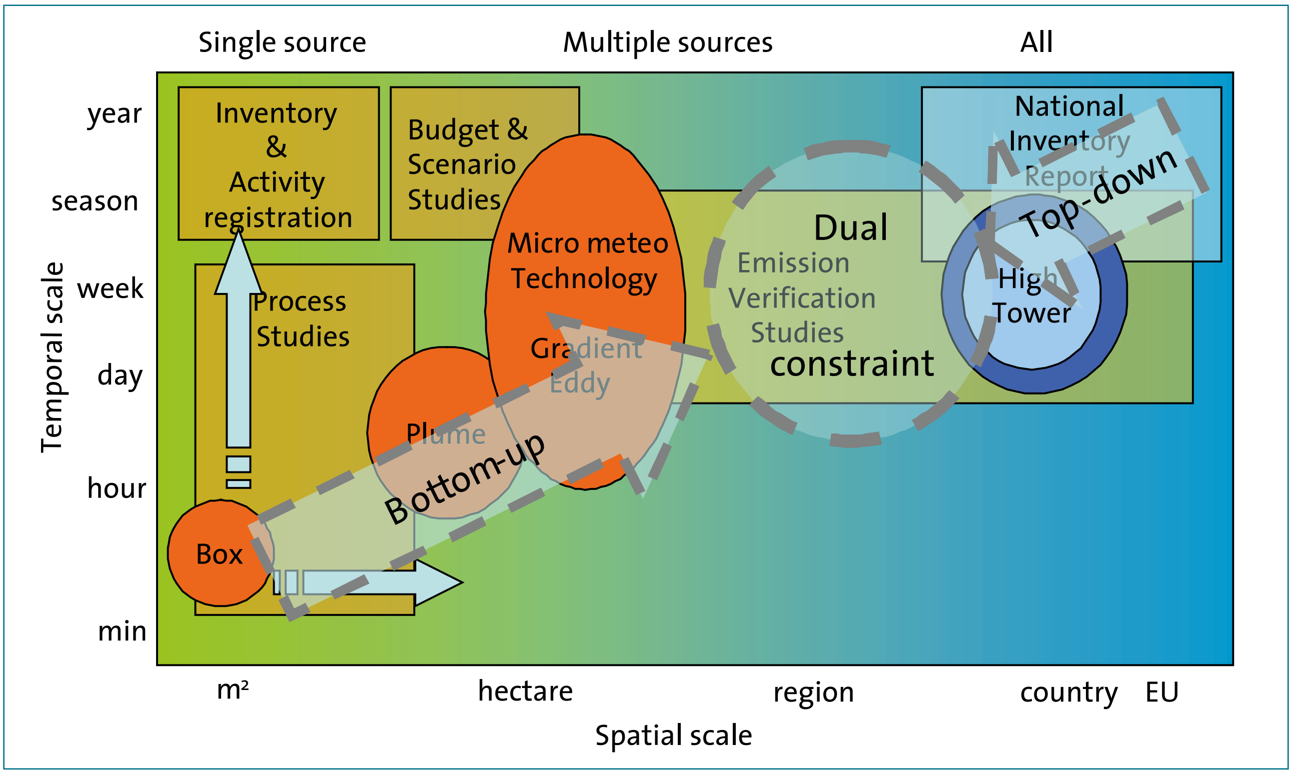

Figure 1.
Dual constraints approach.

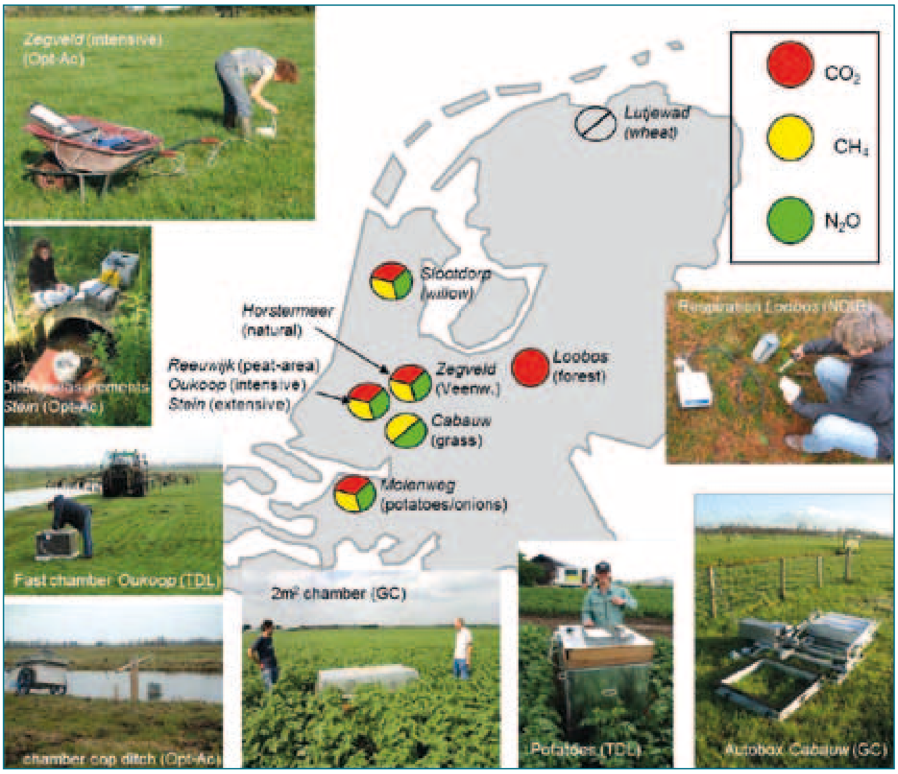

Figure 2.
Overview of the various types of chamber measurements used.

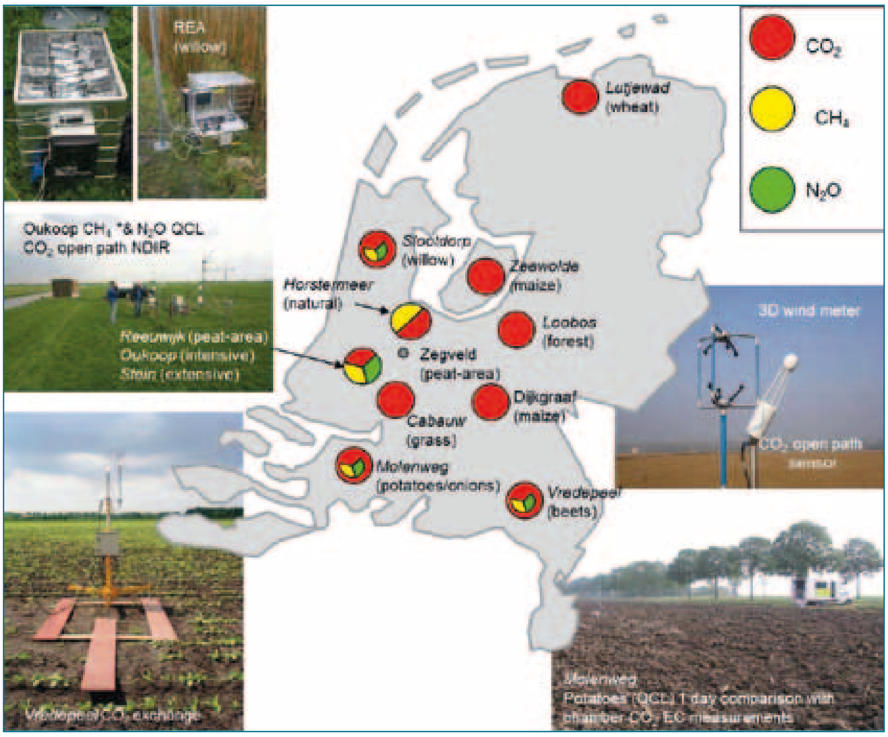

Figure 3.
Overview of the micrometeorological measurements used.

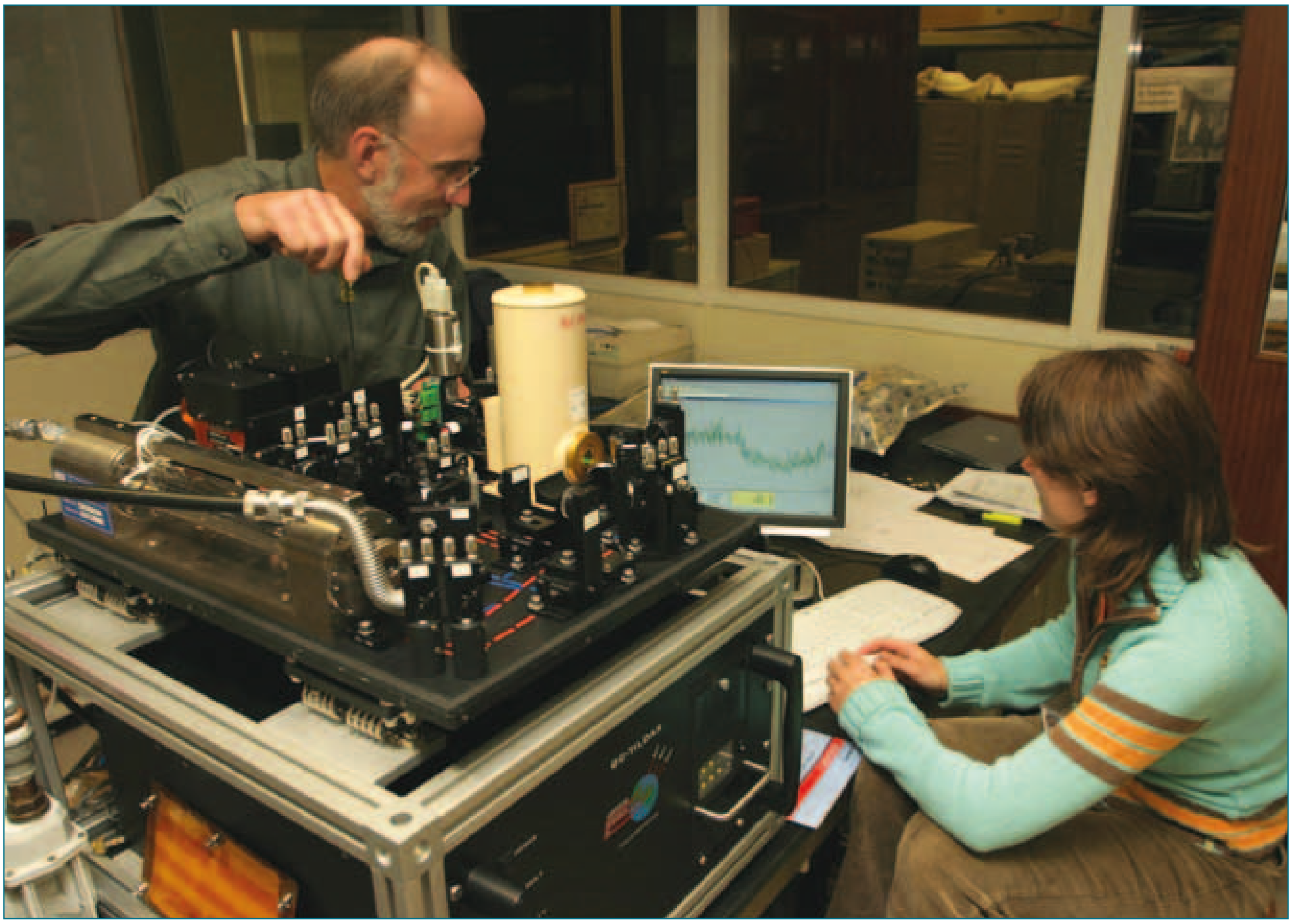

Figure 4.
Quantum cascade laser spectrometer testing in the laboratory of ECN.

Figure 5.
Chamber measurements above a ditch.

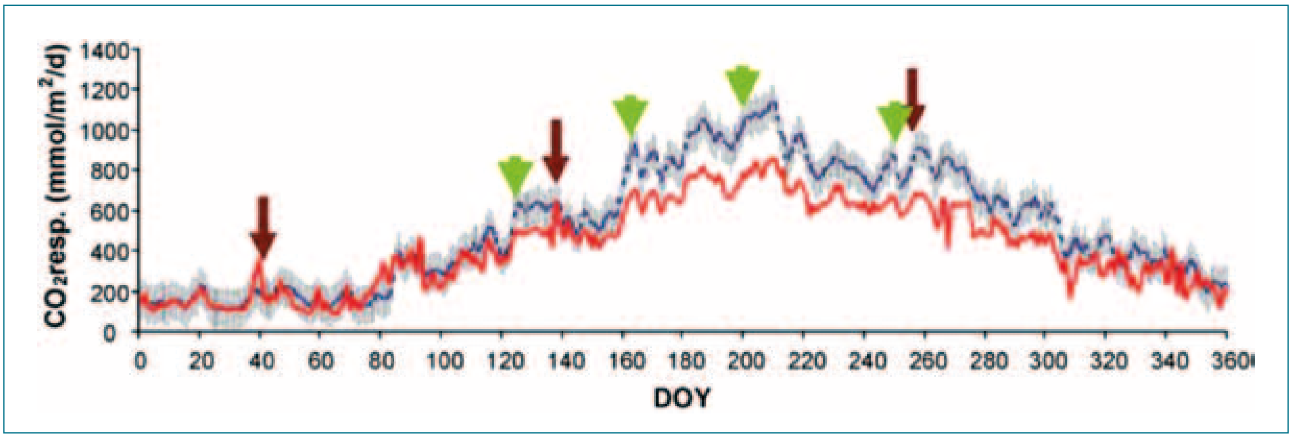

Figure 6.
Comparison of a model based on chamber measurements (blue dashed line) including the different landscape elements and respiration rates derived by EC (red, solid line) for 2006. The uncertainty band around the dotted line represents plus and minus one standard error for mean prediction, based on the regression analysis, and calculated for each day. Arrows indicate manure events (brown, large) and mowing events (green, small) [Schrier-Uijl et al., 2010a].

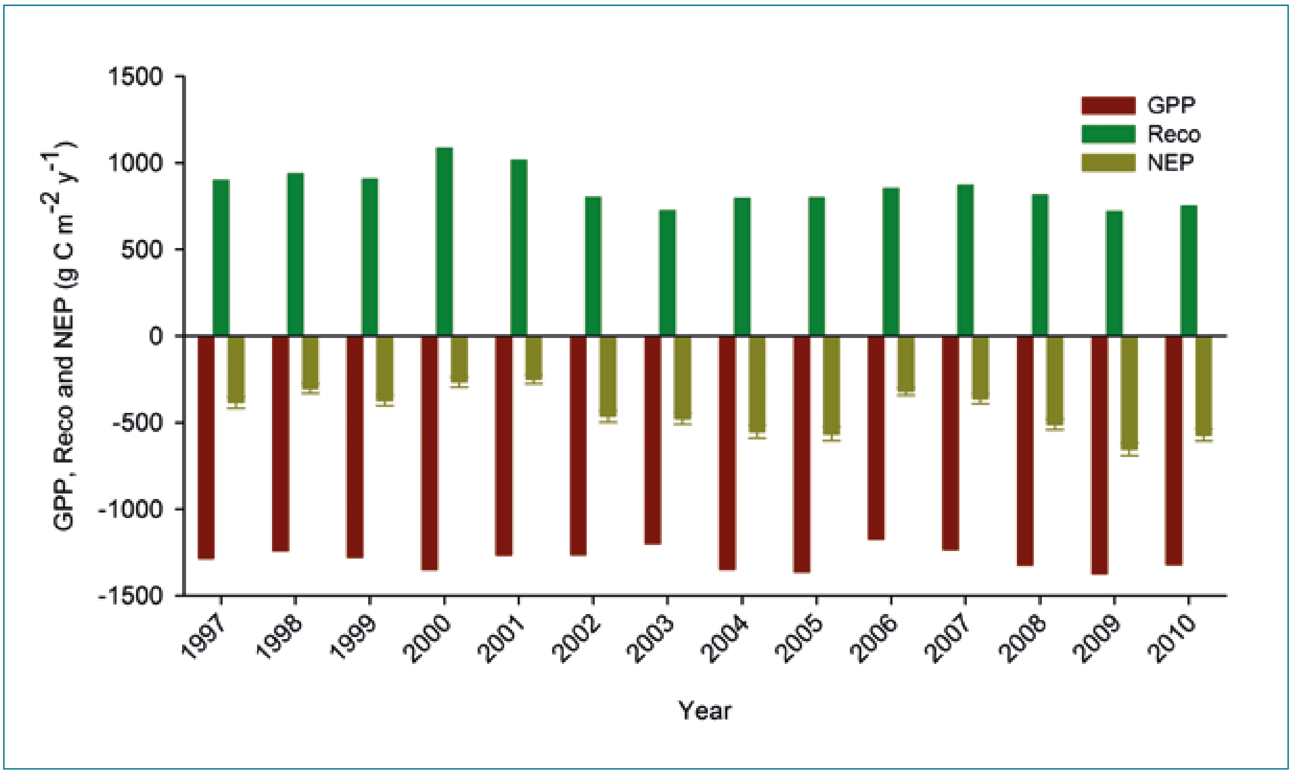

Figure 7.
Interannual variation of GPP, Reco and NEP at the *Loobos* site. Negative values indicate carbon uptake by the ecosystem. Error bars in NEP indicate uncertainty.

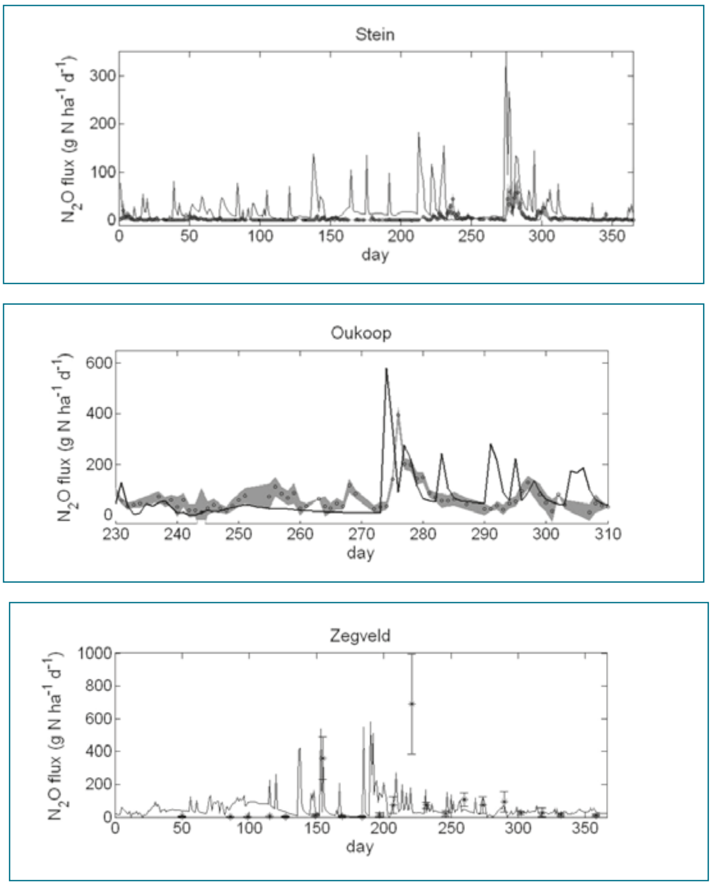

Figure 8.

Comparison of simulated and observed N_2O emissions for *Stein*; an extensively managed peatland (N input 60 kg N ha^{-1} yr^{-1}) (a), *Oukoop*; intensively managed (N input 350 kg N ha^{-1} yr^{-1}) (b), and *Zegveld*; intensively managed, intensive drainage (250 kg N ha^{-1} yr^{-1}) (c). Note different scales for x- and y-axes. Error bars and the grey area represent the uncertainty of the observed fluxes.

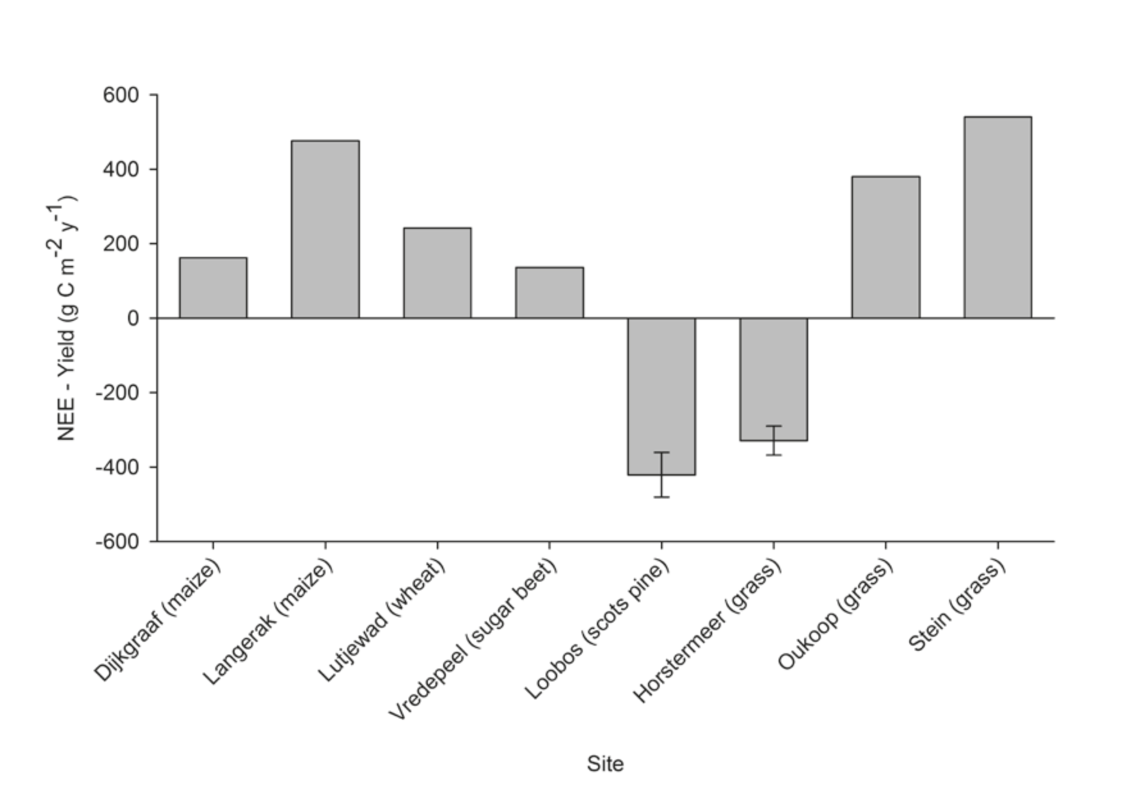

Figure 9.
Net uptake (negative) or release (positive) taking into account the main lateral output, i.e. NEE minus yield (exported harvested biomass).). Lateral output at the *Loobos* site is assumed to be negligible.

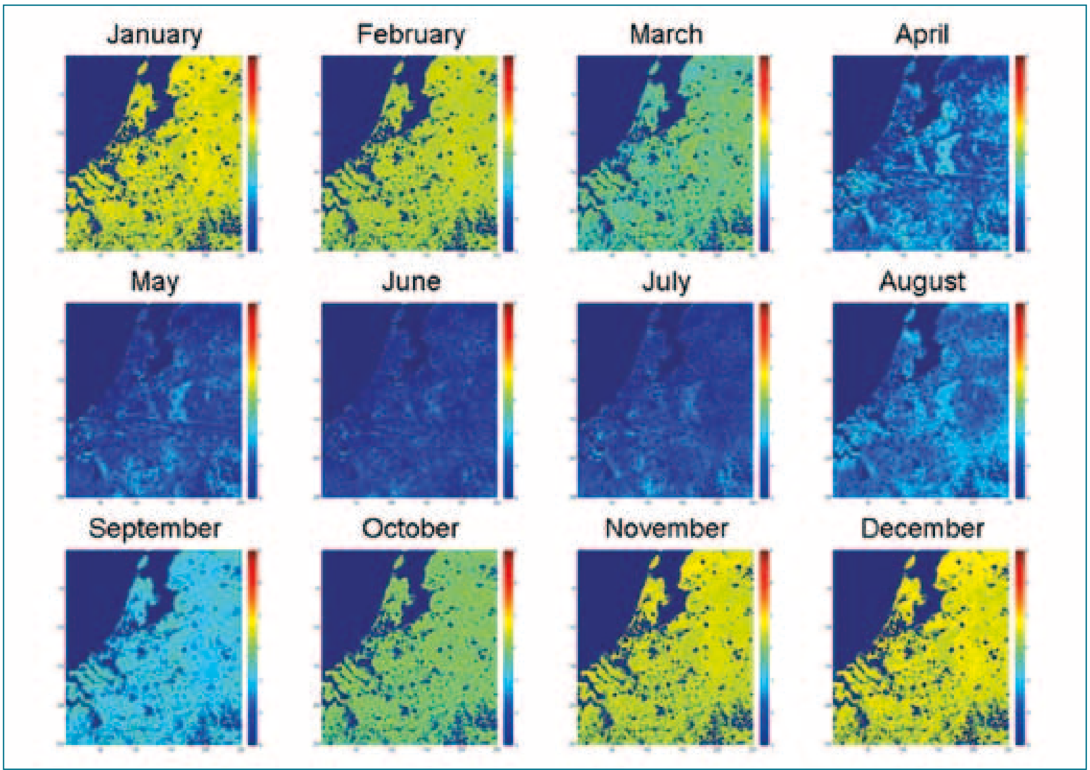

Figure 10.
Average seasonality of NEP over the period 2003 – 2007 (μmol $m^{-2} s^{-1}$ per month). Range from 6.00 (yellow) to -6.00 (blue) μmol $m^{-2} s^{-1}$.

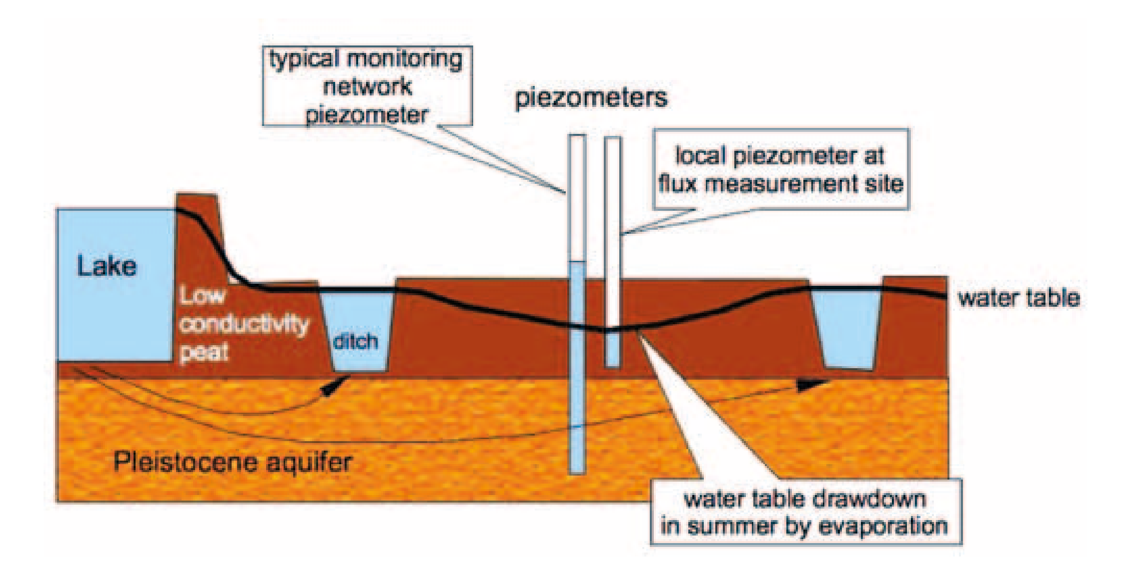

Figure 11.
Small-scale spatial variation in groundwater table which is not recorded by groundwater models.

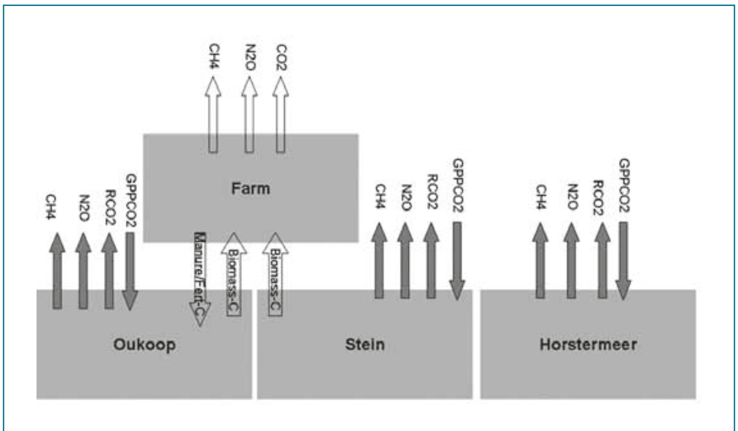

Figure 12.
Terrestrial and farm GHG fluxes (CO_2 respiration (RCO2), CO_2 gross ecosystem production or photosynthesis (GEPCO2), CH_4 and N_2O) and carbon fluxes (CO_2-C, CH_4-C, manure and fertiliser-C, biomass-C) that were considered in the current study for *Oukoop*, *Stein* and *Horstermeer*. White arrows are farm-based fluxes and dark grey arrows are terrestrial fluxes External inputs from imported feeds end outputs to milk and meat are excluded from this balance as are dissolved organic carbon losses (DOC).

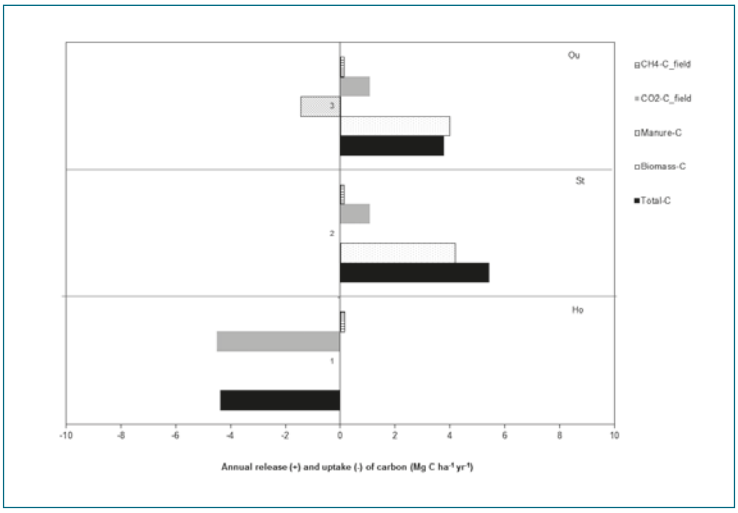

Figure 13.
Summary of carbon fluxes considered in the research areas *Horstermeer* (Ho), *Stein* (St) and *Oukoop* (Ou) averaged over 2005, 2006, 2007 and 2008. The annual carbon balance is presented in Mg C ha^{-1} yr^{-1}, (+) is release and (-) is uptake, and consists of fluxes due to GHG emissions (field-NEP CO_2 and field-NEE CH_4) and fluxes due to management (manure application and biomass removal).

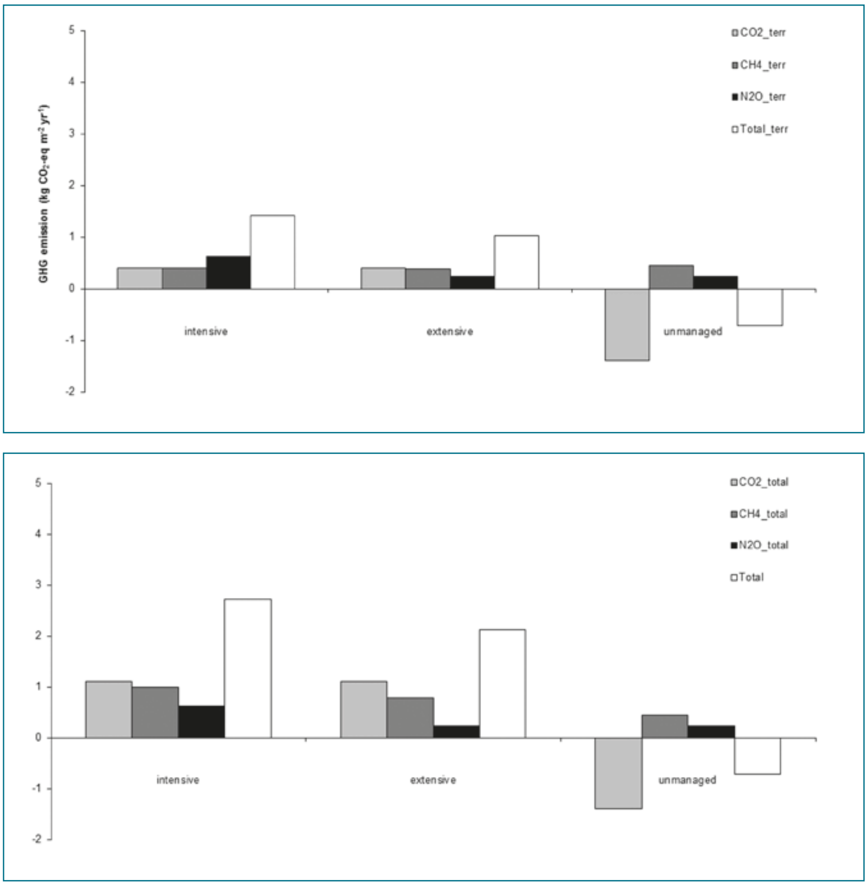

Figure 14.
The GHG balances including CO_2, CH_4 and N_2O for the three sites: intensive (*Oukoop*), extensive (*Stein*) and unmanaged (*Horstermeer*). On the left, excluding farm-based CH_4 and CO_2 emissions and on the right, including farm-based CH_4 and CO_2 emissions, averaged over 2006, 2007 and 2008 (fluxes are given in warming potentials, kg CO_2-equivalents m^{-2} yr^{-1}).

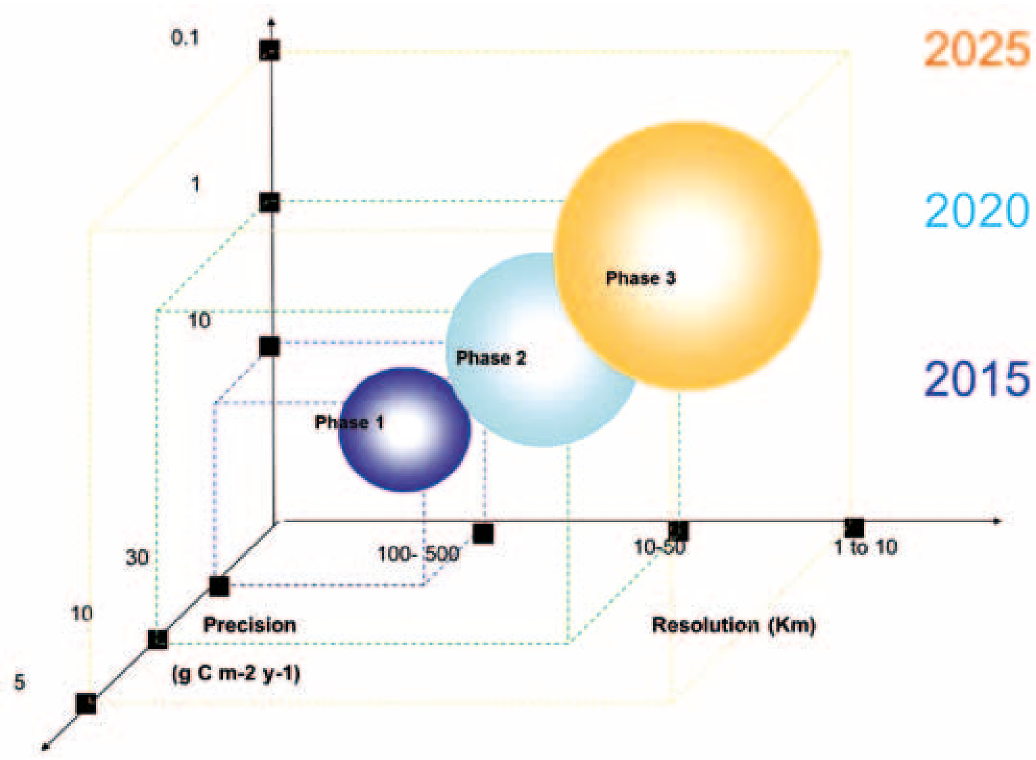

Figure 15.
Future evolution of requirements toward finer resolution and precision capabilities for producing global maps of CO_2 and CH_4 surface fluxes (redrawn from GEO Carbon Strategy, 2010, . Ciais, P., Dolman, A.J., Dargaville, R., Barrie, L., Bombelli, A., Butler, J., Canadell, P., Moriyama, T. (2010). Geo Carbon Strategy Geo Secretariat Geneva,/ FAO, Rome, 48 pp.)

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Climate changes Spatial Planning

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

Mitigation

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

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