# THE DANISH SINKs PROJECT

## Final report on the Danish monitoring project for Land Use, Land Use Change and Forestry under the Kyoto Protocol

Scientific Report from DCE – Danish Centre for Environment and Energy No. 155 2015

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

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## Final report on the Danish monitoring project for Land Use, Land Use Change and Forestry under the Kyoto Protocol

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Abstract: The report describes the outcome of a project (SINKs) conducted from 2007-2013, with the objective to develop new knowledge, methods and report emissions from the Land Use and Land Use Change and Forestry sector (LULUCF) for the Danish reporting obligations to the Kyoto Protocol. 13 subprojects were finalised and provided a new map of the organic soils in Denmark, as well as models and methods for emission inventory in relation to yearly land use change and ensuing changes in the carbon pool in soils and biomass

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# Preface

This report contains the results from a larger research and development project which were conceived to support the Land use, Land Use Change and Forestry (LULUCF) inventories for the Kyoto Protocol (KP) mandatory article 3.3 and the elected article 3.4.

The Department of Environmental Science and DCE - Danish Center for Environment and Energy at Aarhus University (DCE) has been project manager for the project that also involved the Department of Geosciences and National Resource Management at University of Copenhagen and the Department of Agroecology at Aarhus University.

The project contact persons for the Danish Energy Agency (DEA) and DCE are Peter and Steen Gyldenkærne, respectively.

Many people have been involved to support, contribute, comment and review on this project. To all we appreciate their engagement to obtain the best results.

The project has been followed by a steering group involving relevant ministries, agencies and institutions. This group has met once a year, and the following is a list of persons who have attended at least one meeting.

- Martin Lindgreen, (Chair 2007-2010), Danish Energy Agency, Ministry of Climate, Energy and Building
- Jacob Vastrup, (Chair 2010-2012), Danish Energy Agency, Ministry of Climate, Energy and Building
- Stine Leth Rasmussen, (Chair 2013), Danish Energy Agency, Ministry of Climate, Energy and Building
- Simon Kjær Jacobsen, Ministry of Climate, Energy and Building.
- Tage Duer, Danish Energy Agency, Ministry of Climate, Energy and Building.
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- Janne Birk Nielsen, Ministry of Food, Agriculture and Fishery
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- Anne Sofie Nielsen, Environmental Protection Agency, Ministry of the Environment
- Kjell Nilsson, Department of Geoscience and Natural Resources Management, University of Copenhagen
- Erik Steen Kristensen, Department of Agroecology, Aarhus University
- Ole Bjørn Hansen, DCE, Aarhus University
- Hanne Bach, DCE, Aarhus University

Project participants have contributed to the meetings at various occasions and in various ways.

The SINKs project has been carried out for the Danish Energy Agency (DEA), and financed by the (then) Ministry of Climate, Energy and Building – now Ministry of Energy, Utilities and Climate.

# Summary

This report describes the final outcome of the Danish SINKs project. The SINKs project was initiated in 2007 to develop methods for fulfilling the needed documentation for the Danish ratification of the Kyoto protocol according to article 3.3 and the subsidiary voluntary election of Forest Management, Cropland Management and Grassland Management under article 3.4. Article 3.3 covers the mandatory estimation of afforestation and deforestation since 1990 and the related carbon stock changes in the areas involved. Forest Management under Article 3.4 covers land which was forested before 1990. Cropland and Grassland Management covers the area under agricultural management. Because of the complex land use in Denmark and difficulties to differentiate cropland and grassland both Cropland and Grassland Management was elected under Article 3.4.

In total 13 different projects were initiated covering forest and agricultural issues. The outcome from the different projects is documented in the scientific literature, in reports and working papers and in the Danish National Inventory Report (NIR) for greenhouse gas emissions (Nielsen et al. 2010, 2011, 2012, 2013, 2014).

In this report the outcome of the project is split in three main chapters, each covering one main topic. Chapter 5 covers the development of the method for producing a Danish land use change matrix (LUM), Chapter 6 is about forest issues and Chapter 7 is about agricultural issues. This structure assists the understanding of how the different sub-projects contribute to the overall objectives.

The LUM was initially planned to be based on a previous Global Monitoring for Environment and Security (GMES) remote sensing project for the Danish forests combined with auxiliary vector map information. During the project it was realised that the uncertainty related to land use change detection based on remote sensing was high and not suitable for the purpose under the complex land-use / land cover conditions present in Denmark. Because of a continuous development in Danish geo-referenced thematic data it was decided to construct a land use / land cover map for 2011 primarily based on digital thematic maps and only where no other information was available to use remotely sensed information, as for the forested area. Two other land use maps were constructed for 2005 and 1990 respectively based on the best available information and a rule based decision tree. The LUM for the years between these three points in time was based on linear interpolation.

The LUM for 2011 to 2012 and future LUM updates are based on annual updates of the different thematic maps. Some of the vector maps, especially from the Danish Geodata Agency are only updated every fourth year. This creates a time lag for some of the data layers but is found to be the best solution for construction of a suitable LUM for the purpose.

The land use / land cover analysis showed that the forest area in 1990 was 543 973 ha. From 1990 to 2012 the afforested area has been estimated to 94 358 ha and the deforested area to 5 784 ha. In this period the area with settlements and infrastructure increased from 485 543 ha to 511 411 ha. New settlements are primarily located on agricultural land. Analyses of the data

from the agricultural subsidy program has showed that there is a large annual transition between the land use categories Cropland and Grassland and vice versa indicating that the Danish election of both Cropland Management and Grassland Management was a robust decision.

Forest issues included the analysis of biomass expansion factors for forest species, and soil carbon stocks in forest soils. National biomass expansion factors (BEF) was estimated and implemented in the Danish GHG inventory for beech and norway spruce. These are slightly different from the default values in the Intergovernmental Panel on Climate Change (IPCC) 2003 guidelines (IPCC, 2003).

Prior to the SINKs project there was very little information on the carbon stock in the Danish forest soils. The project has estimated carbon stock changes in 110 paired forest soil samples from 1987 to 2009 and in 22 plots converted to forest during 1990 to 2007. Furthermore, carbon stock measurements have been conducted in 278 plots in the national forest inventory (NFI) for a further baseline on the carbon stock changes. The results have shown that the forest soils were not likely a source for carbon dioxide ($CO_2$) in Denmark during the period 1990 to 2012.

If forest soils are drained they may emit $CO_2$ and nitrous oxide ($N_2O$). The current Danish forest policy is to create more natural forests and therefore ditches in the national forests are only maintained to a very low degree or even removed, and as a consequence the water level has increased in many areas. It has been estimated that 336 264 ha of the area was drained in 1990 which was reduced to only 281 567 ha in 2011.

Soil sampling in the agricultural soil sampling grid was made in 2009. The network was previously sampled in 1987 and in 1998. In total 464 paired plots were included in the analysis. In general, the lighter sandy soils showed an increase in the carbon stock (0-100 cm) whereas a decrease in the carbon stock was found on the clay soils. This development is explained with a high cattle and grass density, which increase the organic matter input to the sandy soils and the absence of cattle and grass combined with a frequent removal of straw for energy purposes on the clay soils.

In the reporting to the United Nations Framework Convention on Climate Change (UNFCCC) a dynamical model (C-TOOL) is used to estimate the organic matter turnover and the carbon stock change. The output from C-TOOL is similar to what was measured in the agricultural soil sampling grid on clay soils and slightly lower than measurements on sandy soils. This indicates that C-TOOL is suitable for estimating the carbon stock changes. A new parameterization of C-TOOL with new knowledge is currently taking place. The new version is expected to be implemented in near future.

A new map of the agricultural organic soils has been developed. The new map showed that there were 70 300 hectares of organic soils under agricultural influence in 2010 with an organic matter (OM) content of >20 % OM. Of this, 42 000 hectares were cultivated with annual crops and 28000 with perennial grass. The total area is much lower than expected. In 1975 it was estimated that 243000 hectares were organic according to the Danish classification (>10 % OM). The very high disappearance rate is explained by the very shallow and young organic soils in Denmark.

CO2, methane ($CH_4$) and N2O emissions were measured in eight fields on three locations and with different crops. The measured emissions showed a high variability. Based on the measurements it was only possible to distinguish between annual crops in rotation and permanent grass. The measured emissions were up scaled to annual emission factors. The $CO_2$ emission factors are lower than the default IPCC values for temperate regions (IPCC, 2003) and higher than for cold conditions. Denmark is located in a temperature zone between cold and temperate and therefore the measurements were found suitable for Danish conditions and incorporated in the Danish GHG inventory. The measured $N_2O$ emissions showed a very high variability, with some values much higher than the default values. The reason may be that one of the plots showed to have very special soil conditions favouring $N_2O$ emissions. The measured $N_2O$ values are therefore not included in the Danish GHG inventory, where the default values from IPCC (IPCC, 2003) are used. The measured $CH_4$ emissions are not yet included in the inventory.

The total area with hedgerows and small biotopes not classified as forests were estimated for 1990 and 2005 and a model for the carbon stock in the hedgerows has been developed. It has been estimated that the total area of hedgerows has decreased with 2.0 % but the total volume has increased with 6.4 % and the total carbon stock has increased with 14.2 % in that period. These changes are explained with a large replacement of single rowed conifer hedgerows on the sandy soils with 3- or 6-rowed broadleaved hedgerows. These figures are subject to high uncertainty and they will be investigated further in the near future.

In total LULUCF activities from Afforestation have added 184 Gg $CO_2$ eqv to the Danish reduction commitments in the first commitment period. Deforestation has contributed negatively with 439 Gg $CO_2$ eqv, Forest Management added 1 172 Gg $CO_2$ eqv, Cropland Management 8 250 Gg $CO_2$ eqv and Grassland Management contributed negatively with 552 Gg $CO_2$ eqv. This makes up a contribution of 8 614 Gg $CO_2$ eqv to the reduction commitment in total.

The results from the SINKs project have improved the Danish GHG inventory from LULUCF considerably and resulted in an improved understanding of the carbon dynamics in the Danish landscape.

# Sammenfatning

Denne rapport omfatter de samlede resultater fra det danske SINKs-projekt. SINKs-projektet startede i 2007. Projektets formål var at udvikle metoder og nødvendig dokumentation af de danske drivhusgasudledninger fra arealanvendelse. Dokumentationen anvendes i forbindelse med den årlige afrapportering af de danske drivhusgasudledninger til FNs klimakon-vention (United Nations Framework Convention on Climate Change, UNFCCC) som følge af den danske ratificering af Kyotoprotokollens artikel 3.3 og det danske tilvalg af Forest Management, Cropland Management og Grassland Management under artikel 3.4. Artikel 3.3 omfatter den tvungne indregning af skovrejsning og skovrydning siden 1990 og den hertil relaterede ændring i den lagrede kulstofmængde. Forest Management under artikel 3.4. omfatter arealer som var omfattet af skov før 1990. Cropland Management og Grassland Management omfatter arealer som udnyttes landbrugsmæssigt. Da det danske landskab er meget komplekst og det er vanskeligt at skelne mellem IPCCs definitioner af Cropland og Grassland i en dansk kontekst, blev både Cropland Management og Grassland Management tilvalgt under artikel 3.4.

I alt blev 13 forskellige projekter påbegyndt fordelt på skov- og landbrugsområdet. Resultaterne fra de forskellige projekter er dokumenteret i den videnskabelige litteratur, i rapporter, arbejdspapirer og i den danske "National Inventory Report (NIR) for drivhusgasemissioner (Nielsen et al. 2010, 2011, 2012, 2013, 2014).

I denne rapport er resultaterne opdelt i tre hovedområder med hver sin hovedoverskrift. Kapitel 5 omfatter udviklingen af metoden der producerer den danske arealmatrice (Land Use Matrix, LUM). Kapitel 6 vedrører skovrelaterede emner og kapitel 7 landbrugsrelaterede emner. Denne opdeling er gjort for at hjælpe læseren med at forstå, hvordan de forskellige delprojekter bidrager til det overordnede formål. Arealmatricen blev i starten planlagt til at være baseret på et tidligere satellitmålingsprojekt for de danske skove (Global Monitoring for Environment and Security, GMES) kombineret med vektorbaserede kortinformationer. I projektet blev det imidlertid erfaret, at usikkerheden ved at bruge satellitmonitering, for at finde arealændringer, var for stor og ikke anvendelig i det komplekse danske landskab. Det blev derfor besluttet, med den kontinuerte udvikling der er sket i opbygningen af geografisk refererbare tematiske kort, at fremstille et arealanvendelseskort for 2011, som primært er baseret på digitale tematiske kort og som udelukkende anvender satellitbaserede kort i de tilfælde hvor der ikke fandtes anden information, bl.a. for skovarealer. Herudover blev to andre kort for hhv. 1990 og 2005 fremstillet på baggrund af den bedste tilgængelige information og et regelbaseret beslutningstræ. Arealmatricen mellem disse tre tidspunkter blev bestemt ved lineær interpolation.

Arealmatricen for 2011 og 2012 samt fremtidige arealmatricer er primært baseret på de tematiske kort. Nogle af kortene, specielt fra Geodatastyrelsen, bliver kun opdateret hvert fjerde år. Dette skaber en tidsmæssig forsinkelse for nogle af informationerne, men er alligevel fundet at være den bedste løsning for konstruktionen af arealmatricen.

Arealanvendelsesanalysen viste, at skovarealet i 1990 var 543 973 ha. Fra 1990 til 2012 er skovrejsningen estimeret til 94 358 ha og skovrydningen til 5

784 ha. I perioden er der sket en stigning i arealet med by og infrastrukturer fra 485 543 til 511 411 ha. Nye byområder er primært etableret på landbrugsarealer. Analyser af data fra EU's landbrugsprogrammer har vist, at der er en stor årlig migration mellem arealanvendelseskategorierne Cropland og Grassland og vice versa. Dette indikerer, at det danske tilvalg af både Cropland Management og Grassland Management var fornuftig.

De skovrelaterede emner omfatter analyser af biomasseekspansionsfaktorer (BEF) for forskellige træarter samt skovjordernes kulstofindhold. Nationale BEF er blevet estimeret og implementeret i den danske drivhusgasopgørelse for bøg og rødgran. Disse er lidt forskellige fra dem som er udarbejdet af Intergovernmental Panel on Climate Change (IPCC) 2003 guidelines (IPCC, 2003).

Før SINKs-projektet var der kun meget lidt information om kulstofindholdet i de danske skovjorder. Dette projekt har estimeret kulstofændringerne i 110 parvise prøver udtaget fra 1987 til 2009 og 22 prøver omlagt til skov i perioden 1990 til 2007. Herudover er der målt kulstofindhold 278 steder i den danske skovstatistik (National Forest Inventory, NFI). Disse skal bruges til fremtidige estimater for kulstofændringer i skovjorderne. Resultaterne har vist, at de danske skovjorder højst sandsynlig ikke er en kilde til $CO_2$-udledninger i perioden 1990 til 2012.

Hvis man dræner skovjorder kan de udlede $CO_2$ og $N_2O$. Den nuværende danske skovpolitik er, at der etableres mere ”naturskov”. Det medfører, at grøfter i de statslige skove kun nødtørftigt vedligeholdes eller fjernes helt. Som en konsekvens heraf, er dræningsniveaet ændret mod mere våde skove. Det er estimeret at 336 264 ha var drænet i 1990. I 2011 var dette areal reduceret il 281 567 ha.

I 2009 blev der udtaget jordprøver i landbrugets kvadratnet, hvilket tidligere er gjort i hhv.1987 og i 1998. I alt 464 parrede prøver er inkluderet i analyserne. Generelt viste resultaterne, at de sandede jorde havde en lille stigning i kulstofholdet (0-100 cm) hvorimod der var et fald på lerjorder. Dette kan forklares med et stort antal kvæg og flere græsmarker på de sandede jorde, hvilket er med til at øge tilførslen af organisk stof til de sandede jorder. Manglen på kvæg og græs kombineret med en hyppig fjernelse af halm til energiformål på de lerede jorder, kan være forklaringen på faldet i disses jorders kulstofindhold. I afrapporteringen til FN anvendes en dynamisk model (C-TOOL) til beregning af tilførslen og omsætning af organisk stof i jord og dermed ændringerne i landbrugsjordernes kulstofindhold. Beregningerne med C-TOOL svarede delvist til hvad der var målt i kvadratnettet på de lerede jorde, men noget mindre end hvad der var konstateret på de sandede jorder, hvilket tillægges en underestimering af effekten af græs i sædskiftet. Dette indikerer at C-TOOL er brugbar til at estimere ændringer i jordernes kulstofindhold. En ny parameterisering af C-TOOL er i øjeblikket ved at finde sted på baggrund af nye data. Den nye version forventes implementeret i nær fremtid.

Et nyt kort over de organiske jorde (mere end 20 % organisk stof svarende til mere end 12 % organisk kulstof) indenfor landbrugsarealerne er udarbejdet. Det nye kort viste at 70 300 ha organiske jord var under landbrugsmæssig indflydelse i 2010. Af disse var 42 000 ha med enårige afgrøder eller græs i omdrift, mens 28 000 henlå med vedvarende græs. Det samlede areal med organisk jord er betydeligt mindre end forventet. I 1975 blev det beregnet at der var 243 000 ha organisk jorde i følge den danske jordklassificering, som har en grænse på 10 % organisk stof. Denne høje forsvindingsrate kan forklares med, at de danske organiske jorder er meget tynde og unge hvilket gør at de forsvinder hurtigt.

Udledningen af kuldioxid ($CO_2$), metan ($CH_4$) og lattergas ($N_2O$) blev målt i otte marker på organisk jord på tre forskellige lokaliteter med forskellige afgrøder. De målte udledninger havde en meget stor variation. Baseret på tallene, er det kun muligt at skelne mellem afgrøder i omdrift og vedvarende græs. De målte udledninger blev opskaleret til årlige emissionsfaktorer og indarbejdet de danske opgørelser. De målte $CO_2$-emissionsfaktorer er lavere end IPCC's standardværdi for varme klimatiske forhold og koldere end IPCC's værdi for kolde regioner (IPCC, 2003). Danmark befinder sig mellem disse to zoner og derfor anses resultaterne acceptable for danske forhold. De målte $N_2O$-udledninger viste en meget stor variation og afveg betydeligt fra IPCC's guidelines. Målingerne er derfor ikke inkluderet i de danske opgørelser førend der foreligger fyldestgørende forklaringer på forskellene. De målte $CH_4$-udledninger indgår ikke i afrapporteringsforpligtigelsen og er derfor ikke inkluderet.

Det samlede areal med hegn og småbiotoper, som ikke klassificeres som skov, blev beregnet for 1990 og 2005 kombineret med en model til beregning af kulstofindholdet i hegnene. Det er estimeret, at det samlede areal med hegn er reduceret med ca. 2 % i perioden, at den samlede volumen er øget med 6.4 % og at den samlede kulstofmængde er øget med 14.2 % frem til 2012. Disse ændringer kan forklares med at gamle enkeltrækkede nåletræshegn på de sandede jorder, er erstattet med 3- eller 6-rækkede løvtræshegn. Tallene er forbundet med en stor usikkerhed og vil blive analyseret nærmere.

I alt har arealanvendelsesaktiviteterne fra skovrejsning bidraget med 184 Gg $CO_2$-ækvivalenter til den danske reduktionsforpligtigelse i den første forpligtigelsesperiode (2008-2012). Skovrydning bidrog negativt med 439 Gg $CO_2$-ækvivalenter, skove fra før 1990 bidrog med 1 172 Gg $CO_2$-ækvivalenter, Cropland Management med 8 250 Gg $CO_2$-ækvivalenter og Grassland Management bidrog negativt med 552 Gg $CO_2$-ækvivalenter. Samlet set bidrog arealanvendelsesaktiviteterne med 8 614 Gg $CO_2$-ækvivalenter til den danske reduktionsforpligtigelse.

Resultaterne fra SINKs-projektet har forbedret den danske afrapportering til FN betydeligt samt øget forståelsen for kulstofdynamikken i det danske landskab.

# 1 Background

Denmark ratified the Kyoto Protocol on 31 May 2002. The Danish ratification included the Danish and the Greenlandic territory. By this, Denmark agreed on to reduce its greenhouse gas (GHG) emission with 21 % in the first commitment period (2008-2012) in relation to the base year emission (1990).

The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change, which commits the Parties by setting internationally binding emission reduction targets.

The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005. The detailed rules for the implementation of the Protocol were adopted at COP7 in Marrakesh, Morocco, in 2001, and are referred to as the "Marrakesh Accords." Its first commitment period started 1 January 2008 and ended 31 December 2012.

The Danish ratification includes Greenland but excludes the Faroe Islands. Denmark has in its ratification included a burden sharing decision within the Danish Kingdom with Greenland. Another burden sharing decision was made internally between 15 European Member states (EU-15). In total EU-15 agreed on an 8 % reduction of its greenhouse gas emissions in the first commitment period running from 1 January 2008 to 31 December 2012 compared to the base year emissions in 1990. Within the EU-15 burden sharing decision Denmark has adopted a reduction commitment of 21 % compared to 1990. In the emission estimates all gases must be included, as mentioned in Annex A of the KP, and $CO_2$ emissions from Afforestation, Reforestation and Deforestation made after 1 January 1990 (Article 3.3 of the KP). Furthermore, it was possible, according to article 3.4, to elect activities such as Forest Management (FM), Cropland Management (CM), and Grassland Management (GM) and Re-vegetation (RV) to be included in the reduction commitment.

In addition to the mandatory inclusion of emissions from Afforestation (A), Reforestation (R) and Deforestation (D) in the reduction target as mentioned in Article 3.3 of the KP, Denmark elected the voluntary measures: Forest Management (FM), Cropland Management (CM) and Grassland Management (GM) under article 3.4 to be included in the Danish reduction commitment.

Both the mandatory emissions under article 3.3 and the elected article 3.4 activities need thorough documentation for both the activities since 1990 and for the present emissions. Although Denmark has many data and registries related to the land use, several types of data were missing for a complete reporting. Among other, some of the main missing data were the obligatory estimation of the forest area in 1990 and onwards, the afforested and deforested area since 1990, estimation of the land use change in general, valid estimates of the area with organic agricultural soils and sufficient information on soil carbon stocks in the Danish forests.

Consequently Denmark initiated a larger research and development project in order to document the activities and the emissions. In addition to the development of the reporting framework specific research was carried out on the following topics:

- Developing a land use matrix from 1990 and onwards covering the major six IPCC land use classes (IPCC, 2003) and subdivisions. This classification differs from what normally can be found in the national statistics on land use
- A new map for the agricultural organic soils, as major changes from the latest map on organic soils produced in 1975 was foreseen. Moreover the 1975 classification followed a Danish approach which differed from the classification of organic soils as defined by IPCC in the international guidelines
- Development of Danish emission factors from organic soils
- Documentation of changes in the agricultural mineral soils. For this purpose a modelling approach was chosen corresponding to the IPCC Tier 2 model. Due to a number of measures, which have been introduced in Denmark on crop growing for realising various policy goals it was assumed that a modelling approach would best reflect the overall changes in the soil. This would be based on a model for all biomass input to the soil (above-ground and below-ground biomass for all crop types, combined with a degradation model for organic matter in the soil). Furthermore was it decided to make an independent verification of the soil model by analysing soil samples from the agricultural soil sampling grid (Kvadratnettet). The agricultural soil sampling grid was created in 1987 and is based on a 7 x 7 $km^2$ grid covering the whole area of Denmark. The grid was sampled for the first time in 1987 and part of it in 1998. Hence, it was decided to resample the plots again in 2009 as an independent verification of the carbon stock model of agricultural soils
- Documentation of the amount and changes in the carbon stock in living biomass in the rural landscape (outside the forest). This is primarily hedgerows and smaller biotopes not meeting the forest definitions
- Development of Danish biomass expansion factors (BEF) for beech and spruce
- Documentation that Danish forest soils are not a source and development of a carbon stock baseline for forest soils
- Estimation of drained forest soils and the $N_2O$ emission from these soils
- Documentation of nitrogen leaching in watersheds and to coastal water bodies.

The project was initiated in 2008. Final activities were carried out in 2013. In total 72 million. Danish Kroners (approx. 10 million €) was allocated to these tasks. Of this, 50 % was allocated to soil sampling and production of the new soil map for the organic soils.

The final report is divided into three chapters:

- Development of the land use matrix (Chapter 4)
- Forest issues (Chapter 5)
- Agricultural and other landscape issues (Chapter 6)

This report does not include the latest information on carbon stocks and carbon stock changes over time. For this is referred to the Danish National Inventory Reports for Greenhouse gas emissions at www.dce.au.dk

# 2 The Land Use Matrix 1990 to 2012

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This section describes the current land use matrix (LUM) in the Danish GHG inventory and how it is developed and updated. The current method used in the Danish GHG inventories differs considerable from the initially intended method. The main reason is the fast development in Danish geo-referenced thematic data and registries on many different topics from the very local level, to regional and national levels, which have changed the focus from intensive use of remotely sensed data to a dominant use of thematic data layers in vector format combined with remote sensing data, where no other data are available, primarily on forest areas.

Denmark is now covered by many digital map products and in combination with open access to almost all spatial and registry data on land use it has been possible to develop a rather detailed LUM for the latest years. Future inventories will continue to be produced from these updated data. Back towards 1990 the uncertainty increases, but for future reporting it has been decided to construct the LUM on the currently best and most detailed data. It implies that the uncertainty in the map layers back in time is larger than the present.

The accuracy of remote sensed data is usually not larger than 85 % without using auxiliary information. With the developed methodology it is believed that the accuracy exceeds this level in the LUM for 2011. The accuracy is lower for areas where no good spatial data are available; one example being the location of the boundary between natural habitats and forest.

## 2.1 State of art of data for LULUCF 2006

One of the major task and challenges in the reporting and accounting was to develop an annual land use matrix for the six major land use classes as mentioned in the IPCC guidelines (IPCC, 2003). The six land use classes are:

- Forestry
- Cropland
- Grassland
- Wetlands
- Settlement
- Other Land

While a land use/land cover map had been produced during the latter part of the 1990s (the Area Information System - AIS map), no continuous map update, which would allow the identification of these classes and changes between them existed when Denmark adopted the article 3.3 and 3.4.

The forest area is increasing. In year 1800 it was around 2 % of the Danish area, today around 14 %. A political goal is that 20 % of the area should be afforested in 2080. The forest area was previously estimated from questionnaire based surveys carried out among forest owners, but lack of responses and uncertainties of definitions implied large uncertainties to the estimates. E.g. in 1990 the forest area was estimated to 445 000 hectares and in 2000 the area had increased with 41 000 hectares to 486 000 hectares. Although the aim of the Danish forest policy is to increase the afforested area this increase could also partly be attributed to an increase in number of forest owners included in the questionnaires. For the other IPCC land use classes there was very little information on the development over time.

The agricultural share of the Danish land areas is high. Formerly it covered more than 70 % of the total area. This has gradually decreased over the years and today agriculture covers approximately 62 % of the area according to Statistics Denmark (www.dst.dk).

## 2.2 The planned and the realized project

Since the SINKs project was initiated a rapid development has taken place in Denmark on the amount and accessibility of geo-referenced data. This has changed the initial planned methodology for the land use matrix from being based on remote sensing combined with auxiliary vector data to be based on the most credible vector data combined with remote sensing for areas where no good vector data with applicable IPCC needed information is available. This is primarily for forest.

The Land Use Matrix was planned as a follow up on a previous GMES program (the European Earth Monitoring programme) for Denmark (http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Forest_Monitoring_Services) combined with auxiliary vector data sets.

### Agricultural land use

The agricultural land use is based on the European Union subsidy system for agriculture. This includes information on the crops grown by the individual farmers on each land parcel. A land parcel is defined as piece of land surrounded by relative stable structures in the landscape such as forest borders, roads, streams etc. Within the same land parcel several different crops can be grown. The system was initiated in 1996 but the first reliable dataset was from 1998 or even from 2000. In the early years the subsidy system only included information on about 60 subsidized crops and not on e.g. grassland and fruit plantations etc. Today the Danish system covers more than 270 different crop types. One of the drawbacks for identifying cropland and grassland in the reporting context to UNFCCC within this system is that the information is based on the farmers' interpretation of what is permanent grassland and what is grassland in rotation. A consequence of this is that a piece of land one year could be reported as permanent grassland and the next is reported as being in rotation. The result is that every year a large area is floating from cropland to grassland and from grassland to cropland which creates noise in the reported land use matrix to the UNFCCC.

### Natura2000 dataset

The Natura2000 is a map of a network consisting of protected natural habitats in the European Union. These areas are meant to protect areas hosting threatened species or habitats over the EU territory. In Denmark a total of 252 Natura2000 areas covering 8.7 % of the total Danish land area and 17.7 % of the Danish sea area have been designated as Natura 2000 sites (http://www.naturstyrelsen.dk/Naturbeskyttelse/Natura2000). For each area a conservation plan is produced. Overall the plans aim to avoid the natural re-growth turning grasslands into forest on 130 000 hectares, halt the desiccation of 16 000 ha of wetlands and avoid fragmentation on 20 000 hectares of forest. For each Natura2000 plan there is information on the present status and crop cover. The plans are updated by the Danish municipalities.

### FOT

The FOT (Association for establishing a unified public topographic mapping) data collection was initiated in 2007 to establish a common geographical administration system for all public administration (http://www.fotdanmark.dk/). Today it covers almost the whole Danish territory. The FOT system includes data related to traffic, technical elements, hydrology, natural areas etc. as well as topographical information. The FOT-data are continuously updated by the ministerial agencies, the municipalities and contractors to the public, with irregular intervals for different themes and varying definitions.

All maps are reported in the default Danish classification, ETRS_1989_UTM_Zone_32N.

The first map products were produced by December 2009 for the years 1990 and 2005 respectively and a change map for the years 2005 to 1990. Analysis of the maps showed several severe errors in the products when compared to aerial photos and other map products. Due to these problems an area matrix of yearly land use changes from 1990 to 2005 was developed using additional layers from topographic maps substituting the originally planned method based on the spectral signatures of the Landsat satellite imagery combined with auxiliary data. Multi-temporal imagery was used, implying that additional images for either 1990 or 2005 were used to enhance the quality of the end-product. A second map product was considered as almost finalized by end of 2010, and this LUM contributed to the Danish reporting in spring 2010.

In 2011 it was increasingly realized that the uncertainty related to the satellite based maps were still too large and that the maps generated were not directly useful for the emission inventories, due to inconsistencies with other register data. Hence, a methodological shift was decided, and the land cover matrix for 2011 was based primarily on available thematic data and georeferenced registry data, keeping the satellite image interpretation to producing the forest cover maps for 1990 and 2005.

Despite the LUM is primarily based on thematic maps there are still some gaps in knowledge of the land use in areas not covered with this type of information. This concerns especially some forest areas. It was therefore decided to acquire a map based on remote sensing from 2011.

Based on the methods developed for the 2011 map, methods and procedures for the establishment of the future land cover matrix and emissions is developed and described in the Danish National Inventory Report.

The final version of the LUM and how it is developed is described in a separate Technical Report from DCE (Levin et al., 2014).

## 2.3 Final version

The estimation of land use changes is based on a mapping of the extent and change between the 6 land use types, as defined by the IPCC guidelines (IPCC, 2003). In the final version, wetlands have been divided into fully water covered and partly water covered. Except for forest, the mapping was based on available, pre-classified spatial information. The terrestrial area, which is defined as the inland land area above the highest tidal limit, forms the physical frame for the estimation of land use changes. The coastal area from the inland tidal limit to the seaward extend of vascular plants is very limited in Denmark. In cases where these exist it is often salt marches and these are included in Grassland / Other Land. The land area is based on a vector map from TOP10DK. The total Danish “land area” is estimated to 43 055.5 $km^2$. It is assumed that the total terrestrial area of Denmark has not changed during the period assessed.

The geographical projection applied for all the data layers used is UTM ETRS1989 zone 32 N. Except from the forest layer outside settlements, all input layers is in vector format. All vector data were converted into raster format with a cell size of 25 x 25 $m^2$ (matching the forest layer).

Small updates in the registry data, e.g. higher precision in the location of roads or in the field boundaries can create a land use changes which in fact are not taking place. Therefore, a minimum change of eight pixels, equivalent to a Danish forest minimum mapping unit of 0.5 hectares, has been applied before a land use change is implemented in the maps. This is considered a conservative estimate.

Table 2.1 Prioritization hierarchy of input layers for land use map for 2011.

| Priority | Input layer |
|---|---|
| 1 | Sea |
| 2 | Settlement |
| 3 | Other land |
| 4 | Field parcel map (cropland, grassland, forest) |
| 5 | Wetland (fully water covered) |
| 6 | Forest |
| 7 | Wetland (partly water covered) |
| 8 | Grassland |

### 2.3.1 Settlement - built up land and infra structure

The built-up layer is based on 12 object types derived from FOT (2011), The Area Information System (AIS, 1999) and from the cadastral map combined with the Danish building register (BBR, 2012). The infrastructure layer was based on 4 object types derived from FOT (2011).

### 2.3.2 Cropland and Grassland

Cropland is defined as land intensively utilized for agricultural purposes. Grass in rotation is included in Cropland. No rice cultivation and agroforestry occur in Denmark. Grassland is defined as agricultural permanent grassland which is used for grazing and other areas where the vegetation is maintained at a state not meeting the forest definition or the definition of Settlements, Wetlands and Other land. Grassland includes among other heathland, salt marches, military training areas, power lines etc.

#### Changes in cropland and grassland

Information about agricultural land use has not been available at field parcel scale for the whole country before 2010. Therefore, the estimation of land use changes including cropland and grassland was based on information at field block scale. Field blocks are aggregates of up to 10-15 field parcels. Information about agricultural land use at this scale has been available since 1998.

The Danish map of field blocks (NaturErhverv, 2013) is being adjusted continuously. Consequently, field block boundaries have been altered over the years and are not consistent in time and space. In order to establish one field block map, which is consistent for the period assessed, field block maps from 1998, 2005 and 2011 were overlaid and combined to 203 969 field blocks in 2011 (aggregated field block map).

As information on agricultural land use for the years 1998 and 2005 was only available at the scale of field blocks, LU-changes including agricultural land use could not be precisely located.

### 2.3.3 Wetland - fully water covered

Fully water covered wetlands are defined as lakes and other permanent water bodies which are saturated by water all year round. These wetlands are represented by the object type lake in the registration of protected habitat types. Although registrations of protected habitats do exist for the early 1990s, changes in habitat types, including lakes are mainly the result of changes in registration methods and increasing precision of the demarcation of habitat boundaries, rather than actual changes in habitats. Therefore, estimations of changes involving fully water covered wetlands were carried out in combination with the other input layers. The current maps with lakes are often relatively crude - especially for the smaller lakes that are often mapped larger than they are in reality. The on-going update of the FOT maps increases the precision of the lake map. One result of this is that the area with lakes may decrease in the future. As the lakes are protected in Denmark such update are artefacts and not a result of actual changes. These artefacts are not possible to fully eliminate due to lack of precise data in the past.

### 2.3.4 Wetlands - partly water covered

Partly water covered wetlands are defined as areas covered or saturated by water part of the year and areas with peat extraction. Partly water covered wetlands include: bogs, freshwater meadows, coastal meadows and marshlands if these are not included in Grassland. Historical information for these land use types is not readily available. Therefore, estimations of changes involving partly water covered wetlands were treated in combination with the other input layers as described in section 2.4.

### 2.3.5 Forest

Forest is defined as woody vegetation with a minimum tree crown cover of 10 %, a minimum area of 0.5 ha, a minimum width of 20 m having the ability to be higher than five meters. This also includes newly afforested areas, which in the future will reach a tree height of minimum five meters. In addition the forest area includes temporarily unstocked areas, smaller open areas in the forest needed for management purposes, and fire breaks. Forests in national parks, reserves, or areas under special protection are included. Windbreaks and groves meeting the forest definition are also considered as forests. Conifers for production of Christmas trees and poplar (*Populus spp.*) for energy production are reported under forest.

Fruit plantations for commercial purposes, orchards, gardens etc., which might be able to reach the forest definitions in terms of crown cover are reported in Cropland. Willow (*Salix spp.*) plantations on agricultural soils for bioenergy production are also included in Cropland as these have a harvest rotation period of 2-3 years.

Based on the satellite images forest maps of land cover forest were established for 1990, 2005 and 2011. A minimum mapping unit of 0.5 ha was applied, eliminating minor woody groups in the landscape and minor technical corrections. To obtain forest land use, some additional steps was needed. Primarily, tree cover within settlement areas (e.g. summer houses, parks and suburban areas), were excluded from the forest theme. This was obtained by combination with the settlement layer in the relevant years. It was necessary to determine if a change from forest cover to non-forest cover indeed was deforestation or a temporarily unstocked forest area. The latter can be a result of forest management, as the Danish Forest Act allows a 10 year period for reforestation following a clear-cut. For this purpose supplementary data layers of nature restoration in public forest areas were utilised to confirm transition from forest to grassland. These processes will be further developed in the coming years, as more forest mapping will be performed.

In addition to the satellite based registration of forest, field parcels, which are used for afforestation, are registered in the field parcel map. These field parcels were added to the forest layer.

### 2.3.6 Other land

Other land is defined as areas falling outside the other five classes. It is defined as beaches and sand dunes and have no or very limited carbon stock both as living or dead biomass and as carbon in the soil. Other land as represented in applied input datasets from 2011 were decided to be representative for the whole period from 1990 to 2011. I.e. in the final estimation of land use changes, other land does not change.

## 2.4 Land Use Change from 1990

Due to lack of good forest data and other important data back in time it was decided to use three reference years 1990, 2005 and 2011 only. In this period a linear land use change interpolation has been implemented in the greenhouse gas inventory between 1990 and 2005 and between 2005 and 2011. Future annual updates will be made with annually updated vector data sets for all sectors except forest. Afforestation on subsidized agricultural cropland and grassland is now implemented in the EU Land Parcel Identification System (LPIS) registry and therefore available. This accounts for a major part of the afforestation in Denmark. Deforestation will occur when new updated maps document a permanent transition to non-forest. The FOT data is updated in a continuous process in some cases. In other cases there is a 4-5 years rotation in the updating. For these cases there will be a delay before the effect on the land use change is implemented in the greenhouse gas inventory. This delay will only have limited effect on the actual Danish greenhouse gas inventory.

Figure 2.1 shows an example of the land use change from 2005 to 2011

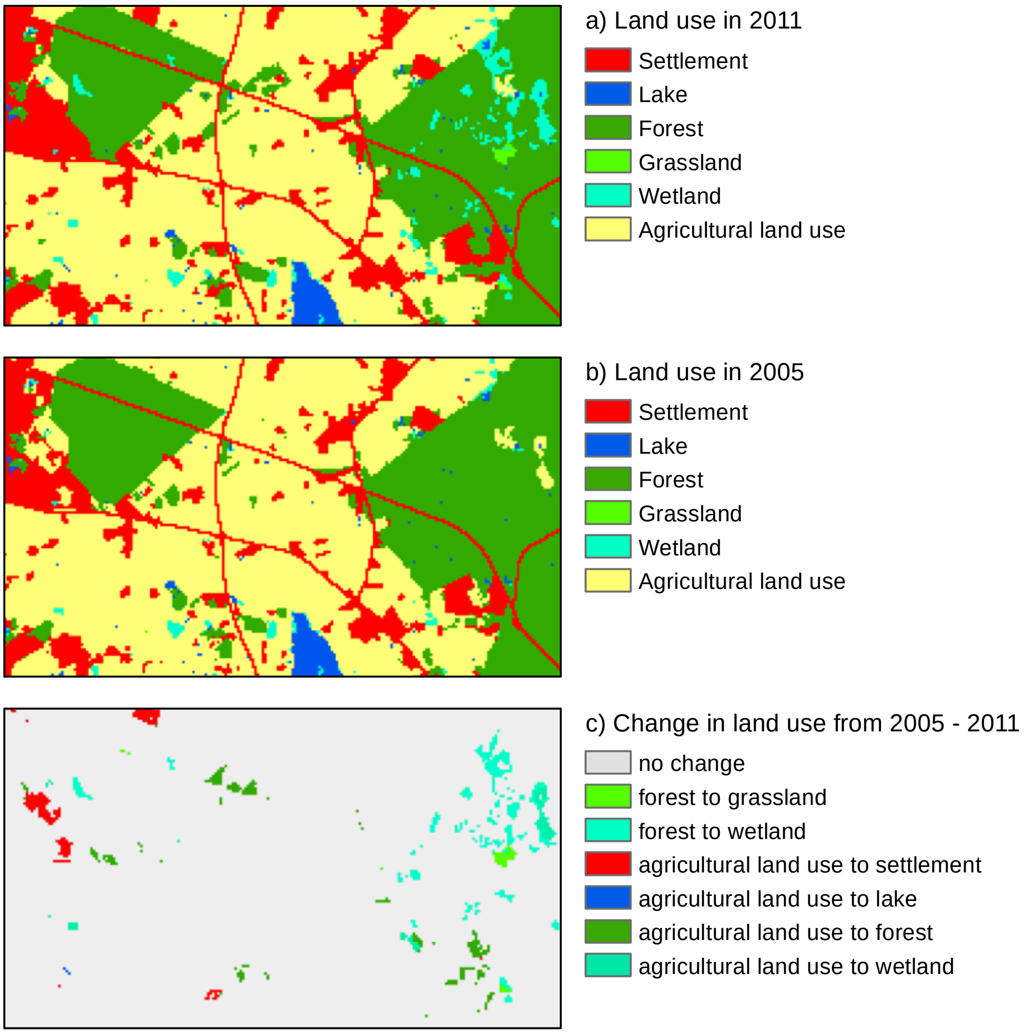


Figure 2.1 Illustration of analysis of land use changes from 2005 to 2011. The land use map for 2011 (a) was overlaid with available land use information for 2005 (b). Based on this overlay, changes were assigned to each cell (c).

In 2011 approximately 135 000 ha (or 3 % of the terrestrial area) remained unclassified. I.e. none of the applied input layers contained information for these cells. Of these, 130 000 ha were narrow zones with a width of equal to or less than two cells (50 meters). Assuming that these unclassified zones were the consequence of topological uncertainty due to uncoordinated registration of applied input datasets, cells within these zones were assigned to the land use / land cover type of the closest adjacent cell. The remaining approximately 6 000 ha unclassified areas were assigned to the grassland layer.

The resulting land use change matrices from 1990 to 2005, from 2005 to 2011 and 2011 to 2012 is shown in Table 2.2, 2.3 and 2.4. The major change is an increase in the area with Settlements mainly from Cropland and Grassland as the urbanisation is taking place on the agricultural land around the major cities. The total new area with Settlements from 1990 to 2012 has been estimated to 25 868 hectares.

The Danish policy to create more natural habitats and wetlands are expressed in the LUM as an increase in the area with lakes of 5 734 hectares and in the area with partly water covered wetlands with 16 859 hectares. A small change from Wetland to Cropland has been observed. Based on interpretation of aerial photos it looks as if the farmers have claimed an increase of grass in rotation at the expense of wet meadows.

A steady increase in the afforested area has taken place giving rise to a forest increase of 88 575 hectares since 1990. The major part of the afforestation is taking place on cropland and grassland which deliberately is not kept open. Deforestation has been estimated to 5 784 hectares. This is mostly due to the increase in settlements and infrastructures, construction of a large wind turbine research facility in Northern Jutland and the governmental policy of increasing the open areas in the state forests.

The area with Cropland and Grassland has decreased in parallel to the increase the Forest and the Settlement area. This corresponds to the surveys from Statistics Denmark.

From 2011 to 2012 the FOT data has been updated for settlements with a changed method from single parcels towards whole settlement areas. This has been sought corrected as it has resulted in larger changes to settlements in some cities.

Table 2.2 Land Use Matrix 1990 to 2005, in hectares.

| 1990 \ 2005 | Settlement | Lake | Forest | Grassland | Other land | Wetland | Cropland | Grand Total |
|---|---|---|---|---|---|---|---|---|
| Settlement | 485 543 | 0 | 0 | 0 | 0 | 0 | 0 | 485 543 |
| Lake | 0 | 58 358 | 0 | 0 | 0 | 0 | 0 | 58 358 |
| Forest | 172 | 94 | 542 219 | 506 | 0 | 74 | 908 | 543 973 |
| Grassland | 6 338 | 1 313 | 31 025 | 350 349 | 0 | 1363 | 11 986 | 402 374 |
| Other land | 0 | 0 | 0 | 0 | 26 433 | 0 | 0 | 26 433 |
| Wetland | 15 | 0 | 1 | 0 | 0 | 70 493 | 0 | 70 509 |
| Cropland | 6 338 | 1 313 | 31 778 | 28 607 | 0 | 10 149 | 2 640 178 | 2 718 362 |
| Grand Total | 498 406 | 61 079 | 605 023 | 379 462 | 26 433 | 82 078 | 2 653 072 | 4 305 552 |

Table 2.3 Land Use Matrix 2005 to 2011, in hectares.

| 2005 \ 2011 | Settlement | Lake | Forest | Grassland | Other land | Wetland | Cropland | Grand Total |
|---|---|---|---|---|---|---|---|---|
| Settlement | 498 406 | 0 | 0 | 0 | 0 | 0 | 0 | 498 406 |
| Lake | 1 | 61 078 | 0 | 0 | 0 | 0 | 0 | 61 079 |
| Forest | 138 | 252 | 601 357 | 1 073 | 0 | 2 071 | 132 | 605 023 |
| Grassland | 6 421 | 1 378 | 14 852 | 313 309 | 0 | 1 913 | 41 590 | 379 462 |
| Other land | 0 | 0 | 0 | 0 | 26 433 | 0 | 0 | 26 433 |
| Wetland | 25 | 6 | 17 | 0 | 0 | 81 472 | 558 | 82 078 |
| Cropland | 6 421 | 1 378 | 14 852 | 8 319 | 0 | 1 913 | 2 620 191 | 2 653 072 |
| Grand Total | 511 411 | 64 092 | 631 077 | 322 701 | 26 433 | 87 369 | 2 662 471 | 4 305 552 |

Table 2.4 Land Use Matrix 2011 to 2012, in hectares.

| 2012 / 2011 | Settlement | Lake | Forest | Grassland | Other land | Wetland | Cropland | Grand Total |
|---|---|---|---|---|---|---|---|---|
| Settlement | 511 411 | 0 | 0 | 0 | 0 | 0 | 0 | 511 411 |
| Lake | 0 | 64 092 | 0 | 0 | 0 | 0 | 0 | 64 092 |
| Forest | 1 | 0 | 630 714 | 133 | 0 | 0 | 230 | 631 077 |
| Grassland | 2 625 | 0 | 109 | 298 784 | 0 | 18 | 21 164 | 322 701 |
| Other land | 0 | 0 | 0 | 0 | 26 433 | 0 | 0 | 26 433 |
| Wetland | 31 | 0 | 0 | 0 | 0 | 87 335 | 2 | 87 369 |
| Cropland | 2 644 | 0 | 1 725 | 12 674 | 0 | 13 | 2 645 415 | 2 662 471 |
| Grand Total | 516 712 | 64 092 | 632 547 | 311 592 | 26 433 | 87 367 | 2 666 811 | 4 305 552 |

### 2.4.1 Future data needs for update of the land use matrix

It is assumed that the thorough monitoring on the activities in the Danish landscape will continue in the near future. It is thus expected that the currently used data on settlements and roads will be available, as well as extraction sites, lakes and rivers. It is further more assumed that Natura 2000 areas will be continuously monitored thus enabling the update of reported land use and land cover.

For the agricultural area the Danish farmers are currently obliged to report the precise location of each individual field every year to The Danish AgriFish Agency. It is assumed that in the future this will take place at the same level as today and hence there is no need for further data collection. The issue mentioned above concerning the conversion between Cropland and Grassland will also continue in the future. This problem is also encountered in many other countries reporting to UNFCCC and cannot easily be solved as the interpretation of permanent grassland in practical farming will often differ substantially from the IPCC terminology.

As Denmark has chosen that ‘Other Land’ only accounts for beaches and sand dunes and a few other marginal areas without any carbon stock, the majority of the area with natural habitats is included in the land use category Grassland where it is managed for nature conservation purposes. Part of this Grassland is allowed to grow into forest if it is outside Natura2000 habitats. A registration of areas developing into forest this way is currently not taking place. Therefore there is a need for an update of specifically these areas either with remote sensing data, LiDAR analysis or vector maps or combinations of these.

The estimated area with partly water covered wetlands has a high uncertainty. Despite that this area may sequestrate carbon it also emits $CH_4$ from the natural decomposition of organic matter. It would therefore be advisable to establish a more close monitoring system of the natural and constructed wetlands which include the water level and fluctuations.

The FOT information update takes place in a 4-5 years rotation. This implies a delay of the implementation of the real land use change in the inventory. Hence it is preferred to report consistent land use changes, and this is in accordance with the reporting guidelines from IPCC.

# 3 Forest issues

The forest area and the carbon stock in the Danish forest were poorly understood in the 1990s. To increase the knowledge on this and other issues a sample based National Forest Inventory was initiated in 2002.

On forest the overall SINKs project included four issues:

- Mapping the forest area in 1990, 2005 and 2011
- Development of Danish Biomass Expansion Factors (BEF) for Norway spruce, beech and oak
- For the carbon stock in forest soils there is very little information available and especially knowledge on the carbon stock change. It was therefore decided to resample the forest plots in the agricultural soil sampling grid (https://www.landbrugsinfo.dk/planteavl/goedskning/naeringsstoffer/kvadratnet-for-nitratundersoegelser/sider/startside.aspx) initiated in 1987 and initialise sampling in the National Forest Inventory network for to establish a reference baseline for these plots in 2008-2010
- The major part of the Danish forests is drained, which results in $N_2O$ emission from the soils. The Danish forest policy is to return the forest to a more natural stage and it was therefore decided to develop a map of the forest soils containing information on drainage status.

## 3.1 Living biomass in forest

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Until 2000 the Danish forest inventory was based on decennial censuses made by Statistics Denmark (www.dst.dk) based on a land owner questionnaire. This census was not complete both in terms of area, tree species and age. In 2000 it was decided to develop a National Forest Programme based on the changing conditions for the Danish forest sector and the obligations outlined in the various international agreements and conventions to which Denmark is a party. The Department of Geosciences and Natural Resource Management (IGN) at the Copenhagen University is responsible for producing the annual Danish National Forest Inventory. See e.g. (Skove og Plantager, 2012)

A new sample-based National Forest Inventory (NFI) was initiated in 2002 (Nord-Larsen et al., 2008). This type of forest inventory is very similar to inventories used in other countries, e.g. Sweden or Norway.

Previously there was no differentiation in the statistics on the Afforestation (A), Reforestation (R) and Deforestation (D) after 1990 as well as Forest Management (FM) as required under the Kyoto Protocol. Further evaluation of the data was wherefore needed to fulfil the requirement for reporting and accounting under the Kyoto Protocol.

### 3.1.1 NFI

The national forest inventory was initiated in 2002. The NFI is a continuous sample-based inventory with partial replacement of sample plots based on a 2 x 2 km grid covering the Danish land surface. In each grid, a cluster of four circular plots (primary sampling unit, PSU) for measuring forest factors (e.g.

wood volume) are placed in a 200 x 200 m grid. Each circular plot (secondary sampling unit, SSU) has a radius of 15 meters.

About one third of the plots is assigned as permanent and is re-measured in subsequent inventories every five years. Two thirds are temporary and are moved randomly within the particular 2 x 2 km grid cell in subsequent inventories. The sample of permanent and temporary field plots has been systematically divided into five non-overlapping, interpenetrating panels that are each measured in one year and constitute a systematic sample of the entire country. Hence all the plots are measured in a 5-year cycle.

Table 3.1 Number of measured clusters and sample plots in the five year rotation 2006-2010. Forest covered sample plots not inventoried in the field are denoted "Missing".

| | Clusters | | | Sample plots | | |
|---|---|---|---|---|---|---|
| Year | Total | Forest | Missing | Total | Forest | Missing |
| 2008 | 2 212 | 804 | 2 | 8 644 | 1 896 | 3 |
| 2009 | 2 195 | 783 | 0 | 8 604 | 1 800 | 0 |
| 2010 | 2 196 | 793 | 0 | 8 614 | 1 855 | 0 |
| 2011 | 2 173 | 850 | 0 | 8 520 | 1 896 | 0 |
| 2012 | 2 200 | 908 | 0 | 8 617 | 1 978 | 0 |
| Total | 10 976 | 4 138 | 2 | 42 999 | 9 425 | 3 |

Each plot is divided into three concentric circles with radius 3.5, 10 and 15 m. Several parameters are collected at each plot, where the data of specific interest for the carbon accounting relates directly to the assessment of living forest biomass, the dead wood pool and the assessment of soil organic matter and soil types. Furthermore, the assessment of the origin of the forest stands is central to the subsequent evaluation of afforestation and reforestation. In cases of removal of forest cover, the subsequent land use is central to the estimation of either temporarily unstocked areas or deforestation.

In relation to the SINKs project a number of calculation programmes and validation procedures have been developed and implemented to be able to document the development in the fully forested area according to the classifications needed. This especially combines the information from the satellite based land use mapping with the NFI field data to obtain stable and consistent estimation of the carbon pools related to all the classes. In this process information on land use mapping in 1990 is combined with real observations from the NFI plots on carbon pools, forest origin (e.g. afforestation) and age of the trees and the forest. For deforestation, the mapping challenge is supported by the NFI field inventory, as the land use can directly be observed. The transformation from temporarily unstocked to the full deforestation is closely linked to the results of the update of the land use matrix.

In the calculations of the carbon pools the results of the forest projects dealing with BEFs, with forest soils and drainage is incorporated in the systematic update of the calculations. For more technical description see the NIR reporting and the regular updated publications on the NFI, e.g. Skove og Plantager 2012 (Johannsen et al., 2013).

Furthermore, the results from the forest projects under the SINKs project have been utilised for the Forest Management Reference Level calculations for the next commitment period.

### 3.1.2 BEF values

In the NFI plots tree diameter and height are measured for the estimation of the total amount of biomass. For estimating the total carbon stock an expansion factor (Biomass Expansion Factor, BEF) need to be applied. The BEF is here defined as the ratio between total tree and above-ground biomass. The BEF is a multiplication factor which takes into account the carbon stock in small branches, leaves and roots. The BEF value varies according to growing conditions, where e.g. a tree grown in an open space will have a large BEF due to many branches and a tall, dense and old forest will have a low BEF due to few branches.

In the project plan Danish BEFs should be developed for Norway spruce (*Picea abies*), beech (*Fagus sylvatica*) and oak (*Quercus robur*). Due to high costs of digging and measuring the roots from large trees it was decided to focus on Norway spruce and beech, which are the main tree species in Denmark.

#### Methods

The objective of this study was to analyze the within-tree allocation of biomass and to develop biomass functions for above- and below-ground components of European Norway spruce and beech in Denmark. Separate functions were developed for stem, branches, below-ground stump and root system, total above-ground biomass, and total tree biomass. For each of these components or aggregate components, models were also developed for the average basic density of wood and bark. To enhance the versatility of the models a function for estimating the biomass expansion factor (BEF) was also developed.

#### Beech

Functions were based on 66 trees measured for total biomass. Predictive performance of the models for above-ground biomass was 25 evaluated based on 74 trees measured only for above-ground biomass. The trees were sampled in 18 different forest stands covering a wide range of tree sizes and stand treatments. Models were estimated using a linear mixed-effects procedure to account for within-stand correlations. The functions for biomass and BEF included only diameter at breast height and total tree height for individual trees as predictor variables. Inclusion of additional variables reflecting site quality and stand density did not improve model performance. The functions for basic density included individual tree diameter, tree height and quadratic mean diameter as predictor variables, indicating an effect of stand density on the basic density of wood and bark.

Material and data for this study originated from 18 different stands of beech in Denmark and were collected and analysed during March 2002 to February 2010. In nine stands, a total of 66 trees were measured for total biomass, including branch wood, stem, stump and roots, while 17 additional trees were measured only for total above-ground biomass or parts thereof. In the remaining nine stands root excavation was undesirable for various reasons, and 57 trees were measured for above-ground biomass or parts thereof.

All stands selected for this study were located on glacial till. All stands were essentially even-aged, of local origin and located on ancient forest land. Eight stands originated from natural regeneration, eight had been seeded and two had been planted. Age ranged from 18 to 111 years, stand residual stem number (N) from 49 to 46 578 trees per ha, stand basal area (G) from 1.4

to 40.8 $m^2ha^{-1}$, and stand top height (H100, arithmetic mean height of the 100 thickest trees per ha) from 4.3 to 32.9 m. The variation in site index was remarkably small. All stands were intact and complete at the time of sampling.

The management record of the selected stands is generally well documented. Fourteen stands were experimental plots in long-term thinning trials, while four stands were operational with no or little record of past management practices. The experimental stands were selected to span the widest possible range of thinning practices ranging from unthinned control plots to plots subjected to extremely heavy thinning at regular intervals. The operational stands were selected to complement the range of site types and age classes represented by the experimental stands. The operational stands generally had been managed with medium to heavy thinning at more or less regular intervals. Plot size generally ranged from 0.08 to 0.43 ha.

Approaching the same issue with a paired t-test, power analyses (Dupont and Plummer, 1990) indicated that the number of sample trees could be reduced to five per stand, assuming similar power specifications and, again, a detection limit at five percent. Lowering the detection limit to the same magnitude as the within-stand coefficient of variation resulted in increasing the recommended number of sample trees per stand to ten, while a detection limit at two thirds of the coefficient of variation would require 20 sample trees per stand. Based on a combination of budget constraints and the desire to detect possible effects of site or silviculture on the basic density of beech, it was consequently decided to preferably sample ten trees per stand in the final phase of the project (subject to the above-mentioned modifications).

The stem was in this study defined as the above-ground principal ascending axis of the tree from which buds and shoots are developed. A total of 136 trees from 18 stands were sampled for stem biomass. Each sample tree was felled and measured for diameter at breast height (dbh), total length or height, and total stem volume. Next, stem discs or stem segments were sampled at regular intervals along the stem for determination of basic density (R) and dry weight (dw).

The below-ground stump and root system (hereafter generally referred to as the root system) is in this study defined as the below-groundbelow-ground part of the tree which includes the below-groundbelow-ground part of the stump and the large perennial roots and smaller feeder roots. A total of 66 trees from 11 stands were sampled for their root system. Root systems for measurement were carefully excavated and extracted from the soil, taking great care to include all roots down to an approximate diameter of two mm or less. Broken-off root fragments were collected and labelled for subsequent measurements. Following extraction, each root system was carefully rinsed in water and any possible loss was assessed (no loss was recorded for any of the root systems included in the investigation).

Developed biomass models included only the effects of individual tree size (diameter and height). In addition to tree size, growing conditions and intertree competition influence the allocation of biomass within the tree (Bartelink, 1998). Consequently, indicators of site quality, stand density and individual tree competitive status have been shown to significantly improve biomass equations for different tree components (Alemdag & Stiell, 1982, Wutzler et al. 2008). Prior to the study, it was expected that owing to the wide range of thinning treatments it would be possible to detect possible effects of stand treatment in the resulting biomass models. However, variables related to growing conditions or inter-tree competition did not improve accuracy of the biomass models for any of the tree components.

In the absence of treatment effects on wood density, the only treatment effects likely to affect beech tree biomass is the effect of treatment on allocation of volume and thus biomass to different tree components (branches, stem and root system).

The BEF was relatively large and highly variable for small trees but rapidly declined to a stable or slightly increasing level around 1.2 when dbh exceeded 20 cm. The overall level of the BEF corresponded well with those reported by Van de Walle et al. (2005) which ranged from 1.23-1.25.

### Results

The main emphasis during model development has been the application with NFI data for predicting Danish national carbon pools. Previous to this project national biomass stocks (and subsequently carbon pools) have been estimated using total above-ground volume functions for beech, a basic density of beech wood of 560 kg $m^{-3}$, and a BEF of 1.2 (Nord-Larsen et al., 2008). Based on data collected during the most recent five-year rotation of the Danish NFI (2005-2009), the total biomass is estimated at 18.71 million tonnes. Using the biomass equations for total tree and above-ground components derived from this study, total biomass is estimated at 19.72 million tonnes and the average BEF is estimated at 1.22. If instead the biomass is estimated from total above-ground volume and the wood density and BEF functions derived from this study, then total biomass is estimated at 19.35 million tonnes.

### Norway spruce

Separate models were developed for branches (including foliage), stem and root system as well as for aggregate components: total above-ground biomass, and total tree biomass. Trees were sampled in 14 forest stands reflecting the range of growth conditions and thinning practises of Norway spruce in Denmark. The data included measurements of biomass and basic density from 114 trees of which two were outliers excluded in the final model estimation. Final models reflected known properties of tree growth and allocation of biomass among different tree components of even aged Norway spruce. The models were successful in predicting biomass, basic density and biomass expansion factors across a wide variety of tree sizes, stand treatments and growth conditions.

All plots were located in landscapes, which were formed mainly during the last ice age. Plots in Central Jutland were located on an outwash plain with soils derived from fluvioglacial deposits in front of the ice margin and influenced by subsequent aeolian processes. All stands were essentially even-aged and of plantation origin.

The resulting biomass models and their parameter estimates reflected the expected effects of tree size as the biomass of all tree components increased with increasing dbh. The observed decrease in biomass for the crown and increase for the stem and roots with increasing h (for a given dbh) is probably an effect of allocation of biomass towards the structural components of the tree when the tree height and thereby stress on the lower part of the stem and roots increases (Nielsen, 1990).

In summary, all available data has been used in calibrating the biomass and basic density models for Norway spruce in Denmark, using contemporary modelling practices. The models were successful in predicting biomass, basic density and BEF across a wide range of tree sizes, stand treatments and site conditions. Thus, they are likely to improve national estimates of carbon pools and biomass resources when applied with NFI data.

Stem basic density decreased with dbh and site index (SI), reflecting the decline in basic density with increased growth and thus increased ring width in soft woods. It may seem counterintuitive that basic density increases with increasing dbh as ring width generally decreases with tree size (above a certain threshold) leading basic density to increase (Bergstedt and Olsen, 2000). However, in the model the general level of stem basic density increases with the quadratic mean diameter (Dg). Differences in growth (and thereby basic density) is subsequently reflected in the lower basic density of fast growing stems.

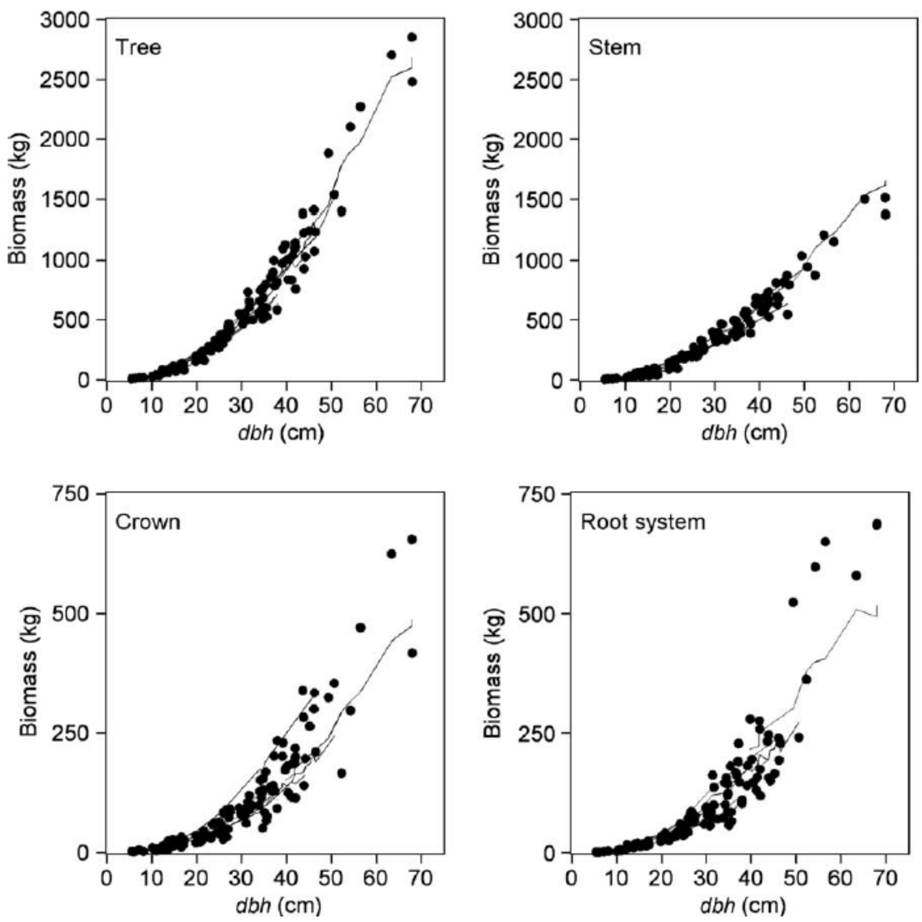


Figure 3.1 Observed and predicted biomass for different biomass components for beech. Legend: ● are observed biomass for sample trees used in the estimation procedure, and ∆ are trees used for model validation. Predictions (full line) are based on the fixed effects only and with correction for logarithmic bias.

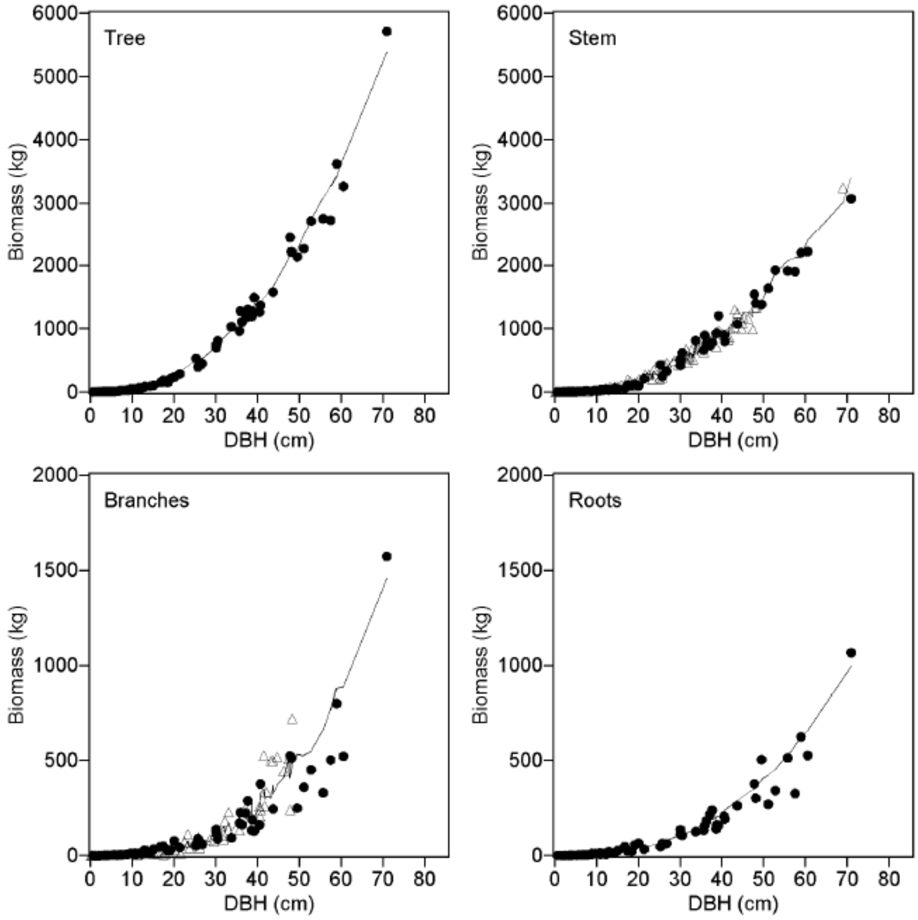

Figure 3.2 Scatter plots of the total tree (including dead branches), stem, crown (including dead branches) and root system biomass in Norway spruce versus dbh for the 112 trees used in the final model. Lines represent predictions for individual plots.

#### Results

The main emphasis during model development has been the application of NFI data for predicting Danish national carbon pools. Previous to this project national biomass stocks (and subsequently carbon pools) have been estimated using total above-ground volume functions from stem biomass to total biomass for Norway spruce a BEF of 1.8 (Nord-Larsen et al., 2008). The new data showed a variable value depending on stem diameter with a mean value of 1.5. The developed model has been implemented in the NFI for Norway spruce. As a consequence the standing C-stock of living biomass has been reduced.

#### Conclusions and recommendations

The overall conclusion from this project is that the previously used BEF values can be updated with national data. The new values has been implemented in the National Forest Inventory and therefore in the reporting to UNFCCC and under the Kyoto Protocol. Furthermore it improves the uncertainty estimate. It is assumed that the new data reflect the national conditions better than the default IPCC values.

## 3.2 Forest soil classification and drainage

This project was initiated to establish a map of forest soil types with the specific aim of qualifying the emission estimates of $N_2O$, $CO_2$ and $CH_4$ from forest soils. It is especially needed to locate areas with emission factors deviating from the main forest soils based on the presence of organic or mineral soil, fertile or poor soil, and moist or dry condition.

The project resulted in a systematic procedure for assigning values related to these factors for all the NFI sample plots. The procedure was validated by comparing the observed values of both the NFI observations of soil characteristics and the results of the forest soil project. The final product is implemented in the forest carbon calculations and is included in the NFI database DKSKOV.

The method is based on categorical combination of the different data sources and with validation by the field data from the NFI. The methods applied are based on the georeferenced values of the NFI plots, in combination with the Geological Soil maps from GEUS. The resulting analyses revealed a higher proportion of organic soils in the afforestation areas than in the forest area established before 1990.

The resulting soil type estimates for the forest area classifications are implemented in the carbon calculations.

Table 3.2 The distribution of the forest area in the NFI on different soil types.

| | Forests established before 1990 | Forests established after 1990 | Total |
|---|---|---|---|
| Soil type | ha | ha | ha |
| Total | 539 080 | 68 998 | 608 078 |
| Loamy | 158 412 | 16 687 | 175 099 |
| Sandy | 354 680 | 46 693 | 401 373 |
| Organic | 25 988 | 5 618 | 31 606 |

The classification of the moist-dry proportions of the forest area is based on the registrations by the NFI. Here the presence of ditches and their state is recorded. Hereby the basic information for the moisture of the forest area is established. There are no ditches on 84 % of the forest area, while the ditches in half of the remaining area are in poor condition. This reflects the reduced efforts to drain the forest area.

The classification of the fertility of the forest area is based on the recorded height, growth and age of the trees. Hereby all the forest area is classified by fertility, reflecting the combination of tree species and growth conditions, i.e. the combined effects of soil, weather, genetic composition and management. This approach is commonly applied in forest growth modelling.

## 3.3 Carbon stocks in forest soils

*Main contributing authors: Lars Vesterdal, Inge Stupak, Ingeborg Callesen*

In 2006 very limited systematic and representative information were available on changes in forest soil C-pools in Denmark, and previous reporting under the Convention has almost solely included above-ground- and below-ground biomass C-pools. New data from the National Forest Inventory (NFI) would also enable reporting on the dead wood C-pool, but soil C changes remained to be addressed. Based on available knowledge and expert opinions, there is little basis for expecting large changes in forest soil C stocks in forests remaining forests compared to 1990. Denmark has therefore applied the “non-source principle” for reporting of forest soil C dynamics under the Kyoto Protocol.

Based on literature and expert knowledge there is little evidence to support that the soil C-pool in remaining forest would change to an extent that would be detectable by sampling. For well-drained soils there may be changes in soil carbon stocks at high spatial resolution (hectare-level) due to clear-cutting and replanting, but for the entire forest area with the whole range of age classes soil carbon stocks can be assumed to be nearly unchanged. In fact, the Danish change in management towards close-to-nature forestry with continuous crown cover and abandonment of clear-cutting suggests an increase in soil carbon stocks rather than depletion (Brunner et al., 2005; Yanai et al., 2000). Areas with wet forest soils have probably been sources for increased $CO_2$ emissions in a period after ditching and drainage activities took place from the late 19th century. These activities led to increased mineralization of peat soils. However, during the last 20 years, drainage activities have diminished strongly and has completely ceased in state forests. Here, the natural hydrological conditions are often actively restored by filling up ditches. It is expected that this change in management will lead to sequestration of carbon as these forest areas gradually get wetter. However, quantitative information is currently not available.

The main documentation for the first commitment period has been obtained by resampling in the national agricultural 7 x 7 km$^2$ soil sampling grid. The soil sampling grid was established in 1986 for monitoring of nitrate leaching from different land uses. 110 of the plots in the grid was forest. These were sampled in 1988. Furthermore, 22 plots were converted to forest during 1990 to 2007.

The forest plots in the agricultural soil sampling grid may fail to provide a picture of C dynamics for wet forest soils, and the number of plots is probably not sufficient to detect probable changes in forest soil C. Power analyses based on non-systematic forest soils data (150-200 sites) indicate that more sites are necessary to detect changes in mineral soil C-pools of <10 % and forest floor C-pools changes of <30-40 %. Additional soil monitoring plots was therefore selected among the permanent plots of the recently established NFI to provide a baseline for later resampling of forest soil C-pools.

For assessment of temporal change in soil C stocks, the historical samples from 1990 from the plots in the 7 x 7 km$^2$ agricultural soil sampling grid were retrieved, and all plots were resampled during the period 2007-2009. The forest plots in soil sampling grid have not been actively monitored since 1993. Sampling of forest floors was area-based. Soil carbon stocks were then estimated based on the measured area-based forest floor dry weights, measured soil carbon concentrations, and bulk density functions (for mineral soil), resulting in estimates by 1990 (forest floors 1994, only 25 plots) and 2007-2009, respectively. The analyses include 122 plots, of which 107 plots are forest remaining forest since 1990 (FRF), and 15 plots are forest afforested since 1990 (AFF).

Table 3.3 Land use matrix for the forest plots in the agricultural soil sampling grid pre 1990 and in 2007.

| | Forest 2007 | Cropland 2007 | Heathland 2007 | Total |
|---|---|---|---|---|
| Forest <1990 | 110 | 1 | 1 | 112 |
| Cropland < 1990 | 15 | | | 15 |
| Heathland <1990 | 1 | | | 1 |
| Grassland < 1990 | 0 | | | 0 |
| | 126 | 1 | 1 | 128 |

The analysis of soil C change relies on the existence of soil samples or their associated C data from around 1990. During the review of sampling protocols, it turned out that forest floors were not initially (1986/87) sampled as a part of the forest soil profile, but was removed before soil coring. The samples are stored in the soil archive of Danish Agricultural Advisory Service (Figure 5.3). The data from agricultural soil sampling grid were reanalysed for C, while estimates of forest floor C stocks around 1990 had to be obtained from the Danish soil profile database, which includes soil profile data from each plot.

Figure 3.3 The soil archive at Danish Agricultural Advisory Service.

#### Methodology

Soil samples were collected from 10 fixed positions along a 70 m transect across the 50 x 50 m agricultural soil sampling grid.

Forest floors were collected from defined areas of 25 x 25 cm whereas mineral soil was sampled from five fixed layers of 0-10, 10-25, 25-50, 50-75, 75-100 cm. The difference from previous sampling methodology is that forest floor mass is quantified directly and that the 0-25 cm mineral soil layer is subdivided, as forest soils are not homogene in this layer as are cropland soils. The bulk density was estimated in three ways, i.e. by using previous information on bulk density and by separately applying two pedotransfer functions developed using the profile information data from the same plots (Vejre et al., 2003; Østergaard & Mamsen, 1990).

The sampling plots within the forest have not previously been georeferenced, but just defined by a marking pole. Therefore a considerable effort was made to locate the marking poles. The marking poles are now georeferenced by use of a Global Positioning System (GPS) as well as the end of the transects across the sampling plots.

Department of Geosciences and Natural Resource Management (IGN) were responsible for sample preparation prior to chemical analyses of carbon (C) and nitrogen (N). The chemical analysis was performed by Agrolab Sarstedt, Germany.

A power analysis of the detectability soil C changes was made, based on the best current knowledge of the statistical variability in forest soil C. A summary of results is given in Table 5.4. The 110 plots of agricultural soil sampling grid with forest remaining forest do not enable a certain assessment of changes in forest floors. However, smaller relative changes would be detectable in the larger mineral soil pool.

Table 3.4 Limits for detectable change in forest floor C-pools, mineral soil C-pools 0-30 cm and mineral soil pools 0-100 cm in case of using level I, agricultural soil sampling grid or Agricultural soil sampling grid +NFI. Power analysis with power=0.90. The variability in soil C stocks used in the analysis includes all tree species with a representation similar to that at the national level.

| | No. plots | Forest floor | | Mineral soil 0-30 cm | | Mineral soil 0-100 cm | |
|---|---|---|---|---|---|---|---|
| | | tC/ha | % | tC/ha | % | tC/ha | % |
| Level 1 | 25 | 10.5 | 84 | 17.8 | 27 | 29.3 | 26 |
| Agricultural soil sampling grid | 110 | 4.8 | 39 | 8.2 | 12 | 13.5 | 12 |
| NFI (estimate) | 700 | 1.9 | 15 | 3.2 | 5 | 5.3 | 5 |
| NFI+ Agricultural soil sampling grid | 810 | 1.8 | 14 | 3.0 | 5 | 4.9 | 4 |

124 plots were included in the analysis, from the 126 forest plots in agricultural soil sampling grid. These are now all georeferenced for later sampling, photos of plot locations, forest floors and mineral soil cores, information on stand types, measurements of forest floor depth, and samples of forest floors and mineral soils are now sampled. See map of agricultural soil sampling grid plots below (Figure 3.4).

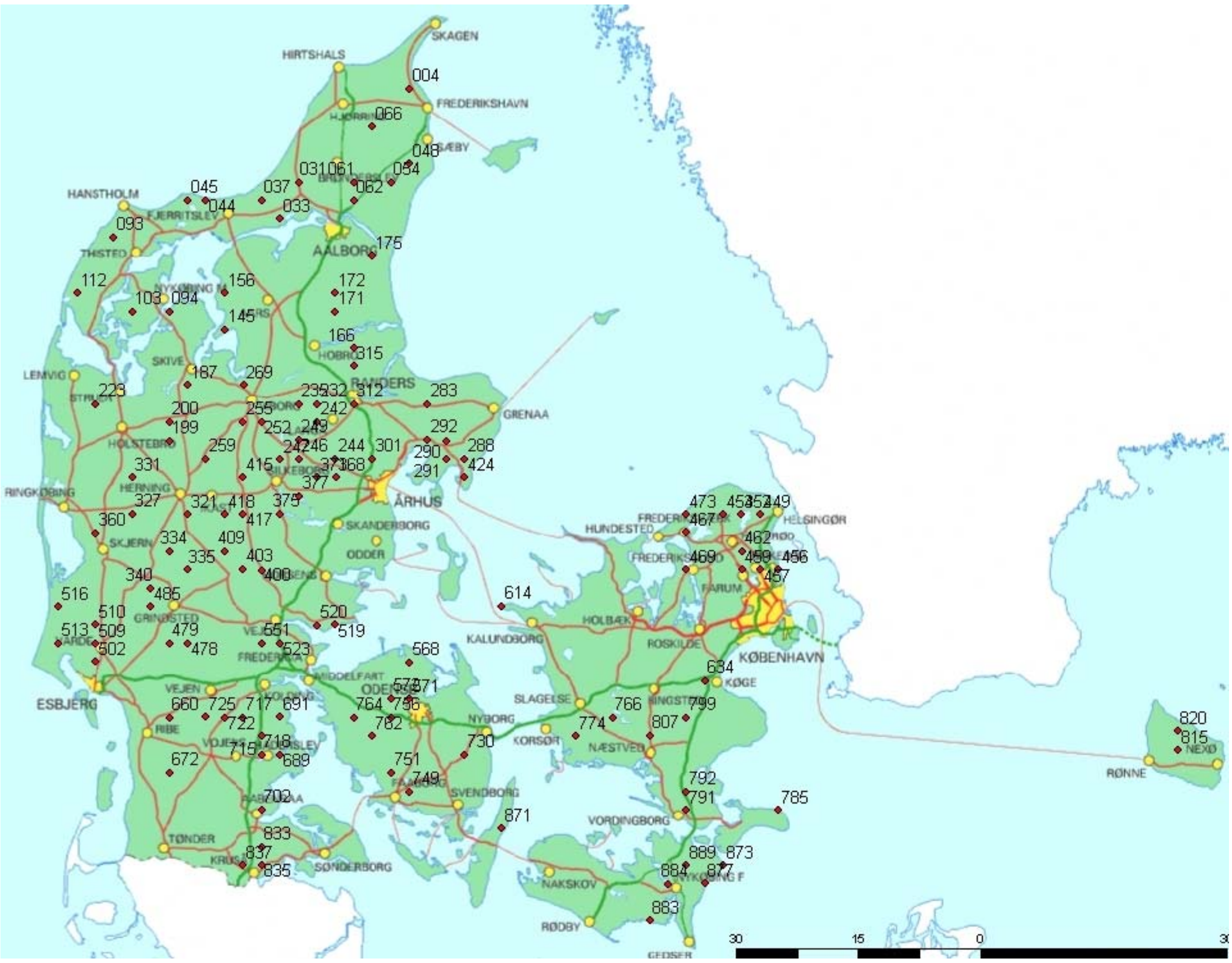


Figure 3.4 Map of the 124 forest locations in a soil sampling grid sampled in 2007-09 (SINKs+Biosoil).

#### Data evaluation for the forest plots in the agricultural soil sampling grid

Forest floor C stocks were evaluated during the resampling at all sites. Forest floors in afforested sites generally have lower C stocks (age <20 years) compared with sites with forest planted before 1990. Figure 3.5 shows a chronosequence analysis of the afforested sites indicating increasing forest floor C stocks with time since afforestation took place. Afforested sites with Christmas tree plantations generally have lower forest floor C stocks.

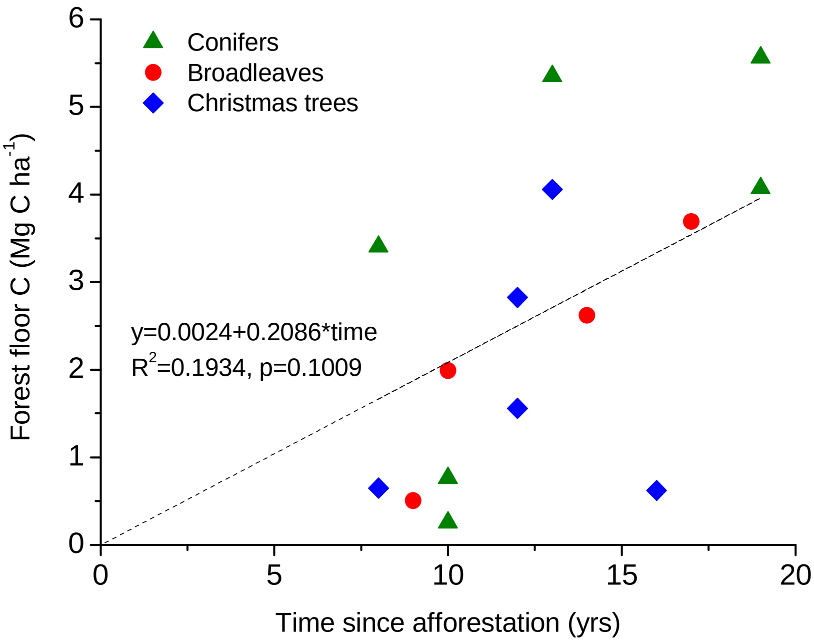


Figure 3.5 Effect of afforestation since 1990 on mass of forest floor C stock in the Agricultural Network. Forest floor C stock along a chronosequence based on 15 afforestation plots. Christmas tree plantation plots and high forest plots of broadleaves and conifers are shown separately.

### Power analyses

In order to analyse the detectability of soil C changes depending on the number of inventory plots for repeated sampling a power analysis was conducted. Figure 3.6 and Table 3.5 shows the results for detectability for forest floor C, mineral soil C in 0-30 cm and mineral soil C in 0-100 cm based on agricultural soil sampling grid alone and the agricultural soil sampling grid plus an additional 300 NFI plots. Based on this, it was concluded that increasing the numbers to more than the forest plots in the agricultural soil sampling grid and the NFI plots did not add significantly to the estimate for the soil carbon stock in forest soils. For future investigations it was therefore recommended to have approximately 400 soil sampling plots in the forests.

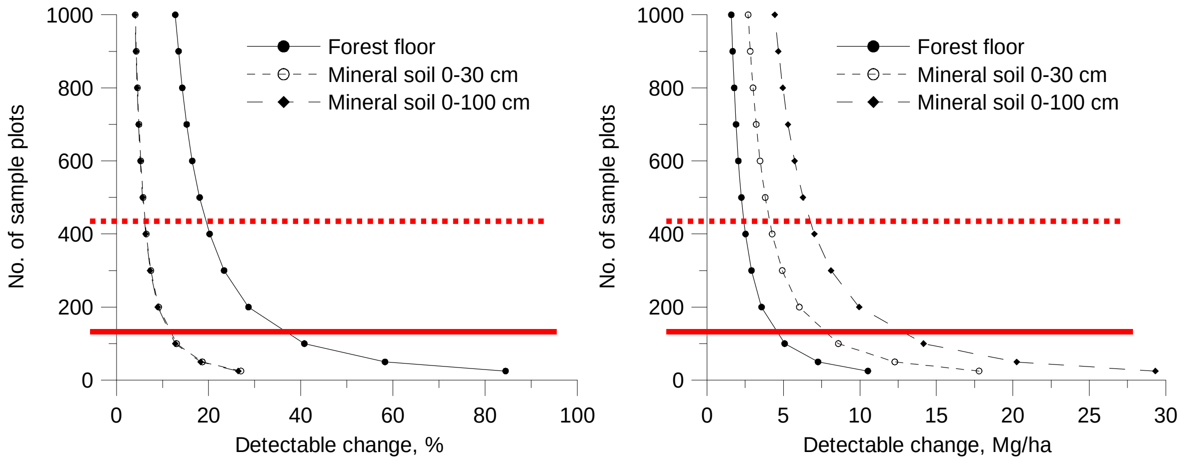


Figure 3.6 Detectable change in soil C based on power analyses for forest floor and two mineral soil compartments. The lower line indicates the detectable change using only the agricultural soil sampling grid and the upper line indicates detectable change based on the agricultural soil sampling grid plots and additional NFI plots.

Table 3.5 Detectable change using level I, the agricultural soil sampling grid, the agricultural soil sampling grid +NFI. Power=0.90. All tree species at national level.

| | No. plots | Forest floor | | Mineral soil 30 cm | | Mineral soil 100 cm | |
|---|---|---|---|---|---|---|---|
| | | tC/ha | % | tC/ha | % | tC/ha | % |
| Level 1/Biosoil | 25 | 12.4 | 101 | 22.0 | 33 | 36.4 | 33 |
| Agricultural soil sampling grid | 124 | 5.4 | 44 | 9.6 | 14 | 15.8 | 14 |
| NFI (suggested) | 300 | 3.5 | 28 | 6.1 | 9 | 10.2 | 9 |
| NFI+ soil sampling grid | 424 | 2.9 | 23 | 5.1 | 8 | 8.5 | 8 |

### Field sampling campaign in National Forest Inventory plots

It was originally planned to sample soils in 300 plots of the NFI as a baseline for later monitoring of temporal change. Soil samples were collected in a subset of 278 plots from the permanent National Forest Inventory plots from November 2009-May 2009. The deviation in the number of plots sampled was mainly caused by discovery that plots did not comply with the definition of Forest Remaining Forest, i.e. with too low forest cover to qualify as forest, or the lack of access to waterlogged plots. The data from the 278 NFI plots have been analysed together with information on biomass and dead wood C stocks and soil C data have been combined with the recent samples from the agricultural soil sampling grid (400 plots) for analysis of soil C stocks and how they vary with environmental variables (e.g. forest type, soil type, drainage) and previous land use (1954-2009).

The sampling design differs from agricultural soil sampling grid as plots are circular with a diameter of 15 m. 278 so-called SSUs (see Figure 3.7) were sampled. This equals 140 so-called PSUs that are clusters of up to four SSUs located in the 2 x 2km grid. SSUs are sampled only if their area is covered by more than 50 % forest (i.e. forest SSUs with >50 % cropland, gardens etc. are not sampled due to too few samples per plot). Apart from the sampling design, the sampling methodology is similar to that described for the agricultural soil sampling grid above.

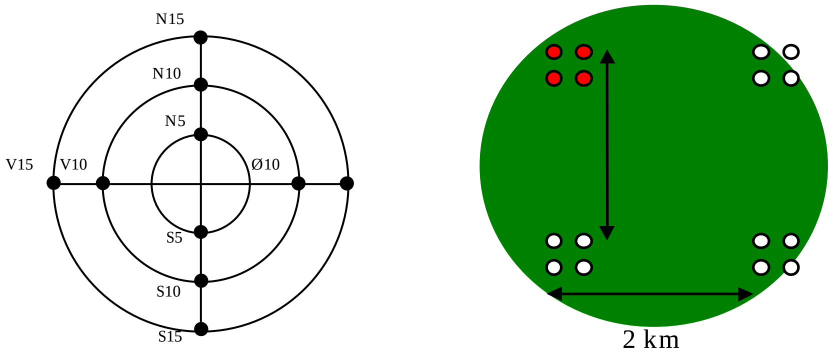


Figure 3.7 Sampling design in NFI plots (SSU, radius 15 m) that are located in a 200 x 200 m square. This cluster of up to four SSUs is called the PSU.

### Soil carbon pools for Forests Remaining Forests since 1990

In Table 3.6 is shown simple statistics of the sampling in the agricultural soil sampling grid.

Table 3.6 Simple statistics on carbon pools in Danish forest soils 0-100 m's depth (i.e. excluding forest floors) as distributed to mineral and organic soils (organic if it contains C concentrations above 10 % in one or more horizons). Results are based on data from forests remaining forest since 1990 from the 7 x 7 $km^2$ grid ("Agricultural soil sampling grid"), a total of 108 plots.

| Soil category | Soil type category | Species category | Number of sites | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|---|
| | | | | | tonnes $ha^{-1}$ | | |
| Mineral soils | - | Broadleaves | 38 | 141 | 30 | 54 | 197 |
| | | Conifers | 52 | 127 | 47 | 19 | 208 |
| | | Mixed | 8 | 141 | 40 | 88 | 189 |
| Organic soils | - | Broadleaves | 6 | 420 | 223 | 255 | 853 |
| | | Conifers | 3 | 323 | 82 | 236 | 400 |
| | | Mixed | 1 | 412 | - | 412 | 412 |

Results from the more comprehensive statistical analyses showed significant differences between soil C stocks in sandy and loamy forest soils (FRF). There was little evidence to suggest that FRF sandy forest soils changed their total soil C stocks during 1990-2009 (Table 3.7), but reductions in soil C stock of deeper soil layers were significant. Loamy soils seemingly increased their carbon stocks significantly, due to increased pools in the upper soil (0-50 cm) and the forest floor.

Table 3.7 Statistical analysis of the data from the Agricultural soil sampling grid, Forest Remaining Forest (FRF) 1990 to 2009

| Depth | $C_{2007-2009}/C_{1990-1994}$ | 95 % confidence interval | | $C_{2007-2009} - C_{1990-1994}$ | Rate of change | P |
|---|---|---|---|---|---|---|
| | | Lower limit | Upper limit | t C $ha^{-1}$ | kg C $ha^{-1}$ $yr^{-1}$ | |
| Loamy soils | | | | | t C $ha^{-1}$ | |
| Forest floor | $1.23^{*}$ | 1.01 | 1.50 | $1.12^{*}$ | $80^{*}$ | 0.041 |
| 0-25 cm | $1.34^{***}$ | 1.26 | 1.43 | $19.65^{***}$ | $1092^{***}$ | <0.001 |
| 25-50 cm | $1.18^{***}$ | 1.10 | 1.26 | $5.09^{***}$ | $283^{***}$ | <0.001 |
| 50-75 cm | $0.95^{ns}$ | 0.88 | 1.03 | $-0.76^{ns}$ | $-42^{ns}$ | 0.242 |
| 75-100 cm | $0.97^{ns}$ | 0.87 | 1.07 | $-0.34^{ns}$ | $-19^{ns}$ | 0.535 |
| 0-100 cm | $1.22^{***}$ | 1.14 | 1.31 | $23.64^{***}$ | $1313^{***}$ | <0.001 |
| 0-100 cm + forest floor | $1.17^{*}$ | 1.00 | 1.37 | $24.77^{*}$ | $1394^{*}$ | 0.046 |
| Sandy soils | | | | | | |
| Forest floor | $0.96^{ns}$ | 0.79 | 1.16 | $-0.59^{ns}$ | $-42^{ns}$ | 0.658 |
| 0-25 cm | $1.04^{ns}$ | 0.98 | 1.11 | $2.66^{ns}$ | $148^{ns}$ | 0.190 |
| 25-50 cm | $0.91^{**}$ | 0.86 | 0.97 | $-3.00^{**}$ | $-167^{**}$ | 0.005 |
| 50-75 cm | $0.74^{***}$ | 0.69 | 0.79 | $-5.47^{***}$ | $-304^{***}$ | <0.001 |
| 75-100 cm | $0.75^{***}$ | 0.68 | 0.83 | $-2.54^{***}$ | $-141^{***}$ | <0.001 |
| 0-100 cm | $0.98^{ns}$ | 0.92 | 1.05 | $-8.36^{ns}$ | $-465^{ns}$ | 0.621 |
| 0-100 cm + forest floor | $0.92^{ns}$ | 0.81 | 1.05 | $-8.95^{ns}$ | | |

Significance level: * (p=0.9), ** (p=0.95), *** (p=0.99)

The average soil carbon stocks were also estimated, taking account of the significant differences between sampling times, soil types, and soil moisture conditions, as there were also significant differences in soil carbon between different moisture regimes (Table 3.8). The higher carbon pools of forests floors for sandy soils compared to loamy soils may also be related to tree species due to confounding between soil type and species, i.e. the proportion of broadleaved stands is larger for loamy soils than for sandy soils. There are significant differences between carbon stocks 0-100 cm in sandy and loamy soils for some soil layers, but the differences are not consistent over time, i.e. for measurements in 1990 compared to measurements in 2007-2009. Data will be analysed further to address the soil profile to 1 m as a whole, and not only separate layers and to fine-tune some other issues, e.g. soil moisture regime at the plots with the current status "unknown" (Table 3.8).

Table 3.8 Median carbon pools in 1990 and 2007-09 in soils of different texture and soil moisture regime.

| Soil type | Moisture | Time | Forest floor | 0-25cm | 25-50 cm | 50-75 cm | 75-100 cm | Total | 0-100 cm |
|---|---|---|---|---|---|---|---|---|---|
| Loamy | Unknown | t1 | 4.6 | 54.5 | 27.2 | 15.3 | 9.9 | 111.5 | 106.9 |
| | | t2 | 5.6 | 73.1 | 32.0 | 14.6 | 9.6 | 134.9 | 129.2 |
| | Well drained | t1 | 4.9 | 57.7 | 28.8 | 16.2 | 10.5 | 118.1 | 113.2 |
| | | t2 | 6.0 | 77.4 | 33.9 | 15.5 | 10.2 | 142.8 | 136.8 |
| | Poorly drained | t1 | 6.1 | 72.5 | 36.2 | 20.4 | 13.2 | 148.4 | 142.3 |
| | | t2 | 7.5 | 97.2 | 42.6 | 19.4 | 12.8 | 179.5 | 172.0 |
| Sandy | Unknown | t1 | 12.9 | 61.0 | 32.9 | 19.9 | 26.3 | 153.0 | 140.2 |
| | | t2 | 12.3 | 63.5 | 30.1 | 14.7 | 19.7 | 140.5 | 128.1 |
| | Well drained | t1 | 13.6 | 64.6 | 34.9 | 21.1 | 27.8 | 162.0 | 148.4 |
| | | t2 | 13.0 | 67.3 | 31.9 | 15.6 | 20.9 | 148.7 | 135.7 |
| | Poorly drained | t1 | 17.1 | 81.2 | 43.8 | 26.5 | 34.9 | 203.7 | 186.5 |
| | | t2 | 16.4 | 84.6 | 40.1 | 19.6 | 26.3 | 186.9 | 170.5 |

### Soil carbon pools for Afforestation since 1990, AR

Different types of data support that there is no significant change in mineral soil C stocks from 1990 to 2009 for soils that has been afforested since 1990 (Fig. 5.8).

No significant changes in soil C stocks 0-100 cm could be detected from 1990 to 2008-2009 for AR (Table 3.9), i.e. no change in soil C stocks 0-100 cm could be detected when cropland is converted to forest. A recent meta-analysis for northern Europe indicated that it usually takes at least three decades before former cropland soils become sinks for C (Bárcena et al., 2014a). Resampling of afforestation chronosequences in Vestskoven, Denmark, also indicated that mineral soils tend to loose carbon during the first three decades following afforestation; however, this loss is compensated by forest floor C sequestration during the first decades (Bárcena et al., 2014b).

Table 3.9 Cropland afforested since 1990: estimated median relative difference between forest soil C in 2007-2009 and 1990 ($C_{2009}/C_{1990}$), with lower and upper limits of the 95 % confidence interval, and p-values.

| Depth | $C_{2007\text{-}2009}/C_{1990}$ | 95 % confidence interval | | P |
|---|---|---|---|---|
| | | Lower limit | Upper limit | |
| 0-25 cm | $0.99^{ns}$ | 0.73 | 1.34 | 0.931 |
| 25-50 cm | $0.92^{ns}$ | 0.68 | 1.25 | 0.572 |
| 50-75 cm | $1.01^{ns}$ | 0.74 | 1.37 | 0.961 |
| 75-100 cm | $1.01^{ns}$ | 0.74 | 1.36 | 0.968 |

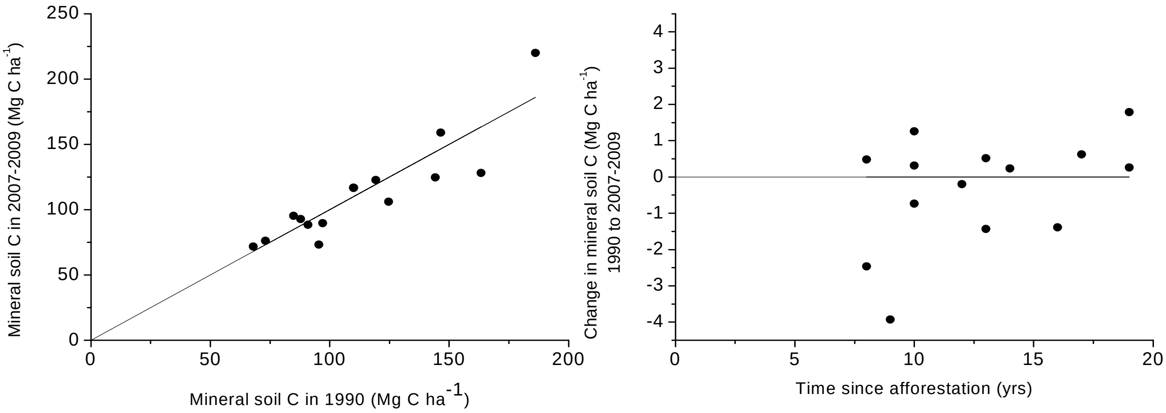


Figure 3.8 Carbon pools in forest floors of plots afforested since 1990 in the Agricultural soil sampling grid (left) and forest floor C stocks in the Agricultural soil sampling grid AFF plots plotted with forest floor C stocks in chronosequence studies and tree species experiments on former cropland. There is no significant change in carbon stocks between 1990 and 2009 for sites which have been afforested since 1990.

Carbon accumulates in the forest floor after afforestation, but it is also strongly influenced by factors other than time since afforestation and tree species (Figure 3.8).

### Comparing Forest Remaining Forest and Afforestation

Differences between carbon pools in FRF and AR soils could be significant for the 0-25 cm soil layer, both in 1990, when the plots were still cropland, and in 2008-2009 after the previous cropland had been afforested (Table 3.9). This may be an indication of a generally higher level of soil C in agricultural soils compared to forest soils, which is also evident for a short range of years after afforestation. A temporal decline in mineral soil C 10-20 years after afforestation has previously been reported from Vestskoven, Denmark (Vesterdal et al. 2002; Bárcena et al., 2014b), and from other countries as well. This decline is usually attributed to decomposition of agriculturally derived carbon while forest-derived carbon inputs to the soil are still low.

In 2008-2009 there was significantly more carbon in FRF than in AR soils for deeper soil layers (75-100 cm). This may be an indication that higher levels of soil C are present in deeper layers of forest soils compared to agricultural soils. However, the data material included rather few AR plots and therefore conclusions should be tempered. The differences may also originate from different distributions to e.g. soil types or moisture regimes among FRF and AR soils.

Table 3.10 Comparing forest remaining forest and forest afforested since 1990: estimated median relative difference between forest soil C in FRF and AR forest ($C_{FRF}/C_{AFF}$), with lower and upper limits of the 95 % confidence interval, and p-values (model [13]).

| Time | Depth | $C_{FRF}/C_{AR}$ | 95 % confidence interval | | $C_{FRF} - C_{AR}$ t C ha$^{-1}$ | P |
|---|---|---|---|---|---|---|
| | | | Lower limit | Upper limit | | |
| t1 | 0-25 cm | 1.40$^{**}$ | 1.11 | 1.76 | | 0.005 |
| | 25-50 cm | 0.98$^{ns}$ | 0.74 | 1.30 | | 0.896 |
| | 50-75 cm | 1.01$^{ns}$ | 0.78 | 1.31 | | 0.941 |
| | 75-100 cm | 1.15$^{ns}$ | 0.88 | 1.50 | | 0.299 |
| t2 | 0-25 cm | 1.62$^{***}$ | 1.29 | 2.03 | | <0.001 |
| | 25-50 cm | 1.14$^{ns}$ | 0.86 | 1.50 | | 0.366 |
| | 50-75 cm | 1.17$^{ns}$ | 0.91 | 1.51 | | 0.227 |
| | 75-100 cm | 1.33$^{*}$ | 1.02 | 1.75 | | 0.038 |

Significance level: * (p=0.9), ** (p=0.95), *** (p=0.99)

### Power analyses

The Agricultural soil sampling grid data originating from two points in time gave the possibility to estimate variances of the differences in carbon stocks between 1990 and 2009 and thus also the possibility to estimate detectable change in soil C stocks given different numbers of sampling plots. With about 400 sample plots (NFI+ Agricultural soil sampling grid) the detectable change would be about 2.4 Mg C ha-1 for forest floor + 0-100 cm, equivalent to a change of about 2 % of the total C-pool in the soil (Figure 3.9).

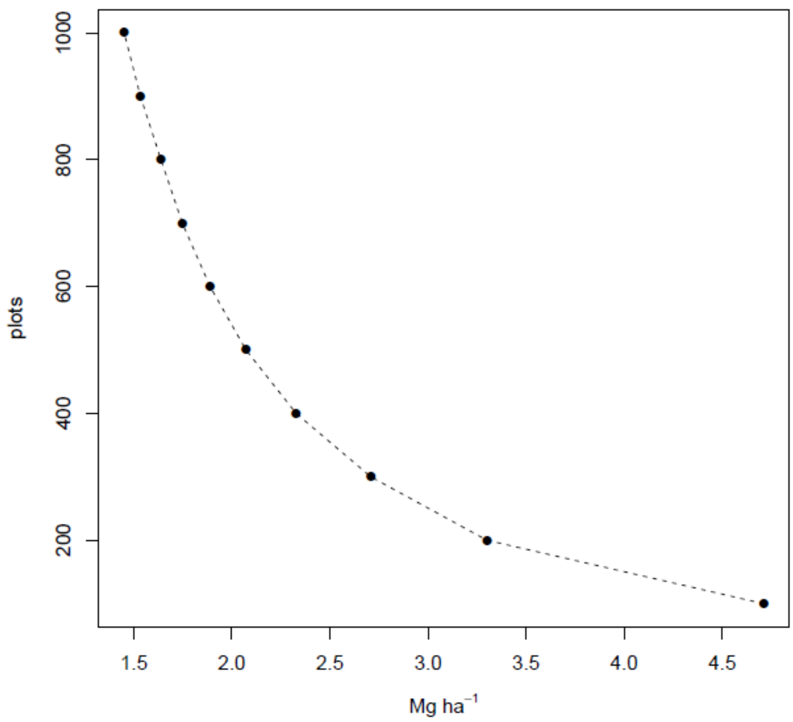


Figure 3.9 The number of plots needed to detect a certain change in forest soil C stocks (forest floor + 0-100 cm), power=0.8.

### Carbon stocks 2010 for the National Forest Inventory plots

The C stock data from NFI plots (278 plots) has increased the spatial density of soil C data at the national scale and also forms an important baseline for repeated sampling after >10 years. A next resampling inventory will therefore have much greater power to estimate possible soil C changes in Danish forest soils and forest C generally.

The average soil C-pools were estimated for the NFI and the agricultural soil grid data (Table 3.10). Pools for forest floors were estimated to be in average 15 tonnes C ha$^{-1}$. The average soil carbon pools, 0-100 cm, are somewhat higher for the NFI plots than for the Agricultural soil sampling grid. We suspect that the plots of the agricultural soil sampling grid might not always be located exactly at the grid intersections to avoid wet or excessively wet soil conditions. Rules were given for relocation of sample plots (200 m N, S, E or W), also when grid intersections were too close to the edge of the forest. We therefore expect that the NFI sampling better represents wetter forest soils that typically have higher C contents.

We have merged forest stand data from NFI with the soil C data from the NFI plots, with similar data being registered for the agricultural soil sampling plots. This allowed us to test differences in soil C-pools for different species, stand ages, soil conditions etc. Based on this combined baseline dataset from 2008-2009 from the agricultural soil sampling grid and the NFI (392 plots), soil C stocks in Danish forest floors are mainly influenced by the factor tree species category followed by previous land use, soil type and stand age. Mineral soil C stocks were mainly determined by soil type followed by soil moisture, previous land use and tree species (Figure 3.10).

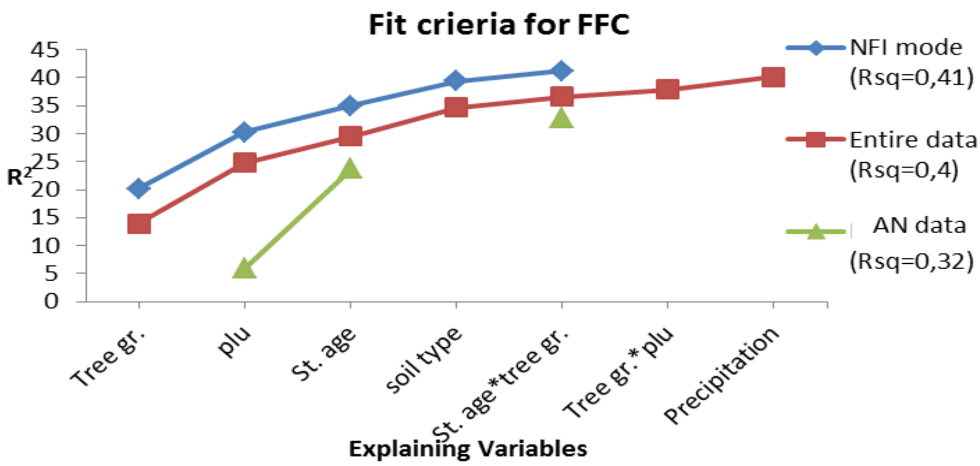


Figure 3.10 Explanatory model for forest floor C stocks. The graph shows the contribution of different site variables to the total explained variance (ca. 40 %) in forest floor C stocks (plu is previous land use).

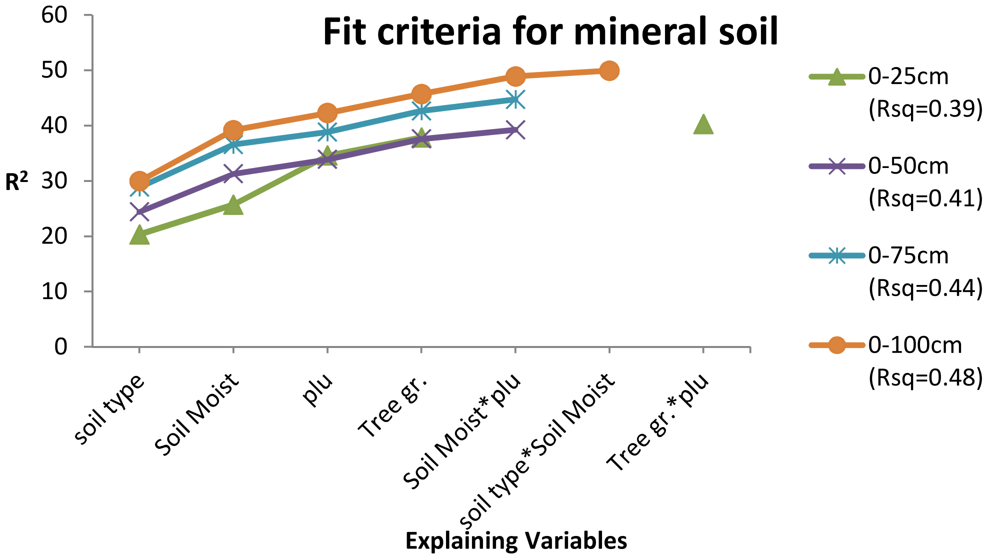


Figure 3.11 Explanatory model for mineral soil C stocks. The graph shows the contribution of different site variables to the total explained variance (ca. 50 % for C stocks 0-100 cm, plu is previous land use).

Separate analyses on NFI data only, including some extra stand and site variables that were only available for the NFI data mainly showed influence of tree species category (conifers, broadleaves and mixed conifers and broadleaves), stand age and precipitation on forest floor C stocks. The effect of precipitation may be confounded with an effect of soil type, as more sandy soils are located in areas with higher precipitation. The soil C stocks 0-100 cm depended significantly on soil type (sandy, loamy, organic) and tree species category, Table 3.11 and Figure 3.12-3.15.

Table 3.11 Simple statistics on measured soil carbon pools, 0-100 cm, in mineral (sandy and loamy) and organic soils in forest, based on the NFI and the agricultural soil sampling grid collected in 2007-2010.

| Soil category | No of sites | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| | | | t C ha$^{-1}$ | | |
| Sandy soil, FRF since 1990 (C conc. < 12 % for 0-25 cm) | 245 | 156 | 81 | 23 | 604 |
| Loamy soil, FRF since 1990 (C conc. < 12 % for 0-25 cm | 107 | 169 | 105 | 91 | 698 |
| Organic soil, FRF since 1990 (C conc. >=12 % for 0-25 cm) | 25 | 387 | 164 | 145 | 682 |
| Sandy soil, AR since 1990 (C conc. < 12 % for 0-25 cm) | 15 | 126 | 31 | 89 | 198 |
| Loamy soil, AR since 1990 (C conc. < 12 % for 0-25 cm | 9 | 108 | 52 | 53 | 220 |
| Organic soil, AR since 1990 (C conc. >=12 % for 0-25 cm) | 2 | 498 | 250 | 321 | 675 |

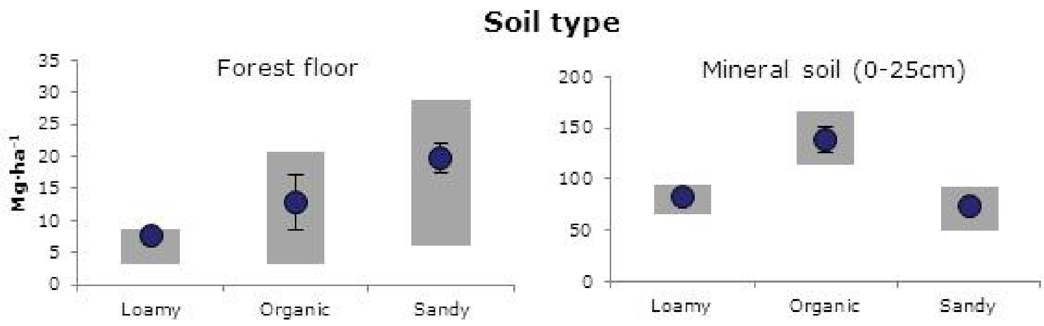


Figure 3.12 Average carbon stocks of forest floor and soil 0-100 cm for different soil types. The bars indicate the standard deviation and the grey boxes the 95 % confidence intervals (75 % percentiles).

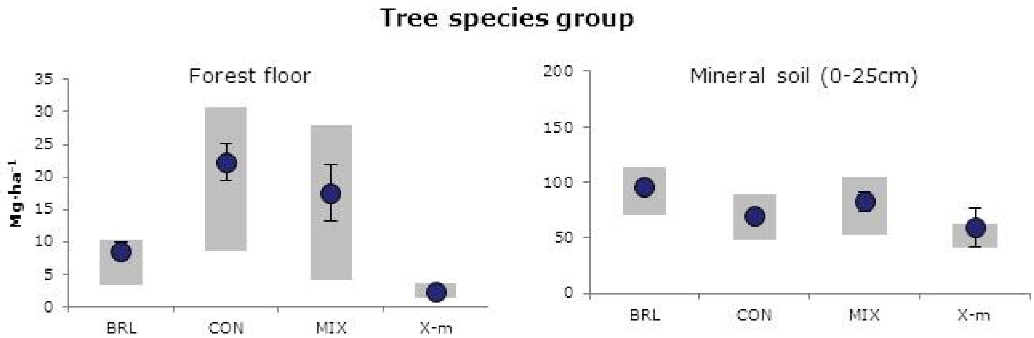


Figure 3.13 Average carbon stocks of forest floor and soil 0-100 cm for different tree species groups. The bars indicate the standard deviation and the grey boxes the 95 % confidence intervals (75 % percentiles). BRL: Broadleaves, CON: Conifers, MIX: Mixed broadleaves and conifers, X-m: Christmas trees.

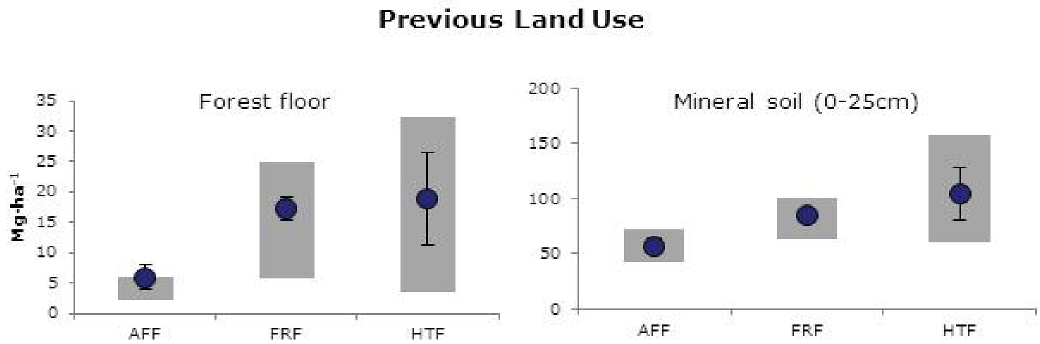


Figure 3.14 Average carbon stocks of forest floor and soil 0-100 cm for different previous land uses. The bars indicate the standard deviation and the grey boxes the 95 % confidence intervals (75 % percentiles). FRF: Forest remaining forest since 1954, AFF: Afforestation of cropland since 1954, HTF: Natural afforestation of heathland since 1954.

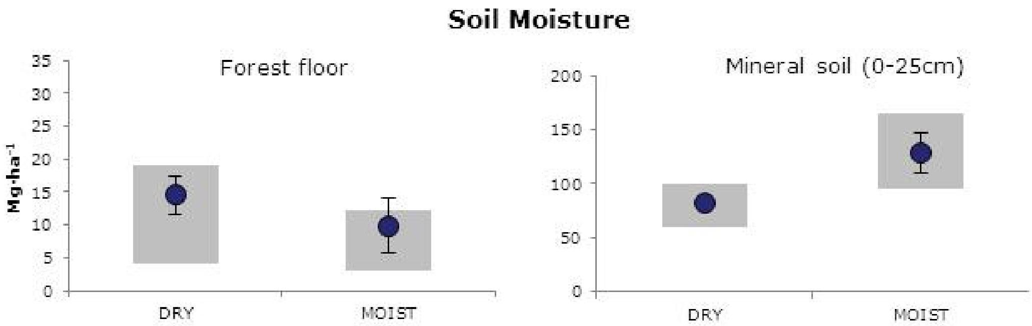


Figure 3.15 Average carbon stocks of forest floor and soil 0-100 cm for different moisture regimes. The bars indicate the standard deviation and the grey boxes the 95 % confidence intervals (75 % percentiles).

**Results**

The project has delivered the first systematic data for forest soil C stocks. The preliminary results indicate no significant changes at the country-scale in forest floor C stock and mineral soil C stocks from forest remaining forest is therefore currently assumed constant in the greenhouse gas inventory.

Land use change effects on soil C stocks were addressed as a minor part of the project although this was not the focus of the project as this was to document that FRF is not a source. 15 plots were found having a land use change since 1990 in the agricultural soil sampling grid.

Organic soils (in this case soils with >12 % C in 0-25 cm) are not dominant in Danish forests which limits the possibility to address changes within this soil type. Most soils in this group are of mineral origin (i.e. not true peat soils), but with “high C concentrations” mainly related to topography and hydrological conditions. The few soils with peat topsoils generally had mineral horizons (C horizons) within 50 cm depth, so C stocks could be quantified. True peat soil with peat below 75-100 cm was only encountered in one forest plot, and this soil type requires deeper sampling and measurements of subsidence to quantify temporal changes. A project strategically dedicated to organic soils would be needed to better monitor those specific soil types. However, based on recent developments in forest management, the less intensive forest management on organic soils followed by reduced or even ceased drainage would imply that organic soils would not be a significant source for C emission but rather a sink.

The obtained data are implemented in the forest NFI database and will be available for other working with the NFI data.

## 3.4 Reporting of forest carbon stocks and emissions

*Main contributing authors: Vivian Kvist Johannsen, Thomas Nord-Larsen, Torben Riis-Nielsen*

In connection with the Danish Kyoto Protocol commitments and especially the Danish election of article 3.4 for Forest Management (FM), procedures and documentation are needed for the reporting of FM. This implied development of administrative routines, databases and identification of information sources to monitor and estimate carbon stock changes and non-$CO_2$ greenhouse gas emissions. This system meets the requirements indicated in the IPCC GPG (IPCC, 2003) and matches the general approaches and Tier levels selected by Denmark. This project has developed tools and the needed documentation for fulfilment of the Kyoto reporting and reviews of reporting, with focus on forests. This has been incorporated in the National Inventory Reports (NIR), starting with the annual report for year 2008.

The project focused initially on the routines and quality control of data for existing forests and the use of these for the Kyoto Protocol reporting. The work included a verification of the National Forest Inventory database and development and documentation of calculation methods in relation to the use of these data.

The NFI database is not directly available for public access, as it contains information on also private forest owners. But results are published on a regular basis in several reports, included in the tables on forests by Statistics Denmark and with respect to the carbon also represented in NIR reports related to the SINKs project.

### 3.4.1 Contribution to the common reporting

In connection with the preparation of the reporting for 2008 a number of procedures, programmes and Excel tools were developed and tested. This has resulted both in the publication listed at the end, an update of that publication is expected later this year, and a number of inputs to national reports / communications.

The resulting estimates of forest carbon pool based on the NFI database DKSKOV and the procedures linked to is submitted to DCE every year for implementing in the National Danish Green House Inventory, according to annual plan agreed by the partners.

# 4 Cropland and Grassland issues

## 4.1 Introduction

The SINKs project included primarily a land use matrix, forest issues and cropland / grassland issues. This chapter include the results from areas primarily used as cropland and grassland. For clarity of the issues covered in the SINKs project and their relation to the overall reporting, other information is included where relevant. For cropland and grassland the major stock and source / sink is the soil. The stock of carbon in the soil globally contains about three times as much carbon as the atmosphere (Jobbágy & Jackson, 2000).

Danish agriculture has been increasingly regulated since the mid 1980s. The regulations were mainly towards reduction of the nitrate leaching into lakes, streams and inner coastal water, due to eutrophication from nitrogen and phosphorous loadings. A dominant issue in the Danish policy was to increase the utilization efficiency of applied nitrogen in order to reduce the leaching. The policy measures included among other a ban on field burning, demands for winter-green crops, establishment of catch crops in the autumn, reduced nitrogen application rates, fertilization only to crops which were harvested the same year etc.

As in all other land use categories the reported carbon stock is divided into the five major classes: above-ground biomass, below-ground biomass, dead organic matter, litter, and soil organic carbon. In cropland and grassland the major carbon stock is in the soil, although there may be some carbon stocks in living biomass such as hedgerows and small biotopes which do not fulfil the requirements for being classified as forest. Furthermore, orchards and fruit plantations, which may comply with the forest definition, can be reported under cropland. In the Danish reporting and accounting fruit trees as well as willow (*Salex spp.*) plantations for energy production are reported under cropland. Poplar (*Populus deltoides*) for energy and Christmas trees is reported under forestry because it typically has longer durations between harvests.

### 4.1.1 Living biomass

By default in the reporting obligation for annual crops, the carbon stock change in living biomass between years in cropland and grassland is zero. When a land use change occurs, it is by default assumed that these areas have an amount of living biomass equivalent to the standing biomass in summer (at peak). In the current reporting and accounting it is assumed that the standing stock in living biomass in cropland is equivalent to the 10-years average C stock in spring barley. For grassland the default value from the IPCC 2003 Guidelines is used.

### 4.1.2 Litter and dead organic matter

The amount of litter and dead organic matter is reported as not occurring, since very small amounts are assumed to be present in cropland and grassland.

The major changes in the living biomass carbon stock in cropland and grassland therefore derive from hedgerows and fruit plantations. In the Danish inventory fruit plantations has been assigned a default carbon stock per hectare. If the land use changes, there will be an increase or loss in the carbon stock. This is because the standing carbon stock/ha is limited in the fruit plantations. The other major component is hedgerows. Planting of hedgerows has in Denmark been subsidised for many years to avoid soil erosion. In early days the planting was primarily single rowed White spruce (*Picea glauca*). Today the hedgerows are dominated by 6- to 9-rowed broadleaved bushes and trees. Little information is available on the carbon stock in the hedgerows and in the SINKs project it was therefore decided to verify existing estimates of changes in carbon content for hedgerows and small biotopes.

### 4.1.3 Soil organic carbon

According to the reporting guidelines the carbon stock in soils shall be split into mineral soils and organic soils. Organic soils are defined as having a soil organic carbon (SOC) content of >12 % C and a depth of the organic layer of 30 cm (IPCC, 2003).

Since the beginning of the 1980s, the high intensity in agricultural production in Denmark has raised questions to the environmental impact from agriculture. Leaching of nutrients to lakes and inner coastal waters has got special attention. As a result, consecutive regulations on land management have been adopted to reduce the environmental pressures. These regulations are e.g. a ban on straw burning, reduced nitrogen input, changed manure management and manure storage demands, establishment of mandatory catch crops, etc. This has affected the way the agricultural soils are managed today compared to 1990. In order to take account of these changes in the reporting of carbon stock change in agricultural soils, it was decided to advance to a Tier 3 modelling approach to improve the accuracy. For this purpose it was decided to use a Danish soil carbon stock change model, C-TOOL (see chapter 6.3). The SINKs project included a reprogramming of the C-TOOL model and an update of the parameters.

It was moreover decided to make a resampling of the soil carbon stock in the Agricultural Soil Sampling Grid for producing an independent verification of the modelled outcome from C-TOOL. This grid was established in 1986 and sampled for soil carbon stock in 1987, partly in 1998 and again in 2009 in the SINKs project.

In 1975 it was estimated that approximately 7 % or >200 000 ha of the agricultural area had soil that was organic according the Danish soil classification system (6 % SOC in 0-30 cm depth). This definition is different from the FAO/IPCC definition and a remapping was needed. The Danish organic soils are very shallow and many of the assumed organic soils might therefore have changed to a mineral soil class. Combined with the different soil definitions and a high rate of change, it was decided to remap the organic agricultural soils. This would improve the Danish inventory, and increase the knowledge of GHG emission from the organic soils.

## 4.2 Living biomass in Cropland and Grassland

*Main contributing authors: Morten Fuglsang, Bernd Münier, Geoff. B. Groom*
The dominant living vegetation in the landscape is composed of hedgerows and small biotopes, which do not meet the forest definition. Living biomass classified in areas such as Wetlands, Settlements and Other Land are not in-

cluded. For these areas the default Carbon stock references from the IPCC 2003 guidelines are used.

As mentioned above the main uncertainty related to living biomass in Cropland and Grassland derives from the carbon stock in hedgerows and small biotopes. The aim of this SINKs sub-project was to:

- Verify existing estimates of changes in carbon content for hedgerows and small plantations
- To explore methods for future estimation of biomass in these land use classes based on available newer data sources and methods, such as LiDAR data.
- To improve/verify the growth model initially used in national estimations of biomass in hedgerows and small biotopes and to present estimates of uncertainty for the results.
- To estimate carbon content for hedgerows and small biotopes in 1990 and yearly changes in this for all hedgerows and small biotopes.

### 4.2.1 Methodology

#### Volume

The estimation of carbon stock and the changes in living biomass from 1990 to 2005 in Cropland and Grassland were based upon visual interpretation of air photos taken around the years 1990 and 2005 for 144 sampling areas of 1 $km^2$ each.

A definition of hedgerows, based on structural parameters (length and width) and vegetation type and cover, which corresponds with other common definitions was decided. The sites were selected by a stratified random sampling, starting from a selection of sites monitored by the Danish Small Biotopes project (Brandt and Holmes, 2007). With the aim to develop an adequate sampling of study areas, relationships between hedgerow densities and biophysical parameters in terms of soil types and slope have been analysed. A first set of 48 sites of 1 $km^2$ each, clustered in 12 sampling areas of 2 x 2 $km^2$ size, were selected. The GIS map based regionalization of Denmark regarding soil type, field size and hedgerow density in 2005 has been undertaken on a 1 $km^2$ grid and divided Denmark into eight types, subdivided by five density classes of hedgerows in the topographic maps (KORT10) to ensure representativeness of the sites selected for air photo mapping. A further set of 96 sites clustered in 24 2 x 2 $km^2$ areas covered landscape and density classes underrepresented in the initial set.

Location, length, width and height of hedgerows were mapped for these 144 sites by stereoscopic interpretation of colour air photos in 2005. This information was transferred to the hedgerow layer from topographic maps (KORT10). Furthermore, results of the air photo interpretation have been checked in the field for three sampling sites, confirming the validity of the method and air photo interpretation. Along with this, development and changes from 1990 to 2005 have been mapped from air photos taken around 1990 by editing maps showing the 2005 hedgerows. Hedgerow area and volume assessed have finally been extrapolated from the 144 sites to the entire country based on distribution of cropland area within the eight landscape types (Figure 4.1). The work flow is seen in Figure 4.2.

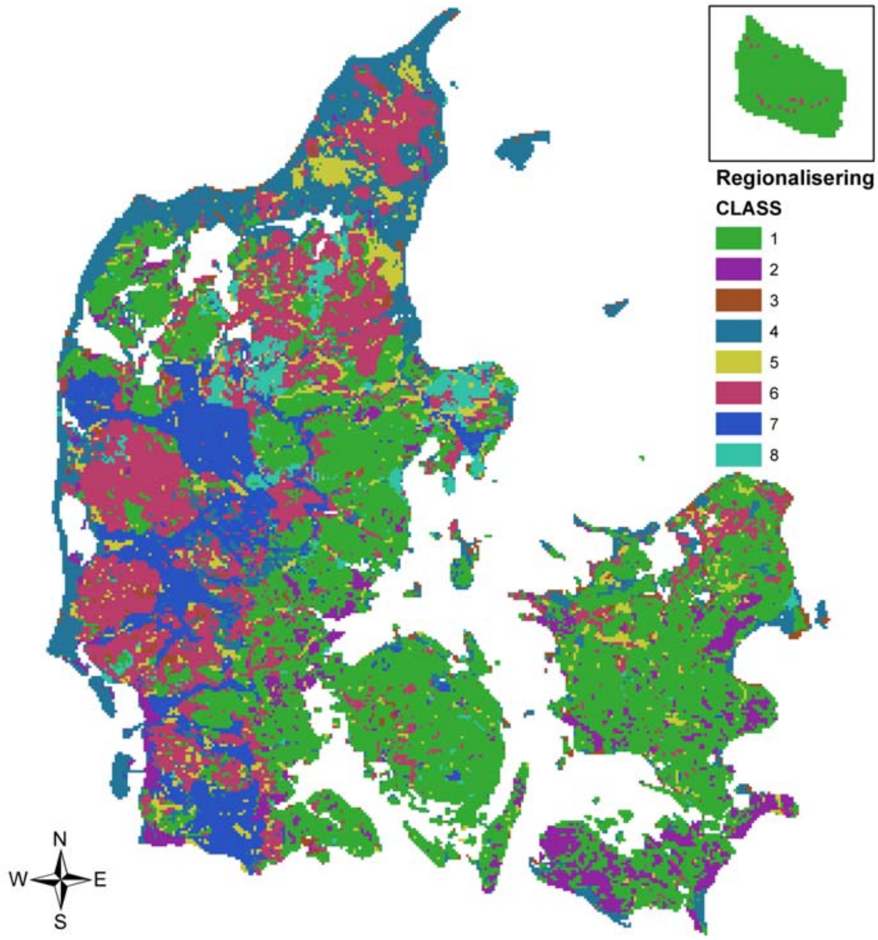


Figure 4.1 Designated areas with different types/classes of hedgerows.

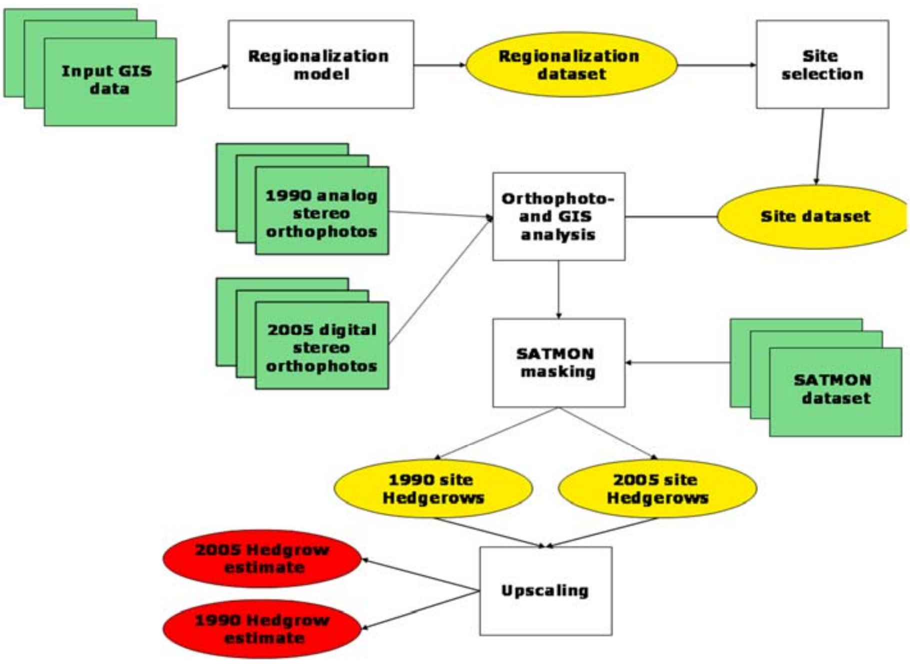


Figure 4.2 Overall data flow of hedgerow mapping and volume assessment.

The mapping exercise revealed that hedgerows cover 1.8 % of the area within the 144 sample sites, or 1.4 % of the total land surface of Denmark. Taking into account only cropland according to land use maps from 2009, hedgerows cover 2.1 % of cropland area within the 144 sample sites and of the total cropland area of Denmark.

Furthermore, the mapping showed that hedgerows are very dynamic elements in Danish landscapes, as illustrated in Figure 4.3 and 4.4. The figure illustrates, that between 20 % and 80 % of all hedgerows have been replaced at every plot, and that removal and replanting activities vary greatly in amount from plot to plot. The planting of the new hedgerows has been widely used to change the field compositions of the landscapes, by finding new locations for the hedgerows, and at the same time removing hedgerows that where not located in optimal positions for the current farming situation.

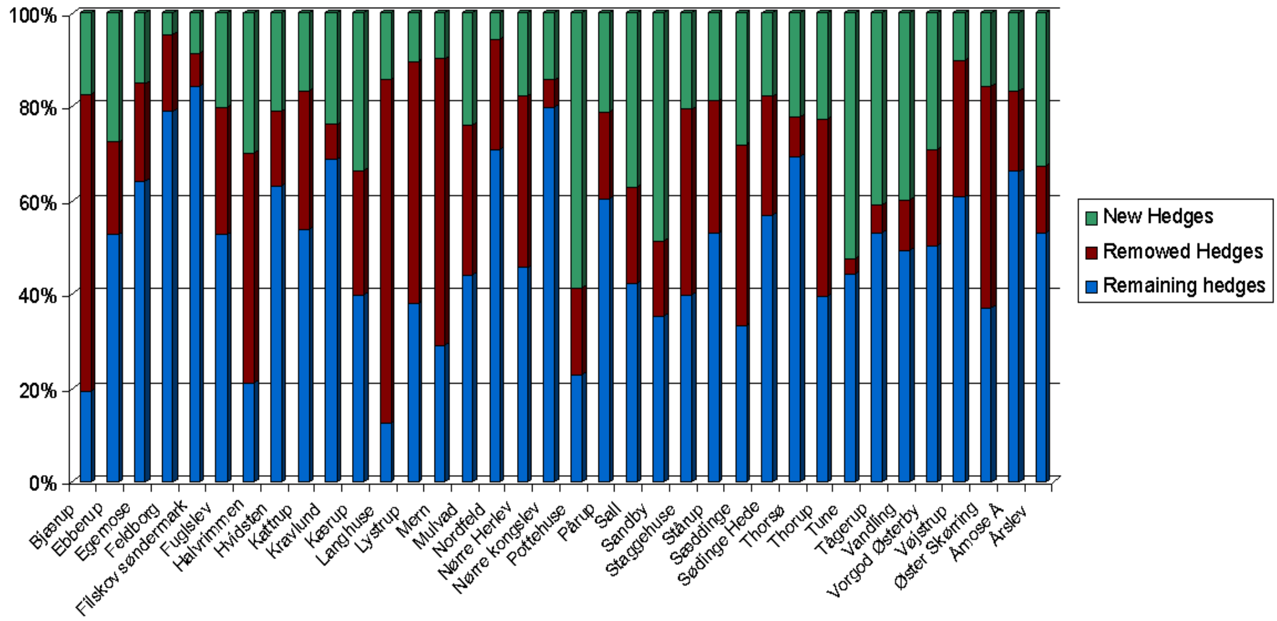


Figure 4.3 Hedgerow dynamics – hedgerows from 1990 compared to 2005 ('remaining hedgerows' are those found in the same location in both mapping years, replacement during this period is not included!).

In Figure 4.4 three samples of the hedgerow dynamics are shown. The blue colour indicates no changes, the red colours are hedgerows which have been removed between 1990 and 2005 and the green colour is new hedgerows established in the same period. Hence, a high dynamic can be observed in the changes in these landscape elements.

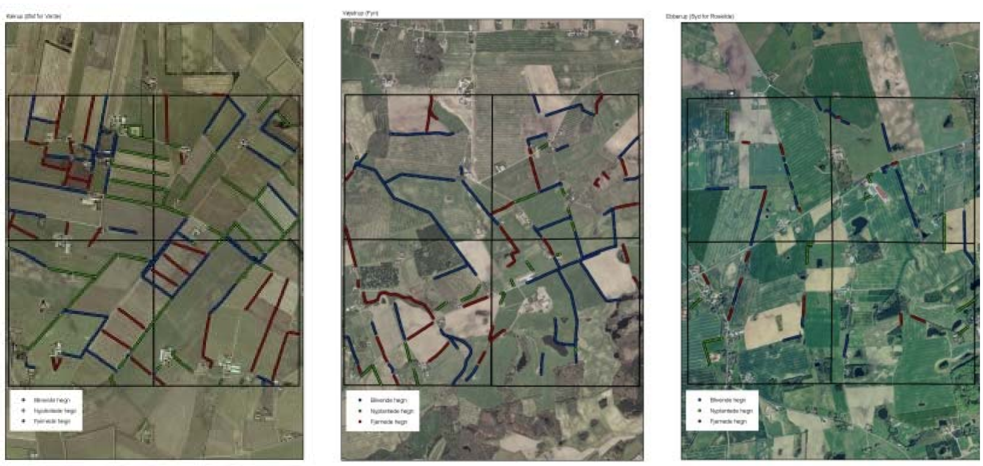

Figure 4.4 The dynamics of hedgerows in the Danish Landscape 1990 to 2005. Blue colour indicates no changes, red colours are removed hedgerows and green colours are new hedgerows (Source: M. Fuglsang, DCE).

In a subtask, the use of a LiDAR point cloud for 2007 for a selection of the sample sites was investigated. Various tools for processing and analysis of the LIDAR point cloud data were identified and in some cases acquired and tested. Furthermore, data from the Danish elevation model (DSM, DTM) based on high resolution point cloud data were investigated for two 40 x 40 $km^2$ areas. The analysis of the point cloud data was associated with hedgerows with known characteristics (X-section profile, species, biomass estimation).

Comparison of hedgerow data characteristics in point cloud and DTM (terrain model, the ‘soil’ surface without vegetation, buildings etc.) and DSM (surface model, i.e. height model of vegetation canopy, roofs etc.) data were performed. The research carried out aimed at determining LIDAR based hedgerow volumes, and focused on recommendations for a method for wall-to-wall mapping of the country with accuracy at least comparable to visual stereo air-photo interpretation, to substitute the sample based method. The study showed a good visual representation of hedgerows when compared to air-photos, but the method still showed large under- and overestimation of individual hedgerows and further work is needed before the method can be applied.

The most promising way regarding a future method is based on locations of hedgerows taken from FOT-maps, only taking into account a 10-15 meter buffer zone around the lines on these maps. This will focus on volume determination using the LIDAR point cloud and mask out most of the other non-hedgerow vegetation. In addition a comparison of biomass volumes based on LiDAR data and measured carbon stocks is needed for LiDAR to be used for estimations of carbon stock and carbon stock changes in hedgerows.

### 4.2.2 Carbon stock estimates

For the estimation of the carbon stock in hedgerows the project received a subset of biomass estimates from the Danish NFI, covering plots with vegetation comparable to hedgerow vegetation. A regression model based on these data provided relationship between hedgerow height and biomass to establish a $m^3$ biomass / volume-factor.

These results were combined with an existing growth model adopted from former assessments and figures on yearly subsidized hedgerow planting and removal that have been used for year to year changes in above and below-groundbelow-ground biomass. As these data only cover hedgerows planted / removed with subsidies, further changes in hedgerow volume found in the mapping exercise have been used to assess the total change in hedgerow biomass by adding a linear change rate over the 15 years from 1990 to 2005 and extrapolating until 2008.

Figures for biomass pr. cubic meter hedgerow volume found during literature surveys have been applied to qualify and quantify the biomass estimates derived from the NFI plots.

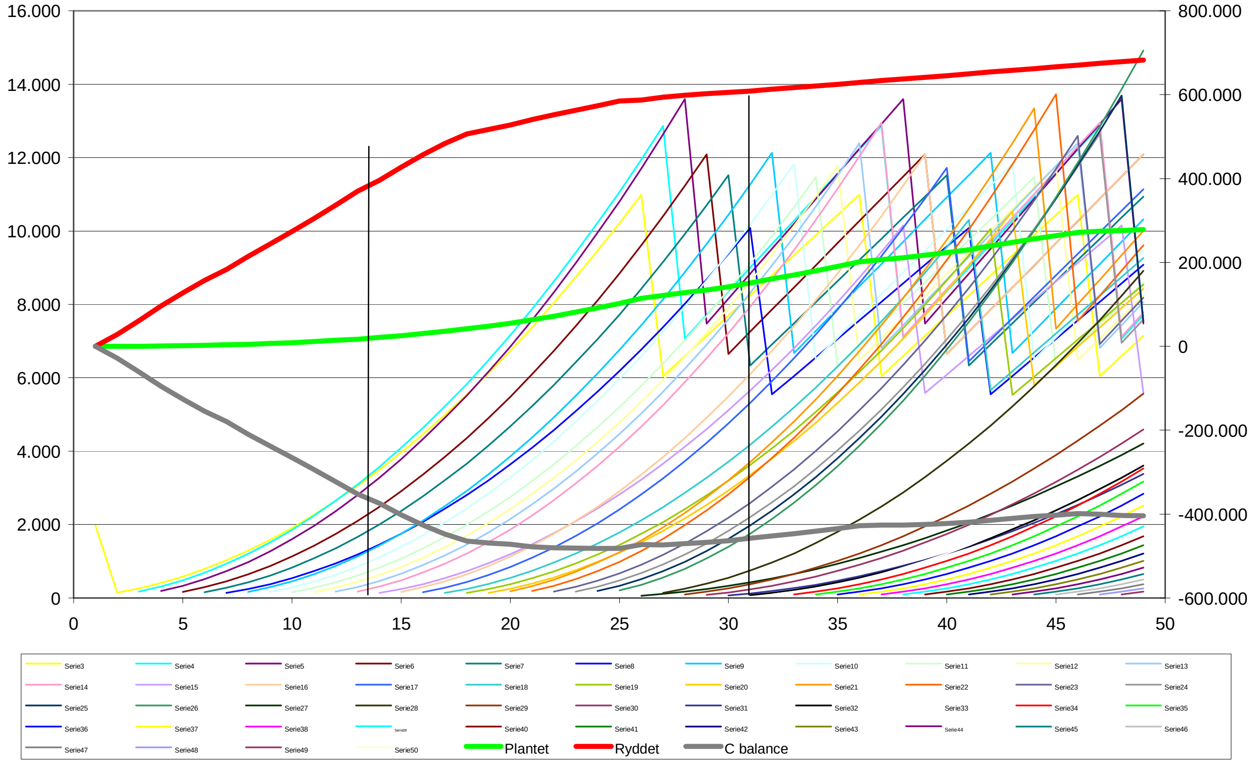


Figure 4.5 Model of total carbon content for hedgerows established/removed with subsidies from 1978 to 2025 (2008-2025 assumed same activity as 2007), individual years (left Y-axis) and sum for new planted, removed and C-balance (right axis) in tonnes (data from ”Plantning og Landskab, Landsforening”, Helge Knudsen, 2009).

### 4.2.3 Results

The project was carried out as originally planned. A major limitation is the obligation to compute hedgerow biomass back to 1990, where the quality of air photos is less good and no digital data are available.

The overall results are shown in Table 4.1. From 1990 to 2005 it is estimated that the total area in Denmark with hedgerows has decreased by 2 % and the total volume has increased with 6.4 %. The total carbon stock in living biomass has been estimated to increase with 14 %. This increase is due to the replacement of single-row hedgerows with 6-9 rowed hedgerows and changes in the species grown in the hedgerows (Table 4.1). These changes contribute with about 0.1 million tonne $CO_2$ $yr^{-1}$ to Denmark’s reduction obligations. There are a high uncertainty connected to these figures and they will be investigated further in near future.

Table 4.1 Main results from the hedgerows project - Totals in cropland 1990-2005.

| | | |
|---|---|---|
| Total area in 2005 | 60 098 | Ha |
| Total volumen in 2005 | 4 402 | Million m3 |
| Total area in DK | -1 233 | Ha |
| Volume change 1990-2005 | 263 | Million m3 |
| C change 1990-2005 | 133 514 | T |
| Area change DK | -2.0 % | Of 1990 |
| Volume change DK | 6.4 % | Of 1990 |
| C change DK | 14.2 % | Of 1990 |

## 4.3 Carbon stock changes in agricultural soils

### 4.3.1 Mineral soils

It was foreseen that the various changes in agricultural management following regulation would affect the input of organic matter to the agricultural soils and therefore have an impact on the SOC stock. Also, it was expected that although the C stock was still declining, at least the management changes would reduce the loss of SOC. Some effects of the regulations were:

- a decrease in fertilization, as the consumption of mineral fertilizers were reduced with 50 % from 1987 to 2012 (www.dst.dk)
- maintenance of the overall dry matter (DM) crop yield in annual crops and in perennial grassland (www.dst.dk)
- a 50 % reduction in the nitrogen leaching from the root zone

At the same time demands for biomass for energy production increased. In the period from 1990 to 2012 the total production of energy from agricultural by-products use for energy increased from 12.5 PJ to 17.5 PJ (1990-2012) (www.ens.dk).

It was decided to use a dynamic modelling tool, based on a Danish developed soil model (C-TOOL) to estimate the SOC and to make an independent verification by a soil resampling in the agricultural soil sampling grid. The resampling was made in 2009 on 464 agricultural locations and 122 forest locations.

### 4.3.2 C-TOOL

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The aim of the development of C-TOOL was to build a robust soil organic carbon (SOC) model that is able to simulate the major trends in the C content of Danish agricultural mineral soils down to 1 m depth. The focus is on long-term trends for C content; consequently the model is not intended to be able to mimic short-term changes accurately.

C-TOOL is a research tool developed for Danish conditions which has been further developed for reporting purposes for the Danish GHG emission from mineral soils (Taghizadeh-Toosi et al., 2014b). It is an input-output model where the input includes all biomass in the field including catch crops and manure. The model also needs environmental information on temperature, soil clay content and the C/N ratio of the soil organic matter. Degradation of Soil Organic Matter (SOM) in the soil is based on a split of the SOM in three compartments: Fresh Organic Matter (FOM) which is newly added biomass, Humified Organic Matter (HUM) which is partly degraded and Resilient Organic matter (ROM). The approximate average half-life times for the three different pools, FOM, HUM and ROM are 0.6-0.7 years, 50 years and 600-800 years, respectively. The main part of biomass returned to soil each year is in the first and easiest degradable FOM pool. This pool consists of mainly fresh straw, fresh manure, root residues, fungi and small animals and fluctuates greatly between years depending on the harvest yield and climatic conditions. This fraction of the total amount of OM is 1-1.5 %. The HUM fraction is around 39 % of the total amount of OM and about 60 % consist of very slowly degradable organic matter (ROM).

A simple diagram of C-TOOL is shown in Figure 6.6.

The decay of carbon in each pool is described by first-order reaction kinetics according to following decay function:

$$\frac{dC_t}{dt} = -k_i C_i$$

where $k_i$ is the decay rate coefficient for pool $i$ ($time^{-1}$), and $C_i$ is the carbon content in pool $i$ (amount). The model is by default updated in discrete steps (4th order Runge-Kutta) by subtracting $D_i\Delta t$ from $C_i$, where $\Delta_t$ is the time step (time). The decay rate $D_i$ of pool $i$ (amount C $time^{-1}$) is by default.

C-TOOL was parameterised and validated against long-term field experiments (100-150 years) conducted in Denmark, UK (Rothamsted) and Sweden and is considered "state-of-the-art".

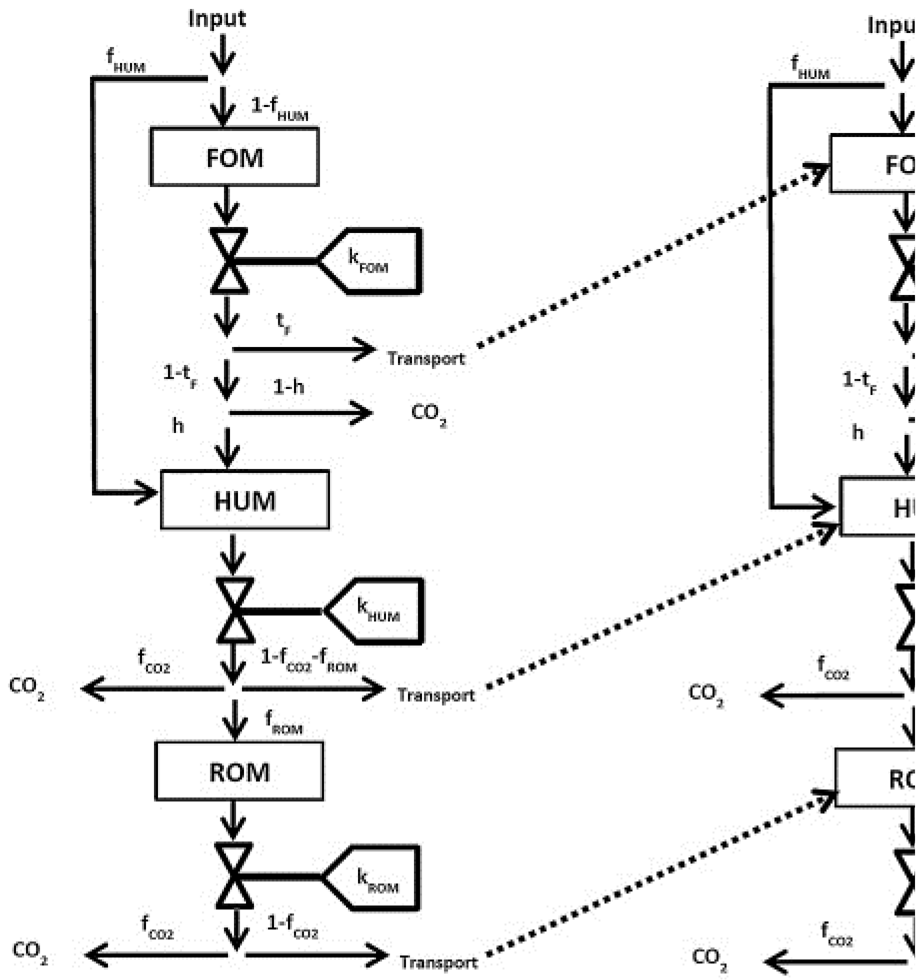


Figure 4.6 A simple diagram of C-TOOL. (Taghizadeh-Toosi et al., 2014b).

### Input data to C-TOOL and output from the model

C stock data measured in the Agricultural soil sampling grid in 1987 and distributed on different soil types (Colour code) from 605 sites are used as initial default C stock in the soils. As there were too few data on some soil types the data set was averaged for Jutland and the islands respectively. The initial default C stock is shown in Table 4.2.

Table 4.2 Initial Soil Organic Carbon stocks (Mg C $ha^{-1}$) for Jutland and the Islands (0-100 cm). Data from the Agricultural soil sampling grid 1987.

| Jutland | | | | |
|---|---|---|---|---|
| Soil Classification/ Colour code | Topsoil | Subsoil | N | C:N-ratio for top soil |
| 1 | 69.6 | 75.8 | 93 | 16.5 |
| 2 | 55.8 | 60.6 | 47 | 12.6 |
| 3 | 76.7 | 78.2 | 148 | 13.3 |
| 4 | 68.3 | 90.7 | 65 | 11.0 |
| 5 | 67.7 | 102.8 | 25 | 10.8 |
| 6 | 109.0 | 101.5 | 9 | 11.1 |
| 7 | 190.9 | 340.6 | 13 | 14.3 |
| **The Islands** | | | | |
| Soil Classification/ Colour code | Topsoil | Subsoil | N | C:N-ratio for top soil |
| 1 | 66.1 | 77.3 | 13 | 14.7 |
| 2(1) | 55.8 | 60.6 | 1 | 12.6 |
| 3 | 63.8 | 81.5 | 67 | 12.1 |
| 4 | 58.5 | 97.0 | 114 | 10.8 |
| 5 | 63.3 | 109.0 | 66 | 9.7 |
| 6(1) | 109.0 | 101.5 | 1 | 11.1 |
| 7(1) | 190.9 | 340.6 | 1 | 14.3 |

Due to a limited number of soil samples on these soil types the average for all samples in Denmark are used.

Upscaled to the entire agricultural area the total amount of SOC down to 1 meter is approximately 434 Tg C (2.88 million ha). These values are used as initial values when the model run was initiated for 1980. As it can be assumed that there have been some carbon losses from the mineral soils from 1980 to 1987 the use of the 1987 data may underestimate the overall carbon stock in 1980. In the accounting under the Kyoto Protocol where net-net accounting is used the impact of this will be small.

The carbon input to each region and soil type (colour code) is distributed according to the area with different crops grown on these soil types. As carbon input to each region for each year the actual crop area and crop yield is used from Statistics Denmark for that particular region and crop species (www.dst.dk Table AFG, AFG07, HST7 and HST77). The amount of agricultural residues returned to the soil is based on the estimations by Statistics Denmark (www.dst.dk Table HALM and HALM1). The amount of animal manure produced and applied to soil is estimated with the same methodology as for the estimation of $CH_4$ and $N_2O$ emissions in the reporting for the Agricultural sector to UNFCCC. Here, annually updated feeding and excretion data are provided for the regulation of the animal production in Denmark, and detailed data on the number of animals, housing and manure types are available at farm level. This also includes information on the extent of conversion of manure to biogas. The manure data are used as input to C-TOOL.

The input to C-TOOL varies between years due to the actual growing conditions in that year. Figure 6.7 shows the overall harvest of dry matter. 2010 and 2011 were medium years for productivity, whereas 2009 was the best cereal year ever in terms of crop yield and in spite of the low fertilisation rates in Denmark. The variation in harvest yields results in a large inter-annual variation in the input to C-TOOL for all years. Other factors which determine the amount of biomass returned to soils is also the ban of field burning in 1990, change in land management and requirements to establishment of catch crops etc. Combined with inter-annual variations in the temperature this creates large inter-annual differences in the net carbon stock change in mineral soils, where low yields combined with high temperatures reduce the total amount of carbon in the soils, whereas in years with a high yield and low temperatures the carbon stock in soils increase.

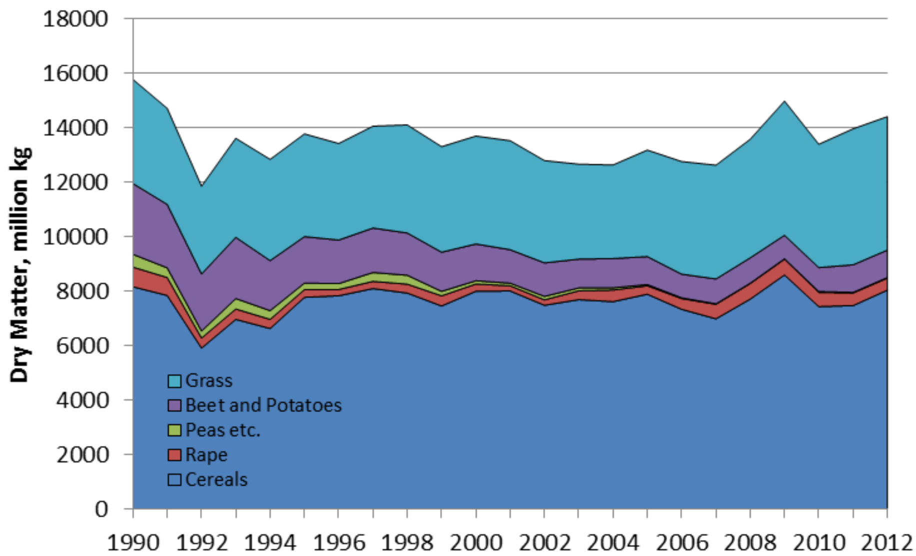


Figure 4.7 Dry matter harvest in Denmark 1990 to 2012. 1990 was a year with high productivity. Despite a decreasing agricultural area and a reduced nitrogen input it has been possible to maintain the dry matter output.

**Results**

Figure 4.8 shows the modelled total carbon stock of 434 million tonnes C in 1980 in the agricultural soils (red line: FOM, HUM and ROM). The blue line represents the total amount of C in the HUM and ROM fraction. Both lines show a decrease of the carbon stock in the agricultural soils. This despite the dry matter production has more or less been maintained. The total input of C to the soil has however increased due to the ban of field burning and more catch crops in the rotation.

Figure 4.9 shows the estimated annual emission from the mineral soils. A large inter-annual variation can be seen. Most of the years the mineral soils act as sources of $CO_2$ and some years they are sinks. The red line in Figure 6.10 include all three pools, FOM, HUM and ROM and the blue line only HUM and ROM. C-TOOL is using monthly average temperatures combined with input of organic matter from plant residues and rhizodeposition to the soils distributed over the months from April to July. Application of manure is assumed to happen in April. The modelled estimates are per 31 December. In years with a large harvest and cold temperatures in the autumn the FOM pool will have a low degradation and the result is an increase in the pool at the time of reporting (31 December). If the harvest is low and the temperature high during autumn, the FOM pool at 31 December will be very low resulting in high modelled carbon losses. The annual emissions from the agricultural soils are therefore heavily dependent on the actual harvested yields, which are functions of management, temperature and precipitation and the soil temperature in autumn. The feasibility of including this variation in the reporting to UNFCCC has been discussed with the UNFCCCs expert review team (ERT). This inter-annual variation which is mainly caused by a temporary slow degradation or a temporary build-up of fresh plant residues has very little impact on the long-term development of the carbon stock in the agricultural soils. To remove the major part of this variability, it has been agreed to report the two major and slower degrading pools, HUM and ROM, only. These two pools account for 98-99 % of the total carbon stock in the mineral agricultural soils.

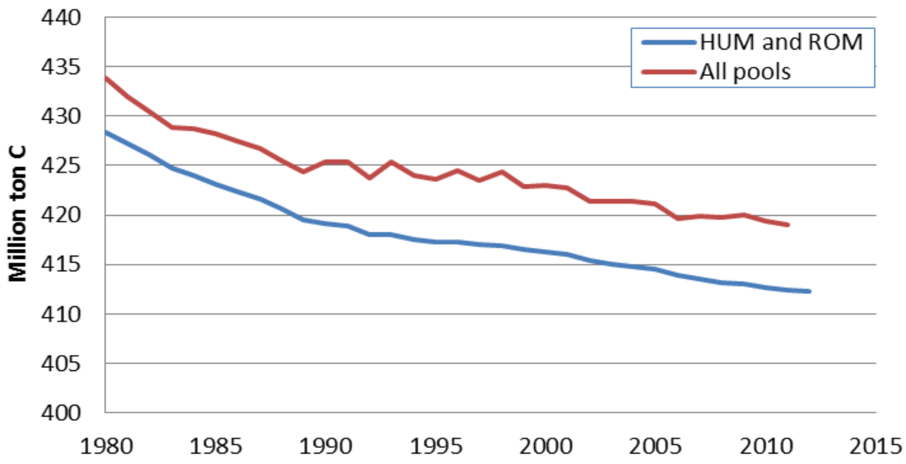


Figure 4.8 The modelled development in the Danish Agricultural mineral soils, 1980 to 2012. Million tonne C.

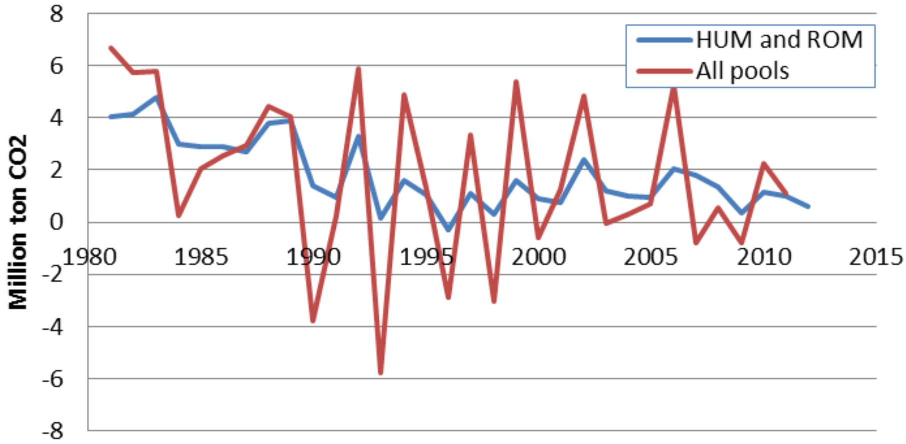


Figure 4.9 The modelled annual $CO_2$ emission from agricultural mineral soils, 1980 to 2012. Million tonne $CO_2$ $yr^{-1}$.

The C-TOOL has been parameterised and tested for soils with a carbon content of less than 6 % organic matter. Soils with 6-12 % organic carbon is therefore treated in the emission inventory as organic soils with an emission factor of 50 % of the organic soils with > 12 % organic carbon. See section 6.5 for estimation of the 6-12 % OC area. This is assumed to be a conservative estimate for the emission.

The overall outcome from C-TOOL is a loss of 16 million tonnes C from 1980 to 2012, equivalent to 3.7 % of the total carbon stock. From 1990 to 2012 the estimated loss is 7 million tonne C equivalent to 1.7 %. When looking at the different regions and loss types in Denmark the modelled data shows a more or less unchanged carbon stock on the sandy soils in the western part of Denmark since 1980, and up to 5-6 % losses on the sandy clay and clay soils in the eastern part of Denmark. This difference can be explained by the fact that most livestock are located on the sandy soils in the western part of Denmark. In the eastern part there are a limited number of livestock and a low frequency of grassland combined with a high removal rate of straw for energy production. These results were also verified in the independent soil sampling in the Agricultural soil sampling grid, see section 4.4.

The overall result is that before 1990 there was an average annual loss of approximately 0.75 million tonne C $yr^{-1}$ for all Danish mineral soils. This has been reduced to approximately 0.3 million tonne C $yr^{-1}$ in recent years due to the different measures introduced in Danish farming practices over the last 25-30 years as response to regulation. However, the loss is still substantial on some soils.

The reduced loss of carbon from the mineral soils since the 1980s has added approximately 1 million tonne $CO_2$ eqv $yr^{-1}$ to the Danish reduction commitment due to the net-net accounting under the Kyoto Protocol.

Currently a recalibration of C-TOOL is taking place. Although the overall national outcome from the modelling is similar to what has been measured in the Agricultural soil sampling grid, the performance of C-TOOL can still be improved. The model has recently been recalibrated for grassland giving a higher soil carbon sequestration. There is also ongoing work to enhance the robustness of the model with respect to simulation root carbon inputs.

### 4.3.3 Independent verification – soil sampling in the Agricultural Soil Sampling Grid

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The Agricultural Soil Sampling Grid was established in 1985 based on a 7 x 7 $km^2$ grid to monitor the nitrate content in the soil. When the grid was established soil sampling was carried out in 25 cm intervals down to 1 meter depth. In total 820 sites were sampled. 608 of these were on agricultural land, 55 on perennial grassland, 46 in deciduous forest, 60 in conifer forest, 16 on heathland, 5 on wet natural land and 30 on other land (Østergaard and Mamsen, 1990). In 1998 a total of 445 sites were resampled (Heidmann et al., 2001). The analyses from 1998 showed an averaged loss of approx. 2 tonnes C $ha^{-1}$ equivalent to 0.2 tonne C $ha^{-1}$ $yr^{-1}$.

In the SINKs project it was decided to resample the soils in the Agricultural Soil Sampling Grid and hereby to establish a time series of measurements to be used for verifying the modelled trends for soil carbon in agricultural soils. Furthermore it was planned to develop statistical methods for quality control of the above measurements, and for the connection between measured and simulated developments in the soil C contents.

As described above the data set on soil carbon measurements was established over a period spanning 22 years, i.e. with soil sampling and analytical campaigns in 1986-1987, 1997-1998, and 2009-2010. A common procedure of soil sampling and analyses was followed as far as possible, but included technological developments and changes of analytical equipment between 1986 and 2010. Potential effects of these differences were assessed by an extended monitoring program in 2009-2010. Data from 1986-1987 and 1997-

1998 has been published by Heidmann et al. (2001, 2002), and the new data is described by Taghizadeh-Toosi et al. (2014a). For simplicity, the years of sampling and analyses are in the following referred to by the starting year of the campaigns, i.e., 1986, 1997 and 2009.

## Methodology

### Soil sampling and C analyses in 1986

In 1986, soil samples were collected from 590 grid areas (50 x 50 $m^2$) located on agricultural soils in the Agricultural Soil Sampling Grid. At each grid area sampling were made at four soil depths; 0–25, 25–50, 50-75 and 75-100 cm. The depths were selected to represent the plough layer (0–25 cm), the main rooting zone (0–50 cm) and the drainage depth (~100 cm). Sixteen soil cores were sampled within each grid area by following three parallel lines across the area. For each grid area and soil depth the 16 samples were mixed into one homogeneous bulk sample.

### Soil sampling and C analyses in 1997

In 1997, soil samples were collected from 445 grid areas (50 x 50 $m^2$) that were retrieved according to 4 cm soil maps (i.e., within 20-40 m from the 1986 sampling areas). The sampling protocol was identical to the sampling in 1986, but only carbon contents were measured. Total carbon (TC) content was determined by IR analysis of the amount of $CO_2$ produced after combustion. TC was interpreted as total organic carbon (TOC) unless a precedent effervescence test indicated the presence of inorganic carbonates. If inorganic carbonates (IC) were present, IC was determined and TOC was calculated as the difference between TOC and IC.

### Soil sampling and C analyses in 2009/10

In 2009, 504 grid points were retrieved and marked out using current GPS technology with a precision of ≈ 0.5 m. The retrieved 50 x 50 $m^2$ grid areas were subdivided in 100 grid cells of 5 by 5 $m^2$ and 16 of these grid cells (selected randomly *a priori*) were used for soil sampling to 1 m depth with division into three depth intervals, 0-25, 25-50 and 50-100 cm as described above.

During all C analyses (i.e., both in 1986, 1997 and 2009) four control soils stored in the air dry state were routinely included to ensure the quality of the analyses. Typically one control soil sample was included for every ten samples. The quality of the analyses was accepted if the measured C content of the four control soil remained within their respective ranges of 0.57-0.64, 1.06-1.12, 1.40-1.54 and 2.66-3.24 %C.

Further, to qualify the reproducibility of the sampling strategy and the analytical methods two tests were performed during 2009. Firstly, the soil sampling at 40 of the grid areas was repeated, but at 16 other grid cells (selected randomly *a priori*) than in the original sampling. These samples were treated and analysed as described above, including separation in the three depth intervals (i.e., $n$ = 120). This test was done to evaluate the role of small-scale variation for the resulting C data. Secondly, 151 individual soil samples (randomly selected among grid areas and soil depths) were subjected to reanalysis in the laboratory using the same methodology as described above to evaluate the role of analytical variation for the resulting TOC data.

### Monitoring of land use and management

For each grid point, the farmer was interviewed each year on the land use and management. This information was categorised into the following land use and crop classes: 1) Grass, 2) Autumn sown cereals and rapeseed with straw removed, 3) Autumn sown cereals and rapeseed with straw incorporated, 4) Spring sown cereals, rapeseed and maize with straw removed, 5) Spring sown cereals, rapeseed and maize with straw incorporation, and 6) Spring sown row crops. For the crop management the following options were used: 1) Main crop followed by cover crop or undersown grass, 2) Soil ploughed, 3) Cattle manure applied, 4) Pig manure applied, and 5) Application of other type of organic material for fertilisation.

### Calculations and statistics

The percentage of TOC in individual soil samples from a given depth interval (*d*) was recalculated to Mg C $ha^{-1}$ as:

$$\text{Mg C ha}^{-1} = C_d\,(\%) \times \rho_d\,(\text{Mg m}^{-3}) \times d\,(\text{cm})$$

where $\rho_d$ is the soil density of the depth interval. Soil densities were not directly measured at the square grid areas, but were retrieved from the Danish Soil Database according to the texture of the individual soil samples as measured in 1986. Mainly due to lack of soil from (one of) the two deeper soil layers (50-75 cm and 75-100 cm) a total of 336 grid areas were available for C analyses. Eleven of the grid areas sampled in previous years were not available for sampling in 2009 due to causes such as occurrence of electric cables.

The average bulk density is calculated on data from 1001 soil profiles from the national Danish soil profile database. From each soil profile, undisturbed samples were taken according to the pedological horizon, for the determination of bulk density.

The data were grouped according to the Danish soil classification. Analyses of variance were performed to test for changes in SOC over time for the different soil types and for all of the soils together.

### Results

The overall results in the carbon stock from 1987 to 2009 are shown in Figure 4.10. Over the top 50 cm there was a significant decrease from the second to the last sampling time when considering all soils. Over the entire period from 1986 to 2009 there was no significant change in SOC (Figure 4.10), although in particular the loamy soils showed a significant decrease (Figure 4.11).

There was little change over time in SOC for the 50-100 cm depth, but a tendency to increase for sandy soils and a decrease for loamy soils (Figure 4.10).

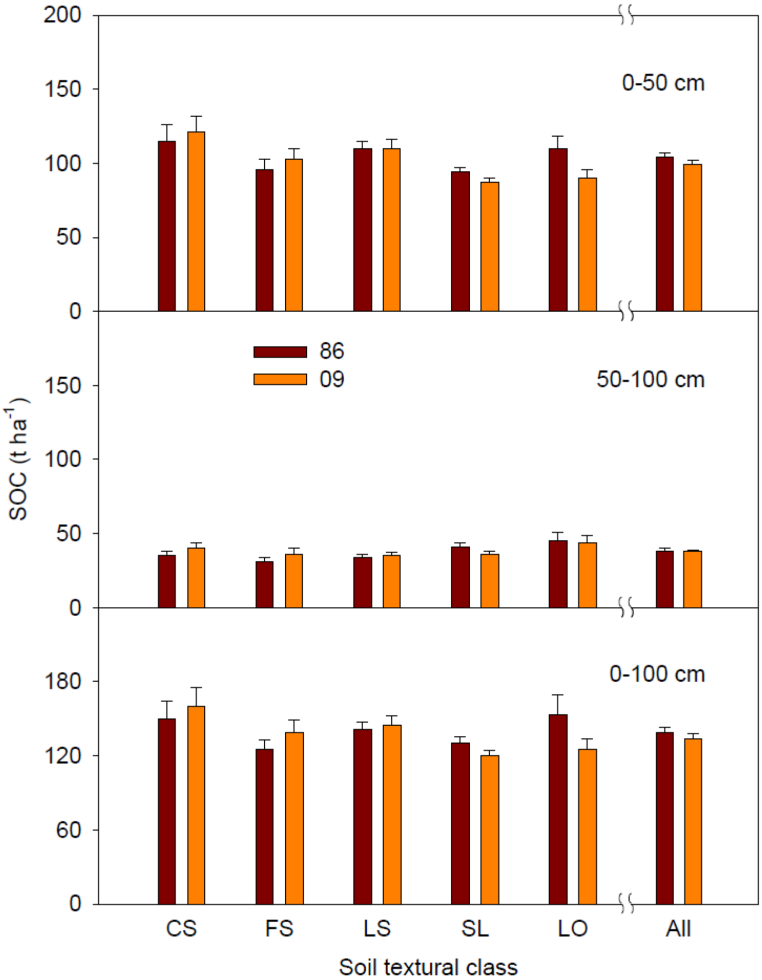


Figure 4.10 Soil organic carbon (SOC) in the layers from 0-50 cm, 50-100 cm and 0-100 cm of different soil textural classes sampled during campaigns in 1986 and 2009. CS, coarse sand; FS, fine sand; LS, loamy sand; SL, sandy loam; LO, loam. The error bars show the standard error of mean.

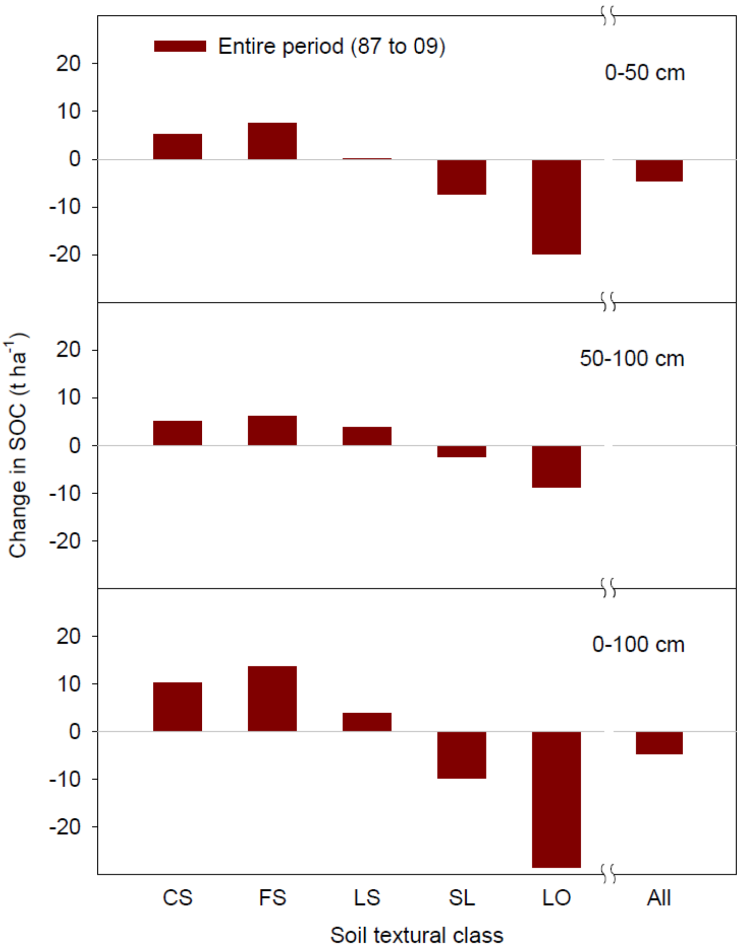


Figure 4.11 Changes in measured carbon contents between 1986 to 2009 for different soil depth intervals (0-50 cm, 50-100 cm, and 0-100 cm) and soil textural classes. CS, coarse sand; FS, fine sand; LS, loamy sand; SL, sandy loam; LO, loam.

For the entire soil profile (0-100 cm) there was an average reduction of 5 Mg C ha$^{-1}$ during the period from 1986 to 2009 (see Figure 4.11). This change was not significant. However, there were a clear tendency of an increase in SOC for the sandy soils and reductions for the loamy soils. This effect may be linked to land use, since grasslands and dairy farms are more abundant in the western parts of Denmark, where most of the sandy soils are located.

The results show a reduction in SOC from 1997 to 2009, in particular at 25-50 cm, whereas there was no change from 1986 to 1997. This difference cannot be explained by any obvious changes in land use and management. A factor that could contribute to the larger reduction in SOC during the last period is the higher temperatures during the later compared with the early period (Figure 4.11). Higher temperature enhances soil organic matter turnover and thus reduces SOC.

#### Effect of land use and management on SOC

The effect of land use and management factor on SOC was analysed separately for the soil depths 0-25, 25-50 and 50-100 cm, and the estimated parameters for 0-25 cm are shown in Table 4.3. For the lowest depth (50-100 cm) there was no significant effect of land use and management on SOC, although the effect of grass is positive and larger than the other investigated effects.

Autumn sown crops (cereals and rapeseed) with straw incorporation increased soil carbon in 0-25 cm depth by 0.40 Mg C $ha^{-1}$ $yr^{-1}$ when compared with spring sown row crops. Assuming that straw incorporation would give an annual addition of about 3 Mg C $ha^{-1}$ and that about 15 % of this carbon is retained (Christensen et al., 2004), straw incorporation would give an annual SOC increase of 0.45 Mg C $ha^{-1}$ $yr^{-1}$, which is very close to the value found in Table 4.3 for the topsoil. Cattle manure was estimated to increase SOC by 0.21 Mg C $ha^{-1}$ $yr^{-1}$ in the 0-25 cm layer (Table 4.3). Assuming an N application rate of 150 kg total-N $ha^{-1}$, which would be equivalent to an annual application of 1.0 Mg C $ha^{-1}$ in manure, and that 30 % of this carbon is retained, application of cattle manure would give an annual SOC increase of 0.31 Mg C $ha^{-1}$. This is within the uncertainty range of the estimated effect in Table 4.3.

All of the significant land use and management effects in the statistical model of SOC changes are therefore in accordance with other experimental evidence.

Table 4.3 Estimated model parameters for effects of land use and management on soil carbon (Mg C $ha^{-1}$) for 0-25 cm depth. Results are shown for both significant and non-significant effects (Taghizadeh-Toosi et al., 2014a).

| Parameter | Estimate | SE |
|---|---|---|
| A | 41.3 | 2.7 |
| $\beta_{sand}$ | -0.024 | 0.010 |
| $\beta_{loam}$ | -0.052 | 0.019 |
| k | 0.510 | 0.228 |
| Grass | 0.952 | 0.362 |
| Autumn sown crops, straw incorporation | 0.397 | 0.167 |
| Cattle manure | 0.213 | 0.116 |
| Non-significant effects | | |
| Autumn sown crops, straw removed | 0.01 | 0.15 |
| Spring sown crops, straw incorporation | -0.22 | 0.33 |
| Spring sown crops, straw removed | -0.12 | 0.20 |
| Cover crop | 0.12 | 0.36 |
| Ploughing | -0.13 | 0.11 |
| Pig manure | 0.07 | 0.09 |

Grass in rotation increased SOC and the effect was 0.95 Mg C $ha^{-1}$ $yr^{-1}$ in the 0-25 cm layer, 0.58 Mg C $ha^{-1}$ $yr^{-1}$ in the 25-50 cm layer and 0.12 Mg C $ha^{-1}$ $yr^{-1}$ in the 50-100 cm layer. This amounts to 1.65 Mg C $ha^{-1}$ $yr^{-1}$ for the entire soil profile. This should be compared with an annual increase in topsoil SOC of 1.1 Mg C $ha^{-1}$ $yr^{-1}$ found in experiments with perennial grasslands (Christensen et al., 2009).

## Conclusion

Data from soil monitoring networks may contribute to reducing the uncertainty in the estimation of changes in soil organic carbon (SOC). In Denmark a soil sampling grid of 7 x 7 $km^2$ was established in 1986 for soil monitoring. This grid was sampled for SOC in 1986, 1997 and 2009 at depth intervals of 25 cm down to 1 m. Several methods were undertaken to test the validity of the sampling and measurement methods, but none of these gave rise to systematic errors or bias between sampling times or sampling locations.

The results showed a significant decline from 1997 to 2009 in the 0-50 cm soil layer. This was mainly attributed to changes in the 25-50 cm layer, where a decline in SOC was found for all soil texture types. Across the period 1986-2009 there was clear tendency for increasing SOC on the sandy soils and reductions on the loamy soils. This effect may be linked to land use, since grassland and dairy farms are more abundant in the western parts of Denmark, where the majority of the sandy soils are located.

The results and the data is used to validate the modelling approach used for accounting of changes in SOC of Danish agricultural soils and for verification of the national inventories of SOC changes in agricultural soils.

### 4.3.4 Agricultural Organic soils

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Figure 4.12 Ready for soil sampling.

The purpose of this work in the SINKs project was to assess the contemporary extent and carbon stock of organogenic soils on agricultural land. The definition of organogenic soils follows the IPCC definition of "soils with at least 20 % organic matter in the topsoil". To be able to assess the disappearance rate of organogenic soils, a new map of the 1975 status was compiled using historic soil data.

In this section, the scope of the project is described and the methods used are explained.

#### State of art in 2006

The first and most comprehensive map of the Danish agricultural soils was established in 1975. In 1975 the area with organic soils were estimated to compose approximately 7 % or >200 000 hectares of the agricultural land according to the Danish soil classification system (6 % SOC in 0-30 cm depth). This definition is different from the FAO/IPCC definition which classify soils as organic if they have >12 % organic carbon (app. >20 % organic matter) and a remapping was needed to accommodate the reporting obligations to UNFCCC. The Danish organic soils are very shallow and many of the "assumed" organic might therefore have disappeared. Combined with the different soil definitions and a high disappearance rate it was decided to remap the organic agricultural soils in order to improve the Danish inventory and initiate studies on the GHG emission from the organic soils.

In the new mapping the IPCC definition is used for the data to be used in the Danish greenhouse gas inventory. The soil definition of organogenic soils is:

Soil containing equal to or more than 20 % organic material in the upper 30 cm

### Methodology

In this project “The soil database of Denmark” was used. This database has been established by different institutions (e.g. Ministry of Agriculture, Ministry of Environment, Geological Survey of Denmark, The National Agricultural Research Centre, the Danish Research Service for Plant and Soil Science, etc.). It consists of four parts: the Danish Soil Classification, the Danish Soil Profile Investigation, the Ochre Classification and the Well Spatial Database (Madsen et al, 1992).

- The Danish Soil Classification was carried out at country level between 1975 and 1980. It compiles the collection of some 14 000 soil samples taken in the wet cultivated lands of Denmark from the plough layer or subsoil (0–20 cm). The frequency of sampling from the plough layer was one sample per 70–80 ha of agricultural land.
- The Danish Profile Investigation is also a national survey, where the topsoil and subsoil (0–170 cm depth) were sampled more recently (1990). Detailed soil profile investigations were separated from each other on a distance of 7 km. Soil samples were taken as composite samples with an auger, and then taken to the laboratory for analysis. Samples which contained more than 10 % organic matter were automatically classified as organogenic soils; and those with less than 10 % organic matter, have been classified as mineral soils.
- The Ochre Classification performed in 1985 was based on drilling through the organogenic soils, describing the parent material in terms of composition and water content.
- The Well Spatial Database (JUPITER) describes the geotechnical water wells that were dug during the last 60 years. It is GEUS' nationwide database of groundwater, drinking water, mining, environmental and geotechnical data. The database is a common public database on the subject and included in the National Environmental Portal. The database contains over 240 000 wells including following information:

  - technical construction of the well,
  - geographical location,
  - administrative information,
  - geological description,
  - water reflections and
  - groundwater chemistry sampling and analysis

The sampling sites using the Ochre Classification and Well Spatial Database were classified in the present study according to certain decision-rules into organogenic and mineral material.

The first step in the mapping of organogenic soils was to identify the maximum area for the soil sampling. Those agricultural areas which are – or has been – wet and therefore potentially could be organic was identified with historical maps. This gave a total area of 730 000 hectares out of the total Danish area of 4.3 million hectares.

The second step in the mapping was to split the maximum area into mineral and organogenic soils. This was done with several databases with point samples of the organic layer from 32 000 point samples (Figure 6.13) combined with other co-variables such as soil type, surface height and slope. This analysis indicated that an area of 243 000 hectares (Figure 6.14) has been covered with peat at some time in the Danish soil history. Within these

243 000 hectares a grid was laid down and over a period of 16 months in 2009 and 2010 approximately 10 000 soil cores were sampled throughout Denmark.

The sampling was planned as an unbiased sampling to make robust statistical assessment of the area covered with organogenic soils with a known standard error. The sampling strategy should be optimal for spatial prediction. For both of these reasons a grid sampling was chosen in this survey. In 2009 we chose a grid size of 500 meter. In 2010 was used a 275 meter grid and 250 meter grid in the 2012 for selected locations.

When arriving to the sample location guided by accurate Differential Global Positioning System (DGPS) receivers (with an accuracy of better than 1 m.) a description of the location was made: date, type of vegetation, the abundance of the grass Soft rush (*Juncus effusus*) which is a plant known for being associated with high emission of $CH_4$, and five photos were taken (Figure 4.16). On each location soil samples were taken using the suction auger enabling sampling in very wet conditions. Samples were taken in the organogenic part of the profile down to the mineral soil however not deeper than 1.2 m. If the organogenic part was deeper than 1.2 m, the depth was measured using a thin probe.

Figure 4.13 Data points in the Danish Soil Classification database.

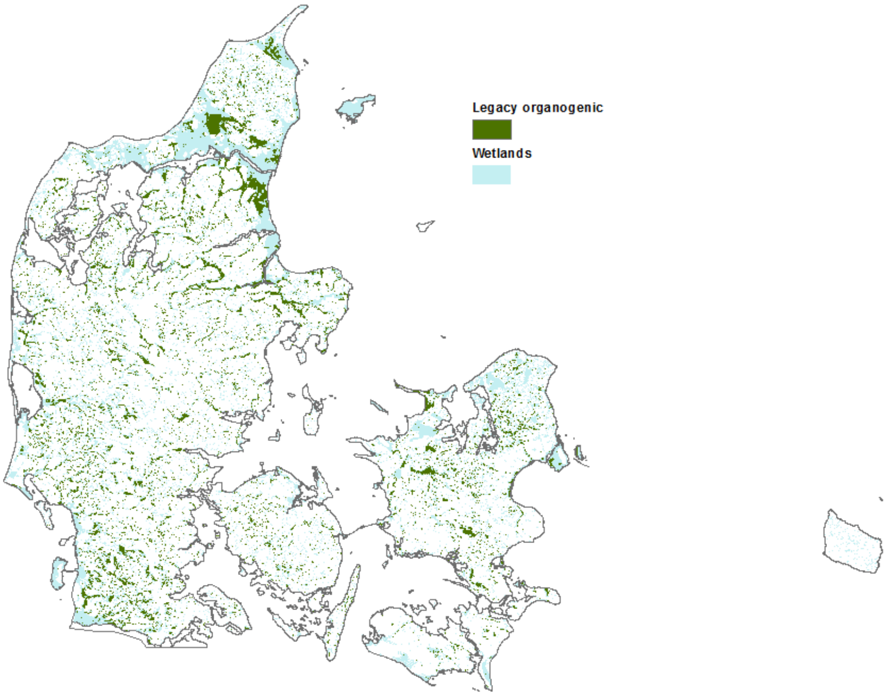


Figure 4.14 First map of the historic organogenic soils and wetland area.

Besides the 10 000 soil sampling sites a detailed electromagnetic (EM) mapping of 7 801 hectares split on seven main areas and 11 subareas were made (Table 4.4 and Figure 4.16). The EM mapping is used for producing the final map.

Table 4.4 Locations for EM measurements.

| Location | Hectares |
|---|---|
| Egeskov, Fyn | 908 |
| SøndersøFyn | 1 000 |
| Valdemarskilde, | 680 |
| Valbygård, | 675 |
| Odder | 1 694 |
| Sørvad | 400 |
| Sørvad/Vind | 340 |
| Vind | 300 |
| Sahl | 703 |
| Ulsted | 441 |
| Hassing | 661 |

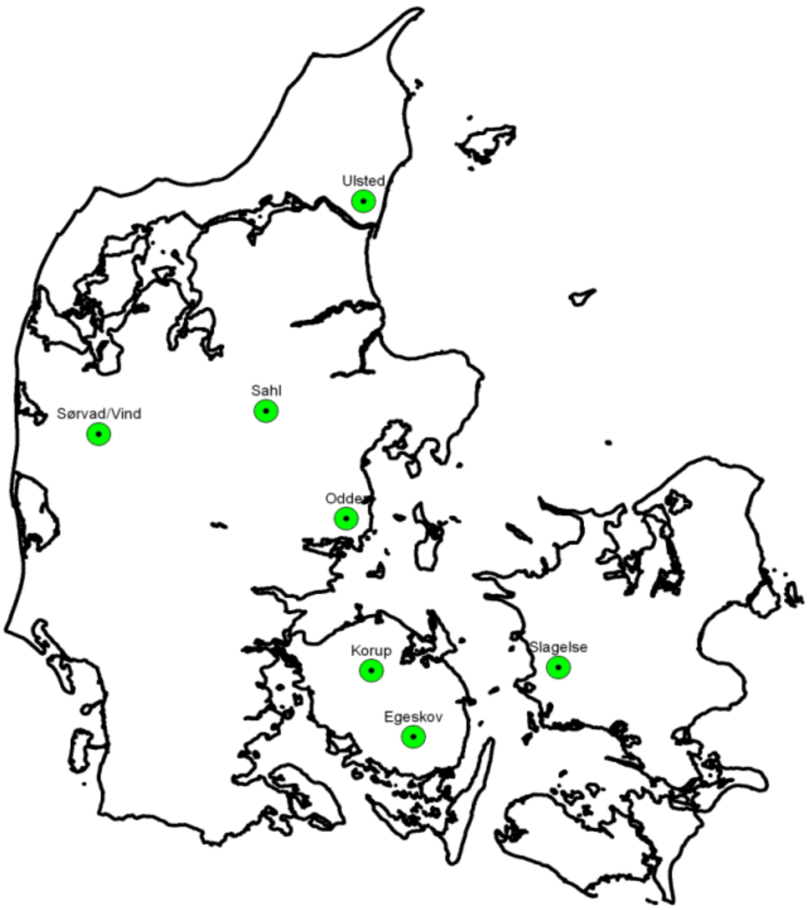


Figure 4.15 Location of the detailed monitoring sites where the electromagnetic measurements were made.

Figure 4.16 Pictures taken from a sampling plot.

The soil samples were extracted from the soil, and the property of each sample was described according to parent material, degree of humification and color. The pH in field moist condition was determined with a pH-meter. After the description, the samples were shipped to the laboratory where the measurements were made. All topsoil was also analyzed for oxalate extractable Fe, Al and P. The total areas and the number of locations for sampling with the different grid sizes are shown in Table 4.5.

As the organic area is not all cultivated the identified organogenic area was overlaid with the field map from the Danish AgriFish Agency (the Land Parcel Information System) to identify the cultivated area.

Table 4.5 Grid sizes and number of sample locations.

| Grid size | Number of locations | Study area; Ha | Study area, % |
|---|---|---|---|
| 250 | 574 | 9 582 | 3.95 |
| 275 | 4650 | 117 579 | 48.52 |
| 500 | 2342 | 115 146 | 47.52 |
| Total | 7568 | 242 307 | 100 |

### A statistical assessment of the extent of organogenic soils

Table 4.6 below shows the estimated percentages of the study area with 20 % organic material and with associated standard errors. The combined estimate is obtained using the percentages in the previous table as weights. From these percentages, estimates of the total area with more than 20 % organic matter can be calculated. The total area classified as organogenic soils under agricultural influence with different carbon content in the topsoil is shown in Table 4.6 and in Table 4.7 is shown the regional distribution of the different carbon areas and contents.

Table 4.6 Area coverage of soil with different C contents in the topsoil of the potential peatland area.

| | Percent of the total area (243,000 ha) | Area |
|---|---|---|
| C>3 | 73.14 (SE=1,03) | 177 230.6 ha (SE=2.501,8 ha) |
| C>6 | 47.16 (SE=1,04)) | 114 270 ha (SE=2.513,5 ha) |
| C>12 | 29.09 (SE=0,95) | 70 481 ha (SE=2.304,9) |
| C>24 | 15.50 (SE=0.77) | 37 550 ha (SE=1.855,8 ha) |

Table 4.7 Area coverage of soil with various C contents in the topsoil in seven regions.

| REGION | C>3 % | C>6 % | C>12 % | C>24 % |
|---|---|---|---|---|
| Hovedstaden | 3 901 | 2 722 | 1 870 | 695 |
| Sjælland | 20 194 | 13 984 | 8 541 | 3 593 |
| Fyn | 6 514 | 4 224 | 2 628 | 1 138 |
| Sydjylland | 41 759 | 22 897 | 11 199 | 4 837 |
| Vestjylland | 31 552 | 20 603 | 13 112 | 6 960 |
| Østjylland | 18 873 | 11 852 | 7 412 | 3 808 |
| Nordjylland | 54 437 | 37 987 | 25 718 | 16 518 |

The new final map of the organogenic soils under agricultural influence with the FAO definitions in Denmark is shown in Figure 4.17.

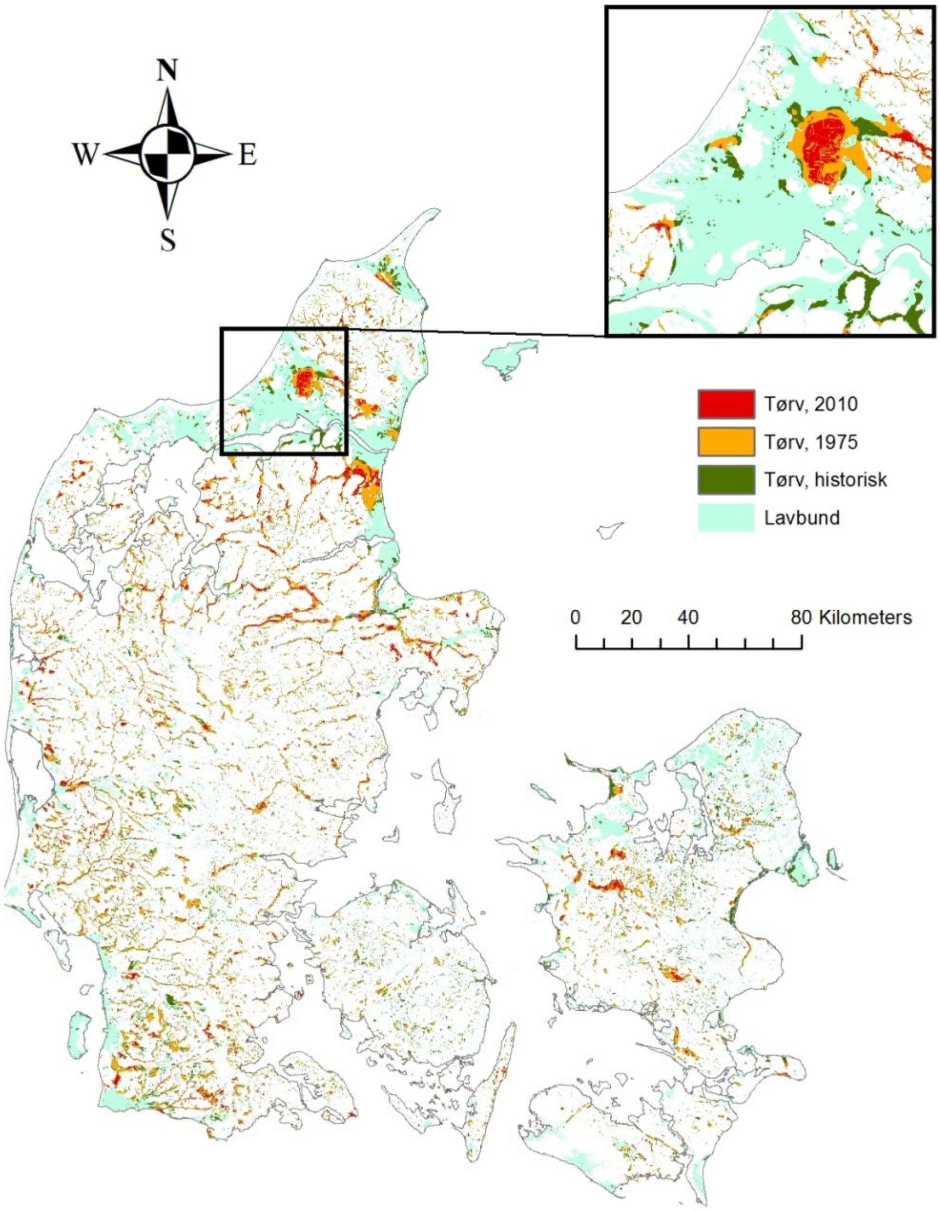


Figure 4.17 The final map. Area with organic soils in 2010 (red). The yellow and the red colour together show the distribution of organic soils in 1975.

### A special case from the mapping

The build-up of organic matter takes many years. Human intervention with drainage and cultivation can rapidly change the organogenic soils to large sources of $CO_2$. Most of the organogenic soils in Denmark are low laying fens. There are only a few raised bogs of which only 12-15 are left in Denmark today. In the Northern part of Jutland there are two quite large raised bogs, Lille Vildmose and Store Vildmose (the enlargement on Figure 6.17). Store Vildmose has a diameter of approximately 8 km and was largely untouched until mid-1930s. In 1935 large areas in the middle of Store Vildmose was drained to establish an isolation area for cattle plague also called rinder pest. The height of Store Vildmose was measured around 1870-1880. The surface height for the whole of Denmark was measured in 2007 with LiDAR with a resolution of 1.6 x 1.6 $m^2$. Figure 6.18 shows the height in 1880, in 2009 and the depth to the mineral soil. Looking at the transect from Northwest to Southeast shows that the Northeastern most part in 2009 has the same height or has even raised since 1880. In the middle, half of the height has lowered 2-2.5 meters due to cultivation and drainage (compaction). This was where the isolation area was located. To the far Southeast the bog has totally disappeared due to peat extraction.

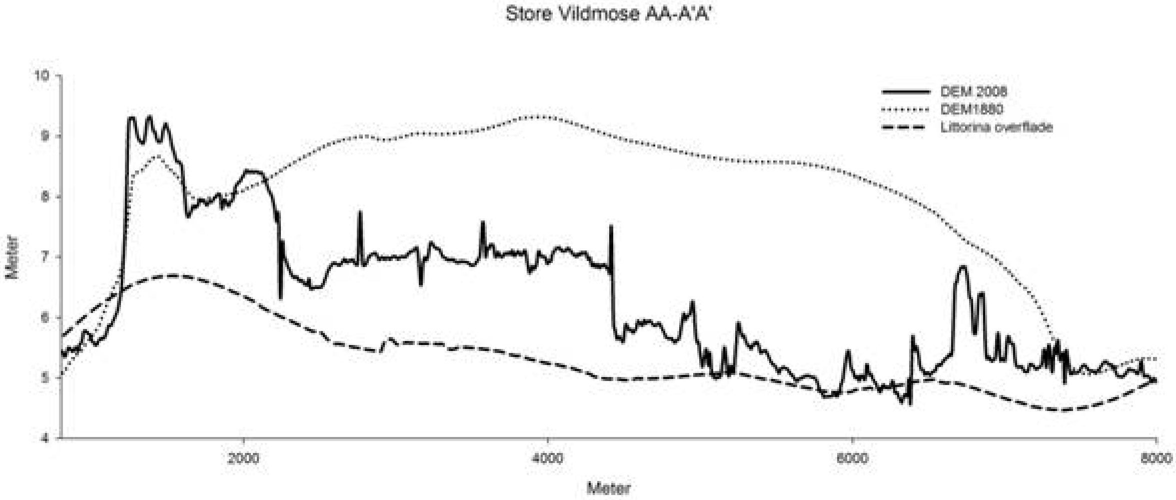


Figure 4.18 The height of Store Vildmose around 1880 and in 2009.

### Total amount of Carbon in soils with carbon content >3 %

In each soil core sample the total amount of carbon was calculated on the basis of the field observations, the measured C content, and calculated bulk density. To calculate the total amount of carbon on national level, we used the same statistical procedure as for the calculation of the national peat area (See above). Briefly: for each of the three sample grid sizes, the area that each of the bores represented was calculated. This was combined and the total amount of carbon could be calculated. The total amount of carbon in the survey area has been estimated to 65 739 219 tonnes C (65.7 teragram). This represents on average a stock of 271 tonnes C $ha^{-1}$ (0-100 cm), for the 242 307 ha mapping area.

### Conclusion

The area with organic soils has been estimated to 107 000 ha in 2010 (Table 4.8). Of this 70 500 ha ± 2 300 ha is located in agricultural fields based on the farmers' mapping of their fields submitted to the Danish AgriFish Agency (the General Danish Agricultural Register or The Land Parcel Information System).

Only 17 % of the samples could be classified as organogenic according to the IPCC definition.

A reclassification of the 1975 map of organogenic soils has been made using the same criteria as in the current 2010 mapping. The reclassified 1975 map can be seen in Figure 4.17. 50 000 hectares of the area which were classified as organogenic in 1975 cannot be classified as organogenic in 2010. In other words, approximately 1 400 hectares of the agricultural area has annually been transformed from organogenic to mineral soils.

Table 4.8 Area with peat/organogenic soils in 1975 and 2010.

| Theme | Area in hectares |
|---|---|
| Low lying areas | 730 000 |
| Historical distribution of peat | 332 785 |
| Historical distribution of peat (agricultural soils) | 243 000 |
| Distribution 1975 | 178 317 |
| Distribution 1975 (agricultural soils) | 118 162 |
| Distribution 2010 | 107 000 |
| Distribution 2010 (agricultural soils) | 70 500 |

### 4.3.5 Emissions from the agricultural organic soils

*Main contributing authors: Lars Elsgaard, Søren O. Petersen, Carl Christian Hoffman, Gitte Blicher-Mathiesen*

Between 2007 and 2010 a monitoring program was planned and conducted to determine, for the first time, net emissions of biogenic greenhouse gases ($CO_2$, $CH_4$ and $N_2O$) from Danish organic soils. In most cases Danish organic soils have a predominantly organic (peaty) upper horizon overlying sandy or loamy mineral soil. The measurements included eight monitoring sites with different crops and both grass in rotation and permanent grassland.

#### Methodology

Three locations in Denmark were selected for the measurements. In the selection of locations for monitoring information about geology and geochemistry, as well as climate variables (insolation, precipitation, temperature) and land use were considered. Three main landscape types were identified: The outwash plains and hill islands of Western Jutland (region W); raised sea bottom of Northern Jutland (region N); and the younger moraine landscape of Eastern Denmark, (region E). Both of the latter regions have areas with high levels of pyrite.

The crops were Permanent Grass (PG), Rotational Grass (RG) and Annual crops (AR).

Greenhouse gas fluxes from soils may be quantified by micrometeorological methods, which are non-intrusive and provide spatial integration, but the requirement for large uniform areas is difficult to fulfil. Enclosure-based methods, on the other hand, rely on extensive replication to cover the inherent variability of fluxes. Automated chamber systems are available that may cover temporal variability, but investment costs are prohibitive if a monitoring program includes many sites. Since representative land use and soil conditions were to be covered in this study, a sampling strategy based on manually operated enclosures was chosen.

The geographic distribution of the eight monitoring sites is indicated in Figure 4.19. At each site six 55 x 55 $cm^2$ sampling points organized in three pairs at 5-10 m distance. Each pair served as a block in the statistical design. Boardwalks were used to minimize disturbance during sampling. Piezometers were installed next to each pair of sampling points, and in a separate position for continuous monitoring of Ground Water Level (GWL). Starting December 2008 concentrations of $CH_4$ and $N_2O$ in the saturated zone were monitored.

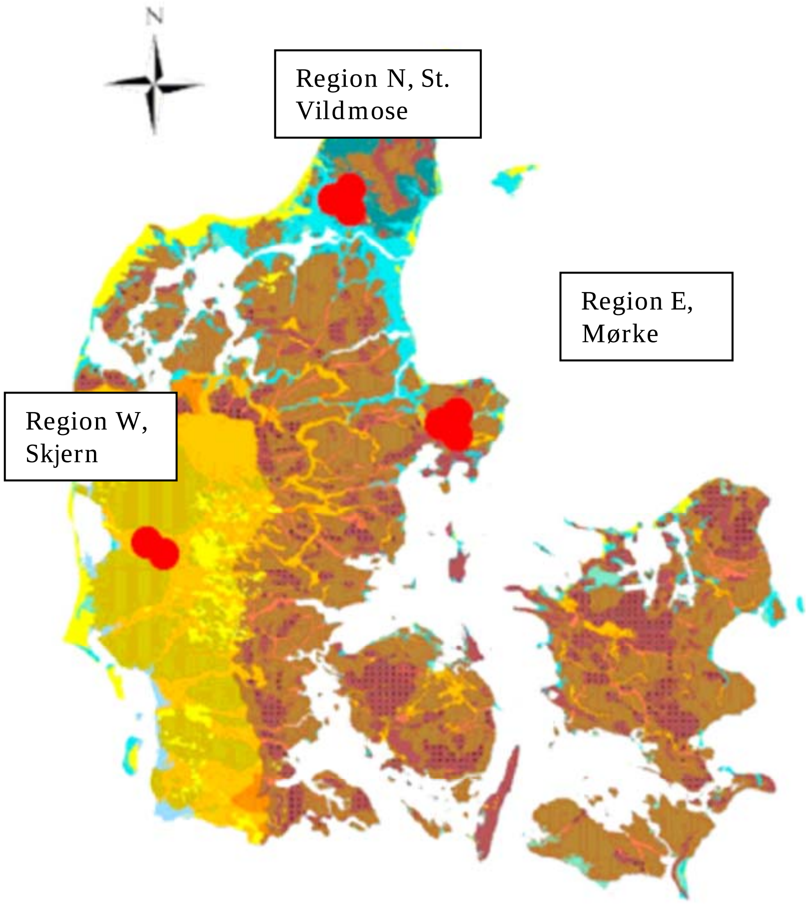


Figure 4.19 Locations of the three experimental locations.

Table 4.9 shows the different crop and soil types where the measurements took place.

Table 4.9 Distribution of the different plots on crop and soil type.

| Land Use | Region W, Skjern Outwash plains/hill islands | Region N, St. Vildmose Litorina/Yoldia | Region E, Mørke Djursland Younger moraine |
|---|---|---|---|
| Perm. Grassland (PG) | $L_2$ | $L_5$ | $L_6$ |
| Rotational Grass (RG) | - | $L_3$ | $L_7$ |
| Crops in rotation (AR) | $L_1$ | $L_4$ | $L_8$ |

A notation for Region and Crop is used throughout this section. E.g. W-PG means region West with Permanent Grassland and E-AR is region East with Annual crops in rotation.

Campaigns to determine, respectively, NEE (Net Ecosystem Exchange) which is the net $CO_2$ emission, $CH_4$ and $N_2O$ fluxes and record supporting information were conducted at approximately 3-week intervals between late August 2008 and early October 2009. The use of a relatively extended sampling interval of three weeks may be problematic if short-term events driven by, for example, rainfall is missed. Using the models for NEE and $CH_4$ emissions this error was assessed for selected 3-week periods by comparing interpolated and hourly-based model results.

Fluxes of $CH_4$ and $N_2O$ were determined using vented static chambers. Headspace gas samples ($n$ = 5) were taken over the course of 1 hour and analyzed by gas chromatography. Stringent procedures were adopted for data compilation and quality control. Fluxes were calculated using a nonlinear approach where appropriate (Pedersen et al., 2010).

Two-part vented enclosures used for flux measurements were constructed from 4 mm white PVC largely as described by Drösler (2005), Figure 4.20. Dimensions of the chamber unit were 60 x 60 x 41 $cm^3$. Inter-sections of the same dimensions were used when required due to plant height. The chamber headspace was mixed by a fan during measurements.

Figure 4.20 Two-part vented enclosures used for flux measurements.

### Definitions and equations for the $CO_2$ emission estimates

Net ecosystem exchange of $CO_2$ represents the difference between the $CO_2$ fluxes of ecosystem respiration ($R_{eco}$) and gross photosynthetic $CO_2$ uptake (GPP). In the present study, annual accounts of $R_{eco} \pm SE_{RECO}$ and GPP ± $SE_{GPP}$ were derived (see below) from field studies of eight organic soils under agricultural management either as permanent grasslands (n = 3) or as sites with crops in rotation (n = 5). Net ecosystem exchange of $CO_2$ for each site was calculated as NEE = $R_{eco}$ – GPP and the uncertainty ($SE_{NEE}$) of the estimate was calculated as:

(eq. 1) $$SE_{NEE} = \sqrt{SE_{RECO}{}^2 + SE_{GPP}{}^2} \,/\, \sqrt{2}$$

Average emission factors were calculated for permanent grassland sites (PG, n = 3) and rotational sites (RT, n = 5) and likewise the uncertainty of these estimates were calculated, respectively, as:

(eq. 2) $$SE_{PG} = \sqrt{SE_{PG1}{}^2 + SE_{PG2}{}^2 + SE_{PG3}{}^2} \,/\, \sqrt{3}$$

(eq. 3) $$SE_{RT} = \sqrt{SE_{RT1}{}^2 + SE_{RT2}{}^2 + SE_{RT3}{}^2 + SE_{RT4}{}^2 + SE_{RT5}{}^2} \,/\, \sqrt{5}$$

The average results ± SE are presented as tonne C per ha per year in Table 4.10

#### Ecosystem respiration

The relation between $R_{eco}$ and soil temperature was modelled for each block (pair of collars) according to the respiration model of Lloyd and Taylor (1994):

(eq. 4) $$R_{eco} = R_{10} \exp[E_0 \times (1 / (283.15 - T_0) - (1 / T - T_0)]$$

The estimated model parameters $R_{10}$ ± SE (the respiration at a reference temperature of 10ºC) and $E_0$ ± SE (the ecosystem sensitivity coefficient) were used to estimate the average $R_{10}$ and $E_0$ for each site with their associated SE ($SE_{avg}$):

(eq. 5) $$SE_{avg} = \sqrt{n_1 \times SE_1{}^2 + n_2 \times SE_2{}^2 + n_3 \times SE_3{}^2} \,/\, \sqrt{n_1 + n_2 + n_3}$$

where $n_i$ is the number of fluxes measured at collar pair $i$ and $SE_i$ is the SE for the parameter estimate ($R_{10}$ or $E_0$) for collar pair $i$ ($i$ = 1 to 3).

Annual sums of $R_{eco}$ were calculated by summing the contributions from hourly estimates of $R_{eco}$ based on eq. 5, the derived model parameters (average $R_{10}$ and $E_0$), and continuous time series of soil temperatures from the individual monitoring sites. To account for the uncertainty at a 95% confidence interval level, annual sums were also derived from the upper and lower values of $R_{10} \pm 1.96 \times SE_{avg}$ and $E_0 \pm 1.96 \times SE_{avg}$. The range of these annual sums was used as a measure of the uncertainty (*cf.* Drössler, 2005), i.e., annual $R_{eco}$ ± SE

#### Gross primary production

The relationship between PAR and GPP was modelled by a rectangular hyperbolic saturation curve as frequently applied in ecosystem analyses (Burrows et al., 2005):

(eq. 6) $$GPP = (a \times PAR \times GPP_{max}) / (a \times PAR + GPP_{max})$$

where $a$ is the initial light response efficiency and $GPP_{max}$ is the asymptotic maximum rate of GPP at increasing PAR. Photosynthetic light response curves were analysed for all individual field days and specific model estimates ± SE for $GPP_{max}$ and α were derived by non-linear regression.

Annual sums of GPP were estimated on the basis of interpolations of $GPP_{max}$ and $a$ between all consecutive measurement days to synthesize a series of continuous half-hourly parameters. Annual sums were then calculated by summing the contributions from half-hourly estimates of GPP based on eq. 6, the derived continuous model parameters for $GPP_{max}$ and $a$, and the continuous time series of PAR from the individual monitoring sites. To account for the uncertainty at a 95% confidence interval level, annual sums were also derived from the upper and lower values of $GPP_{max} \pm 1.96 \times SE_{avg}$ and $a \pm 1.96 \times SE_{avg}$. As for $R_{eco}$, the range of these annual sums was used as a measure of the uncertainty, i.e, annual GPP ± SE

### NEE, biomass C removal and net ecosystem carbon balances

The annual NEE for each of the eight sites was calculated as the difference between the annual estimates of ER (Ecosystem Respiration) and GPP (Gross Primary Production). The uncertainty of annual NEE estimates was derived from the uncertainty of GPP and ER added in quadrature (IPCC, 2006 http://www.sciencedirect.com/science/article/pii/S0167880912003258 -bib0350).

The C exported in above-groundabove-ground biomass was quantified according to the cutting and harvest regimes adopted by the farmers. Biomass was harvested either directly in the collars, or at similar vegetation patches next to the collars. Samples were dried at 80°C until constant weight, and exported C was calculated by assuming a carbon content of 44 % in the dry biomass. For N-AR, the gross yield of potatoes was estimated from information from the farmer and region-specific yield statistics (Statistics Denmark, 2011)

Net ecosystem carbon balances (NECB) for the organic soils were derived by summing the flux-based C removal (NEE of $CO_2$-C) and the removal of C in harvested biomass, thus defining NECB as the net C loss from the soils. This simplified derivation of a full carbon balance (Chapin et al., 2006; Smith et al., 2010) was deemed appropriate, as there was no C flow associated with animal grazing or excretal returns at the study sites, and C flows by other mechanisms (such as leaching) were considered to be of minor importance (cf. Kutsch et al., 2010). This was confirmed explicitly for methane fluxes that were low (−1.2 to 35 kg C $m^{-2}$ $yr^{-1}$) at all eight sites.

## Results

### Ecosystem respiration

Model fits showed that temperature was a main driver of ER (Figure 6.21). Generally, among the air and soil temperatures, the best correlations were found for the 5 and 10 cm soil temperatures. However, the goodness-of-fit (non-linear coefficient of determination) deviated among the sites ($0.29 < R^2 < 0.84$), with the lowest values obtained for W-AR. The reasons for the relatively poor fit of the ER model to the data from W-AR were uncertain, but on some occasions during early winter (December 2008 and January 2009), unexpectedly high ER (>500 µg $CO_2$ $m^{-2}$ $s^{-1}$) were recorded at upper soil temperatures of less than 3–4°C (Figure 6.21). These data, not considered as outliers, caused the goodness-of-fit to decrease from 0.48 to 0.29. Site W-AR had a deep peat layer (2–3 times deeper than at the other sites), possibly enlarging the contribution from microbial respiration in deeper soil layers, but not obviously explaining the scatter in the $CO_2$ flux data for W-AR.

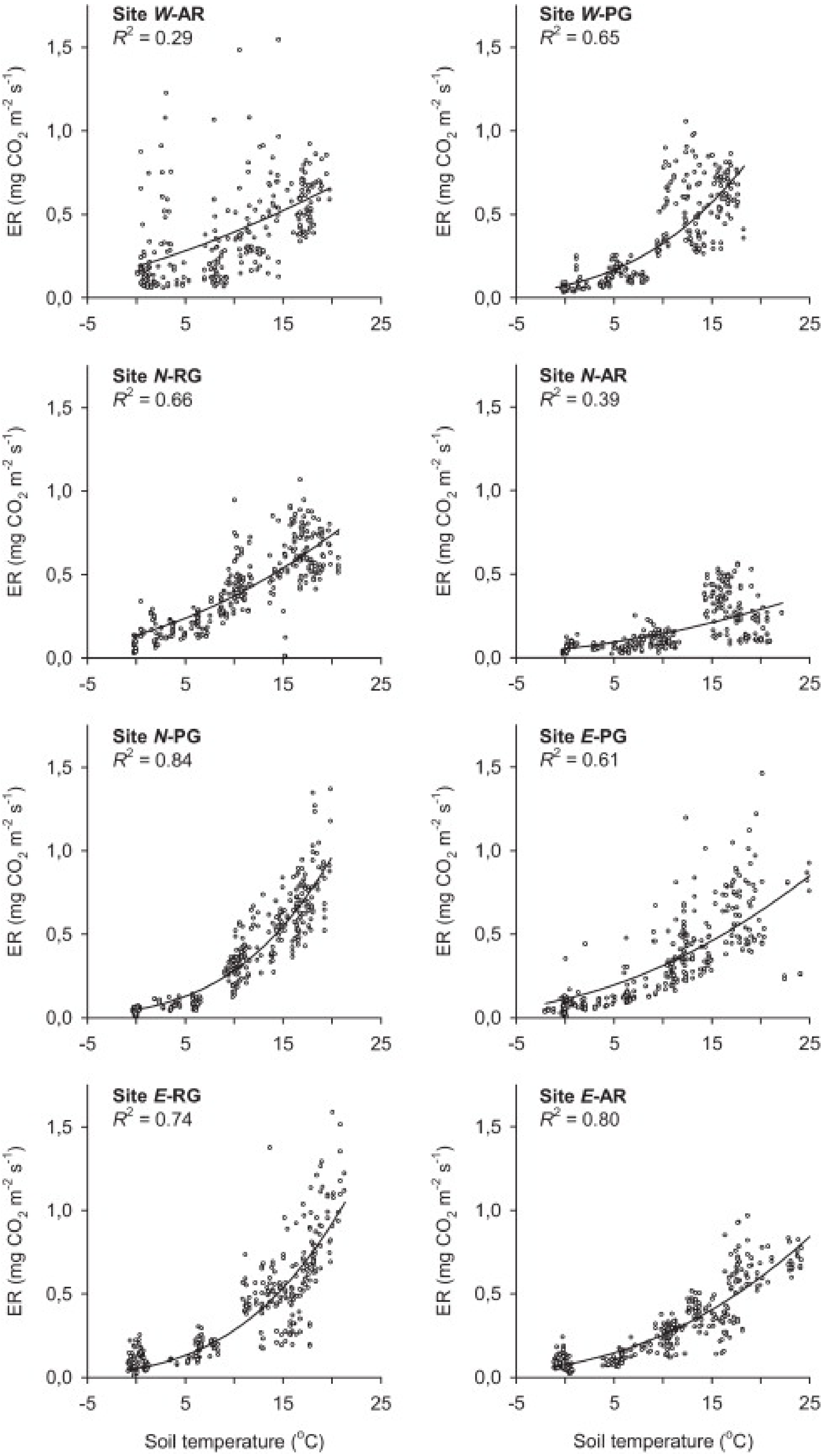


Figure 4.21 Ecosystem respiration (ER) as a function of temperature at 5-cm soil depth at the eight sites. Lines represent the fits to raw data using Eq. (1). All regressions were highly significant ($P$ < 0.001) and the goodness-of-fit ($R^2$) is indicated.

### Net ecosystem exchange

NEE calculated from modelled ER and GPP were highly and significantly correlated to the observed NEE fluxes at the individual sites (Figure 4.22). Modelling efficiencies ranged from 0.62 to 0.87 with the lowest value found for W-AR, where also the ER model was least satisfactory (Figure 4.21). The mean bias between modelled and observed NEE was nearly neutral or negative at all sites (i.e., modelled NEE > observed NEE), but only statistically significant by *t*-test for E-PG ($P > 0.05$). The *F*-test for unit slope and zero intercept, however, always had significant $P$ values ($P < 0.05$) and likely reflected a tendency of the model to slightly over-predict the observed NEE fluxes.

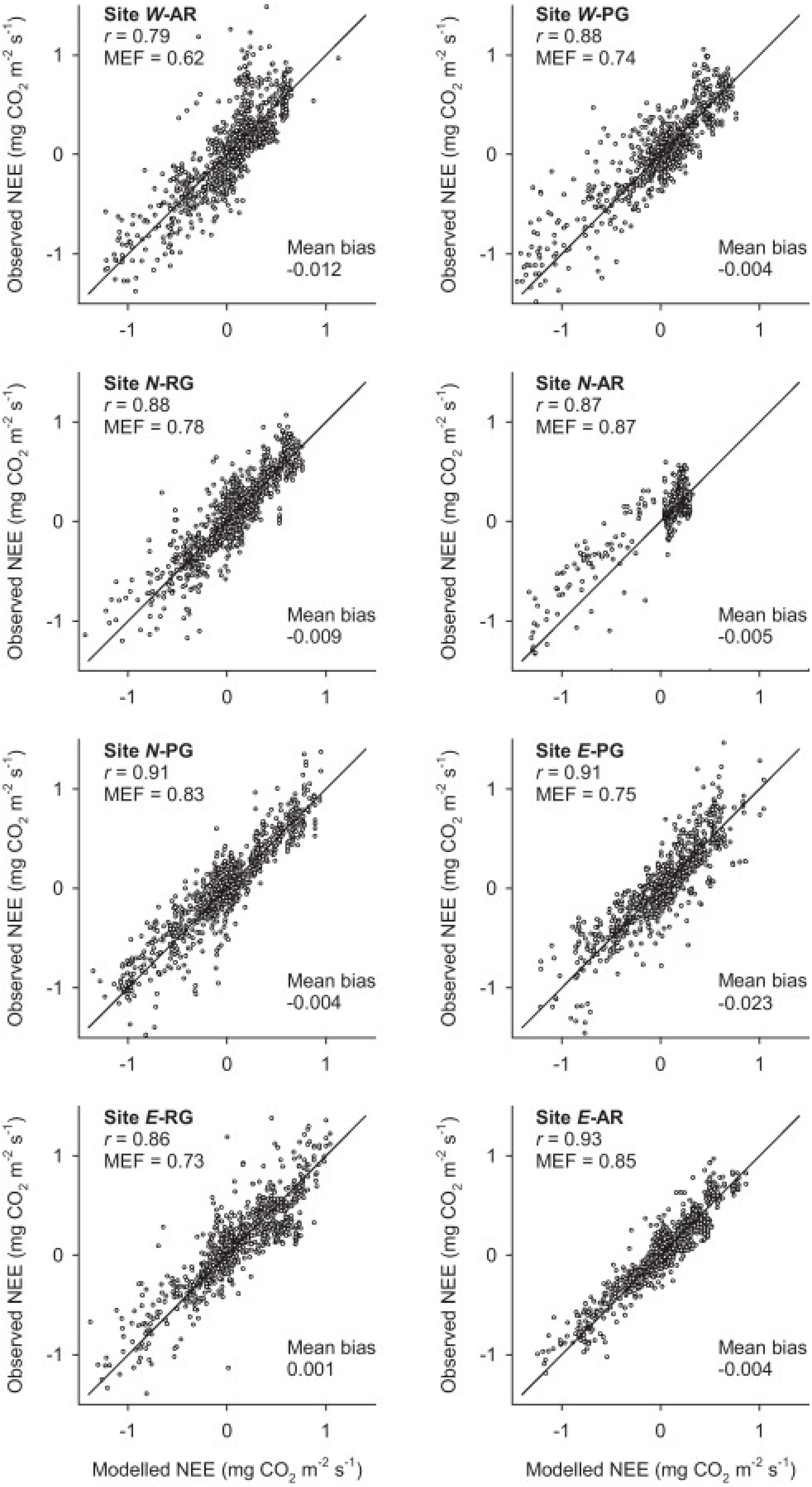


Figure 4.22 Observed vs. modelled plots of NEE for the eight sites. Correlation coefficients (r), modelling efficiencies (MEF) and mean bias are indicated. Correlation coefficients were always highly significant ($P < 0.001$) whereas mean bias by t-test was only significant for E-PG ($P < 0.05$). Solid lines indicate the 1:1 lines for a perfect fit.

Annual NEE for the eight sites ranged from 1.3 to 5.0 kg $CO_2$ $m^{-2}$ $yr^{-1}$, thus always signifying a net annual loss of $CO_2$ from the organic soils equivalent to 3.5–13.6 Mg C $ha^{-1}$ $yr^{-1}$. For the land use types PG and RT, respectively, the average NEE was $5.1 \pm 0.9$ and $8.6 \pm 2.0$ Mg C $ha^{-1}$ $yr^{-1}$ thus pointing to higher NEE for sites in rotation, although this was not statistically significant ($P = 0.181$). Excluding N-AR from the RT group increased the NEE estimate from $8.6 \pm 2.0$ to $9.8 \pm 2.0$ Mg C $ha^{-1}$ $yr^{-1}$, though still not significantly different from the NEE estimate for PG ($P = 0.103$).

### NECB and emission factors for managed organic soils

The estimated NECB (Net Ecosystem Carbon Balance) ranged from 6.9 to 16.7 Mg C $ha^{-1}$ for the eight sites (Table 4.10), with averages (±SE) for the land use types PG and RT of $8.4 \pm 1.0$ and $11.5 \pm 2.0$ Mg C $ha^{-1}$, respectively (means not significantly different, $P = 0.214$). These NECB values, calculated from NEE and C removal in biomass, are in principle analogous to the subsidence or flux based carbon stock change emissions factors reported in the guidelines from IPCC on National Greenhouse gas inventories under the United Nations Framework Convention on Climate Change (IPCC, 2006; Cowenberg, 2011). However, some inconsistency seems to exist in the notion of flux based emission factors, as the same terminology (emission factors) is applied to net $CO_2$ fluxes as well as to net $CO_2$ fluxes adjusted for the removal of C in yield, which is an important C flow in agro-ecosystems (Alm et al., 2007; Couvenberg, 2011; Somogyi et al., 2011). The importance of proper definition of emission factors is stressed by the fact that organic soil ecosystems may often act as a net sink of $CO_2$-C whereas they actually show a net loss of C after correction for biomass removal (e.g., Veenendal et al., 2007; Hatala et al., 2012). Here, we consider emission factors as combined emission / removal factors (i.e., representing NECB; assuming instantaneous emission of harvested biomass) and emphasize that it should be explicitly reported how emission factors are conceived.

Table 4.10 Ecosystem respiration parameters ($R_{10}$ and $E_0$), temperature coefficients ($Q_{10}$) and annual ecosystem respiration (ER), gross photosynthesis (GPP), net ecosystem exchange (NEE), yield exports and net ecosystem carbon balances (NECB) for eight Danish organic soils under agricultural management. The sites are identified by the geo-region (*W*, West; *E*, East;*N*, North) and the management (AR, arable crop rotation; PG, permanent grasslands; RG, rotational grasses). Uncertainties (shown in parentheses) are standard error (SE) estimates.

| Site | $R_{10}$ ($\mu g\ CO_2\ m^{-2}\ s^{-1}$) | $E_0$ (K) | $Q_{10}$ (10–20 °C) | ER ($kg\ CO_2\ m^{-2}\ yr^{-1}$) | GPP ($kg\ CO_2\ m^{-2}\ yr^{-1}$) | NEE ($kg\ CO_2\ m^{-2}\ yr^{-1}$) | NEE ($Mg\ C\ ha^{-1}\ yr^{-1}$) | Yield export ($Mg\ C\ ha^{-1}\ yr^{-1}$) | NECB ($Mg\ C\ ha^{-1}\ yr^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| *W*-AR | 394 (19) | 193 (26) | 1.7 (0.1) | 12.2 (0.7) | 7.6 (1.5) | 4.7 (1.6) | 12.7 (4.5) | 2.6 (0.1) | 15.3 (4.5) |
| *W*-PG | 340 (12) | 355 (22) | 2.6 (0.2) | 10.6 (0.8) | 9.2 (1.8) | 1.4 (2.0) | 3.9 (5.4) | 3.0 (0.2) | 6.9 (5.4) |
| *E*-AR | 254 (7) | 317 (11) | 2.4 (0.1) | 8.5 (0.3) | 6.8 (1.0) | 1.8 (1.1) | 4.8 (2.9) | 2.4 (0.1) | 7.2 (2.9) |
| *E*-PG | 311 (12) | 266 (15) | 2.1 (0.1) | 9.3 (0.4) | 7.7 (1.6) | 1.7 (1.6) | 4.5 (4.4) | 3.4 (0.6) | 7.9 (4.4) |
| *E*-RG | 283 (14) | 437 (23) | 3.3 (0.2) | 11.4 (0.9) | 6.4 (1.0) | 5.0 (1.3) | 13.6 (3.6) | 3.3 (0.2) | 16.7 (3.6) |
| *N*-AR | 143 (8) | 259 (25) | 2.0 (0.2) | 4.4 (0.3) | 3.1 (0.6) | 1.3 (0.7) | 3.5 (1.8) | 3.5[a] | 7.0 (1.8) |
| *N*-PG | 283 (9) | 454 (17) | 3.4 (0.2) | 10.4 (0.5) | 7.9 (1.4) | 2.5 (1.5) | 6.9 (4.0) | 3.5 (0.1) | 10.4 (4.0) |
| *N*-RG | 372 (9) | 253 (13) | 2.0 (0.1) | 11.2 (0.3) | 8.2 (1.7) | 3.0 (1.7) | 8.2 (4.7) | | |

Couwenberg, (2011) compiled best-estimate emission factors from various climate zones and land use types. For the boreal climate zone, $CO_2$ emission factors for grassland and cropland were 2.6 (range −0.7 to 7.5) and 6.8 (range 2.1–11.2) Mg C $ha^{-1}$ $yr^{-1}$, respectively, whereas for the temperate climate zone the emission factors for grassland was 5.5 (range 4.1–7.6) Mg C $ha^{-1}$ $yr^{-1}$. No data were available for emission factors for temperate cropland, but analysis of preliminary results suggested an emission factor between 9.2 and 11.2 Mg C $ha^{-1}$ $yr^{-1}$ (Couwenberg, 2011). Denmark, with a mean annual temperature of 8.5 °C since 1990, has a cool temperate climate in a position between the boreal and temperate climate zones. Consequently the emission factors presented here for Danish permanent grasslands and croplands on managed organic soils appear to be representative and comparable to a wider range of high-end emission factors derived from aggregate boreal and temperate climate zones (Couwenberg, 2011) and also comparable to emission factors derived from studies in neighbouring counties, such as Sweden (Berglund and Berglund, 2010), Norway (Kløve et al., 2010) and Germany (Oleszczszuk et al., 2008).

### Emissions of $CH_4$ and $N_2O$ at the eight monitoring sites

Based on measurement results representing the period 21 September 2008 to 20 September 2009 annual net fluxes of $CH_4$ and $N_2O$ were calculated. A brief account of the calculations and annual emissions of $CH_4$ and $N_2O$ is given here:

Daily fluxes of $CH_4$, $N_2O$ and $R_{eco}$ were calculated for each monitoring site and block by interpolation between adjacent sampling days. Accumulated fluxes representing the period 21 Sept 2008 to 20 Sept 2009 were then calculated. Annual fluxes at the block level ($n$ = 15 for soils in rotation, $n$ = 9 for grassland) were tested for normality. Annual $N_2O$ fluxes were normally distributed ($P<0.05$ for grasslands, $0.05<P<0.1$ for soils in rotation). Annual fluxes of $CH_4$ from soils in rotation were also normally distributed ($P<0.05$), whereas strong non-normality was found for $CH_4$ emissions from grassland, even after transformation.

The fluxes reported here represent little more than 12 months of measurements, which precludes evaluation of inter-annual variability. As an alternative, models for NEE and $CH_4$ fluxes were investigated with example data sets using temperature data from the years 1990-91 to 2007-08.

Systematic effects of region or land use on annual fluxes of $N_2O$ and $CH_4$ were tested by a linear mixed model. To control variance heterogeneity $CH_4$ fluxes were square-root transformed and $N_2O$ fluxes ln-transformed prior to analysis.

### Seasonal fluxes of CH4 and $N_2O$

#### $CH_4$

Methane fluxes are presented in Figure 4.23 below. With the exception of two experimental blocks at sites N-PG and E-PG, respectively, fluxes of $CH_4$ were mostly in the range –100 to +200 µg $CH_4$ $m^{-2}$ $h^{-1}$. The two exceptions were characterized by the presence of tussocks of soft rush at one (site E-PG) or two (site N-PG) sampling points. Soft rush is an aerenchymous plant with a known ability to transport $CH_4$ if concentrations build up in the root zone. The dry weight of soft rush in cuts taken during the monitoring period was related to the annual mean flux. However, a follow-up measurement program in 2010 at new sampling locations to elucidate the role of soft rush could not establish a simple relationship between presence of this plant and $CH_4$ flux, possibly because soil conditions in many situations did not favour accumulation of $CH_4$ (unpublished results).

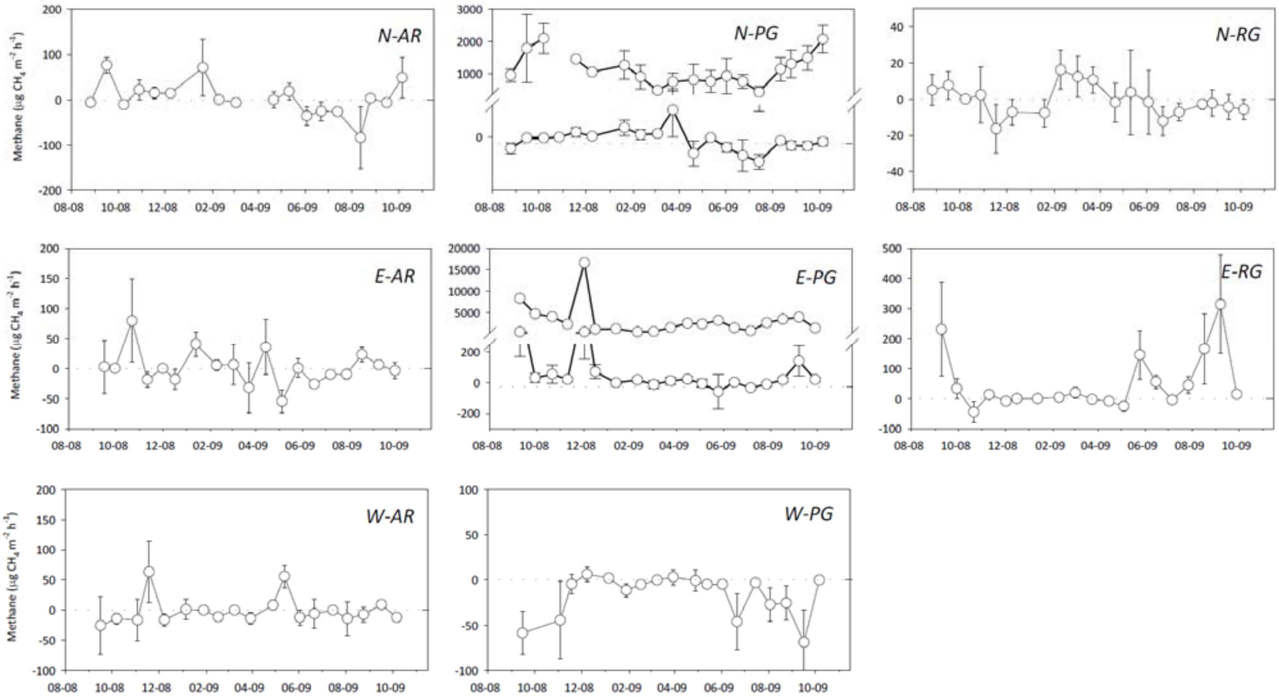


Figure 4.23 Measured methane fluxes.

### $N_2O$

Fluxes of $N_2O$ from permanent grasslands (PG) were always low, 0 to 500 µg $N_2O$ $m^{-2}$ $h^{-1}$ (Figure 4.24). In region E low $N_2O$ fluxes were also observed with land use AR and RG. The highest fluxes were observed at the site with spring barley in region W (site W-AR) and the site with potato in region N (site N-AR). In contrast, emissions with spring barley in region E were negligible. It should be noted that at site W-AR there were six cases during early autumn 2008 where a flux could not be estimated as the highest concentrations were more than five-fold above the reference gas used for calibration; hence the annual flux reported below for site W-AR is conservative. Site N-RG showed a consistent increase in $N_2O$ emissions during spring despite the absence of any fertilization or cultivation. Ground water level declined from –30 to –100 cm during this period, and presumably $N_2O$ was derived from a pool of mineralizable organic matter.

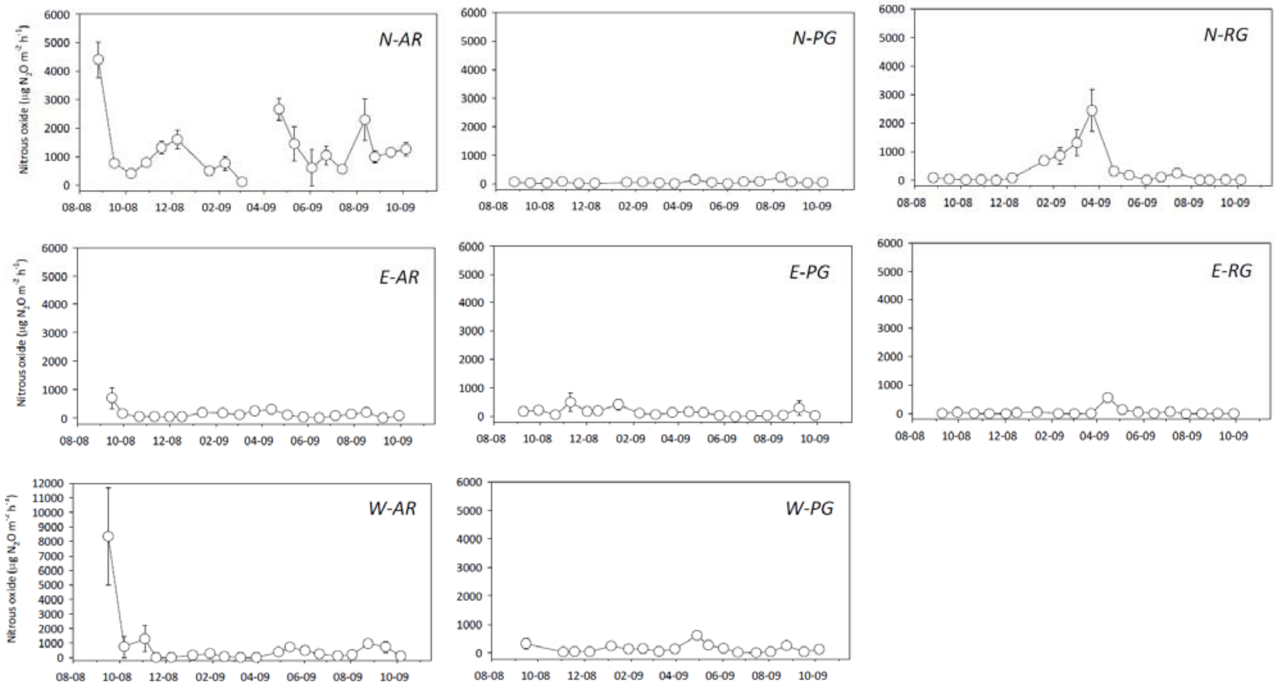


Figure 4.24 Measured $N_2O$ fluxes.

### System effects

In the test of system effects (region, land use) on $N_2O$ and $CH_4$ fluxes the two blocks with soft rush were omitted to avoid extreme variance heterogeneity. It was assumed that effects of region and land use were independent, which was confirmed for $CH_4$, but not for $N_2O$. For $CH_4$ there was a significant effect of region, but no effect of land use. Hence, in the absence of emission hotspots such as those observed on permanent grasslands in this study, there was no significant difference in $CH_4$ flux between soils in rotation and permanent grassland. The variation in $N_2O$ flux between monitoring sites was significantly larger than the difference between blocks within a site. The system analysis showed no effect of region, but an effect of land use, but as there was a significant region × land use interaction with $N_2O$ this result must be interpreted with caution.

### Effects of soil conditions

There were no consistent effects of soil conditions on fluxes of $CH_4$ or $N_2O$, as determined by a multiple linear regression analysis.

### Effects of soil conditions and climate, $CH_4$ + $N_2O$

The significant effect of land use on $N_2O$ fluxes observed in the system analysis was probably a result of the high levels of $N_2O$ emission observed at the two arable sites W-AR (spring barley) and N-AR (potato). However, there was also an arable field with spring barley in region E (site (E-AR) where emissions of $N_2O$ were consistently low despite slurry application during 2008 (cf. Figure 4.25). Hence land use alone is a poor predictor of $N_2O$ emissions, and it is clearly necessary to investigate further the interactions between land use and site-specific soil conditions.

One influencing factor is seasonal variation in ground water level (GWL), which was largely absent at site E-AR with low $N_2O$ emissions. Rapid changes in GWL may result in nitrification and / or denitrification taking place under $O_2$-limited conditions. The second mechanism suggested to explain the high $N_2O$.

Two of the permanent grasslands were significant sources of $CH_4$, though only as a result of a high emission from a few sampling points at sites N-PG and E-PG (fluxes shown separately in Figure 4.23) that included tussocks of soft rush.

### Annual $CH_4$ and $N_2O$ emissions

Annual fluxes of $CH_4$ and $N_2O$ were calculated on the basis of average emissions from each experimental block and interpolation between sampling days (Table 6.11). Annual fluxes of $CH_4$ ranged from -0.03 to +4.7 g $m^{-2}$. Due to the large spatial variability the annual estimates at sites N-PG and E-PG (permanent grasslands) are highly uncertain.

A total of six very high $N_2O$ fluxes observed at site W-AR at the first two samplings had to be disregarded, since they could not be quantified with the analytical conditions used in this study. Still this site, as well as site N-AR, showed $N_2O$ emissions well outside the uncertainty range of 2-24 kg $N_2O$-N $ha^{-1}$ $yr^{-1}$ proposed by the Intergovernmental Panel on Climate Change (IPCC, 2006). The remaining sites ranged from 0.5 to 3.7 g $N_2O$ $m^{-2}$ $yr^{-1}$, corresponding to between 0.3 and 2.4 kg $N_2O$ -N $ha^{-1}$ $yr^{-1}$.

Table 4.11 Measured annual $CH_4$ and $N_2O$ emissions, 1 g $m^{-2}$ = 10 kg $ha^{-1}$.

| Region | Land use | $CH_4$ | SE | C.V. | $N_2O$ | SE | C.V. |
|---|---|---|---|---|---|---|---|
| | | g $m^{-2}$ | | % | g $m^{-2}$ | | % |
| W | AR | -0.02 | 0.07 | 421 | 6.0 | 2.4 | 46 |
| | PG | -0.16 | 0.06 | 56 | 1.3 | 0.3 | 27 |
| N | AR | 0.03 | 0.08 | 380 | 9.6 | 1.6 | 29 |
| | PG | 2.8 | 2.9 | 176 | 0.5 | 0.2 | 85 |
| | RG | -0.03 | 0.03 | 957 | 3.7 | 0.6 | 85 |
| E | AR | 0.38 | 0.23 | 190 | 1.0 | 0.1 | 21 |
| | PG | 4.7 | 4.5 | 104 | 1.4 | 0.9 | 109 |
| | RG | 0.03 | 0.03 | 167 | 0.6 | 0.1 | 33 |

### Total measured GHG balance

The total measured GHG balances are presented in section Figure 4.25 using the Global Warming Potential (GWP) from the IPCC 2006 guidelines (IPCC, 2006) with a GWP of 25 for $CH_4$ and 298 for $N_2O$. As can be seen from Figure 4.23 is $CH_4$ mainly located to permanent grassland where high water tables can be found. On these lands are the share of $N_2O$ low probably to the unfertilized conditions and the higher lower release of N from the degradation of organic matter.

In the interpretation of the results caution should be made for especially the $N_2O$ emission from some of the soils in rotation as they showed very high $N_2O$ emissions. As the high $N_2O$ emissions can be an artifact or located to specific soil conditions with pyrite these measurements are not up scaled to the total Danish territory and used in the current Danish GHG inventory. Instead is used the current default values from the IPCC 2003 guidelines (IPCC, 2003).

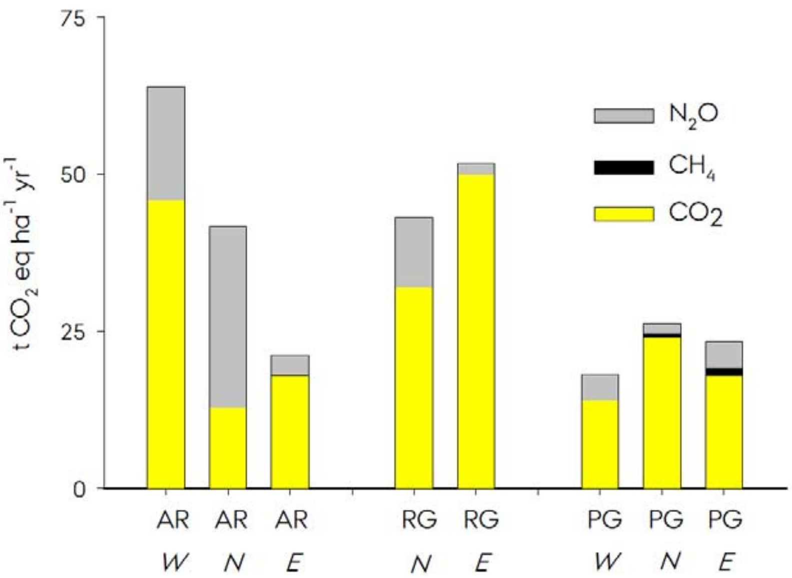


Figure 4.25 Total measured GHG balances from the plots split on $CO_2$, $CH_4$ and $N_2O$, t $CO_2$ eqv ha$^{-1}$ yr$^{-1}$.

In view of the statistical analysis of system effects and overall variability of measurement results it was decided to distinguish only between crops in rotation and permanent grasslands, i.e., to pool arable crops and rotational grass, for the derivation of emission factors for $CO_2$, $CH_4$ and $N_2O$. Summary results of these emission factors are given in Table 4.12.

Table 4.12 Summary statistics for the emission factors, including uncertainty ranges, as calculated from the experimental data of this study.

| | NEE (t C ha$^{-1}$ yr$^{-1}$) [b] | | $CH_4$ (g m$^{-2}$ yr$^{-1}$) | | $N_2O$ (g m$^{-2}$ yr$^{-1}$) | |
|---|---|---|---|---|---|---|
| Land Use | Rotation | Grassland | Rotation | Grassland | Rotation | Grassland |
| n | 5 | 3 | 15 | 9 | 15 | 9 |
| Median | 8.7 | 5.1 | 0.011 | 0.47 | 2.5 | 0.5 |
| Mean | 8.7 | 4.9 | 0.016 | 0.05 | 3.3 | 0.8 |
| Confidence interval, mean[a] | 5.3 to 12.6 | 3.5 to 6.7 | -0.005 to 0.08 | -0.1 to 2.9 | 1.4 to 4.5 | 0.2 to 1.6 |

[a]Confidence intervals based on descriptive statistics of data at site (NEE) or block scale ($CH_4$ and $N_2O$).
[b]NEE is the net-flux of $CO_2$, given as the amount of C.

### Uncertainty

#### $CO_2$

While the standard errors associated with the experimentally determined estimates are high, there is a strikingly good agreement between the mean values for arable soils and grassland as derived previously based on literature data (Gyldenkærne et al., 2005). It should be acknowledged that the variability contains random error associated with measurements, but also an inherent variability due to crop growth and soil conditions around the year.

#### $N_2O$

Very high emissions of $N_2O$ (around 60 and 96 kg $N_2O$ ha$^{-1}$ yr$^{-1}$) were observed at two sites with arable crops (spring barley and potato), which resulted in mean annual emissions for organic soil in rotation outside the range proposed by IPCC. Fertilization and grazing followed normal practice in 2008, prior to the monitoring period. Therefore N inputs may have been involved in high emissions observed during spring and winter. On the other hand, a field with spring barley in a third region emitted only around 6 kg $N_2O$ ha$^{-1}$ yr$^{-1}$, indicating that land use alone is a poor predictor of $N_2O$ emissions. Instead it may be necessary to consider site-specific interactions between soil mineral N and factors such as groundwater table dynamics or pyrite oxidation.

### $CH_4$

The net flux of $CH_4$ was very low for soils in rotation, whereas permanent grasslands were characterized by a very high variability. This was caused by a small number of sampling points with consistent emissions of $CH_4$ throughout the year. Incidentally these sampling points included tussocks of soft rush (*Juncus effusus*), an aerenchymous plant that may be involved in transporting $CH_4$ to the atmosphere if concentrations build up in the root zone.

## 4.4 Nitrogen leaching from agricultural soils

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### Nitrogen leaching and Run-off

Nitrogen, which is transported through the soil, can be transformed to $N_2O$. The IPCC (IPCC, 1997) recommends an $N_2O$ emission factor of 0.025 used, of which 0.015 is for leaching to groundwater, 0.0075 for transport to watercourses (in IPCC definition called rivers) and 0.0025 for transport out to sea (in IPCC definition called estuaries). The $N_2O$ emission from nitrogen leaching is a sum of the emission for all three parts calculated as:

$$N_2O_{leaching} = (N_{leach\text{-}ground} \cdot EF_{ground} + N_{leach\text{-}rivers} \cdot EF_{rivers} + N_{leach\text{-}estuatires} \cdot EF_{estuatires}) \cdot \frac{44}{28}$$

Denmark is surrounded by water and precipitation falls all year round. In winter there is a surplus leading to run-off and in summer there is a net evaporation. The amount of nitrogen leached out of the root zone depends on several factors: the amount of N applied, time and method of application, N uptake by plants, precipitation, soil properties, water flow in the soil, denitrification rates in the soil, denitrification and sedimentation in the streams and lakes etc. Figure 4.26 shows maps of Denmark illustrating the difference in precipitation, geomorphological types, geo-regions and rivers and lakes.

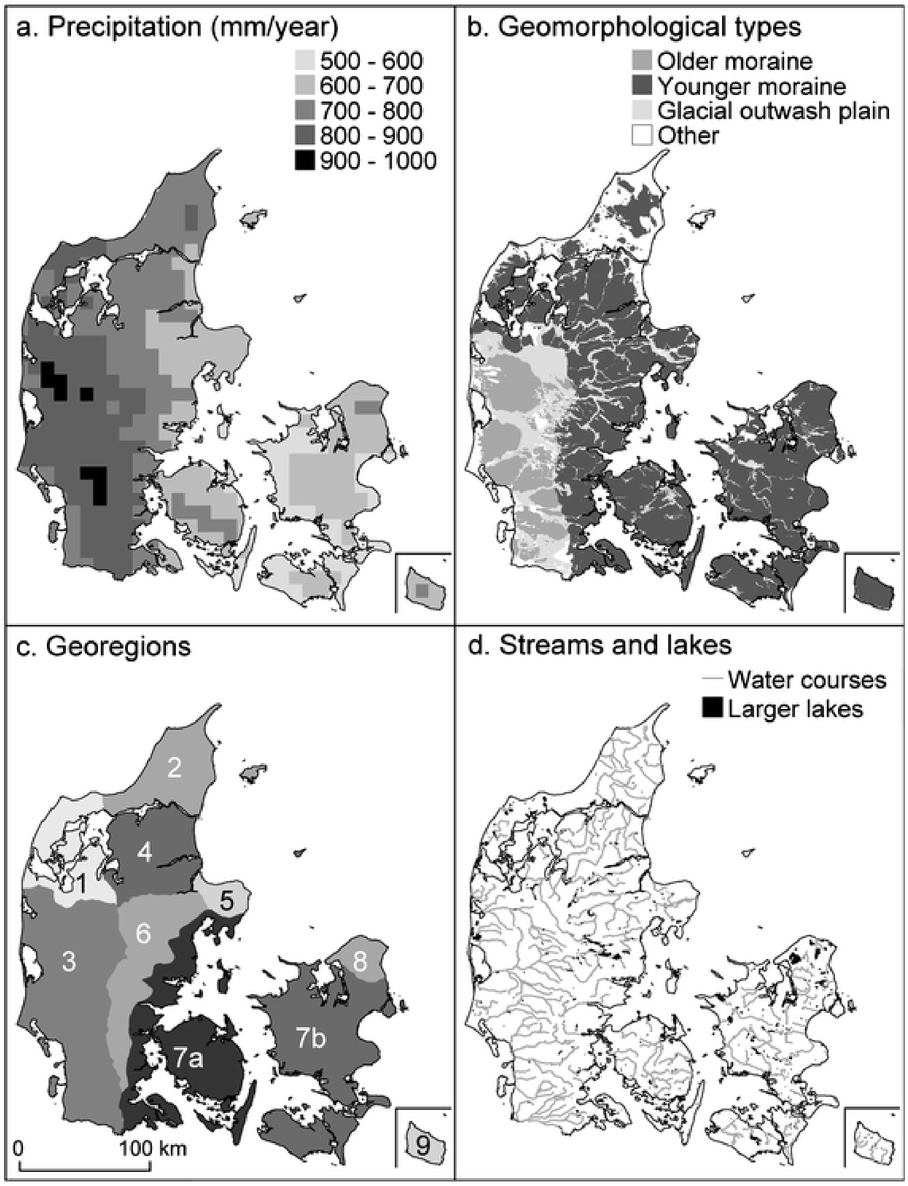


Figure 4.26 Conditions and properties for different regions in Denmark. Mean annual precipitation in 10 x10 $km^2$ grids (a), major geomorphological landscape types (b), georegions (c) and location of watercourses (larger streams) and larger lakes (d) in Denmark.

### N leaving the root zone

In the Action Plans for the Aquatic Environment, nitrogen leaching to groundwater (N leaving the root zone) has been modelled. The calculation of N to the groundwater is based on two different models: SKEP/DAISY and N-LES (Børgesen & Grant, 2003) carried out by DCA and DCE, Aarhus University. SKEP/DAISY is a dynamical crop growth model taking into account the growth factors, whereas N-LES is an empirical leaching model based on more than 1500 leaching studies performed in Denmark during the last 15 years. The models produce relatively similar results for nitrogen leaching on a national basis (Waagepetersen et al., 2008). The SKEP/DAISY model has estimated the total N leached from 2003-2007 to be 172 decreasing to 159 thousand tonnes N, whereas N-LES model has estimated the total N leached to be 163 000 decreasing to 154 000 tonnes during the same period. An average of the results from the two models is used in the emission inventory.

### N entering streams and estuaries

Since the late 1980s a wide range of regulatory measures, addressing both point sources and diffuse N pollution from agricultural land, have been implemented in estuary catchments to reduce the land based nitrogen (N) load to the Danish aquatic environment. Monitoring has been undertaken of key agro-environmental N indicators for different parts in 10 catchments (covering 35 % of the Danish land area) and their estuaries during the period 1990–2009. The N load to these 10 estuaries has been reduced by 39 % in total. For all the 10 linked catchments and estuaries decreasing trends have been reported for various indicators, amounting to 40–53 % for the catchment N surplus, approximately 30 % for the efficiency of use of cattle slurry N and approximately 40 % for pig slurry N, 18–55 % for the mean flow-weighted total N concentrations in inlet water to estuaries, and 24–62 % for total N concentrations in the upper and middle reaches of the estuaries.

In eight catchments and their estuaries a direct response (<5 years) of the diffuse N loads from catchments to reductions in the agricultural N surplus was found, the response differing between catchments due to wide variations in N removal in groundwater and surface waters. In two of the catchments and estuaries only, a time delay of N in groundwater aquifers was a major factor (decadal), possibly due to oxic groundwater in chalk aquifers.

The national monitoring program for estuaries, coastal and open marine waters was initiated in 1989 and the present study includes data from 1989–2009. Total N concentrations were measured from discrete water samples taken from the surface layer, as well as from the bottom layer if the water column was stratified. For most of the estuaries monitoring stations were located to represent upper, middle and lower reaches. Sampling frequencies varied from 12 to 46 times per year. Mean annual total N concentrations were calculated for each station using a general linear model with seasonal and trend components (see Carstensen et al., 2006 for more details).

Annual flow-weighted concentrations of N surplus ($N_{surplus}$) were calculated based on the annual catchment field surplus (kg) divided by the annual freshwater discharge to the estuary ($10^3$ $m^3$). Annual flow-weighted concentrations of total N in inlet waters to estuaries ($N_{inlet}$) were calculated based on the sum of monitored and modeled annual total N loads (diffuse and point sources) divided by the annual freshwater run-off from the catchments. The fraction of these concentrations deriving from point sources was estimated as total point source discharges divided by annual freshwater run-off ($N_{point}$).

Trend analysis of data was performed as a linear regression analysis using SAS software version 9.3. Normalisation of the area specific diffuse N load (kg N $ha^{-1}$ $yr^{-1}$) from the catchment to each estuary was undertaken to account for large inter-annual variations in precipitation and discharge and to facilitate comparisons between catchments. Normalisation as conducted by constructing a catchment-specific linear run-off/load (QT) relationship for log-transformed water run-off (Q for the agrohydrological year (mm $yr^{-1}$)) and the log-transformed calculated area-specific total N load from diffuse sources (T, (kg N $ha^{-1}$ $yr^{-1}$)) for the same year. The relationship for data from the period 1990–1997 is thus estimated as:

Eq. 6.1 $$\ln T = \alpha + \beta \ln(Q)$$

after which the log-transformed and run-off normalised relation can be expressed as:

Eq. 6.2 $\ln T_{norm} = \ln T - \beta \times (\ln Q - \ln(Q_{mean}))$

where T (kg N $ha^{-1}$) is the total N area specific load from diffuse sources in a given year, Q is water run-off (mm) in the same given year, and b is the estimated slope. $Q_{mean}$ in the equation is average annual run-off (mm) for the whole period used for normalisation. Subsequently, back transformation is performed (Ferguson, 1986) to calculate the run-off-normalised area specific annual N load ($T_{norm}$) from diffuse sources (kg N $ha^{-1}$ $yr^{-1}$):

Eq. 6.3 $T_{norm} = K_{kor} \exp(\ln T_{norm})$

where $K_{kor}$ corrects for the use of log-transformed data to estimate $T_{norm}$. $K_{kor}$ varies for the individual catchments for which run-off-normalised N load is determined. $K_{kor}$ is calculated as:

Eq. 6.4 $K_{kor}$ = exp(half; x MeanSquareError)

Ideally, the impact of the year-to-year fluctuations in water run-off is not reflected in the run-off-normalised diffuse N load. However, the method is not well adapted for generating a completely realistic value for very dry years such as 1995/96. If point source discharges (urban waste water treatment plants, industrial plants, fish farms and urban storm waters) from the individual years are added to the run-off-normalised diffuse N load (agriculture and background load), an estimate is obtained for the total N input for the given year at average annual water run-off. Some output from the model is shown in Figure 4.27. A good relationship is found for the modelled and the measured N amount in the streams.

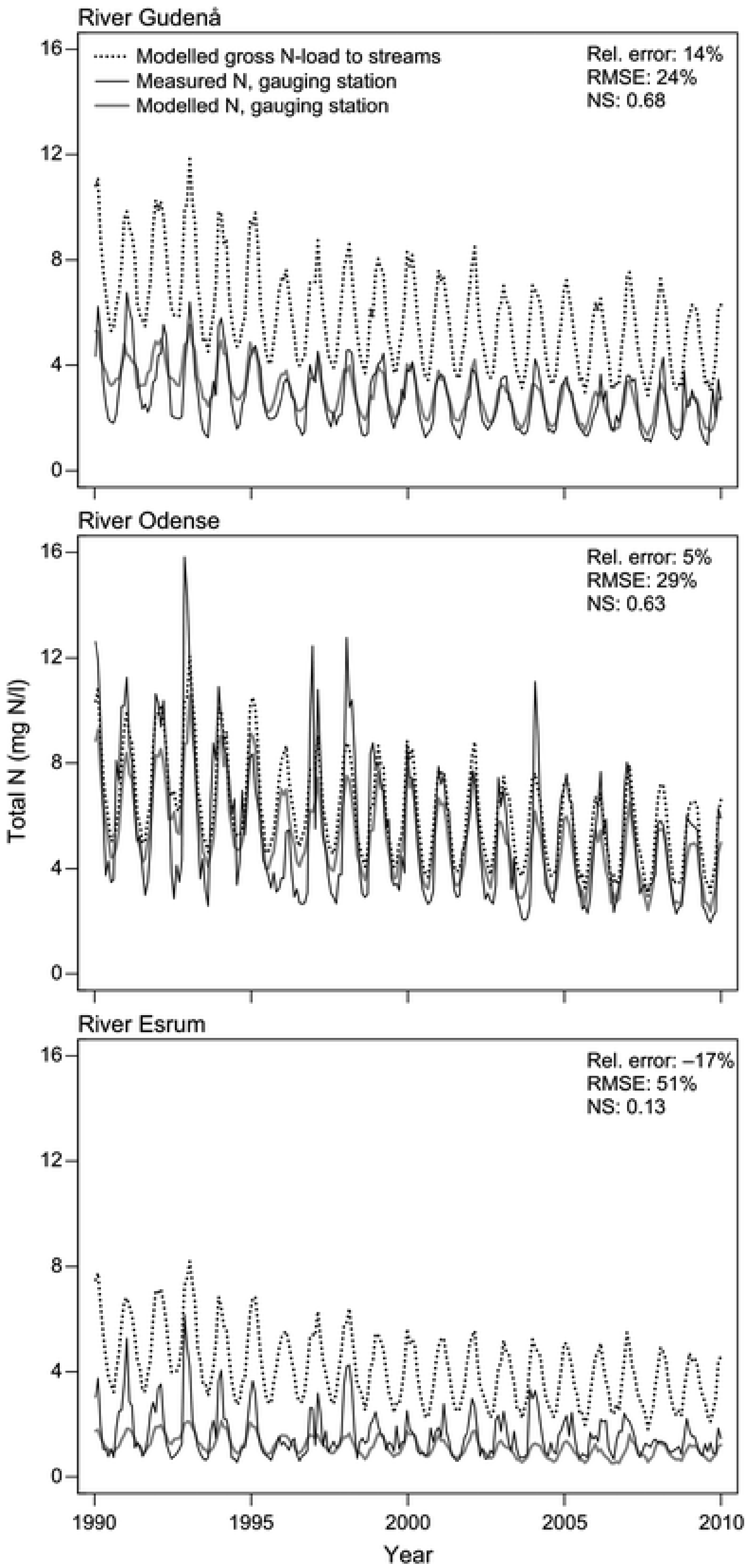


Figure 4.27 Modelled monthly gross and net total nitrogen concentration and measured monthly total nitrogen concentration at three gauging stations: River Guden_a (upper), River Odense (middle) and River Esrum (lower). Relative errors, RMSE and Nash–Sutcliffe (NS) listed for each river.

## Nitrogen concentrations in estuaries

The observed total N concentrations in the 10 estuaries were significantly linked to the observed total N loads expressed as flow-weighted total N concentrations in inlet freshwater to the estuaries for all catchments. These results are consistent with those reported in Carstensen and Henriksen (2009). The slopes in the relationships indicate that the estuaries are affected quite differently by nutrient inputs from land due to variations in hydrologic residence times across estuaries, ranging from a few days in Randers Fjord to about three months in Ringkøbing Fjord (Rasmussen and Josefson, 2002), in the location of monitoring stations along the salinity gradient, and in total N concentrations at the mouth of the estuary. For more detailed explanation see Windolf et al. (2012). Estuaries with short retention times will typically display a linear mixing pattern of nutrients along the salinity gradient, whereas estuaries with longer retention times typically have a curvilinear relationship with salinity because N removal increases with retention time through denitrification and permanent burial. Thus, policy measures adopted to reduce N surpluses in the catchments will often have a direct (<5 years) effect on the N concentrations in estuarine waters, and this is the main cause of the declining (i.e. improving) nutrient trends observed in Danish estuarine and coastal waters (Carstensen et al., 2006). Slow responses of the natural environment to changes in N loads from land following adoption of mitigation measures in catchments are a major factor to be considered when predicting responses (Maier et al., 2009). Moreover, the responses observed in estuaries are modulated by residence times such that longer residence times stimulate the retention of N within the estuary and thus reduce the export of N to the open coastal waters.

### Conclusions

The Danish regulatory approach to diminish agricultural N pollution during the last 25 years has mainly involved implementation of general mitigation measures. On a national scale, the outcome has been successful; the total land based N load to Danish coastal waters has been reduced by approximately 50 % derived from 18 500 t N reduction from point sources and 32 000 t N $yr^{-1}$ reduction from diffuse sources during the period 1990–2009. The regional responses have, however, varied widely.

New evidence of N attenuation in catchments and their estuaries (N-removal and time lag) by demonstrating significant and highly variable regional reductions in N during the last 25 years in response to the adopted policy measures has been documented. We have found examples of 6 catchments responding directly (<5 years) with marked and significant reductions in the N load to the estuaries to the adopted agricultural mitigation measures and of two catchments showing a direct but less marked response due to the presence of large lakes. Finally, two other catchments show almost no response in N load due to lag times in flows of nitrate-rich groundwater. We therefore conclude that attenuation of N (removal and time lags) in catchments may significantly impact the outcome of management plans targeted at obtaining N load reductions to estuaries and/or may delay the responses so that trend reversal is not detected for decades. Such delays will have an impact on the temporal distribution of the $N_2O$ emission in the national GHG inventories.

### $N_2O$ from nitrogen leached into groundwater, rivers and estuaries

Figure 4.28 shows leaching from groundwater estimated in relation to the nitrogen applied to agricultural soils as livestock manure, synthetic fertiliser and sludge. The average proportion of nitrogen leaching from groundwater has decreased from around 39 % in the middle of the nineties to around 33 % in 2011. The decline is due to an improvement in the utilisation of nitrogen in manure. The reduction in nitrogen applied is particularly due to the decline in the use of synthetic fertiliser, which has been reduced by 50 % from 1990 to 2011.

The proportion of N input to soils lost through leaching and run-off ($Frac_{LEACH}$) used in the Danish emission inventory is higher than the default value of the IPCC (30 %). The high values are partly due to the humid Danish climate, with the precipitation surplus during winter causing a downward movement of dissolved nitrogen. $Frac_{LEACH}$ has decreased from 1990 and onwards. At the beginning of 1990s, manure was often applied in autumn. Now the main part of manure application takes place in the spring and early summer, where there are nearly no downward movements of soil water. The decrease in $Frac_{LEACH}$ over time is due to increasing environmental requirements and banning manure application after harvest. The data based on model estimates from DCA and DCE reflects the Danish conditions and is considered the best estimate.

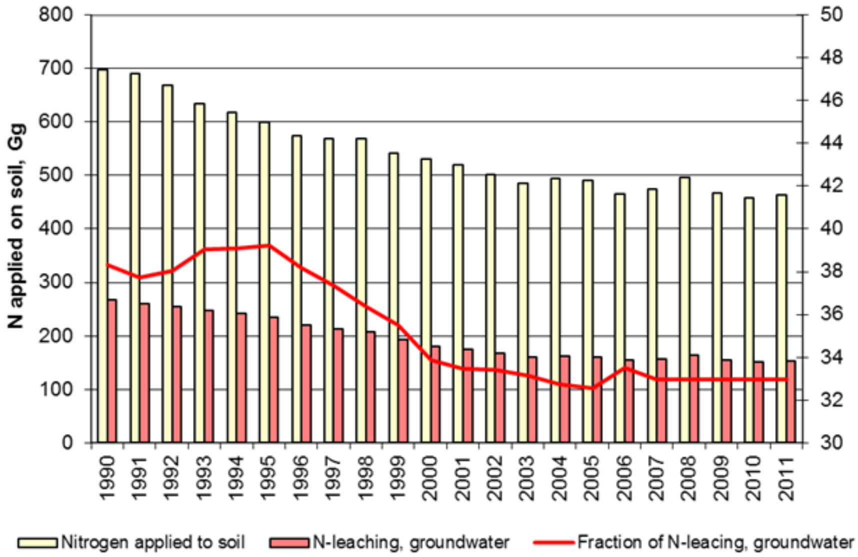


Figure 4.28 Nitrogen applied to agricultural soils and N-leaching, groundwater 1990-2011.

Total N concentrations were measured utilising a sampling frequency of 12–26 (average 18) per year (1990–2009) at the 118 monitoring stations used in this study for validation of the DKQN model. Data concerning the N-leaching to rivers and estuaries is based on data from NOVANA (National Monitoring program of the Water Environment and Nature) to estimate the annual N leaching to rivers and estuaries. The outcome from the model is shown in Table 6.13. These data are used in the Danish GHG inventory to estimate the $N_2O$ emission from leaching and run-off combined with the default emission factors from the IPCC 1996 Guidelines (IPCC, 1996).

Table 4.13 N leaching to groundwater, rivers and estuaries in Gg, 1990-2012.

| | 1990 | 1995 | 2000 | 2005 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|
| Groundwater | 267 | 235 | 179 | 160 | 163 | 154 | 151 | 153 | |
| Rivers | 102 | 104 | 95 | 67 | 80 | 59 | 68 | 73 | |
| Estuaries | 100 | 91 | 81 | 56 | 65 | 49 | 55 | 59 | |

### Impact on the Danish Green House Gas inventory

Based on the measured nitrogen concentrations in streams, lakes and inner coastal water a model for the whole nitrogen leaching in Denmark has been established. The data indicates that a high denitrification takes place in the soil before the nitrogen enters the streams. On an average the denitrification rate is around 60 % for whole Denmark but with a high variability between soil types. Furthermore around 15-20 % of the nitrogen entering the streams is deposited in lakes, denitrified into the atmosphere as $N_2$ or lost through other pathways. The IPCC guidelines (IPCC, 1996 & 2000) assume that only nitrogen at the different locations is sources for $N_2O$. N lost before these locations can therefore not be a source for $N_2O$ formation and therefore is the estimated / modelled amounts of N a better estimate for the $N_2O$ formation than the loss out of the root zone. The actual measured and modelled amounts of nitrogen for streams and lakes and estuaries was therefore recommended to be used in the Danish GHG inventory instead of the default values of 30 % of the nitrogen applied to fields.

The overall impact on the Danish inventory is shown in Figure 4.29. Compared to the emission factors from the IPCC 1996 Guidelines and IPCC 2000 Good Practice Guidance (IPCC, 2000) the $N_2O$ emission has been estimated to approximately 18-20 % lower than the default values. This is mainly due to high denitrification in the soil of leached nitrogen to the root zone before it enters the streams and lakes. This denitrification rate is highly soil dependent.

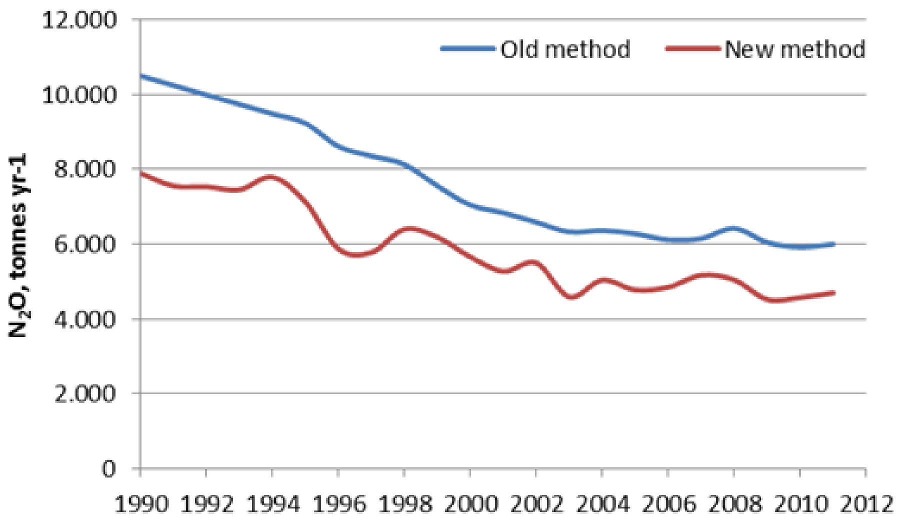


Figure 4.29 Reported $N_2O$ emission from leached nitrogen with the default IPCC model and the Danish model.

The use of actually monitored nitrogen in the streams and in the estuaries has a high variability between years. In general the monitored concentration in the run-off is relatively uniform between years. This is probably due to the strict Danish regulation for application of N to the crops which allows the crops to empty the soil before senescence. The amount of leached N is therefore dependent on the degradation of organic matter after senescence and the through flow precipitation in winter. As a result high nitrogen loads are connected with high precipitation rates which creates a high variability between years compared to the IPCC default model.

The concentration and the related emission of $N_2O$ from the streams and estuaries have not been monitored. It is recommended to monitor these emissions for improving the national emission estimates taking into account the variability in the leached nitrogen.

## 4.5 Reporting on emissions from Cropland and Grassland

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The overall aim of the SINKs project was to improve the Danish reporting and accounting from Cropland Management and Grassland Management as well as inclusion of the forest data into the Danish inventory.

DCE is responsible for the overall reporting to UNFCCC under the climate convention and under the Kyoto Protocol.

All new information and data obtained in the different sub-projects of the SINKs programme has been evaluated, discussed and implemented in the Danish national GHG inventory by DCE if valid documentation for the proposed activity data and emission factors was found documented to a high scientific standard.

Updated figures on living biomass, dead organic matter and litter is received from IGN and implemented in the national inventory.

Annual quality checks are performed on the data received from IGN.

DCE has participated in several meetings in Bruxelles and at Joint Research Centre, ISPRA in Italy in order to discuss the KP reporting and dissemination of the results.

All data used for the reporting / accounting is published in the National Inventory Reports (NIR). These can be found at www.dce.au.dk.

# 5 Overall conclusions on the SINKs project and recommendations

## 5.1 Conclusions

The SINKs project has provided documentation for $CO_2$, $CH_4$ and $N_2O$ emission from Danish forestry and agriculture. The research and development project improved the Danish GHG inventory for LULUCF (Land Use, Land Use Change and Forestry) considerably with solid documentation for the activity data and the currently used emission factors.

The project has provided new information on the following topics:

- A new Land Use Matrix covering the period 1990 to 2012
- BEF values for Norway spruce and beech
- The area and drainage status of the forest soils
- Documented that there is no basis to suggest that Danish forest soils has been sources for $CO_2$ since 1990.
- Estimations of the area, volume and the carbon stock in Danish hedgerows and small biotopes
- Further developing a dynamical tool to estimate the carbon stock changes in mineral soils (C-TOOLS)
- Carried out soil sampling in the agricultural soil sampling grid as an independent verification of the changes in agricultural soils
- Produced a new map of the agricultural organic soils following the IPCC/FAO definitions
- Estimated $CO_2$ and $N_2O$ emissions from organic soils
- Estimated the amount of leached nitrogen to streams, lakes and inner coastal waters
- Added substantially to the reporting of the GHG emission from the Danish territory.

In the forest sector the new land use matrix has documented both afforestation and deforestation. The effect of afforestation since 1990 on the Danish GHG accounting has been a small sink effect of 184 Gg $CO_2$ in the period 2008 to 2012 or at an average of 36.7 Gg $CO_2$ $yr^{-1}$. The total afforested area since 1990 to 2012 has been estimated to 94 358 hectares. The low accounting figure under article 3.3 is partly caused by the fact that in two out of five years has the measurement in the NFI plots shown a decrease in the carbon stock compared to the previous year (2007-2008 and 2011-2012) and that a certain carbon stock must be removed when an area is converted from another land use to forestry (equal to the summer peak biomass in annual and perennial crops). The removed carbon stock on afforested land is calculated as instant oxidation when the land use change takes place and therefore a land use conversion during 2008 to 2012 can be a source, if the total amount of sequestered carbon in all afforested plots since 1990 to that particularly year in the commitment period is lower than the removed carbon from land use conversion in the same year.

The deforested (D) area has been estimated to 5 784 hectares from 1990 to 2012. Although the Danish forest is protected, deforestation may take place for establishment of settlements, for wind turbine parks or for creation of open natural habitats, which are not fulfilling the forest definition. A more thoroughly analysis showed that part of the deforestation is due to conversion of christmas tree plantations in agricultural fields to annual crops. In the first commitment period (2008-2012) the deforested areas has been estimated to release 440 Gg $CO_2$ or at an average of 88 Gg $CO_2$ $yr^{-1}$.

For Forest Management (FM) in forests established before 1990, the results from the NFI have showed that these are large sinks. The average carbon sequestration from 2008 to 2012 has been estimated to 4 050 Gg $CO_2$ $yr^{-1}$. This amount is much larger than the Danish CAP on forestry which is 917 Gg $CO_2$ for the first commitment period.

It has been estimated that the overall annual emission from land use in the agricultural (Cropland) sector is reduced from 5.1 to 3.8 million tonnes $CO_2$ eqv (Table 5.1). In the agricultural sector the main reduction is caused by a reduced emission from the mineral soils and a disappearance/depletion of the organic soils combined with a reduced leaching of nitrogen, reduced lime consumption, and increased carbon storage in hedgerows and small biotopes.

From 1990 to 2012 almost all areas in the inventory has been updated with new activity data and new emission factors. The new map of the organic soils has produced new insight on the distribution of the organic soils and showed that much of the organic layer has disappeared. The measured $CO_2$ emission from the remaining organic soils are higher than the default IPCC values and the modelling of the mineral soils with C-TOOL showed that although the overall output from C-TOOL is more or less as expected with a carbon loss on the loamy soils and an increase/steady state on the sandy soils it also showed that there is a high loss from intermediate soils having a carbon content of 6-12 % organic carbon and that C-TOOL is not able to model these emissions. These soil types are not included in the IPCC inventories with an emission factor although the carbon content is elevated and therefore subject to a $CO_2$ loss when utilized for agricultural purposes.

It is not meaningful to estimate the emission from the LULUCF sector before 2006 and with the updated knowledge. E.g. the establishment of the NFI in 2002 has produced new data and insight in the carbon turnover in the Danish forests; data which has changed the inventory in many ways. Another example is the new map of the agricultural organic soils combined with new emission factors for organic soils and modelling of the carbon turnover in mineral soils.

Table 5.1 Reported emissions from Afforestation, Deforestation, Forest Management, Cropland Management and Grassland Management, 1990 to 2012.

| | 1990 | 1995 | 2000 | 2005 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|
| Afforestation | 76.6 | 27.5 | -52.2 | -616.8 | 393.4 | -216.2 | -279.8 | -119.2 | 37.8 |
| - living biomass | 77.8 | 42.0 | -6.9 | -385.6 | 361.8 | -119.2 | -171.0 | -110.0 | 64.7 |
| - dead organic matter | 0.0 | -6.8 | -30.3 | -208.3 | 59.6 | -67.1 | -77.4 | 23.7 | 6.6 |
| - mineral soils | -2.1 | -12.3 | -22.6 | -32.9 | -39.2 | -41.3 | -43.4 | -45.4 | -46.3 |
| - organic soils | 0.9 | 4.7 | 7.7 | 10.0 | 11.1 | 11.4 | 12.0 | 12.5 | 12.8 |
| | | | | | | | | | |
| Deforestation (annual loss) | 30.3 | 31.6 | 32.8 | 79.1 | 81.0 | 80.5 | 82.0 | 84.7 | 108.5 |
| - living biomass | 24.8 | 25.9 | 26.9 | 67.8 | 70.2 | 70.1 | 70.9 | 73.5 | 91.9 |
| - dead organic matter | 5.7 | 5.6 | 5.5 | 10.9 | 11.7 | 11.8 | 12.8 | 13.4 | 19.2 |
| - mineral soils | 0.1 | 0.3 | 0.6 | 0.5 | -0.8 | -1.2 | -1.6 | -2.0 | -1.8 |
| - organic soils | NO | NO | NO | NO | NO | NO | NO | NO | NO |
| - $N_2O$ from disturbance (a) | -0.2 | -0.2 | -0.2 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.8 |
| | | | | | | | | | |
| FM | 43.8 | -987.6 | -716.8 | 1227.9 | -6113.7 | 243.5 | -3770.6 | -6195.9 | -4495.2 |
| - living biomass | 0.0 | -1070.5 | -839.1 | 582.2 | -4301.3 | 356.4 | -1674.4 | -5177.8 | -3521.4 |
| - dead organic matter | 0.0 | 43.0 | 86.3 | 613.6 | -1842.2 | -141.8 | -2125.1 | -1047.0 | -1002.7 |
| - mineral soils | NO | NO | NO | NO | NO | NO | NO | NO | NO |
| - organic soils | 49.6 | 45.2 | 40.8 | 36.4 | 33.7 | 32.8 | 32.8 | 32.7 | 32.7 |
| - $N_2O$ from drained soils (a) | -5.8 | -5.3 | -4.8 | -4.3 | -4.0 | -3.8 | -3.8 | -3.8 | -3.8 |
| | | | | | | | | | |
| Cropland (reported under LULUCF) | 5136.1 | 4652.8 | 4006.6 | 3723.6 | 3972.8 | 2864.7 | 3586.1 | 3390.3 | 4574.4 |
| - hedgerows and biotopes | 20.3 | -45.6 | -58.8 | -71.9 | -82.6 | -91.0 | -93.8 | -96.1 | -96.5 |
| - perennial wooden vegetation | -21.9 | 18.7 | -9.2 | 1.6 | 0.1 | -10.7 | -34.4 | -19.7 | -1.6 |
| - other living biomass | -78.7 | 91.3 | 119.3 | 79.8 | 81.5 | 71.2 | 97.1 | 89.3 | 269.8 |
| - mineral soils | 1416.0 | 1070.8 | 920.8 | 979.5 | 1363.5 | 374.3 | 1168.9 | 1000.8 | 601.8 |
| - organic soils | 2887.3 | 2686.1 | 2484.8 | 2283.6 | 2162.8 | 2122.6 | 2082.3 | 2045.0 | 1980.7 |
| - liming | 622.9 | 561.6 | 300.0 | 221.4 | 230.1 | 184.9 | 156.7 | 165.5 | 192.3 |
| | | | | | | | | | |
| - $N_2O$ from drained organic soils (b) | 290.2 | 270.0 | 249.8 | 229.5 | 217.4 | 213.4 | 209.3 | 205.3 | 198.3 |
| - $N_2O$ from leached nitrogen (b) | 2447.1 | 2209.1 | 1754.3 | 1479.9 | 1563.8 | 1401.0 | 1416.6 | 1455.6 | 1429.5 |
| | | | | | | | | | |
| Grassland | 162.2 | 128.9 | 133.8 | 198.2 | 230.9 | 217.8 | 206.7 | 236.6 | 421.5 |
| - living biomass | 55.7 | 30.7 | 43.8 | 116.4 | 154.1 | 142.7 | 133.2 | 163.2 | 347.4 |
| - mineral soils | -0.2 | -0.9 | -1.7 | -2.5 | -3.0 | -3.2 | -3.4 | -3.6 | -4.5 |

(a) GWP of 310 is used to convert from $N_2O$ to $CO_2$ eqv.

(b) the emission is reported in the agricultural sector (4D) and not in the LULUCF sector.

The LULUCF sectors addition to the Danish reduction commitment under the Kyoto Protocol

Besides the mandatory inclusion of article 3.3 activities in Danish GHG reduction commitment, Denmark further elected Forest Management, Cropland Management and Grassland Management under article 3.4 of the Kyoto protocol. In Table 5.2 the preliminary estimated accounting quantities for the LULUCF sector are shown.

Table 5.2 Preliminary accounting parameters for Denmark for Art. 3.3. and Art. 3.4. activities.

| | Net emissions/removals | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| GREENHOUSE GAS SOURCE AND SINK ACTIVITIES | Base year | 2008 | 2009 | 2010 | 2011 | 2012 | Total | Accounting Parameters | Accounting Quantity |
| | Gg $CO_2$ equivalent | | | | | | | | |
| A. Article 3.3 activities | | | | | | | | | |
| A.1. Afforestation | | 393.4 | -216.2 | -279.8 | -119.2 | 37.8 | -183.9 | | -183.9 |
| A.2. Deforestation | | 81.3 | 80.9 | 82.4 | 85.1 | 110.2 | 439.8 | | 439.8 |
| B. Article 3.4 activities | | | | | | | | | |
| B.1. Forest Management | | -6 097.5 | 259.4 | -3 754.7 | -6 180.0 | -4 479.3 | -20 252.0 | | -1 172.6 |
| 3.3 offset | | | | | | | | 255.9 | -255.9 |
| FM cap | | | | | | | | 916.7 | -916.7 |
| B.2. Cropland Management | 4 844.7 | 3 768.0 | 2 663.5 | 3 388.5 | 3 196.1 | 2 957.7 | 15 973.8 | 24 223.3 | -8 249.5 |
| B.3. Grazing Land Management | 177.4 | 235.1 | 223.2 | 213.4 | 244.5 | 523.2 | 1 439.4 | 887.0 | 552.4 |

For afforestation the estimated accounting quantity between years in the first commitment period is very variable because in two of the years, 2008 and 2012 the measurements in the NFI sampling plots for areas afforested after 1990 showed a decreased carbon stock. The total accounting estimate for afforestation has been estimated to be a net sink of 184 Gg $CO_2$ equvalents.

Deforestation since 1990 has been estimated to be a net source of 439 Gg $CO_2$ equivalents.

Forest Management has been estimated to be a net sink of 20 611 Gg $CO_2$ eqv. Denmark has a CAP on forest management of 917 Gg $CO_2$ eqv. Because of the off-set accounting rules (i.e. that if the emission from Deforestation is higher than the sink in Afforested areas under article 3.3.) the difference between Deforestation and Afforestation can be added to the Danish CAP under Forest Management. This increases the Danish accounting under Forest management to 1 172 Gg $CO_2$ eqv in the first commitment period.

Cropland Management has been estimated to add 8 250 Gg $CO_2$ eqv to the Danish reduction commitment, while Grassland Management has been estimated to add negatively to the Danish Commitment. The negative impact from Grassland Management is partly explained by a lack of special activities taking place in Grassland to reduce the emissions. Moreover, it is caused by the large difficulties in categorizing the agricultural land to either Cropland or Grassland and the large area flow between the two categories. The emission from Grassland Management in 2012 in Table 5.2 is very high. The reason for this negative impact on the accounting estimate is mainly due to changes in living biomass caused by changes in the land use matrix and in the data received from Statistics Denmark (See Table 5.1). Large interannuel changes in the background data may have a large impact on the emission estimates and the emission estimates for individual years should not be seen as predictions for the trend in the emissions.

# 6 Resulting publications

## 6.1 Land Use Matrix

Levin, G., Blemmer, M.K., Gyldenkærne, S., Johannsen, V.K., Caspersen, O.H., Petersen, H.S., Nyed, P.K., Becker, T., Bruun, H.G., Fuglsang, M., Münier, B., Bastrup-Birk, A.-M. & Nord-Larsen, T. 2014: Estimating land use/land cover changes in Denmark from 1990 - 2012: Technical documentation for the assessment of land use/land cover changes for estimation of carbon dioxide fixation in soil. DCE Technical Report 38. Available at: http://dce2.au.dk/pub/TR38.pdf

## 6.2 Forest issues

### BEF

Skovsgaard, J.P. & Nord-Larsen, T., 2010: Functions for biomass, basic density and biomass expansion factor for European beech (*Fagus sylvatica* (L.)) in Denmark.

Skovsgaard, J.P., Bald, C. & Nord-Larsen, T. 2010b: Functions for biomass and basic density of stem, crown and below-ground stump and root system of Norway spruce in Denmark

### Drainage of forest soils

Johannsen, V.K., Nord-Larsen, T., Riis-Nielsen, T., Suadicani, K. & Jørgensen, B.B., 2013: Skove og plantager 2012, KU/IGN, Skov & Landskab, Frederiksberg, 2013. 189 s. ill.

### Forest soils

Nordic Seminar "Estimation of soil organic carbon in forest soils for the reporting of GHG emissions", Norwegian Forest and Landscape Research Institute, Ås, Norway, March 11-12, 2010: Vesterdal, L., Stupak, I., Repeated sampling of soils in Danish forests for supporting reporting of soil C under KP art. 3.3 and 3.4.

Seminar at Laboratory of Forestry, Ghent University, April 28, 2010: Vesterdal, L., Stupak, I., Repeated sampling of soils in Danish forests for supporting reporting of soil C under KP art. 3.3 and 3.4.

European Geosciences Union General Assembly 2010, Vienna, May 3-7, 2010: Vesterdal, L., Hansen, K., Stupak, I. et al., How much will afforestation of former cropland influence soil C stocks? A synthesis of paired sampling, chronosequence sampling and repeated sampling studies. Talk in session BG2.20 "Greenhouse gas budget of soils under changing land use".

UNFCCC in-country review of the Danish 2010 GHG inventory submission, Danish Energy Agency, Copenhagen, September 6-11, 2010: Vesterdal, L. & Stupak, I., 2010: Monitoring and reporting of forest soil carbon in Denmark.

Seminar on Inventory and Monitoring of Natural Resources - in connection with appointment of Adjunct Professor Göran Ståhl. Faculty of Life Sciences, Copenhagen, September 22, 2010. Ingerslev, M., Vesterdal, L., Raulund-Rasmussen, K. & Stupak, I. 2010: Intensive ecosystem monitoring.

Meeting in the Nordic Nordforsk network “Forest Soil C-sink”, Forest & Landscape Denmark, Copenhagen, October 26, 2010: Vesterdal, L., Stupak, I. The Danish soil carbon inventory.

Meeting in the Nordic Nordforsk network “Forest Soil C-sink”, Norwegian Forest and Landscape Institute, Ås, Norway, October 1, 2012: Georgiadis, P, Vesterdal, L. & Stupak, I., Carbon Stocks in Danish Forest Soils.

Meeting in the Nordic Nordforsk network “Forest Soil C-sink”, Norwegian Forest and Landscape Institute, Ås, Norway, October 1, 2012: Stupak, I., Boveland, J., Vesterdal, L. & Georgiadis, P., Carbon stocks in Danish forest types.

Boveland, J. 2012: MSc. thesis, European Master Programme in Environmental Sciences, Swedish University of Agricultural Sciences, Sweden & University of Copenhagen, Denmark. Available at: www.stud.epsilon.slu.se/4805/1/boveland_j_120913.pdf

Denmark’s National Inventory Report 2010. Emission Inventories 1990-2008. - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol, NERI Technical Report no. 784, National Environmental Research Institute, Aarhus University.

Denmark’s National Inventory Report 2011. Emission Inventories 1990-2009. - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol, NERI Technical Report no. 827, National Environmental Research Institute, Aarhus University.

Denmark’s National Inventory Report 2012. Emission Inventories 1990-2010. - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol, Scientific Report from DCE – Danish Centre for Environment and Energy no. 19, Aarhus University.

#### Contribution to education (post.doc., Ph.D. projects, M.Sc. theses)

The project has led to a MSc. thesis by Judith Boveland (European Master Programme in Environmental Sciences, awarded highest degree): “Carbon stocks in Danish forest types”. This thesis was based on soil C stocks, biomass and dead wood C stocks in the 278 NFI plots.

The study of environmental and previous land use controls on soil C stocks based on the 400 NFI+KN plots will probably be included in the Ph.D. project of Petros Georgiadis.

#### Forest reporting

National Inventory Report, 2010

National Inventory Report, 2011

National Inventory Report, 2012

National Inventory Report, 2013

National Inventory Report, 2014

Johannsen, V.K., Nord-Larsen, T., Riis-Nielsen, T., Bastrup-Birk, A., Vesterdal, L. & Møller, I.S. 2010: Revised: Acquiring and updating Danish forest data for use in UNFCCC. Forest & Landscape Working Papers No. 54-2010, 47 pp. Forest & Landscape Denmark, Frederiksberg.

Nord-Larsen, T. & Suadicani, K., 2010: Træbrændselsressourcer fra danske skove over ½ ha – opgørelse og prognose 2010. Arbejdsrapport nr. 113, Skov & Landskab, Københavns Universitet, Frederiksberg, 53 s.

Johannsen, V.K., Nord-Larsen, T., Riis-Nielsen, T., Suadicani, K. & Jørgensen, B.B., 2013: Skove og plantager 2012, KU/IGN, Skov & Landskab, Frederiksberg, 2013. 189 s. ill.

## 6.3 Cropland and Grassland issues

### Hedgerows

Fuglsang, M. & Münier, B. Estimation of hedgerows for the Kyoto protocol - area, biomass and carbon sequestration. GI-Norden/ScanGIS scientific conference, Stockholm, Conference Paper.

### C-TOOL

Taghizadeh-Toosi, A. et al. 2014b: C-TOOL: A simple model for simulating whole-profile carbon storage in agricultural soils. Ecological Modelling (in prep).

### Sampling in the Agricultural soil sampling grid

Christensen, B.T., Greve, M.H., Elsgaard, L., Kristensen, K., Olesen, J.E., Thomsen, I.K. & Østergaard, H.S. (submitted). Dyrkningsfaktorers effekt på jordens kulstofindhold. Plantekongressen 2013. 16

Taghizadeh-Toosi, A., Olesen, J.E., Kristensen, K., Elsgaard, L., Østergaard, H.S., Lægdsmand, M., Greve, M.H. & Christensen, B.T., 2014a: Changes in carbon stocks of Danish agricultural mineral soils during 1986 -2009: effects of management. European Journal of Soil Science (submitted).

### Mapping of the organic soils

Adhikari, K., Minasny, B., Malone, B.P., McBratney, A.B. & Greve, M.H., 2012: Continuous depth function mapping af soil pH variability in Denmark, abstract from 4th International Congress EUROSOIL 2012, Fiera del Levante, Bari, Italien.

Knadel, M., Deng, F., Greve, M.H. & Thomsen, A.G., 2012: Development of a Danish national vis—NIR soil spectral library for SOC determination, paper presented at 5'th global workshop on Digital Soil Mapping 2012, Sydney, Australien.

Knadel, M., Deng, F. & Greve, M.H., 2012: Development of a Danish national vis—NIR soil spectral library for SOC determination, Digital Soil Assessments and Beyond: Proceedings of the 5th Global Workshop on Digital Soil Mapping 2012, Sydney, Australia. (red.) Alex B McBratney. Taylor & Francis Group, London, UK : C R C Press LLC, 2012.

Adhikari, K., Bou Kheir, R., Greve, M.H., Bøcher, P.K., Greve, M.B., Malone, B.P., Minasny B. & McBratney, A.B., 2012: Digital Soil Assessments and Beyond: Proceedings of the 5th Global Workshop on Digital Soil Mapping

2012, Sydney, Australia. (red.) Alex B McBratney. C R C Press LLC, 2012. s. 445-451.

Greve, M.H., Bou Kheir, R., Greve, M.B. & Bøcher, P.K., 2012: Quantifying the ability of environmental parameters to predict soil texture fractions using regression-tree model with GIS and LIDAR data : The case study of Denmark, Ecological Indicators, Vol. 18, 2012, s. 1-10.

Deng, F., Knadel, M., Peng, Y., Heckrath, G.J., Minasny, B. & Greve, M.H., 2012: Soil profile organic carbon prediction with Visible Near Infrared Reflectance spectroscopy based on a national database. Paper presented at 5th global workshop on Digital Soil Mapping 2012, Sydney, Australien.

Deng, F., Knadel, M., Peng, Y., Heckrath, G.J., Greve, M.H. & Minasny, B., 2012: Soil profile organic carbon prediction with visible-near infrared reflectance spectroscopy based on a national database, Digital Soil Assessments and Beyond: Proceedings of the 5th Global Workshop on Digital Soil Mapping 2012, Sydney, Australia. (red.) Alex B, McBratney. Taylor & Francis group, London, UK : C R C Press LLC, 2012.

Knadel, M., Rossel, R.A.V., Deng, F., Thomsen, A.G. & Greve, M.H., 2012: Using visible-near infrared spectra to describe the distribution of Danish topsoils, Poster session presented at EUROSOIL 2012. Soil Science for the Benefit of Mankind and Environment. 4th International Congress of the European Confederation of Soil Science Societies (ECSSS), 2-6 July, Bari – Italy, Bari, Italien.

Knadel, M., Deng, F., Thomsen, A.G & Greve, M.H., 2012: Vis-NIRS sensor fusion for local, regional and global calibrations of SOC content, Abstract from EGU, Vienna, Østrig.

Knadel, M., Thomsen, A.G & Greve, M.H., 2012: Multisensor On-The-Go Mapping of Soil Organic Carbon Content, Soil Science Society of America. Journal, Vol. 75, Nr. 5, 30.09.2011, s. 1799-1806.

Deng, F., Knadel, M., Peng, Y., Abdollahi, L., Thomsen, A.G. & Greve, M.H., 2012: Feasibility of using Vis-NIR spectroscopy to determine soil organic carbon in subsoil, Book of abstracts - Pedometrics 2011 Innovations in Pedometrics. 2011. s. 106-106.

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Petersen, S.O, Greve, M.H., Hoffmann, C.C., Lærke, P.E. & Schäfer, C., 2011: Tørvens klimabalance, Aktuel Naturvidenskab, Vol. 3, 2011, s. 24-28.

Greve, M.H., 2011: Variation i jordens tekstur: Regionalt og lokalt, Jordanalyser - kvalitet og anvendelse. DCA - Nationalt center for fødevarer og jordbrug, 2011. s. 85-96 (DCA Rapport; Nr. 002).

Bou Kheir, R., Bøcher, P.K., Greve, M.B. & Greve, M.H., 2010: The application of GIS based decision-tree models for generating the spatial distribution of hydromorphic organic landscapes in relation to digital terrain data, Hydrology and Earth System Sciences, Vol. 6, Nr. 14, 01.06.2010, s. 847-857.

Adhikari, K., Toth, G., Mako, A. & Greve, M.H., 2010: Assessment of spatial variability pattern of surface soil moisture content : a geostatistical perspective, 1st International Conference and Exploratory Workshop on Soil Architecture and Physico-Chemical Functions "CESAR". Aarhus Universitet, Det Jordbrugsvidenskabelige Fakultet, 2010. s. 17-24.

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### *Offspring from the project*

The DP6 subproject of SINKs has helped in educating four Ph.D. students, one of which is now engaged in a post.doc position at Agro.

Maria Knadel, title of Ph.D. thesis: 'Sensor based mapping of organic soils in Denmark'. Ph.D. granted in December 2011.

Kabindra Adhikari, preliminary title of Ph.D. thesis: 'National scale soil mapping in Denmark using DSM techniques'. Expected dissertation in March 2013, partly financed by SINKs.

Fan Deng. Working with NIR spectroscopy and digital soil mapping techniques in her Ph.D.

### $CO_2$, $N_2O$ and $CH_4$ from organic soils in Denmark

Elsgaard, L., Görres, C.M., Hoffman, C.C., Blicher-Mathiesen, G., Schelde, K. & Petersen, S.O., 2012: Net ecosystem exchange of $CO_2$ and carbon balance for eight temperate organic soils under agricultural management. Agriculture Ecosystems and Environment 162:52-67.

Schäfer, C.M., Elsgaard, L., Hoffman, C.C. & Petersen, S.O., 2012: Seasonal methane dynamics in three temperate grasslands on peat. Plant and Soil 357:339-353.

Petersen, S.O., Hoffmann, C.C., Schäfer, C.M., Blicher-Mathiesen. G., Elsgaard, L., Kristensen, K., Larsen, S.E., Torp, S. & Greve, M.H., 2012: Annual emissions of CH4 and N2O, and ecosystem respiration, from eight organic soils in Western Denmark managed by agriculture. Biogeosciences 9:403-422.

Görres, C.M., Kutzbach, L. & Elsgaard, L., 2014: Comparative modelling of annual $CO_2$ flux of temperate peat soils under permanent grassland management. Agriculture Ecosystems and Environment, in press.

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Nielsen, A.H., Brix, H., Petersen, S.O., Bøcher, P.K. & Sorrell, B.K., 2011: Lysesiv– er der hul igennem? Aktuel Naturvidenskab 3, pp. 29-32.

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**Other**:

Elsgaard, L, 2012: Net ecosystem exchange and carbon balance at Danish peatlands under annual and perennial cropping regimes. Oral presentation at the workshop "Regulation of soil organic matter and nutrient turnover in agriculture", 15th and 16th of November 2012, Witzenhausen, Germany.

Elsgaard, L, 2013: Contemporary GHG flux monitoring in Danish cultivated peat soils and restored wetlands. Invited presentation at the 2. Methoden-workshop “Bestimmung von Treibhausgasflüssen in und aus Böden“ Rostock, 25.04.2013 – 26.04.2013

Workshop arranged, Monitoring of greenhouse gas emissions in organic soils Sandbjerg Slot, 18 March 2008.

Workshop arranged, Preliminary results and further direction of the data handling in the SINKs project 7. Presentations given by invited experts and project members, Two-day expert workshop held on Hotel Comwell, Kolding, 4-5 March 2010

**$N_2O$ emission from leached nitrogen**

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# THE DANISH SINKs PROJECT

Final report on the Danish monitoring project for Land Use, Land Use Change and Forestry under the Kyoto Protocol

The report describes the outcome of a project (SINKs) conducted from 2007-2013, with the objective to develop new knowledge, methods and report emissions from the Land Use and Land Use Change and Forestry sector (LULUCF) for the Danish reporting obligations to the Kyoto Protocol. 13 subprojects were finalised and provided a new map of the organic soils in Denmark, as well as models and methods for emission inventory in relation to yearly land use change and ensuing changes in the carbon pool in soils and biomass.

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