PROJECTS
ME01 Integrated observations and modelling of: greenhouse gas budgets at the ecosystem level in the Netherlands
ME02 Greenhouse Gas budgets at the national level in the Netherlands
ME03 Soil carbon dynamics and variability at the landscape level

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Full carbon accounting: mission impossible?

Quantifying mitigation efforts against a large background variability is a demanding task, in which scientific complexity and manageable, transparent accounting systems have difficulty to meet. Can we bring these together?

To mitigate climate change, demanding greenhouse gas emission reduction targets are being negotiated. Meeting these targets requires putting to work a broad and integrated range of reduction options, including those related to land use. To merit the reduction achievements by motivated stakeholders in all sectors and to prevent leakage to less committed players requires a form of full carbon accounting.

Accountability

The above holds equally for emissions and reduction options associated with the use of fossil fuels in power generation, industry and transport, as well as for emissions associated with biomass production and consumption in managed and natural ecosystems. However, the first category basically comprises the uni-directional input of greenhouse gases (GHGs) to the atmosphere through heterogeneous, but largely man-controlled conversion processes of fossil carbon, extracted at a limited number of sites, i.e. coal mines, oil/gas wells. Biogenic emissions, on the contrary, are a small net result of large, spatially diffuse fluxes into and out of the atmosphere, only rudimentary controlled by humans and characterized by a strong temporal asymmetry ('slow in, fast out'). In this field therefore big challenges arise to the development of truly effective mitigation options, to the development of an appropriate accounting system that prevents, or at least shows leakage in space and time. It also increases the need for independent verification of reduction claims. To tackle some of these challenges, in 2005 we started an ambitious, integrated, combined modeling and monitoring programme. This should, then and now, serve as a basis for the development of *and* viable mitigation options *and* of fool-proof reporting systems *and* of ways to independently verify emission reduction claims, focusing on biogenic emissions.

The projects

To do so we developed a measurement programme that addresses the quantification of magnitude and variability of *fluxes* of carbon dioxide, methane and nitrous oxide in various ecosystems, as these provide more direct insight in drivers. Furthermore we work on quantification of carbon stocks, mostly the more permanent organic carbon in and on the soil, as these carbon stocks integrate long term processes and are closest to current accounting concepts based on changes in stocks.

Both C-stocks and GHG fluxes are being studied along gradients of land management or in manipulative experiments in order to study potential

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mitigation options. At the regional scale tall towers provide high precision GHG measurements that can be used to constrain regional to national scale fluxes using inverse methods, complemented by aircraft observed fluxes along transects covering representative Dutch Landscapes. Measurements at all these scales have been complemented by modeling efforts. In the following we will present some selected research highlights leading to the question whether full carbon accounting is possible.

Emissions from Dutch grasslands

A large biogenic source of GHGs in the Netherlands is found in the low-lying peat areas in western Netherlands. These are generally under grazing but increasingly frequent also under crops, made possible through tight controlled lowering of groundwater tables. This leads to the oxidation of organic soils. To better quantify this source, an extensive programme was setup jointly between several groups, using flux towers and chamber measurements to quantify fluxes of CO_2 and CH_4

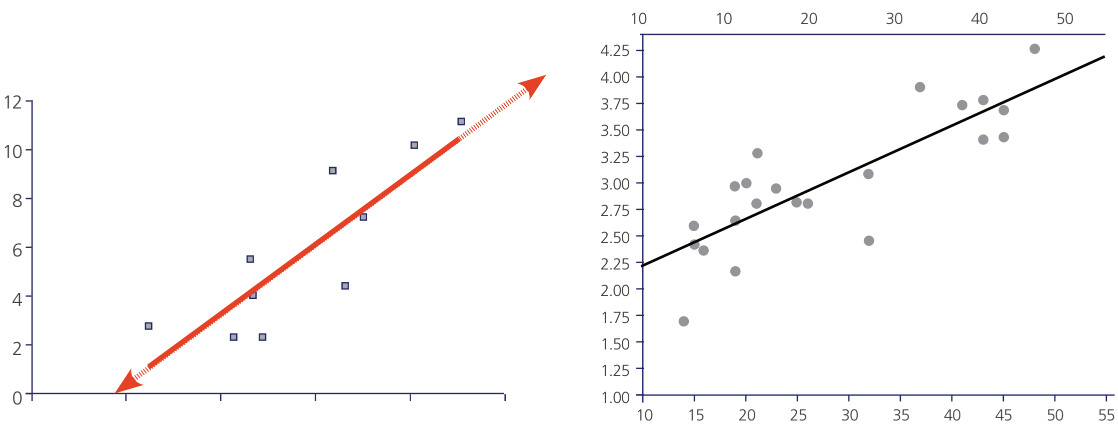

FIGURE 1. N_2O (left) and CO_2 (right) emissions as a function of ground water level in Dutch organic soils. Such simple relations are ideal to improve reporting methods.

and N_2O. Having completed a number of years of sometimes technically advanced measurements[1, 2, 3]. The data revealed a number of dependencies of emissions of all three GHGs on local water and land management conditions.

A comparative analysis of grassland fluxes in de Netherlands revealed a strong relation of the CO_2 exchange with general land management and underlying soil[4]. In general grasslands on mineral soils are a small sink of only 3.3 tonnes of CO_2 per hectare per year, but varying by almost the same amount from year to year.

On organic soils however, grasslands on average are a source of 8.1 tonnes of CO_2 per hectare per year with an interannual variability of about 40%, but systematically varying with land management: natural grasslands (restoration projects) are a small sink, drained grasslands under intensive grazing a highly significant source. The latter is mostly caused by strong oxidation of soil organic matter as a function of groundwater level (see figure 1, bottom), producing more than 27 tonnes CO_2 per hectare per year when groundwater is close to the surface to twice that number for groundwater levels half a meter below the surface[5].

For N_2O production a similar relation with groundwater has been found (figure 1, top): less than 2% of nitrogen applied as fertilizer is mineralized to N_2O on nearly inundated soils to more than five times that amount at groundwater levels half a meter below the surface[6].

Finally, also methane fluxes from these de-facto wetlands could be successfully quantified[7] showing emissions varying between roughly 2.5 tonnes CO_2-equivalents per hectare per year from intensively managed grasslands to almost threefold that number from extensively used fields (figure 2). Modeling work on all three GHG emissions from these peatlands is underway. Flux measurements have also been performed on croplands. A typical maize field on mineral soils in the Netherlands seems to be a net source of CO_2, even when accounting for the carbon input from manure application[8].

Carbon stocks of Dutch soils

Carbon stocks exhibit with various sources of variability and uncertainty. This variability is partly caused by spatial distribution of natural factors in the landscape, but is also strongly influenced by

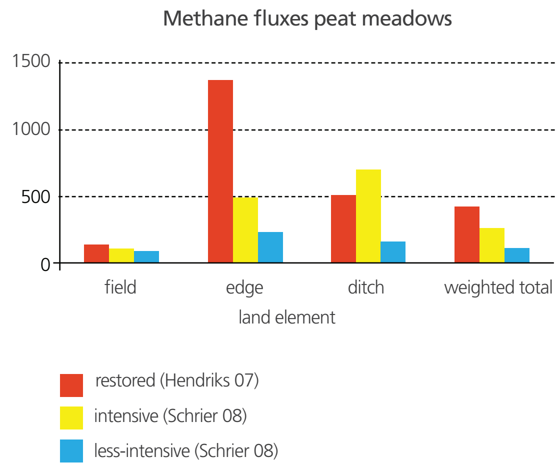

FIGURE 2.
Annual methane emissions as for various elements of the landscape in Dutch fen meadow areas[7,18].

past and present land use. Management in forestry and agriculture does not only provide us with an explanation of the observed variability and thus enables stratification in inventory based accounting methods, but enables us to make choices in respect to climate change mitigation. Above ground, living biomass stocks (forests) are generally well known, below ground stocks though estimated to be of similar size much less.

Insight in the determinants of the spatial distribution of soil organic matter (SOC) and forest floor carbon stock (FFC) can help us to improve estimation of the total carbon stocks. The influence of tree species, stand age and management on the SOC and FFC stocks has been investigated, on the base of two case studies on forest on representative poor sandy soil[9]. Tree species, age of the stand as well as management proved to be a an important source of variability on both the SOC as the FFC (Figure 3).

The influence of land use history on the carbon stock has also been studied[10]. The historical land use proved to explain a larger part of the variability than the present land use, r^2 =0.20 for 1850 land use and r^2= 0.14 still for 1780 land use as compared to against r^2= 0.02 for present day land use (the remaining variability explained by soil texture and groundwater). Including this land use history in a national-scale inventory of SOC and FFC stocks improved the SOC and FFC stocks by 5-10%. Increasing the sample density did not decrease the error of SOC in agricultural lands[11].

It is expected on the other hand that the FFC will benefit from collecting more additional data. For

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de- and afforestation could be improved. Including historical land use could be beneficial to estimations in other countries with a comparable land use history.

Stocks and emissions at farm level.

Area and site based studies are important for processes and large scale accounting methods. Development of mitigation options, however, is better served with studies at appropriate management levels. An example in the current context is the farm level. Model based studies on the influence of dairy farm management on soil carbon stocks and integral GHG emissions have been made by Van Evert & Verhagen (in prep.)

Dairy farming in the Netherlands is a significant source of greenhouse gasses but it also has substantial mitigation potentials. Thus the question arises how a dairy farm can be managed in such a way that carbon storage is maximized and the emissions of nitrous oxide and methane are minimized. Since management options that lead to emission reduction may lead to a decrease in carbon sequestration, and vice versa, these processes are considered simultaneously using the FARMIN model[12].

Four trends in management have been simulated. Grassland productivity and application of manure significantly affect soil organic matter, the former because a large amount of dead roots is added to the soil, the latter because it adds organic material. Increased dairy cow productivity has an effect on (mostly methane) emissions because the relative fraction of feed used for body maintenance is reduced. Grazing time has hardly an effect on either stock or emissions.

Regional scale assessments using direct airborne flux measurements.

Using small aircraft it is possible to directly observe GHG fluxes over larger areas. During the full seasonal cycle of 2008 three transects covering the most relevant landscape types in the Netherlands were alternately flown on a weekly basis. This way a large dataset has been created that is currently under analysis. An example of CO_2 fluxes along one such transect is given in figure 5.

Regional scale assessments using inverse methods. Changes in atmospheric concentrations of GHG's in the well mixed planetary boundary layer integrate flux variability at much larger scales. These changes can be used to estimate average fluxes of large scales using so-called inverse methods.

Our project's new observational infrastructure includes high precision measurements of multiple GHG's at two tall towers and medium precision at two lower towers. We have build up datasets that are now increasingly used in national and interna-

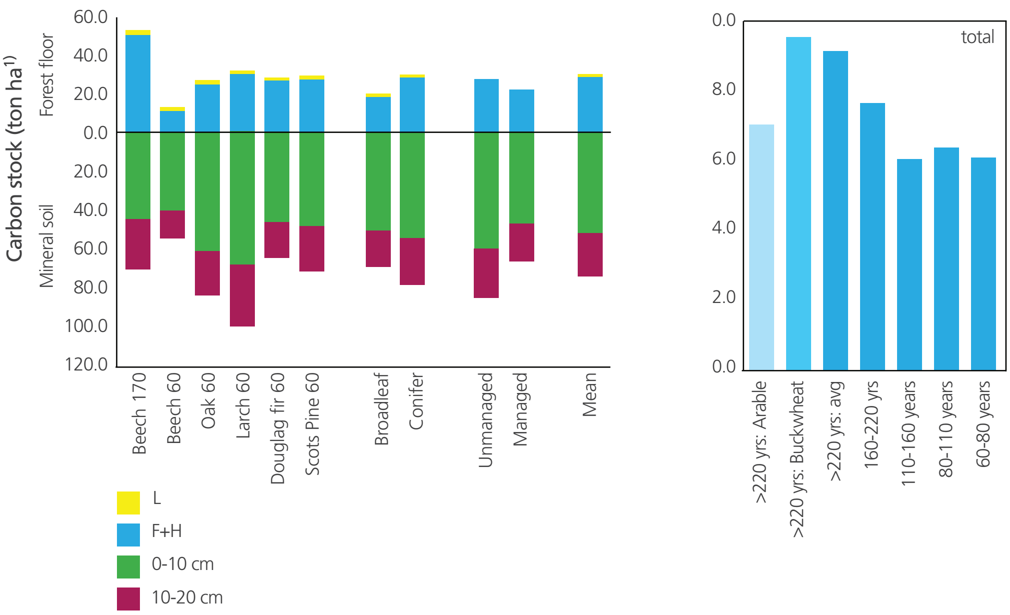

FIGURE 3. (top) Soil carbon and forest floor stocks (ton/ha) in forest stands as a function of management and tree species; (bottom) SOM contents (%) for different reclamation age groups averaged over soil types[9,10].

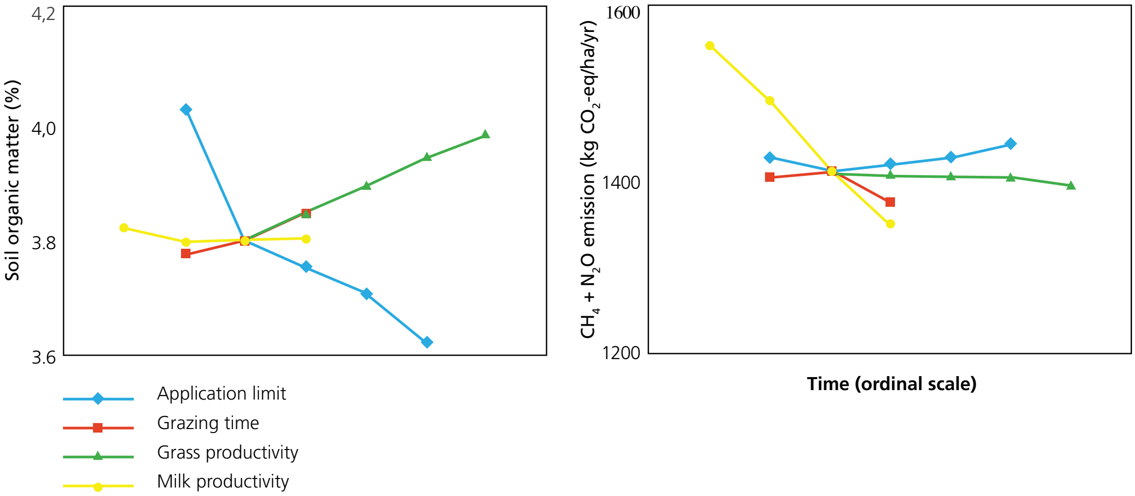

FIGURE 4. Effects of dairy farm management options on soil organic matter (left) and emissions of N_2O and CH_4, suggesting the potential for mitigation and for activity based reporting methods.

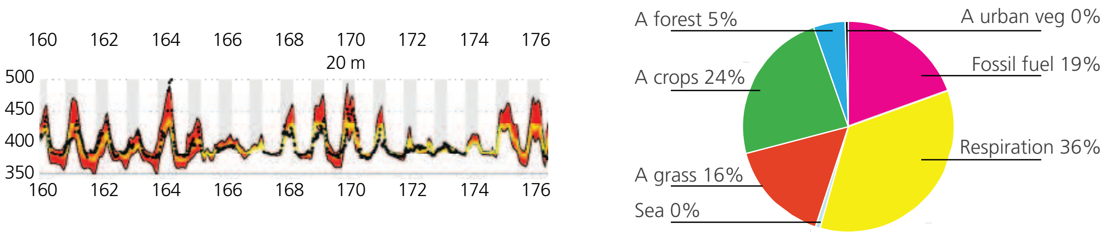

FIGURE 5. Effect of uncertainties in simulated biogenic fluxes on the concentrations observed at Cabauw (red band). These are considerably larger than transport errors and thus confirm the potential for inversion methods to better constrain these fluxes. The diagram at right shows the contribution of various emission sources/sinks to the Cabauw signal suggesting a potential of inversions to discriminate between the four main categories[17].

tional studies. The data can be used directly when concentration changes in the GHG of interest correlate with another tracer (here Radon) of which the flux is known. Based on the Lutjewad tower data, which with typical SW winds is downwind of the Netherlands, successful event-based data inversions have been made for CH_4 and N_2O[13]. Based on 2006-2007 data the Dutch annual emissions have been estimated at 631 +/-220 kton CH_4 and 37.4 +/- 12.5 kton N_2O. These estimates are close to the NIR reported emissions (2006–2008 averages) of respectively (760 ± 137) kton CH_4, and (54.0±24.9) kton for N_2O. In CO_2 equivalents for both together the 26.9 +/- 9.2Mt CO_2-equiv observed is lower but not significantly different from the 35.0 +/- 10.8 in the NIR. Attempts to apply the same method for CO_2 emissions are in preparation, but this appears to be more complicated.

Inversions for all three GHGs, based on different combinations of emission-, transport- and inversion-models are showing progress. Source aggregation methods using lagrangian transport models[14] provide first attempts at CH_4 estimates for the Netherlands. Contrary to the above mentioned data inversions, this model inversion estimates CH_4 emissions to be almost double the NIR estimates and do not show the downward trend reported in the latter. Resolving the discrepancy between the two estimates is subject to further work.

Pixel based CO_2 inversions for Europe are confirming inter-annual variations (e.g. the 2003 drought) and come steadily closer to bottom up estimates[15]. The resolution of forward models is greatly increased and the analysis shows that emission signals are significantly larger than transport and heat flux induced PBL errors, which is promising for inversions at this scale[16,17]. Work in progress using the same high resolution model, shows the added value of additional observations in constraining fluxes for areas the size of the Netherlands.

Conclusions

The examples presented here, are a few of the more integrative results bringing together measurements across multiple sites from various partners. Over the past five year we have collected

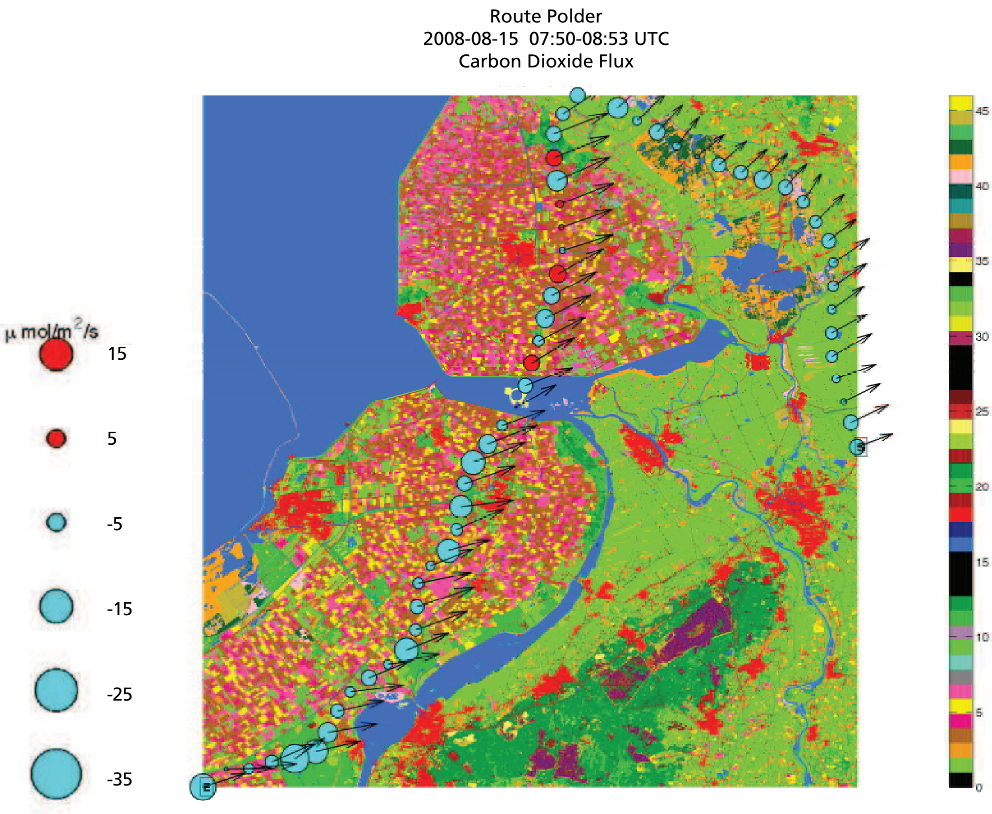

FIGURE 6.
Example of aircraft observed CO_2 fluxes over the IJsselmeerpolders in mid- August. The big variation reflects the differences between harvested and still growing crops in this season.

a great wealth of data on biogenic GHG emissions and made some significant progress in simulating these findings.

The flux measurements on each of the three main GHGs have shown considerable variability within various land use types across our country, and could be explained in terms of physiographic and management features. This makes more country specific reporting on emissions possible.

The insights regarding forest soil carbon stock are being used to update the methodology of the National Inventory Reports for this category. Land use history could also be used as it is relatively well documented in the Netherlands (as in many parts of western Europe) through detailed topographical maps dating back to mid and early 19th century.

The opportunity to sequester carbon on Dutch dairy farms seems limited, given the limits on manure application for other reasons. The opportunity to reduce the emission of greenhouse gases by raising productivity seems limited in the Netherlands where productivity is high already, but may exist in other parts of Europe.

All in all this study reveals mitigation options at practical management levels and provides a basis for activity based reporting methods. Methods for verification of emissions by atmospheric methods is progressing fast, with resolutions quickly increasing to levels making them useful for small countries like the Netherlands. For the gases N_2O and CH_4 that exhibit diffuse sources only the downscaling goes faster than for CO_2 with both diffuse sinks and spatially more concentrated sources. Though absolute estimates exhibit large uncertainties, diverse models generally agree much better on trends and interannual variability. Application of inverse methods in legal procedures over emission reduction claims requires these uncertainties to come down and also a more rigorous benchmarking and eventually even certification of the tools used.

More integration steps remain to be taken in the last stages of the projects. Nevertheless we believe the results presented here are already useful in improving emissions estimates, by making them more country specific. They provide ways forward in activity based reporting for mitigation. Also, the verification of reported emissions through independent atmospheric approaches seems feasible in the foreseeable future. We are therefore positive about the scientific possibilities for full carbon accounting, and believe that negotiations on future emission reduction commitments should move in this direction.

This paper reflects the personal interpretations of the authors, not necessarily completely coinciding with those of the many research collaborators in the ME projects of Climate Changes Spatial Planning, who kindly provided the results and graphs used here.

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We are positive about the scientific possibilities for full carbon accounting.

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