Thesis for the degree of Doctor of Philosophy

Land use GHG emissions and mitigation options, simulated by CoupModel

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Doctor Thesis A158
University of Gothenburg
Department of Earth Sciences
Gothenburg, Sweden 2015

ISBN: 978-91-628-9684-3
ISSN: 1400-3813

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ISBN: 978-91-628-9684-3

ISSN: 1400-3813

Internet ID: http://hdl.handle.net/2077/41176

Printed by Ineko AB

Distribution: Department of Earth Sciences, University of Gothenburg, Sweden

Abstract

Climate change and greenhouse gas (GHG) emissions are one of the major challenges to the humankind of 21st Century. This thesis focuses on understanding, estimating and suggesting mitigation of the GHG emissions (mainly N_2O and CO_2) from the land use sector, specifically from forest ecosystems on drained peatlands but also from willow production on agricultural clay soil. This is achieved by merging a detailed process-oriented model, CoupModel with available data collected with state of art measurement techniques.

The results show the CoupModel is able to simulate soil N_2O and CO_2 emissions for both land use types, despite not precisely capturing each measured N_2O peak, which still remains a challenge. Model analysis reveals the major N_2O emission controlling factors for afforested drained peatlands are vegetation and groundwater level, while fertilization and soil water status are the controlling factors for willow production on clay soil. Over a full forest rotation the forest trees act as a C sink and the drained peat soil as a source, of fairly similar size and the forest ecosystem is an overall GHG sink. However, also including the fate of the harvested forest, indirect GHG emissions, would switch this extended system (from the production site to the fate of the products) into an overall large GHG source. The modelling also predicts rewetting spruce forest on drained peatlands into willow, reed canary grass or wetland could possibly avoid GHG emissions by 33%, 72% and 89% respectively. In a cost-benefit analysis, the two wettest scenarios, wetland and reed canary grass, the monetized social benefits exceed the costs, when using social costs of carbon as a proxy for the value of GHG emissions, beside profits made from sold products and also value of biodiversity, avoided CO_2 due to both replacement of cement and steel in buildings as well as fossil fuels for heating and electricity production.

These findings provided in this thesis fill some knowledge gaps of modeling N_2O emission and GHG balance over full forest rotation on drained peatlands, provide perspectives for mitigation GHG emissions from drained peatlands and bioenergy production on clay soil. In addition, the calibrated parameters and correlations between the parameter and variables in this thesis provide guidelines for future modeling of GHG for similar types of systems.

Keywords: GHG; CO_2; N_2O; forest; drained peatland; clay soil; willow; soil nitrate leaching; modeling; CoupModel; Generalized likelihood uncertainty estimation (GLUE); Land use; mitigation option; Cost benefit analysis

Populärvetenskaplig sammanfattning

Utsläpp av växthusgaser (GHG) och klimatförändringa är ett av de allvarligaste hoten mot mänskligheten detta århundrade. Denna avhandling fokuserar på att förstå, uppskatta och föreslå minskning av växthusgasutsläppen, främst lustgas och koldioxid (N_2O och CO_2) från markanvändningssektorn, särskilt från skogsekosystem på dränerad torvmark och också från produktion av energigröda (salix) på lerjord, genom att använda en stor mängd fältdata av hög kvalitet i processmodellering med CoupModellen.

Resultaten visar att CoupModellen acceptabelt kan simulera markens utsläpp av både N_2O och CO_2 för både dränerad torvmark och lerjord trots att modellen inte klarar av att hitta varje uppmätt N_2O topp, vilket därför fortfarande är en utmaning. Analysen visar att de viktigaste påverkansfaktorerna för N_2O-emission från dikad beskogad torvmark är vegetation och grundvattennivå, emedan gödsling och markvattenstatus är de viktigaste faktorerna för N_2O emission i samband med videproduktion på lerjord. Växande skog fungerar som en C-sänka av ungefär lika storlek som utsläppen från den dränerade torvjorden, där skogsekosystemet i sin helhet fungerar som en GHG sänka. Men när skogen skördas frigörs det uppbundna kolet, vid användning av skogsprodukter, varvid det totalt blir stora GHG-utsläpp. Modelleringsanalysen föreslår att återvätning av granskog på dränerade torvmarker kan undvika utsläpp av växthusgaser med 33%, 72% och 89% i olika scenarier med vide, rörflen och våtmark. Kostnads-nyttoanalys visar ett positivt resultat uttryckt som pengar endast för de två blötaste scenarierna, rörflen och våtmarker, där förutom vinster från sålda produkter och värdet av biologisk mångfald värderas även värdet av växthusgasutsläppen inkluderas med hjälp av ’social cost of carbon’, samt undvikande av CO_2 där timmer kan ersätta betong och stål i byggnader och där biomassan kan ersätta fossila bränslen.

Denna avhandling försöker fylla kunskapsluckor vid modellering av N_2O emission och växthusgasbalanser över en hel skogsrotation på dikad torvmark, och ger perspektiv på hur utsläpp av växthusgaser kan minimeras från både dikad torvmark och energigröda producerad på lerjord. Kalibrerade parametrar och korrelationer mellan dessa och uppmätta variabler som finns i denna avhandling kan användas för fortsatt modellering av växthusgaser från liknande system.

Preface

This thesis consists of a summary (Part I) followed by four appended papers (Part II).

Paper I

He H., Jansson P.-E., Svensson M., Meyer A., Klemedtsson L. and Kasimir Å., Factors controlling Nitrous Oxide emission from a spruce forest ecosystem on drained organic soil, derived using the CoupModel, *Ecological Modelling*, 2016, 321C, 46-63, 10.1016/j.ecolmodel.2015.10.030 (in press)

Paper II

He H., Jansson P.-E., Svensson M., Björklund J., Tarvainen L., Klemedtsson L. and Kasimir Å., Forests on drained agricultural peatland are potential large sources of greenhouse gases – insights from a full rotation period simulation, accepted for publication as *Biogeosciences Discussions*

Paper III

Kasimir Å., Coria J., **He H**., Liu X., Nordén A. and Svensson M., An Ecological-Economic analysis of climate mitigation through rewetting of drained peatlands, submitted to *Ecological Economics*

Paper IV

He H., Jansson P.-E., Hedenrud A., Weslien, P., Rychlik S., Klemedtsson L. and Kasimir Å., Nitrous oxide and nitrate losses - influencing factors in willow cropping investigated by modelling, *manuscript*

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I. Summary

II. Papers I-IV

List of Symbols and Acronyms

Symbol	Description	Unites
C	carbon	
N	nitrogen	
P	precipitation	mm day^{-1}
T_a	air temperature	^oC
u	wind speed	m s^{-1}
R_{is}	global short wave radiation	J m^{-2} day^{-1}
h_r	relative humidity	%
n_c	total cloudy fraction	%
$R_{n,tot}$	total net radiation	J m^{-2} day^{-1}
q_h	soil surface heat flux	J m^{-2} day^{-1}
T	soil temperature	^oC
θ	soil water content	%
GWL	groundwater level	m
NEE	net ecosystem exchange	g C m^{-2} day^{-1}
N_2O	N_2O emission rate	g N m^{-2} day^{-1}
LAI	leaf area index	-
C_{tot}	total soil Carbon	g C m^{-2}
PG	the annual plant growth	g C m^{-2}
$C_{peat\text{-}CO2}$	soil peat decomposition	g C m^{-2} day^{-1}
LE	total latent heat flux	J m^{-2} day^{-1}
H	total sensible heat flux	J m^{-2} day^{-1}
R^2	coefficient of determination	
ME	mean error	
NPP	net primary production	g C m^{-2} day^{-1}
NEE	net ecosystem exchange	g C m^{-2} day^{-1}

Part I

Summary

Introduction

Reducing anthropogenic greenhouse gas (GHG) emissions is one of the great challenges that humanity is facing. The IPCC's fifth assessment report concludes that it is necessary to reduce GHG emissions substantially in the decades to come and reach values close to zero by the end of the century (IPCC, 2014b). Globally, fossil fuel combustion is the main source of anthropogenic GHG emissions. However, the land-use sector-'Agriculture, Forestry and Other land use (AFOLU)'-contributes 20-24% to annual anthropogenic GHG emissions (IPCC, 2014b).

A major driver of the emissions from the land use sector is the global population increase. To feed the increasing global population, it is a need to increase crop yields to produce food, fiber as well as energy. This ultimately leads to an intensified land use in most regions of the world, causing land use GHG emissions. For example, global emissions from agricultural sector (crops and livestock) have continued to increase during the last 50 years from 2.7 billion tonnes carbon dioxide (CO_2) in 1961 to 5.3 billion tonnes in 2011 (FAO, 2014, www.fao.org). Owing to the invention of Haber–Bosch process, which converts inert atmospheric N_2 into reactive NH_3, mankind is now overall introducing 120 Tg N annually (mainly as mineral fertilizer) into the terrestrial ecosystems, already triples the natural sources of N, 63 Tg N yr^{-1} (Galloway et al., 2004, Fowler et al., 2013). The extensive use of synthesized fertilizer also direct causes an increase of the atmosphere N_2O concentrations (Smil, 1997). Today and most probably in the near future, increasing land areas are and will continue to be managed for food and fiber production. Management of these land areas alters the sinks and sources of GHG. Therefore, good management of the land requires additional understanding of the land use GHG emissions.

Besides, European renewable energy directive (Directive 2009/28/EC, European Union) has provided a legislation framework for increasing the share of renewable energy sources to secure the energy supply and to reduce the GHG emissions. According to the directive, each member state should reach a 20 % share of energy from renewable sources by 2020. To reach this goal, land use for biomass production is becoming increasingly important. Biomass can be produced as a by-product of forestry management or from crops designated for energy biomass (i.e. willow). For instance, logging residues from forestry and harvest products from short rotation coppices (SRC) are being widely used for heat production in Sweden (Gustavsson et al., 2006). However, concerns also arise for possibly increased soil N_2O emissions by biomass production coupled to fertilization (Crutzen et al., 2008, Smith et al., 2012, Kasimir Klemedtsson and Smith, 2011), reduced biomass pools and soil degradation (Schulze et al., 2012). To achieve an overall reduction of GHG emissions, soil emissions from biomass energy system must be accurately accounted for.

Sources and sinks of GHG from land use sector so far is still the most uncertain term among all sectors (Houghton et al., 2012). Much research efforts have been made to quantify the GHG fluxes for various terrestrial ecosystems, from which rough estimates of the emission rates are also now available and uncertainties in global budget have been reduced (Syakila and Kroeze, 2011, IPCC, 2014b). Still, a central question in these aspects is how to use the measured fluxes and link the multi influencing factors (both natural and also anthropogenic factors) through different scales (spatially from genes to microorganisms to plants to field and temporally from hour to days to years to decades). Also, how to use the available information and knowledge to guide our current management practice? There is both a need to achieve complete understanding of the responses, feedbacks as well as functionalities of the soil-plant-atmosphere continuum and create possibilities to upscale current knowledge and test different scenarios or management practices. Quantitative evaluations of biomass production and GHG emissions should be the basis for decisions. Thus, there is a need to further develop experimental research, monitoring and modeling to reduce the current uncertainty of these quantifications.

Background

Hotspots of GHG emissions from drained peatlands and SRC productions

Worldwide, peatlands and other organic soils cover only 3% of the land area but contain 30% of the soil carbon (FAO, 2012, Gorham, 1991). Natural unmanaged peatlands accumulate C as partially decayed vegetation, and the decay processes emit C in the form of CO_2 and CH_4. Overall, the net GHG balance of the photosynthesis and decomposition is generally positive with a normal C sequestration rate of between 10 to 80 g m^{-2} yr^{-1} (Belyea and Malmer, 2004, Yu, 2012, Chmura et al., 2003). Thus undisturbed peatlands are considered to be C sinks contributing to an attenuation of climate change (Gorham, 1991). However, in many northern as well as tropical countries, land use management over the last centuries has promoted peatland drainage. The reason has been to provide tradable goods like animal feed, food and fibers at the expense of other important ecosystem services like regulation of C and plant nutrient storage, water storage and infiltration, and biodiversity (Turner et al., 2000). When peatlands are drained for forestry (or agriculture), resulting in a lower groundwater level, the aerobic soil volume increases (Fig. 1a). The previously water-logged peat soil then decomposes aerobically, losing soil C stock as CO_2 plus the physical collapse of peat after initial drainage thus lowering of the soil surface (so called surface subsidence), also emitting N_2O but CH_4 emissions are normally decreased and could even become a small uptake (Eggelsmann, 1976, Limpens et al., 2008). During the first few decades after planting, the development of the plant roots and the leaf area cover increase the transpiration and evaporation interception losses which will deepen the groundwater level (Fig. 1b). In other words, a growing forest will partly keep the soil drained and increase the air filled porosity. However, the drainage would become less efficient with time due to subsidence and filling of ditches by litter and mosses, all of which would lead to an increased water table (Fig. 1c) why ditch clearing or maintenance to keep the ditch level to the original depth is performed. After ditch maintenance the forest ecosystem restarts at the well-drained state (Fig. 1d), until the final clear cutting when re-drainage has to be conducted. Then the entire cycle starts again and can continue until all the peat is gone.

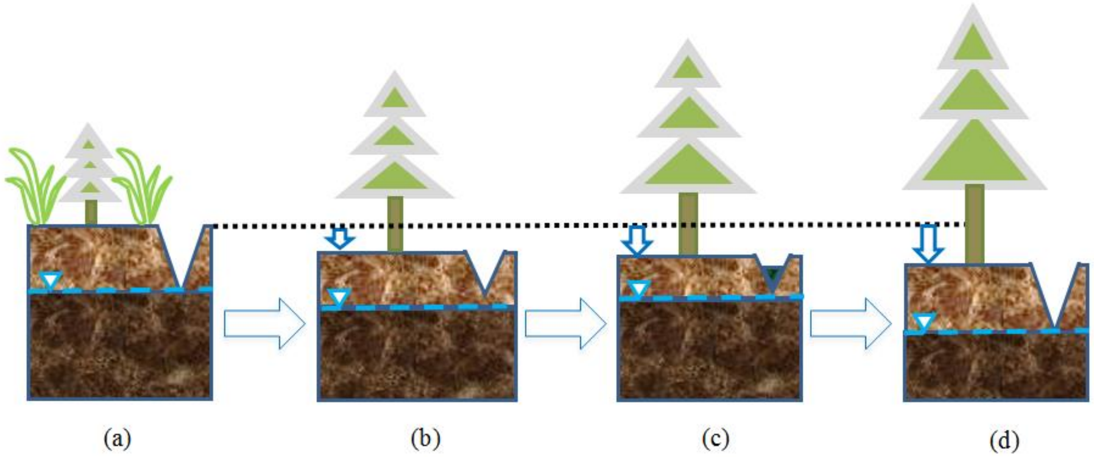

Figure 1. Conceptual representation of the dynamics of plants and peat soil development over a forest rotation period. Spruce tree and understorey vegetation, e.g. grasses are considered for a-b, but for clarity understorey vegetation is only shown in a. The blue line indicates the groundwater level and blue arrow at the surface indicates the surface subsidence. Any variation of climate during the forest development in this conceptual figure is not considered.

Drained peatlands are thus hotspots for GHG emissions (Couwenberg et al., 2011, Davidson and Janssens, 2006, Meyer et al., 2013). Overall, one quarter of AFOLU emissions comes from and is due to the draining of peatlands. Globally 10-20% peatlands have now been drained for agriculture or forestry and this overall contributes to 6% of global anthropogenic CO_2 emissions (FAO, 2012). In the EU, peatlands are estimated to be a net source of 70 Tg C yr^{-1}, equivalents to about 20% of the C sequestered by the forest sector (Janssens et al., 2003). In Sweden, 300 kha of agricultural drained peatlands exist, which is 8.6% of total agricultural land (Berglund and Berglund, 2010) and 1.5 Mha (6%) of a total 23 Mha productive forestry area have drained peatlands cover (Ernfors et al., 2007). The Swedish National Inventory Reporting (NIR) to the UN climate convention (UNFCCC) shows drained peatlands to have emissions about 11 Tg CO_2eq yr^{-1}, almost as high as the road traffic, 18 Tg CO_2eq yr^{-1}. Therefore, mitigating emissions from drained peatlands are urgently needed both at regional and the global scale.

Besides, another issue that also attracts much interests of scientists is the bioenergy production on agricultural land where emissions of N_2O have been found to be essential in determination of the total GHG neutrality of the bioenergy system (Crutzen et al., 2008, Smith et al., 2012, Kasimir Klemedtsson and Smith, 2011). N_2O emissions from bioenergy crop production could possibly offset or cause even larger global warming as that avoided by replacing fossil fuel. For instance, in Sweden, ca 11000 ha land is now used for willow cultivation which constitute nearly half the total willow planted area in entire Europe (Don et al., 2012). Today two types of fertilizer are commonly used for willow plantations in Sweden, commercial mineral N fertilizer and sewage sludge, an end product of wastewater treatments (Dimitriou and Aronsson, 2011). Overall, approx. 80-90% of all willow fields in Sweden have been fertilized with sewage sludge (and wood-ash if available). There is a need for knowledge on the N_2O emissions size and its main influencing factors, affected by management practices. This important knowledge is of need when aiming for GHG mitigation by SRC production.

Modeling soil GHG emissions

Understanding of the complex GHG production pathways in soil and emissions have been built into process based models founded on measurements and experiments. Over the past years, a number of models have been developed and applied to simulate the soil GHG emissions (Li, 2007, Blagodatsky and Smith, 2012, Chen et al., 2008). These models can be divided into two major categories; the first use simple empirical models derived from regression analysis of measured ecosystem data and GHG emissions, like IPCC emission factors (EF) compiled on measured data in available literature. This gives a rough estimation of the GHG size for a specified land use type at national or continental scale (IPCC, 2014a). The other category is the mechanistic process-oriented models (e.g. CoupModel (Jansson, 2012)), which is based on existing knowledge on ecosystem processes and detailed description of the site/ecosystem specific factors (Blagodatsky and Smith, 2012, Butterbach-Bahl et al., 2013). Both types of models could estimate GHG emissions at various spatial and temporal scales. However, since process-based models integrate knowledge from different scales and disciplines, with deeper understanding of the underlying interacting processes these could be applied to study the process controls of GHG emissions. Moreover, process-oriented models are also able to predict the various soil responses to changes in the environment, land use, and also to various management practices (Butterbach-Bahl et al., 2013).

In a review by Maljanen et al. (2010) on GHG emissions of drained peatlands in Nordic countries it was pointed out that specific controlling factors that regulate the N_2O emissions from forests on drained peatland are still unclear, and that there is a lack of understanding the GHG balance over the full forest rotation since most studies so far have only covered a few years at most and in many cases restricted to only CO_2 as GHG. So far modeling studies for drained peatlands are few (Stolk et al., 2011), since most modeling studies on soil GHG emissions have been conducted for mineral soils, e.g. Nylinder et al. (2011), Van Oijen et al. (2011), de Bruijn et al. (2011), Metivier et al. (2009) and Rahn et al. (2012) or from peatlands without forest cover (Metzger et al., 2015) or wetlands with forest cover (Gärdenäs et al., 2011). In the need to fill the knowledge gaps, a detailed process-oriented model, the CoupModel (Jansson, 2012, Jansson and Moon, 2001) was used in this thesis work, to model the GHG emissions and their influencing factors, simulating GHG balance over a full forest rotation period and also suggesting mitigation options.

Aims of the thesis

This thesis focuses on the issue of GHG emissions in connection to biomass production. This was addressed from an applied perspective by investigating the GHG (mainly N_2O and CO_2) emissions and their influencing factors, aiming for possible mitigation options for forest ecosystems on drained peatlands (Paper I, II and III) and conventional bioenergy plant (willow) on an agricultural site (Paper IV).

Specific objectives are:

- Calibrating the CoupModel for a drained peatlands site, to test if (1) the model can describe the measured data and (2) analyze N_2O controlling factors (Paper I)

- Upscaling the calibrated model to a full forest rotation period and quantify the overall GHG balance (Paper II)
- Modeling GHG mitigation scenarios of drained peatlands with economic analysis, with the aim to provide new insights into the social value of drained peat areas currently used for spruce plantations and compare this with different wetter options (Paper III)
- Modeling the N losses from a conventional willow plantation in Sweden with sewage sludge application and mineral fertilizer and investigate the influencing factors. And evaluation of different management practices for N_2O mitigation (Paper IV)

Material and Method

CoupModel

The CoupModel platform (coupled heat and mass transfer model for soil-plant-atmosphere systems) is an updated (coupling) version of the previous SOIL and SOILN models (Jansson and Moon, 2001, Eckersten et al., 1998). Figure 2 shows a brief, conceptual overview of the CoupModel. It is developed to simulate the water, heat, C and N fluxes of the soil-plant-atmosphere continuum under user-defined temporal and spatial resolutions. The main model structure is a one-dimensional, vertical layered soil profile (see water and heat model in Figure 2). The model is normally driven by meteorological data of; precipitation, air temperature, wind speed, air humidity and global radiation, with the soil and plants being parameterized (Jansson, 2012). The core of the model is the surface energy balance (see big leaf model in Figure 2) and mass balance. At the soil surface, evaporation and snow dynamics are calculated by assuming that net radiation would be balanced out by the turbulent sensible heat & latent heat flux and also the soil heat flow (Alvenäs and Jansson, 1997, Gustafsson et al., 2004, Klemedtsson et al., 2008). The C and N dynamics are simulated based on the mass balance principle where the model simulates these by coupling aboveground and belowground processes. These processes are further coupled to the soil water and temperature simulations and can feed back to the surface energy balance by modifying the plant growth and aerodynamic resistance (Jansson et al., 2007). The model can simulate multiple plant layers with mutual competition between water, radiation and N. For more detailed description of the model and specific model settings for each study, see the respective paper.

Site description and measurements

The data used for the first three papers (I, II and III) were obtained from the Skogaryd research site (Table 1), a Spruce forest (*Picea abies*) ecosystem on a drained peatland. The soil was earlier a fen, with a peat depth of more than 1 meter (measured in 2006), and was initially drained by ditches in the 1870s and used for agriculture (cereal and grass production) until 1951. Norway spruce (*Picea abies*) was then planted and the stand is now a mature mixed coniferous forest with dominance (95% by stem volume) of Norway spruce trees, with sparse scots pine (*Pinus sylvestris*) and silver birch (*Betula pubescens*) (Klemedtsson et al., 2010). Skogaryd is a well-established research site with intensive monitoring programs started in 2006 and still ongoing. Management of the forest during the rotation period includes one thinning in 1979 and some trees harvested after a storm in 2010.

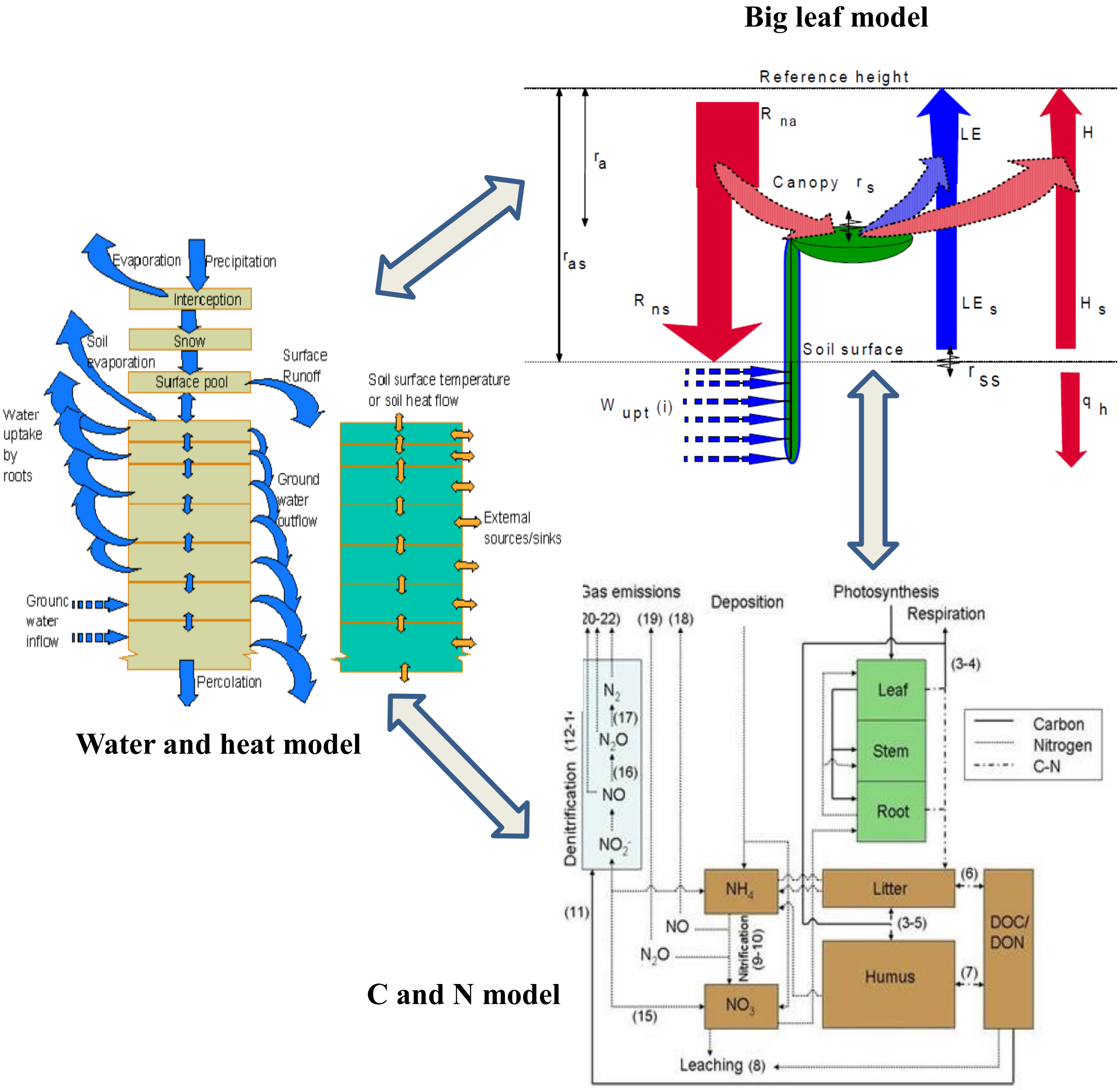

Figure 2. Brief conceptual representation of the CoupModel, adjusted from CoupModel manual, available at http://www.coupmodel.com/default.htm and also (Nylinder, 2010). The gas emission modules were implemented from DNDC model by Norman et al., (2008). No pools of microbes are shown since they are implicitly simulated by the C and N model within the soil litter pool.

Data for paper IV was obtained from Skrehalla field experiment site, a conventionally managed willow (*Salix viminalis*) coppice plantation in south-western Sweden (Table 1). The field was previously used for wheat production before changed to willow plantation in 1994. The soil is a heavy clay soil, drained by a tile pipe drainage system. When the field experiment started in 2012, the willow was at the stage of one year before its fifth harvest. In 2012 approximately 100 kg N ha^{-1} of mineral N fertilizer (ammonium-nitrate) was added, and in 2013, 270 (±190) kg N ha^{-1} sewage sludge was applied after the harvest conducted at end of March.

Table 1. Brief overview of the site characteristics included in this thesis: the Skogaryd research site (Paper I, II and III) and Skrehalla site (Paper IV).

Site characteristics	Skogaryd	Skrehalla
Latitude, Longitude	58°23′N, 12°09′E	58°16′N, 12°46′E
1961 to 1990		
Mean annual air temperature (°C)	6.4	6.2
Mean annual Precipitation (mm)	709	683
Major tree species	Norway spruce (*Picea abies*)	Willow (*Salix viminalis*)
Ground understory vegetation	low- herb type	-
Soil type	Mesotrophic peat	Heavy clay soil
Soil pH	4.4	5.8
Soil C/N ratio	24.8	12
Management	Thinning, Storm harvest	Mineral fertilization, sewage sludge application, harvest

Both sites have been intensively measured and monitored with both eddy covariance techniques and chambers, providing high resolution abiotic and biotic data including CO_2 and N_2O fluxes that could be used to drive and calibrate/validate the model. At Skogaryd, N_2O emissions were measured with manual, closed chambers every other week, whereas at Skrehalla, we measured with a half-hour-resolution using the eddy covariance technology. For details of the measurement instruments, experiment design, field management and site descriptions, see the respective papers and references therein (Paper I, II, III, and IV).

Modeling approach

The thesis combines merging data with the model (Paper I and IV), model upscaling (Paper II) and scenario predictions (Paper III). I assume that the model provides an overall consistent theory for how different components are linked in the real-world system. The model could thus after calibration be used to upscale, extend in time and test different management practices. Following this assumption, in paper I, the CoupModel was calibrated using the Generalized likelihood uncertainty estimation (GLUE) method (Beven and Binley, 1992, Beven, 2006) with all available three year data (2007 to 2009) to constrain the major model parameters and also to evaluate the influence of different factors on N_2O emissions. The latter was done by sensitivity analysis. In paper II, the calibrated model was up-scaled and extended, over the entire rotation period (1951 to 2011 and also up to 2031) to investigate the GHG balance. For validation of the model predictions, we used measured biomass data inferred from tree rings (1966 to 2011) and extended abiotic data (2006 to 2011) (Table 2). In paper III, different land use strategies rewetting the drained peat soil to different extents were compared with business as usual spruce forest. Scenarios considered: spruce forest, willow, reed canary grass (RCG) and wetland. The vegetation was chosen following the paludiculture concept (FAO, 2012) covering a time span of 80 years, a normal forest rotation period in south Sweden (Bergh et al., 2005), assumed for all the land use options. Both ecological and economic assessment was made. The three latter scenarios were parameterized by compilation of data from literature. Sensitivities regarding unknown initial soil conditions (1951) and drainage status for paper II and III were also assessed. In paper IV, the GLUE method was applied to calibrate the model on data from the willow plantation. The calibrated model was applied to assess different management scenarios. An overview of the modelling and data in this thesis is shown in Table 2.

Table 2. Overview of data, parameters and models in this thesis, for the meaning of the symbols, see list of Symbols and Acronyms.

Paper	Site	Forcing data	Model resolution	Calibration/ validation data	Calibrated parameters	Assessed scenarios
I	Skogaryd	P, T_a, u, R_{is}, h_r	Hourly	$R_{n,tot}$, q_h, T, θ, GWL, NEE, N_2O	20	-
II		P, T_a, u, n_c, h_r	Daily	$R_{n,tot}$, T, GWL, NEE, LAI, C_{tot}, PG, $C_{peat\text{-}CO2}$	-	3
III		P, T_a, u, n_c, h_r	Daily	PG, $C_{peat\text{-}CO2}$	-	3
IV	Skrehalla	P, T_a, u, R_{is}, h_r	Hourly	$R_{n,tot}$, LE, H, T, θ, NEE, N_2O	33	2

GLUE

GLUE is an informal method widely used for model calibration and uncertainty estimation. One of the core concepts of this method is “equifinality” which states that there can be several different model constructs or model parameter sets that produce similar performance (Beven and Binley, 1992, Beven, 2006). Thus GLUE does not include a formal residual error model to understand the likelihood of the suggested model but selects or rejects models using informal performance indicators, i.e. coefficient of determination, R^2 or mean error (ME) by comparing the model simulations with the measured data. The R^2 value indicates the variability in the measured data explained by using linear regression method with the simulated data as independent variable. However, the regression line may not have a slope of unity or an intercept of zero, which means that additional systematic errors may exist. Thus ME also need to be considered as an auxiliary performance index. In this thesis, the measured variables that show more pronounced seasonal cycle (e.g. soil temperature, net radiation) and have ME close to zero in prior models, R^2 is mainly used to select the posterior model. The criteria ME is more used to select the size of the emissions as it is the main model interests.

Cost - benefit analysis

Cost–benefit analysis (CBA) was used to assess the economic viability of the designed four land use strategies (Paper III). CBA is an economic tool to evaluate the economic viability of different scenarios or management options, by calculating the expected benefits and costs in monetary terms of each scenario discounted into present values, and predict whether the benefits of a scenario outweigh its costs and compare the net benefits across scenarios (see Table 2 in Paper III). The price of the products was according to the market price in recent years and the discount rate was assumed to be 3%, a level normally used in Swedish forestry.

Results

Correlations between N_2O emission rate and measured environmental factors

By statistical analysis it is often difficult to correlate emissions to environmental conditions, here illustrated by data from Skogaryd, where no statistical significant correlation was found (Figure 3). Combined environmental factors did neither show any statistical significant relations with the emissions (data not shown). Similar results are also found for the measured flux data from Skrehalla (not shown). At an annual scale, however, the N_2O emissions show some correlation with groundwater level (6 year compilation of Skogaryd data, not shown). A major problem is that an emission at a certain time point will never be explained by a single variable as the appropriate independent variable. Instead the emission is the integrated results of a number of processes that are integrated during an unknown durations (from seconds to years). These results confirm the non-linearity and complex process controls of the N_2O emissions but also suggest the need of detailed process-oriented modeling.

GHG from forests on drained peatlands (Paper I, II and III)

GLUE calibration constrains major parameter values when simulating the water, heat, C and N cycling of the Skogaryd forest ecosystem from 2007 to 2009. The calibrated model reproduces the measured high-resolution data including soil abiotic properties, surface energy fluxes and also the net ecosystem exchange (NEE) (He et al., 2015). The model also simulates the accumulated N_2O emission, however, still has some difficulties to capture individual measured N_2O emission peak even after calibration (Figure 4).

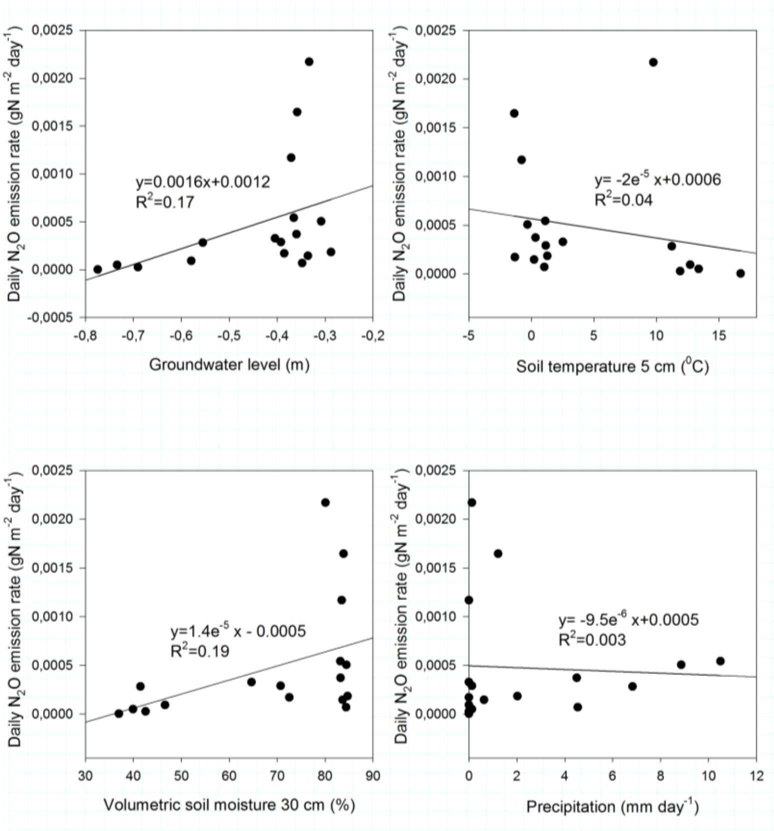

Figure 3. Regression relationships between daily N_2O emission rates (chamber measured data from Skogaryd) and measured environmental conditions the day the measurements were performed.

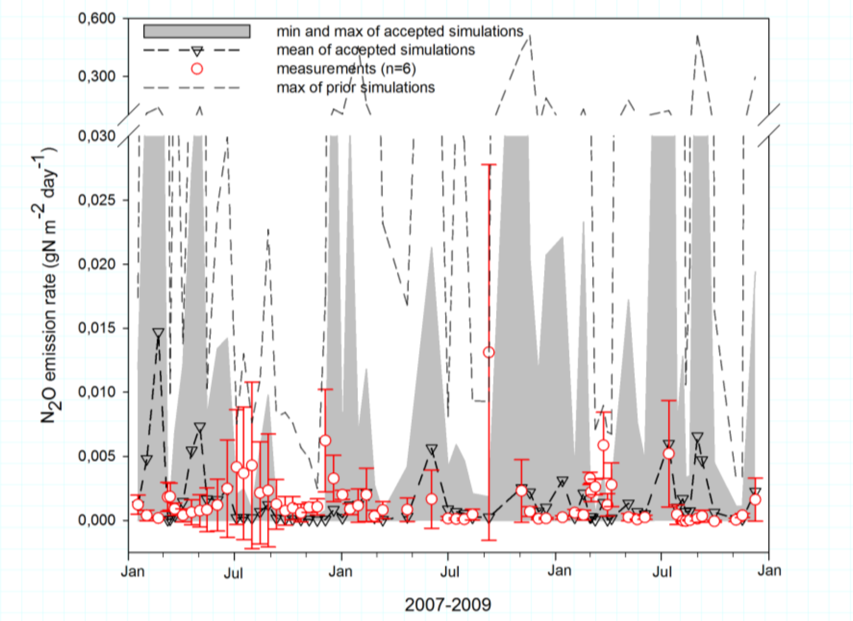

Figure 4. N_2O emission rate, measured (red hollow circles) and simulated (black dashed line with triangles, mean of 97 accepted simulations) with the same time frame as the measurements. The uncertainties in the accepted simulations are given as the gray shadow area. The dashed line is the simulated range of the prior model. Error bars of the measurements represent the standard deviation for N_2O emission rate measurements (n=6).

The calibrated model was then used to upscale and extend to a full forest rotation period (1951 to 2011). The extended model was found to be able to simulate the major dynamics of plant and soil (see Figure 2, 3 and 4 in Paper II), and reproduced the measured tree ring data well (Figure 5). Over the full 60-year time period the forest trees acted as a C sink and the soil as a source, of fairly similar size (Figure 5). The model predicts the total soil C loss to be 590 Mg CO_2 ha^{-1} over the 60 years, while plant growth (including spruce forest and understory vegetation) sequestered 602 Mg CO_2 ha^{-1}. The accumulated NEE shows the young forest ecosystem to be a net CO_2 source, and it is not until 1990, 39 years after the forestation, that the ecosystem reaches zero CO_2 emission before becoming a continuous sink (Figure 5). If including N_2O emissions during the 60-year rotation period, the source strength of the forest ecosystem increases and the system did not reach GHG neutrality until 1998 after 47 years of spruce forest (Figure 5). However, if the removed biomass during the thinnings in 1979, which usually goes into paper production, is included, these indirect CO_2 emissions switch this extended system (from the production site to the fate of the products) from an overall GHG sink to a GHG source of 162 Mg CO_2 ha^{-1} by the end of the simulation (Figure 5). Of the total GHG emissions during last 60 years, 59% comes from the peat soil decomposition into CO_2, 28% from the indirect CO_2 emissions and 13% from the N_2O emissions. Soon, the whole forest will be ‘ripe’ for harvesting. Only a very minor part of the carbon stored in the timber will be stored in long-lasting products, and a large part of the captured carbon, 601 Mg CO_2 ha^{-1} (total plant biomass in 2011) will be released into the atmosphere again (Figure 5). If everything were released from these soils there would be 763 Mg CO_2 ha^{-1} released over a period of 60 years. Forests on drained agricultural peatlands are therefore large GHG sources.

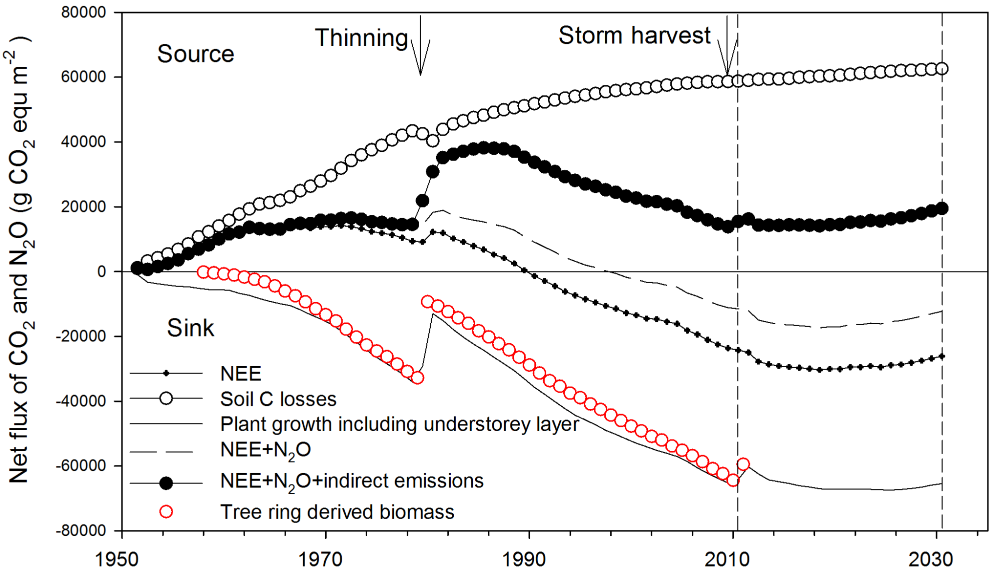

Figure 5. Simulated total GHG balance for the forest ecosystem from 1951 to 2011 and extended to 2031. The simulated results of 2011 to 2031 are obtained by running the reference model with extended meteorological files using meteorological data from 1991 to 2011 duplicated to represent the climate of 2011 to 2031. The red circles show measured tree ring data. It should be noted that the GHG balance presented in this figure assumes no final harvest.

To mitigate the large GHG emissions, an ecological and economic analysis of possible mitigation options for rewetting drained peatlands was further conducted (Paper III). The modelling was based on the calibration made on Skogaryd data for four land use scenarios: Spruce, willow, RCG and wetland, with increasing wetness in order. Simulation results reveal the vegetation growth, as net primary production (NPP) to be of similar size for the spruce, willow and RCG scenarios, and accumulated over 80 years are 790, 720 and 700 Mg CO_2 ha^{-1} respectively (Figure 6). For the spruce and willow scenarios, due to a deeper drainage the GHG emissions (CO_2 and N_2O) were 1800 and 1200 Mg CO_2eq ha^{-1} in total during the 80 year period (Figure 6). The peat C loss for the first three scenarios is 440, 280 and 140 Mg C ha^{-1} over 80 years. The rewetting to wetland scenario has a larger NPP than mineralization from the soil, resulting in a small net uptake of CO_2 amounting to 1.3 Mg ha^{-1} yr^{-1}, expressed as NEE, resulting in a sink of 28 Mg C during the 80 years. However the gain is counterbalanced by CH_4 losses, expressed as CO_2eq of double that size (Figure 6). Still, the losses are much smaller than the three drained scenarios. By rewetting the spruce forest into the willow, RCG or wetland, the simulations showed a possibility to avoid emissions in the size of 8, 17 or 21 Mg CO_2eq ha^{-1} yr^{-1}, or expressed in percentages, a 33%, 72% and 89% mitigation of GHG emissions respectively.

Figure 6 also shows the cost benefit analysis of the four scenarios, with the most preferred as follows: wetland >RCG > spruce forest > willow. For the two wettest, wetland and RCG, the monetized social benefits exceed the costs. Overall negative outcome was found for the more drained scenarios, spruce forest and willow, mainly due to the high GHG emissions, which have high product values and CO_2 avoidances could not compensate (Figure 6). For the wetland scenario there were no products sold that could replace or avoid CO_2 emissions. However, this scenario is more valuable because it holds larger biodiversity (see Table 2 in Paper III). Even though business as usual (spruce forest) is most profitable from a land owner's and the market's perspective, the cost benefit analysis also confirms that profitability decreases sharply when considering the social costs of emissions (Figure 6). Thus, changing the land use from spruce production to wetter conditions could be economically and socially profitable for the society. By doing so, a social cost of 600-900 SEK ha^{-1} yr^{-1} (i.e., difference between the net annuity value in scenarios: spruce, RCG and wetland) can be avoided. However a landowner loses 1700 SEK ha^{-1} yr^{-1} from lost revenue due to a lower price for RCG than spruce timber. By rewetting into wetland the landowner loses more than 3000 SEK ha^{-1} yr^{-1} from lost production revenues plus rewetting costs, where a governmental payment may need to compensate the landowner.

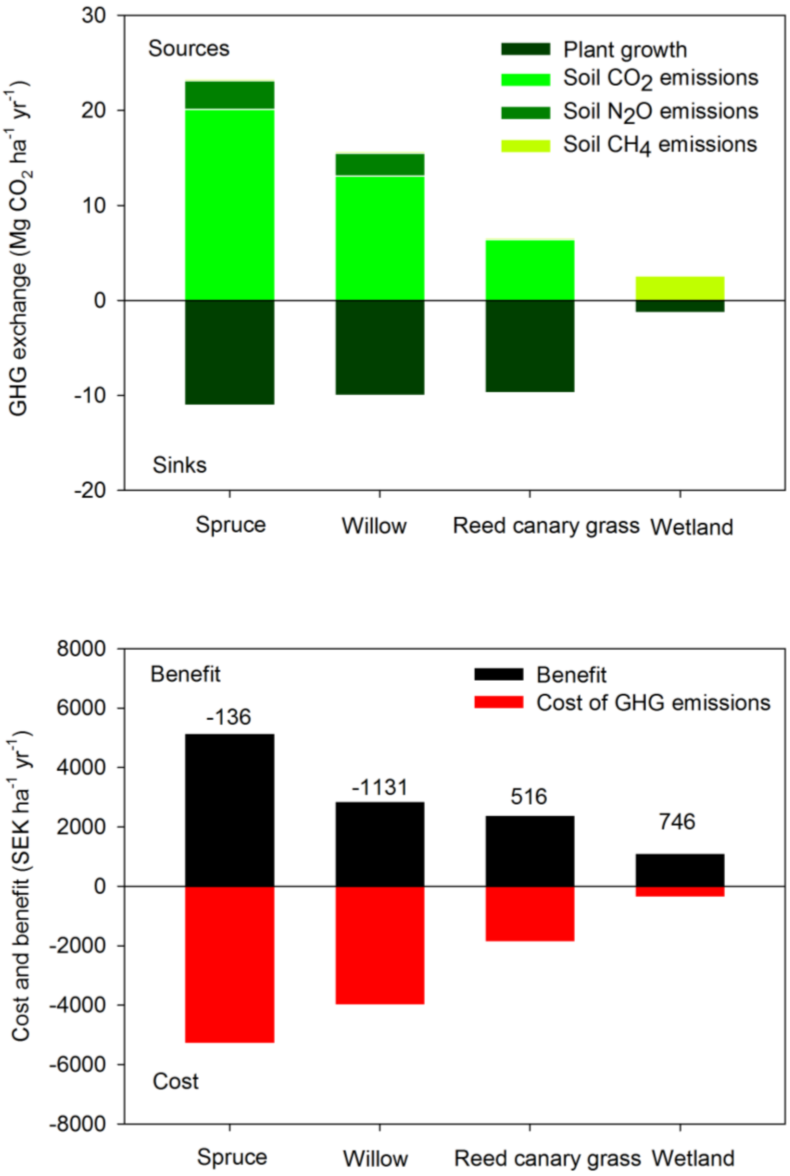

Figure 6. Simulated total GHG balance of four land use scenarios, data plotted is average of 80 year period, and results of cost and benefit analysis. Numbers show the balance. For more detailed information see Paper III.

Willow bioenergy crops on agricultural clay soil (Paper IV)

GLUE calibration applied for Skrehalla Willow coppice ecosystem largely reduced the parameter uncertainties. The calibrated model reproduces well: the measured energy fluxes, abiotic data, plant growth and NEE data. Besides, the calibrated model also simulates the N_2O reasonably well (R^2, 0.1 to 0.3). The simulated emission in 2012 after addition of commercial fertilizer was 0.05 (0.02 to 0.15) g N_2O-N m^{-2} similar to the measured 0.035 g N_2O-N m^{-2}. The simulated emissions after the sewage sludge application in 2013 was estimated to be 0.2 (0.1 to 0.37) g N_2O-N m^{-2} which was again similar to the measured 0.17 g N_2O-N m^{-2} (Figure 7).

By using the model, the response on N losses and biomass growth of different dosages of mineral fertilizer and sewage sludge fertilizer, was tested. The biomass scaled N_2O emissions (g N_2O-N emitted per g C in biomass growth) were found to decrease at low dosages, increase at higher dosages, reaching a minimum value when mineral fertilizer application rate was between 50 and 100 kg N ha^{-1}. This was similar for sewage sludge application where the biomass scaled N_2O emissions reaches its minimum value between 150 and 300 kg N ha^{-1} totally in the sludge. using the heating value of willow, 19.8 MJ kg dry weight^{-1} (Heller et al., 2003), the biomass scaled N_2O emissions results in a range from 14.7 to 20.2 g CO_2 equivalent MJ^{-1}. The willow production thus, comparing to crude oil emitting 73.3 g CO_2 equivalent MJ^{-1}, has a 70% to 80% GHG savings. According to the renewable RES directive (EC directive 2009/30/EC), the savings of greenhouse gases needs to be at least 35%, compared to fossil fuel, which will increase to 50% in 2017 (Kasimir Klemedtsson and Smith, 2011). Thus the willow plantation meets criteria of the sustainability standards for biofuels with a relatively large margin.

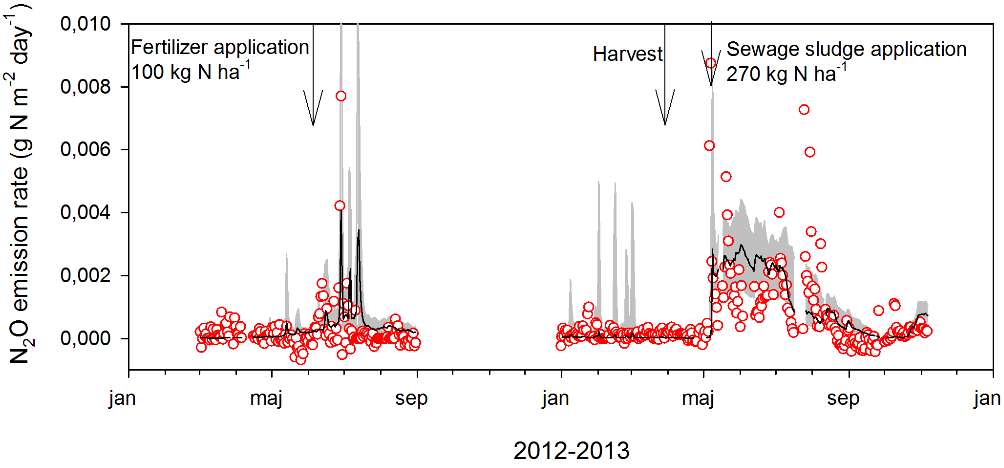

Figure 7. Simulated N_2O emission rate (black line with grey band indicates the minimum and maximum value of accepted model simulations) and measured (red circles). The emission data used to plot is expressed in a daily interval.

Calibrated parameters

GLUE calibration by merging model and data successfully reduces the parameter uncertainties (Paper I and IV) for 16 out of 20 calibrated parameters in Paper I, and 29 out of 33 calibrated parameters in Paper IV. These parameters changed from uniform distributions into normal distributions or log normal distributions after calibration. In Paper I, four parameters changed significantly after calibration: bypass water flow (a_{scale}), oxygen diffusion ($o_{diffred}$ and o_b) and soil freezing (d_3). In Paper IV five parameters changed significantly after calibration: willow transpiration (g_{max}), oxygen diffusion ($o_{diffred}$ and o_b), nitrification ($g_{mfracN2O}$) and snow processes (k_{snow}). Calibrated parameters did also show a high degree of interconnectedness, as several parameters are highly correlated with more than one of the other calibrated variables and there are also co-correlations between the parameters. For instance, in Paper I, the highest co-correlation is between the drain depth parameter z_p and hydraulic conductivity parameter $k_{sat(1)}$, where z_p is highly correlated with eight other parameters, the most of any parameter, indicating the importance of drainage in regulating the overall system. In Paper IV many parameters show high co-correlations after calibration: the plant transpiration parameter, g_{max} and the water retention curve parameter, $\psi_a(3)$; the snow thermal conductivity parameter, k_{snow} and snow melt coefficient, m_T; the soil frost and freezing parameter, d_3 and the water retention curve parameter, $\psi_a(2)$; the soil nitrate response parameter during denitrification, $d_{hrateNxOy}$ and the maximum fraction of N_2O during nitrification process parameter, $g_{mfracN2O}$.

Parameter sensitivity analysis reveals that for forest ecosystem on drained peatlands (Paper I) N_2O emission size is highly influenced by: the plant growth (r_{CNc1}) during growing seasons, gas transport by oxygen diffusion (o_b) and snow melting (m_T) during winter seasons. But for the willow plantation on clay soils (Paper IV), the N_2O emissions were found to be highly correlated with the nitrification process ($g_{mfracN2O}$), soil nitrate availability by response parameter during denitrification process ($d_{hrateNxOy}$) and soil physical characteristics (λ_2). Different parameter sensitivities and correlations in the studied two ecosystems reflect the different nature of the process controls for each ecosystem type and management practice. Besides current estimated parameter density distributions, the covariance matrix of estimated parameters and the correlation between parameters and variables also provide useful information when applying the model on other peat soil sites and for further model improvements.

Discussion

GHG emissions from drained peatlands and mitigation options

The modelled CO_2 emission factor (EF) 22-26 (the range reflects the simulated uncertainty) tonnes CO_2 ha^{-1} yr^{-1} (Paper I) in this thesis (Figure 8) agrees with the short term measured data, 22-30 tonnes CO_2 ha^{-1} yr^{-1} (Meyer et al., 2013) and the simulated N_2O emissions (Paper I, II and III) and dissolved organic carbon (DOC) leaching (Paper III) are similar with the reported IPCC EFs (Figure 8). However, present simulated CO_2 emissions are found to be much larger than the IPCC EFs (Figure 8). This high EF of CO_2 can be explained both by the high site fertility and also deep drainage (Drösler et al., 2008). Skogaryd peat soil was a formed as a fen and then drained and used for agriculture now having a soil C / N ratio of 24.8 which reflects the high soil fertility of this site. Besides, the measured groundwater level (2006-2011) in Skogaryd is around 0.4 m and becomes even deeper during the full forest rotation period (see Figure 5 in Paper II), which is much deeper than most of the studies compiled for the IPCC EF. Several studies suggest the groundwater level to be the major regulator of the size of the CO_2 emissions for drained peatlands (Couwenberg et al., 2011, Limpens et al., 2008, Leppelt et al., 2014). The new IPCC wetland supplement has also presented EFs categorized as drained or rewetted soils. The combined EFs for all three GHGs (CO_2, CH_4 and N_2O) indicate an emission of 6.9 tonnes CO_2eq ha^{-1} yr^{-1}, for drained nutrient-rich forest soil in a boreal climate and double this in a temperate climate (Figure 8). Rewetting results in much lower emissions: 2.8 tonnes CO_2eq ha^{-1} yr^{-1} (IPCC, 2014a). The deep and long lasting drainage can thus justify the high emissions for the studied site.

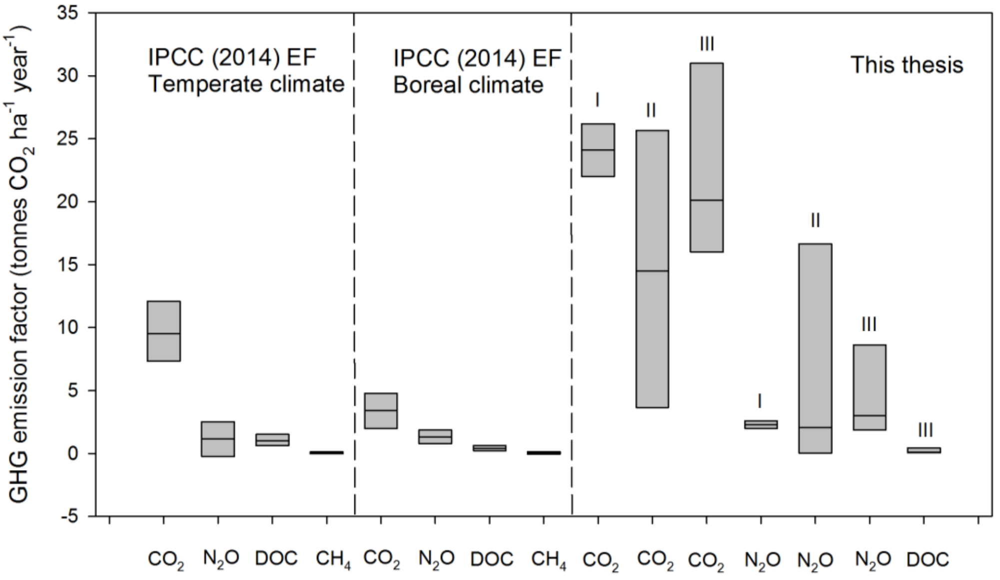

Figure 8. GHG emission factor (EF) for drained afforested peatlands both in the IPCC (2014) wetland supplement and in this thesis, where the roman number indicates from which paper. The uncertainty ranges of the boxes are the minimum and maximum values in the accepted simulations.

When soil CO_2 emission was modelled over the full forest rotation this resulted in a smaller CO_2 EF (Paper II) than just during a few years in a mature forest (Paper I), and a higher EF for an extended rotation period (Paper III) (Figure 8), however with a larger uncertainty. This is because the simulated emissions were the largest at the beginning of the forest rotation (Figure 5 Paper II) but gradually decrease with time due to surface subsidence. However, it also need to be noted that the measured high CO_2 emissions in 2008 (Meyer et al., 2013) was not captured in the simulation over the forest rotation. This is probably due to a ditch clearing management was conducted a few years before the measurements which increase the aerobic volume of the peat soil, thus increase the peat decomposition, but this is not accounted for by the long term model simulation (see discussions on future perspectives of modeling organic soil). Another explanation could be a warmer and wetter climate during the 60 year period, where annual air temperature shows an increasing trend and a higher precipitation is found during 2001-2011 (SMHI), which fits with Jansson et al., (2007) predicted an increased soil heterotrophic respiration of forest ecosystems in south Sweden under a climate change scenario with increasing temperature and precipitation. Thus the measured higher peat decomposition at the end of the forest rotation in this thesis could also be driven by the climate.

A wetter peat soil would reduce the peat decomposition (Paper III), where the modelled GHG emissions were found to be within the range of reported literature values (Table 3). The simulated results of different land use scenarios again show the crucial importance of groundwater level in determining the overall GHG balance for peatlands. Annual water level below 20 cm depth, as for spruce and willow, show the soil to be an overall GHG source but a water table within 0-20 cm, as for RCG and wetland, reduce emissions which even can be reversed into an overall sink. This also agrees with Karki et al. (2014) who measured the

GHG emissions from a rewetted Danish drained agricultural peatland for RCG cultivation and found the NEE of CO_2 was close to zero when water level was between 0 and 10 cm, but became a significant net sources of GHG when the groundwater level was below 20 cm. However, the literature reported CH_4 emissions from rewetted peatlands, show a large variation, from 140 to 1232 g CO_2 m^{-1} yr^{-1} (Table 3). In this thesis the CH_4 emissions from the first three scenarios are not modelled but taken from the IPCC values (see Table 1 Paper III). This could be biased as many studies found a high correlation of soil CH_4 emissions with groundwater level. High emission can be expected when groundwater level is within 0-20 cm and water table below 30 cm mostly result in negligible CH_4 emissions due to the restricted methane production and an increased methane oxidation (Karki et al., 2014, Couwenberg et al., 2011). The CH_4 emission could in this thesis have been under estimated for the RCG scenario, however this did not change the overall ranking of the scenarios if taking the value reported in Karki et al., (2015) instead of the IPCC EF, since the dominant GHG emissions would still be CO_2 for the first three scenarios. For the simulated rewetting scenarios, N_2O contributes to a considerable proportion of GHG when the groundwater table was below 15 cm but negligible when the water table was between 0-15 cm, which also agrees with measurement results from rewetting peatland studies (Couwenberg et al., 2011). In addition, the avoidance of GHG emissions found in this thesis is 8 to 21 Mg CO_2eq ha^{-1} yr^{-1} which is generally comparable with the compiled literature field measurement studies where 4.5-17 Mg CO_2eq ha^{-1} yr^{-1} savings by rewetting compared to drained state were reported (Table 3).

It needs to be noted that for both spruce and also bioenergy crops, cultivated on drained peatlands, the biomass production processes will inevitably lead to peat soil decomposition (Figure 6). The C fixed in the biomass (i.e. willow stems and RCG) will also be released back to the atmosphere soon after used by mankind. Only if used for building material a small proportion can be stored for a longer period, mainly as wood buildings in the spruce scenario, however not for thousands of years as is the age of the soil peat. Thus, biomass products on drained peatlands should not be seen as renewable products as is the usual case, but rather at a cost of soil peat. The “cost” differs between scenarios, mainly determined by the depth of drainage. Thus from a peatland conservation perspective, drainage surely needs to be abandoned. It is also needed to note that present ecological and economic analysis cannot cover all the aspects or a full life cycle of the ecosystem services provided by different land use options. This is particularly true for monetizing and valuing the ecosystem services. The monetary results provided in this thesis should thus be more perceived as a comparison between different land use options rather than absolute values. But the results do highlight the importance of including GHG emissions when analyzing the value of land use options. A major problem in current peatland land use is that its use results in costs, for which forest owners have no incentives. Instead, past drainage operations have been promoted by state subsidies for increasing the net benefits of biomass production. Thus this work also suggests policy instruments are now needed to oppose drainage on peatland, designed to create incentives of rewetting for land owners.

Table 3. Rewetted soil peat CO_2, N_2O and CH_4 emissions in this thesis (paper III) and values published in literature. The unites for the GHG gases are g CO_2 m^{-1} yr^{-1}. The peat decomposition was obtained by assuming 50% of measured soil respiration to have originated from root- based activity, when direct measurements of peat decomposition is not available.

CO_2	N_2O	CH_4	Ecosystem type	Annual water table (cm)	References
438	-	230	Rewetting temperate fen peat for *Phragmites*	-10	(Günther et al., 2015)
475	-	230	Rewetting temperate fen peat for *Typha*	-14	
542	-	940	Rewetting temperate fen peat for *Carex*	-1.5	
600	106	336	Rewetting temperate fen peat for reed canary grass	0	(Karki et al., 2015, Karki et al., 2014)
1075	80	210	Rewetting temperate fen peat for reed canary grass	-10	
1550	53	140	Rewetting temperate fen peat for reed canary grass	-20	
1642	-	1232	Rewetted temperate agricultural peat meadow	-	(Hendriks et al., 2007)
886	-	-	Reed canary grass on boreal peat extraction	-	(Shurpali et al., 2009)
657	-	610	Rewetted cut-away boreal peat	-20	(Maljanen et al., 2010, Tuittila et al., 1999)
1310	240	20	Rewetting Skogaryd to willow	-22	This thesis
640	<1	20	Rewetting Skogaryd to RCG	-13	
-	0	260	Rewetting Skogaryd to wetland	0	

In Sweden forest areas on fertile drained peat, like Skogaryd, cover around 500 kha, and most of these forests were planted in the middle of 19th century thus close to the stage of final harvest today (Bergh et al., 2005). After a final harvest (in 2031 assuming 80 year forest rotation), there will be an excellent time window for a change of current land use management. These forests on fertile drained peat emit in total 12 Tg CO_2eq every year, based on our modeled GHG emissions in paper III. But this would be possible to reduce, reaching emissions of 8, 3 or 1 Tg, if changing from spruce on well-drained soil into wetter soil conditions and more adapted plants like willow, RCG or wetland land use scenarios. If all of this area would be converted into wetter conditions, this could reduce emissions by 33%, 72% or up to 89%. And bear in mind that the willow scenario shows the worst cost-benefit results.

These findings reported here thus provide perspectives in future management of peatlands in Sweden, and also for other countries with large peatland covers.

N_2O emissions from bioenergy production on clay soil

Both mineral fertilizer and sewage sludge applications on conventional willow planation generally cause minor impact for the soil nitrate leaching and also N_2O emissions (Figure 1 in Paper IV). Present reported GHG savings (70% to 80%) only consider soil N_2O emissions, however if the increase soil C sequestration during the willow plantation was also included, the GHG savings will further increase.

Soil water status plays an important role in regulating the N_2O emissions. As predicted by the model, denitrification was the major emission production process when mineral fertilizer was applied while nitrification was more important when sewage sludge was applied. The mineral fertilizer (ammonia-nitrate) provides available N that is easy to use for the microbes, therefore after rainfall available nitrate and the soil anaerobiosis will promote denitrification. Increased denitrification and N_2O emissions after rainfall events following fertilizer application was also reported in previous studies for agricultural soils (Skiba and Smith, 2000). However, in sewage sludge there is small amounts of mineral N, why the mineralization besides nitrification is more important regulating N_2O production. This is also consistent with the widely accepted concept of water filled pore space (WFPS) as a predictor for differentiating N_2O production from microbial nitrification and denitrification (Davidson, 1993, Bollmann and Conrad, 1998). An estimation of the soil total porosity was made by assuming the highest water content during winter periods to approximately reach saturation. Thus the WFPS for the simulated soil layers during growing season in 2012 was mostly higher than 60%, resulting in high denitrification activity but was mostly below 50% during 2013, hence nitrification were most important (Figure 2B in Paper IV).

Modeling different management scenarios also suggest that there are optimum fertilization rates that give the minimum N_2O emissions per biomass growth (Figure 4 in Paper IV). The optimum fertilizer ranges found in this thesis provide guidelines for the fertilizer management in similar site conditions in Sweden. However, it should also be noted that the suggested ranges are only tested under current site condition.

The scale issue in modelling N_2O emissions

GLUE calibration (Paper I) use all the available N_2O emission data: 6 chambers from three plots. However, a separate calibration using only emission data from 2 chambers (one plot) was conducted earlier. The model forcing, parameters and model structure were kept the same for both calibrations and data used to calibrate the model was also similar. But the calibrated model was found to simulate the measured two chamber emissions rather well (Figure 9), with better simulated emission dynamics compare to using all the data (Figure 4, Paper I). The R^2 between the modelled and measured emission rate is 0.1 to 0.25 for 2 chambers, much higher than that of 0.01 to 0.06 for the 6 chambers (Paper I). In other words, the model performance of N_2O emissions becomes worse as more emission data are included in GLUE calibration. This is somehow contradiction from a model calibration perspective, as including more measured data into the calibration, more constraining of the parameter values should be expected, thus reducing the model uncertainty in reproducing the emissions. One explanation of this could be incorporating the other measured chambers has increased the uncertainty in the measured data due to the spatial variation. The increasing number of replicates introduced large spatial variations that are difficult to capture by the model. Moreover, the real system also becomes more uncertain and complex when the spatial scale increases. The simple average of the measured data from replicates might not reflect or even mislead what really happens in the field since the measured different plots most likely have different soil properties, boundary and drainage conditions. These spatial heterogeneities all create difficulties for integrating these plots into one model representation. To overcome this, separate model calibration for each measured plots is suggested, as it could increase the model performance and also help to improve the understanding of spatial variation on the emission process controls. On the other hand, it could also be possible to use the parameter uncertainties to generate the site spatial variation when conduct model calibration by taking all the data (e.g. this thesis). However, this needs to include more parameters (e.g. parameters describe the soil properties, boundary and drainage conditions) than separate model calibration. Thus, the complexity also increases. High N_2O emissions were measured at plots located close to the flux tower, which could either be explained by the higher soil water content at this spot or by disturbances introduced by the presence of the flux tower on sensitive soil like peat having a “sponge” structure. These artifacts surely cannot be considered in the model which further explains the model difficulties when more data were used.

Our model calibrations also show time shifts in emission peaks measured and modelled or peaks are completely missed (Figure 4 and 7). The ability of the CoupModel to catch soil abiotic factors and soil microclimate variables but having difficulty to capture the exact emission peaks suggest that description of soil microbial processes might need to be improved. However, there is very few information about the soil microbial properties and processes for both studied fields. Therefore the parameterization of these processes although validated by some few stable isotope measurements (for Skogaryd), still introduces uncertainty of the modeling of nitrification or denitrification. Besides, current understanding of microbial processes of N is still incompletely incorporated into CoupModel. The challenge of predicting the emissions at the exact hot moments therefore both suggests the need of a more accurate representation of the microbial processes in a much finer scale but also more measured N cycling data are needed to calibrate or validate the model. One possible alternative could be instead simulating the emissions in a larger temporal scale, i.e. weekly or monthly emissions. However, as emissions are mostly events driven and mostly occur only for a short period, modeling the emissions in a larger temporal resolution might possibly smooth these events out. Further model application and tests are needed to find the best scales both spatially and temporally in simulating the N_2O emissions.

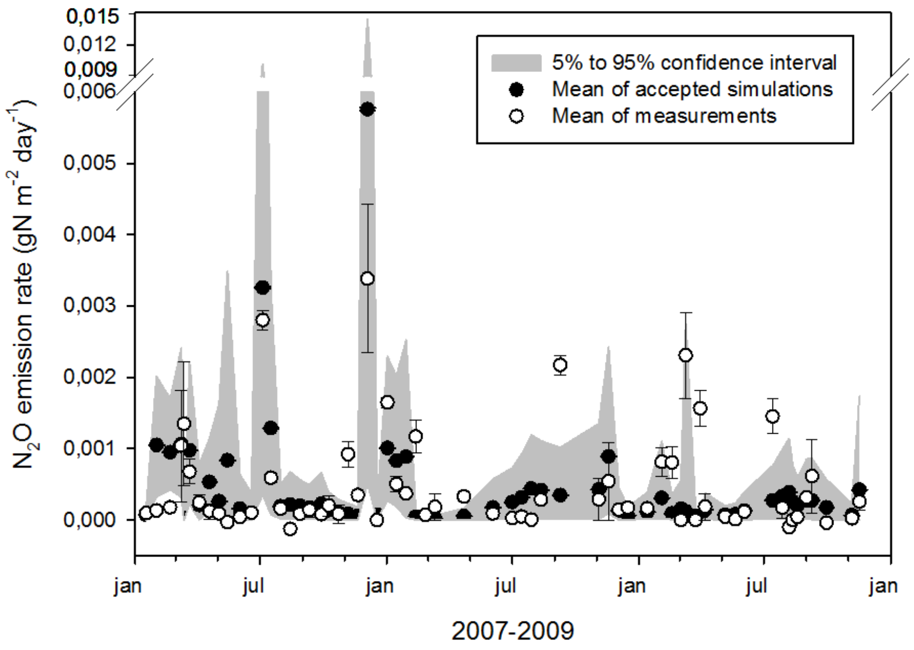

Figure 9. Skogaryd spruce forest on drained peat soil. Simulated and measured N_2O emission rate (g N m^{-2} day^{-1}) from 2007 to 2009. The measured emission data is only from one plot with two chambers (n=2).

Model calibration and N_2O emission controlling factors

A critical issue of applying GLUE in model calibration is the subjective criteria used to select the accepted simulations. One might argue this type of parameter selections are not optimal if the aim was to find the best model, i.e. the best agreement with all data. For instance, the N_2O emissions in the accepted ensemble might be better if less emphasis had been placed on other abiotic factors, or the emission dynamics should be better simulated if the model was not constrained by the total emission size. When the accepted criteria were defined there are also contradictions of the model performance with one variable or another and the aim is not to find the optimum but rather for acceptable simulations for all measured variables. I also placed more emphasis on some components of the model compared with others when rejecting prior models, for instance, the mean value of N_2O flux is more important than some other abiotic factors due to it’s the main model interests. I believe that these accepted simulations show an accepted “equifinality” degree of similarity with the measured data.

The results of calibrated parameters and correlations give insights to the complex interconnectedness and relative importance of the environmental controls on N_2O emissions. However, it should be noted that such analysis was only conducted for the parameters /processes included in the GLUE calibration. The influencing factors that are not included in the calibration can therefore not be evaluated, for instance the soil pH effect for Skogaryd (Paper I). A new model calibration by including parameters describing the soil pH reveals that including soil pH declines the importance of spruce plant growth, gas transport and snow melting in regulating the emissions. However, the rankings of the parameter sensitivities in regulating N_2O emissions do not change. This is because soil pH is not antagonistic with the processes of gas transport or snow melting during winter. Although the soil pH shows some influence of the soil microbial activity and N_2/ N_2O production ratios thus slightly influence the plant-microbe competitions, however this impact seems still marginal under current model settings. The modelled process controlling of N_2O emission might be different compare to that measured in the field (i.e. the influence of plant C allocation) due to these processes are just modeling configurations. However the parameter sensitivity analysis of the soil-plant-atmosphere continuum does have some implications on the overall understanding of the process controls. For instance, the reduced soil N_2O emissions in the presence of plants and altered soil N cycling was also later found by Holz et al., (2015). Besides, it is also needed to point out that the correlation analysis used to rank the parameter sensitivities in this thesis could also have some shortages as the controlling effects of some factors on N_2O might be none- linear.

Future perspectives of modeling organic soils

The modeling applications in this thesis also reveals two major issues that need to be further accounted when modeling long term dynamics of drained peatlands. One is the need of explicitly specify the nature of soil organic matter for peat soil. The other is the need of introducing new feedbacks for change of soil physical properties due to soil biochemical decomposition, to better describe the dynamics of peat soil (Figure 10). Farmer et al., (2011) reviewed the existing peatland models for their applicability for modeling GHG emissions, they pointed out that all the reviewed models use a C pool approach (as also CoupModel) to simulate the organic matter decomposition and divide the soil organic matter into three major pools: litter (fast turnover plant detritus), microbes and humus (slow turnover organic matter) (names of the pools can be different with different models). Decomposition of litter or microbe pool is assumed to add resistant organic matter into the humus pool (Johnsson et al., 1987, Parton et al., 1993). This concept of the model has been developed based on mineral soils for which it also works well (Smith et al., 1997, Ryan and Law, 2005). But when applying this to peat soil, the peat has to be assigned as a mixture of soil litter and humus because most of these models do not have an explicate pool of peat, which is a material which could be easily decomposed only it is exposed to oxygen in contrast to more resistant humus pools. To initialize the model pools, a spin up or assumed equilibrium state between the pools are commonly used (Yeluripati et al., 2009), however, drained peatlands do not have the commonly assumed equilibrium state between the different pools. Thus the model user has to assume an unknown fraction of litter and humus for the initial conditions based on literature measurement studies (Paper I, II, III). However, the chemical composition as well as substrate quality of humus over time changes when old peat decomposes and resistant organic matter is continuously added through decomposition of plant litter. This composition change becomes apparent during long term simulations and also important for land use change conditions, i.e. the soil surface litter and humus in Skogaryd was mostly composed of cereal plant residues in 1951 but gradually change into spruce forest residues (Paper II). Although most existing models do not explicitly specify the nature of the organic matter (Smith et al., 1997), they can still simulate the total organic matter dynamics for mineral soils fairly well. For organic soils however, the modelled humus pool consists both of historical peat and newly added plant resistant fraction, and the decomposability of the substrates also change over a forest rotation period. Therefore the decomposition coefficient must also change over time accordingly. However, so far this has seldom been accounted for and the few modeling studies on drained peatlands also do not include this into their model configurations (Minkkinen et al., 2001, Hargreaves et al., 2003, Metzger et al., 2015). In order to understand the long-term dynamics of organic matter in peat soils, which differs in origin and components, a more precise consideration of the changes of soil organic matter characteristics for current multi C pool models are needed.

For mineral soils in which the physical structure of the soil does not normally change over time, the CoupModel (also most other models) soil physical subroutine works well for simulating the water and heat flow linking this to the biochemical processes by response functions of water moisture and soil temperature (Figure 10). However, this is not the case for organic soils where the soil structure is mainly built by soil organic matter, which gradually disappears through decomposition. Thus the soil's physical characteristics also change over time. Moreover, decomposition also makes the topmost meter of soil to almost disappear, resulting in surface subsidence (Leifeld et al., 2011). These processes have not so far been implemented in the CoupModel, which cannot currently account for surface subsidence, mainly due to the model lacking a feedback coupling between the soil's chemical and physical properties (Figure 10). To overcome this model structure issue, model sensitivity analysis was conducted in this thesis and reveals the surface subsidence could have significant impact on the simulated results of soil C and N (Paper II and III). Therefore it should be considered in future model developments, important when modeling long term dynamics of organic soil.

A need of close work between modelers and experimentalists

Modeling needs data for 1) defining initial and model boundary conditions, 2) for parameterization 3) calibration/validation and also 4) to drive the model. Especially for modeling N_2O emissions, there is a large demand of information from the field. However, experimental studies and modeling studies are mostly driven by different philosophies: while the former is normally driven by understanding detailed processes, conducting controlled experiments and measuring gas fluxes, the latter uses a "system biology" approach, aiming to understand the complex soil-plant-atmosphere ecosystem. These differences in disciplines are potentially highly beneficial for science but they also create tension in the timing and collaboration efforts. A closer linkage between experimentalists and modelers can be made by explicitly defining measurable quantities needs for the modelling, while the modeling could also create guidelines for field measurements, i.e. a pre-modeling exercise before field measurements starts could help to improve the design of the measurement scheme and also to decide what to measure and how often we need to measure. This could be done by running the model with data assimilation approach where the importance of the data could be checked by how much it affect the system dynamics and predictions. Overall, the most important issue is how to design efficient experiments that, in combination with equally well designed modeling will improve our understanding and management of complex systems.

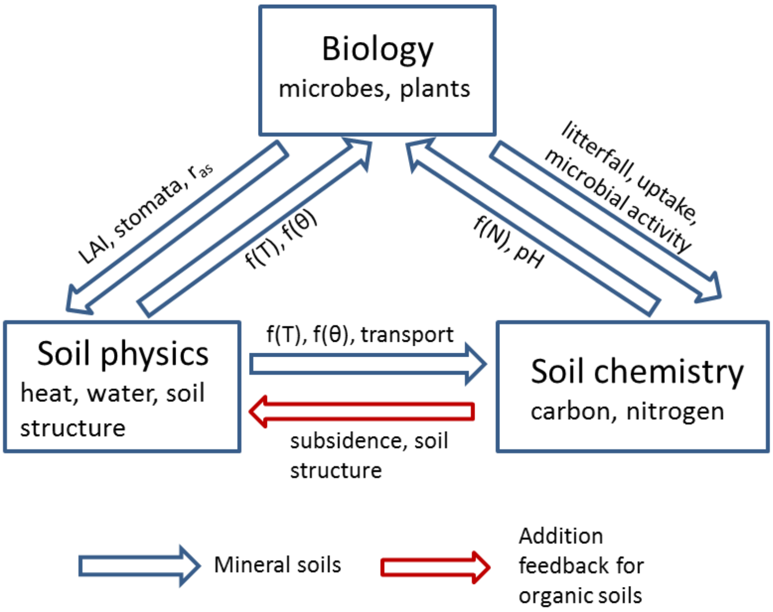

Figure 10. A simple conceptual model derived from CoupModel to illustrate the conceptual difference between modeling mineral and organic soil. The blue arrows indicate the model structure for mineral soils and the red arrow indicates the additional feedbacks needed to simulate organic soils. The texts aside with the arrows indicate the response and feedbacks.

Conclusions

This thesis overall provides detailed insights into GHG emissions and biomass production for drained peatlands and agricultural clay soils. The main conclusions can be summarized as follows:

- For afforested drained peatlands, plants and groundwater level controls N_2O emissions.
- Over a full forest rotation, the plants growth can compensate the large soil losses from drained peatlands. However, when indirect emissions from harvested wood products are also included forests on drained agricultural peatland are a large GHG source.
- Ecological and economic analysis suggests raising water table for fertile drained peat soils could significantly reduce GHG emissions as well as social costs. This needs to be considered for land use planning and policy-making.
- N_2O emissions and soil nitrate leaching are generally minor for Swedish conventional willow plantation. We suggest the optimum application rate of mineral fertilizer should be within a range of 50 to 100 kg N ha^{-1} and for sewage sludge within 150 to 300 kg N ha^{-1}, to minimize the biomass scaled N_2O emissions.
- This thesis also provides estimated parameter density distributions, the covariance matrix of estimated parameters and the correlation between parameters and variables information that are useful when applying the model on other peat soil sites or agricultural bioenergy production sites.
- Future model improvements regarding more explicitly needs to specify the nature of soil organic matter and introduce an inverse coupling of soil biochemical process into soil physical module for a better description of long term organic soil dynamics.

Acknowledgements

First, I would acknowledge my supervisor, Åsa Kasimir for giving me the opportunity to work with such an interesting issue during the past 4 years. Thanks for your patience, eyes for detail and encouragement makes my PhD journey so enjoyable. The continuous dialogue with my assistant supervisor, Per-Erik Jansson, a person full of wisdom and scientific views has been extremely beneficial for heading my way to be a PhD. I always feel so happy to work with you since I was a master student. I would also like to thank my examinator Anders Omstedt for your trust, your wise and great humor. I also thank Leif Klemedtsson for your great passion, energy and help.

It has been so lucky for me to be in a diverse and friendly research group called BLUES. The interesting discussions, fruitful Monday meetings, short conversation or lunch talks with BLUES folks broad up my views and also make the daily life so enjoyable. Your valuable advices and suggestions are fuel to my thesis trip, without which I would surely not reach so far. Many thanks for the staffs at the entire Department of Earth system sciences, for sharing your great experiences and knowledge. I also had the great fortune to have Ann as my mentor outside academic. I would surely not forget the talks, laughs and conversations we had.

I also gratefully acknowledge financial support from Swedish Energy Agency, the project “practicable tool for estimation of nitrous oxide when cropping biomass in agriculture and forestry”, project number 32652-1. I also thank part-funding by LAGGE (Landscape and Greenhouse Gas Exchange), BECC (Biodiversity and Ecosystem services in a Changing Climate) and SITES (Swedish Infrastructure for Ecosystem Science). I also thanks for the courses, seminars, conferences provided by BECC and MERGE (Modelling the regional and global earth system) projects.

This thesis is also dedicated to my parents and family who have always support me during all the past years. Lastly, these past years cannot be so colorful and lovely without my dear girlfriend, Linnan. There are darknesses in life and there are lights, and you are one of the lights, the light of all lights.

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