Thesis for the Degree of Doctor of Philosophy in Physical Geography

Instruments for Reaching Climate Objectives -

Focusing on the Time Aspects of Bioenergy and Allocation Rules in the European Union's Emissions Trading System

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To Elin and Joel

In dear memory of Per

Abstract

The Europeans Union's (EU's) climate and energy strategy aims at reducing the emissions of greenhouse gases (GHG) by 20 % (compared to 1990) and to increase the share of renewable energy to 20 % by the year 2020. Increased use of bioenergy is considered key in these efforts. Moreover, the EU regards the Emission Trading System (ETS) to be the main policy instrument for reaching these objectives. This thesis investigates the effectiveness of these instruments for reaching climate policy objectives in the EU. Focus lies on the climate impacts from bioenergy due to how they affect atmospheric carbon dioxide (CO_2) over time; the climate impacts of peat; and how allocation rules in the EU ETS should be designed to reduce emissions in a cost effective way. The analysis shows that there is a climate impact from using forest residues for energy which depends on how fast the CO_2 emission pulse is compensated by uptake of atmospheric CO_2 (or avoided emissions in the reference case). Assuming all other factors equal, biofuels with slow uptake rates have a stronger climate impact than biofuels with fast uptake rates. The time perspective over which the analysis is done is crucial for the assessment. Over a 100 year perspective the use of branches and tops are better for climate mitigation than stumps which in turn are better than coal. Over a 20 year time perspective this conclusion holds, but the relative differences between these fuels are smaller. The climate impacts from using peat for energy can vary considerably depending on the characteristics of the peatland in question, the choice of after-treatment strategy and assumptions regarding after-treatment parameters. Over 300 years, we estimate the climate impacts from peat to range from being lower than the impacts of natural gas to higher than those of coal. In phases I and II of the EU ETS emission allowances have to a large extent been allocated free of charge to firms based on historic emissions, so called grandfathering. As production levels change, old installations are closed and new installations opened, Member States wish to limit the entitlement to allowances and update the allocation. However, the analysis shows that adjusting the initial allocation may affect firms' behaviour and significantly reduce their incentives to become more CO_2 efficient. Benchmarking (allocation based on production and sector common benchmarks or a prescribed cap) may offer a way to move from grandfathering in phase I and II of the EU ETS toward the long term goal of auctioning. Benchmarking preserves firms' incentives to become more CO_2 efficient, but involves a production subsidy. Climate efficient use of bioenergy and peat should be incentivized, taking into consideration effects on carbon stocks, while also considering other ecosystem services. This could for instance be accomplished by establishing a credit system for land-use related CO_2 reductions, which could be linked to the EU ETS.

Key words: Climate Policy, Climate Impacts, European Union, Bioenergy, Forest residues, Carbon Dioxide, Radiative Forcing, Peat, EU ETS, Emissions Trading, Allocation, Incentives, Benchmarking.

Preface

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Zetterberg, L. and Chen, D. 2011. The time aspect of bioenergy - Climate impacts of bioenergy due to differences in carbon uptake rates. Manuscript to be submitted to Biomass and Bioenergy.

II Zetterberg, L., Uppenberg, S., Åhman, M. 2004. Climate Impact from peat utilisation in Sweden. Journal of Mitigation and Adaption Strategies for Global Change Vol 9(1), pp 37-76.

III Åhman, L. and Zetterberg, L. 2005. Options for Emission Allowance Allocation under the EU Emission Trading Directive. Journal of Mitigation and Adaptation Strategies for Global Change, Vol 10(4), pp 597-645.

IV Åhman, M., Burtraw, D., Kruger, J., Zetterberg, L. 2007. A Ten-Year Rule to guide the allocation of EU Emission Allowances. Energy Policy Vol 35, pp 1718-1730, Elsevier B.V.

V Zetterberg, L. Forthcoming. Benchmarking in the European Union Emissions Trading System: Abatement Incentives. Forthcoming in J. Energy Economics.

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In Paper **I**, I was responsible for model development, data collection, numerical calculations, and analysis. In Paper **II**, I was responsible for developing the method. All authors were collectively responsible for literature study, data collection and analysing the results. The method was implemented in a numerical model by Uppenberg and Åhman. In Paper **III**, both authors were equally involved in literature studies, meetings with experts, authorities and stakeholders and the analytical work. In Paper **IV**, the analysis was mainly done through literature studies followed by a four day workshop, involving all four authors. In Paper **V**, I was responsible for the whole paper, including the development of the two-period analytical model. Valuable guidance was provided by Torvanger, Burtraw and Löfgren.

In addition, the following peer-reviewed papers are related to this work, but not included in the thesis:

Zetterberg, L., Wråke, M., Sterner, T, Fischer, C., Burtraw, D. Short run allocation of emission allowances and long term goals for climate policy. Accepted for publication in Ambio Special issue, February 2012.

Wråke, M., Burtraw, D, Löfgren, Å., Zetterberg, L., What have we learnt from the European Union's Emissions Trading System? Accepted for publication in Ambio Special issue February 2012.

Contents

List of abbreviations

AGWP	absolute global warming potential
CDM	Clean Development Mechanism
CO_2	carbon dioxide
COP	Conference of Parties
CH_4	methane
EJ	exajoule, 10^{18} J
EU ETS	European Union's Emissions Trading System
GDP	gross domestic product
GHG	greenhouse gas
ha	hectare
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kton	kiloton, 10^9 g
MJ	megajoule, 10^6 J
N_2O	nitrous oxide
NAP	national allocation plan
nJ	nanojoule, 10^{-9} J
nK	nanokelvin, 10^{-9} K
PJ	petajoule, 10^{15} J
RRFC	relative radiative forcing commitment
TWh	terrawatthour, $3.6 \cdot 10^{15}$ J
UNFCCC	United Nation's Framework Convention on Climate Change
μW	microwatt, 10^{-6} W

1. Introduction

…Dad, we can't go to Thailand this year because then we can't drive our car for at least a year.

Sure we can, if we plant a tree.

But Dad, it will take a really long time for that tree to grow up

Elin, 10 years

1.1 Climate change and climate policy

Global climate change is one of the main environmental, technical, economic and political challenges facing society. Human activities have increased the atmospheric concentrations of the greenhouse gases (GHG) carbon dioxide, CO_2, methane, CH_4 and nitrous oxide, N_2O considerably since preindustrial time. Emissions of CO_2 are mainly due to the use of fossil fuels and land-use change while emissions of CH_4 and N_2O are mainly due to agriculture (IPCC 2007a). Most of the observed increase in global average temperature since the mid 20th century is very likely due to the observed increase in anthropogenic GHG concentrations. The Intergovernmental Panel on Climate Change (IPCC) estimates that, depending on how emissions develop over this century, the global average temperature may increase by 1.1 - 6.4 °C over the next 100 years (IPCC 2007a). This would have serious impacts on ecosystems, water, food, coasts, settlements, industry, health and society in general. Some regions and sectors are likely to be especially affected by climate change, for instance the Arctic, Africa, small islands, low lying coastal areas, water resources and agriculture at low latitudes. Anthropogenic warming could lead to impacts that are abrupt or irreversible, depending on the rate and magnitude of climate change (IPCC 2007b). If the global temperature change is to be kept within 2.0 -2.4 °C above pre-industrial levels, global CO_2 emissions need to peak before 2015 and decrease by 50 % to 85 % by the year 2050. The IPCC concludes that it's possible to achieve this reduction by deploying a portfolio of technologies that are currently available or expected to be available in coming decades, including fuel switching from fossil fuels to bioenergy. This transition requires that effective incentives are implemented (IPCC 2007b). Considerable emissions reductions are available at low or even negative costs. McKinsey & Company (2009) estimate that there is a potential to reduce global GHG emissions sufficiently to keep global warming within 2 degrees to a cost of less than 1 per cent of forecasted global GDP in 2030.

As a global problem, mitigating climate change requires global participation and collective actions. The United Nation's Framework Convention on Climate Change, UNFCCC, was established in 1992 to provide a framework for international efforts to tackle climate change. Negotiations within the auspices of the UNFCCC resulted in an international agreement to limit GHG emissions, the Kyoto protocol which entered into force in 2005. The Kyoto Protocol sets legally binding targets for 37 industrialised countries and the EU to reduce their emissions of six GHG by an average of 5 % by 2012. All signing parties except the United States have ratified the protocol. Under the Kyoto protocol, the 15 older EU Member States committed to collectively reduce their emissions by 8 % by 2008-2012, as compared to 1990 (European Commission 2011).

The technical, economic and political dimensions of climate change and the growing awareness of voters and consumers has placed climate change on top of the political agenda and on the table of company boards. Combating climate change requires political determination and leadership. At the UNFCCC climate meeting in Copenhagen 2009, so called COP 15, the presence of heads of states from practically all major economies gave evidence of the importance of the issue. However, the leaders were not able to sign a binding agreement on how future emissions reductions should be distributed and the meeting was therefore seen by many as a failure. On the positive side the leaders agreed on an accord that global warming should be limited to two degrees compared to pre-industrial time and that parties to the convention should present their plans for actions for 2020. Following the meeting, more than 100 parties to the convention have presented action plans for reducing GHG emissions.

Although the EU only accounts for 11 % of global GHG emissions the EU plays, by example, an important role in the global community regarding climate mitigation. The EU aims at reducing GHG emissions by 20 % by the year 2020 and 80 % - 95 % by the year 2050 (European Commission 2008a and 2011). The EU Emissions Trading System, in operation since 2005 and covering almost 50 % of CO_2 emissions in 30 countries, is by far the largest emissions trading system in the world (European Commission 2003). The EU ETS also provides demand and finance for emissions reductions in developing countries by supporting the Clean Development Mechanism (CDM). Together with the CDM, the EU ETS forms the basis for a global market for carbon dioxide emissions.

This thesis addresses the roles of bioenergy, peat and emissions trading for reaching the climate objectives of the EU.

1.2 The climate benefits and impacts of bioenergy

Bioenergy accounted for approximately 10 % (50 EJ) of the total global energy supply (493 EJ) in the year 2008 and is by far the largest renewable energy source (Chum et al. 2011). There is considerable potential to increase this share. In a literature review Chum et al. (2011) concludes that the potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ. As a renewable fuel, bioenergy is considered key in global efforts to replace fossil fuels and hereby reduce CO_2 emissions. In Sweden, renewable energy accounts for 45 % of the total energy supply. This makes Sweden the EU Member State with the largest share of renewable energy use. In 2005 the use of bioenergy, peat and waste accounted for 114 TWh, or 25 % of the total energy supply (not including losses in nuclear power production). Of this, 73 TWh were bi-products from the forest industry, 17 TWh roundwood, 7 TWh forest residues and 17 TWh from waste, peat and other biofuels (Swedish Energy Agency 2006). Stumps constitute a large unused potential for bioenergy. The Swedish Forest Agency (2008) estimates that the use of branches and tops can increase to at least 24 TWh/year and that the use of stumps can increase to a level of 29 TWh/year or more. There is also good potential to establish energy crops since Sweden has more agricultural land than is needed for food production (Hansson et al. 2006). However, decisions on alternative use of agricultural land need to consider a set of potential services including food production, bioenergy, biodiversity, recreation and culture (Lindborg et al. 2009).

When biomass is combusted the carbon that once was bound in the growing biomass is released, thus closing the biogenic carbon cycle. For this reason bioenergy is often considered CO_2 neutral. For instance, CO_2 emissions from the combustion of bioenergy are not included in the EU ETS. However, bioenergy production may influence biogenic carbon stocks and atmospheric CO_2 significantly in either a positive or negative way (IEA 2011). Using logging residues or stumps for energy instead of leaving them in the forest, will lead to lower carbon storage in litter and soils (Eriksson and Hallsby 1992, Melin et al. 2010 and Walmsley and Godbold 2011). But this effect is of transient character. If forest residues or stumps are left, the major part will decompose over time and release carbon to the atmosphere. According to Chum et al. (2011) harvest residues left in the forest will retain organic carbon for a considerably longer time than if used for energy. Such delayed GHG emissions can be considered a benefit in relation to near-term GHG mitigation, and this is an especially relevant factor in longer-term accounting for regions where biomass degradation is slow (for instance boreal forests). On the other hand, using forest residues for energy instead of leaving them on the ground to decompose could replace fossil energy and have a net benefit on climate. According to Lindholm et al. (2010) and Zetterberg and Hansén (1998), the use of forest residues and stumps for energy can be seen as shifting the emissions earlier in time compared to leaving them on the ground to decompose. Lindholm et al. (2010), Kirkinen (2010) and Repo et al. (2010) show that the climate impact from using forest residues for energy is mainly due to impacts on ecosystem carbon.

Bioenergy production can also affect carbon stocks in a positive way. For instance, establishing bioenergy plantations on previously unforested land will generally reduce atmospheric CO_2, at least until the bioenergy is harvested (Berndes and Börjesson 2003). Use of bioenergy may also have a climate impact due to other factors. For instance, the use of fossil fuels for harvest, collection, transport, refining and storage will lead to CO_2 emissions. There may also be emissions of methane (CH_4) and nitrous oxide (N_2O) related to land use or combustion. Incomplete combustion of bioenergy may lead to emissions of particles and hydrocarbons which may form tropospheric ozone. Establishing new forests or energy crops may change the albedo of the surface and affect the absorption of incoming radiation. In addition to these direct effects, there may be indirect effects, like the substitution effect when bioenergy replaces fossil fuels. Another indirect effect is relocation of agricultural production if bioenergy crops are established on land previously used for agriculture.

The use of bioenergy is supported by various policies at different levels. In the EU, the climate and energy package aims at reducing emissions by at least 20 %, increasing the use of renewables to 20 % and increasing the use of biofuels in the transport sector to 10 % by the year 2020 (European Commission 2008a). The renewables target of 20 % applies to the EU as a whole, with differentiated targets for each Member State. For instance, in Sweden the renewables target is set at 49 % by the year 2020. The EU Directive on renewables (European Commission 2009) defines sustainability criteria for biofuels, i.e. the GHG savings required for a fuel to be called renewable, and how these GHG emissions are to be calculated. The EU emissions trading system is the main instrument for reducing emissions in the EU and hereby an important instrument for promoting bioenergy. With the EU ETS and the emission reduction target, there is now a cost associated with fossil fuel use with the result that bioenergy and other renewables are more competitive than before 2005. Bioenergy is also promoted for other reasons than climate mitigation, for instance to create employment opportunities in rural areas (Berndes and Hansson 2007). In addition to the EU policies, there are important policies on the national level. In Sweden there is a general CO_2 tax throughout the economy on fuels, but excluding bioenergy and peat[1]. In addition, a system for green certificates supports the development of power production from renewable sources and peat (Swedish Energy Agency 2010).

In order to prioritize between different bioenergy options, decision makers need to understand the climate impacts of bioenergy due to the effects on ecosystem carbon stocks and atmospheric CO_2

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[1] For industries participating in the EU ETS, the tax is currently 157.5 SEK/ton (approximately 16.4 €/ton) and for industries outside the EU ETS 220.5 SEK/ton (approximately 22.9 €/ton), based on an exchange rate of 1 €= 9.61 SEK. By comparison, during phase II the EU ETS allowance price has been fairly stable around 15 €/ton (Wråke et al 2012). Electricity production is excluded from paying the Swedish CO_2 tax.

over time. Policies and incentives need to be implemented that encourage sustainable use of bioenergy and replacement of fossil fuels.

1.3 Climate impacts from using peat for energy

Peatlands in Europe have served as a significant sink for atmospheric CO_2 since the last glacial maximum and they currently hold approximately 42 Gt carbon in the form of peat (Byrne et al. 2004). Peatlands are also significant emitters of methane (CH_4) and in some cases also nitrous oxide (N_2O). Peatlands provide a wide set of ecological functions including habitats, sequestration of water runoffs, safeguarding of regional water supply as well as offering production functions to society, mainly for agriculture, forestry and energy.

In Sweden, peat constitutes a modest share of the total energy use, approximately 2.0 TWh or less than 0.4 % (Swedish Peat Producers Association, 2010). However, approximately 25 % of Sweden is covered by peatland, and the potential for increased use is significant (SOU 2002:100). Being a domestic fuel it has the potential to provide both job opportunities and security of supply. However, exploitation of peatland is often in conflict with other interests, for instance habitat preservation. From a climate point of view, CO_2 emissions from peat use in Sweden are not insignificant. Emissions from combustion of peat in Sweden 2009 were approximately 0.8 Mton CO_2, corresponding to 1.7 % of the total Swedish CO_2 emissions[2]. But using peat also affects GHG fluxes in other ways. Pristine (virgin) peatlands serve as a sink for atmospheric carbon dioxide and emit methane. Drained peatlands emit CO_2 and in some cases N_2O due to the oxidation of peat, while the methane emissions cease. Some options for after-treatment of harvested peatland may create new sinks for atmospheric carbon dioxide, but also affect fluxes of CH_4 and N_2O. Figure 1 shows schematically what fluxes may be involved when a pristine mire is drained, harvested for peat and then restored as a new wetland.

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[2] Based on 2.0 TWh peat and an emission factor of 107.3 g CO_2/MJ peat (Swedish Environmental Protection Agency 2011a). Sweden's total CO_2 emissions in 2009 were 46.6 Mton (Swedish Environmental Protection Agency 2011b)

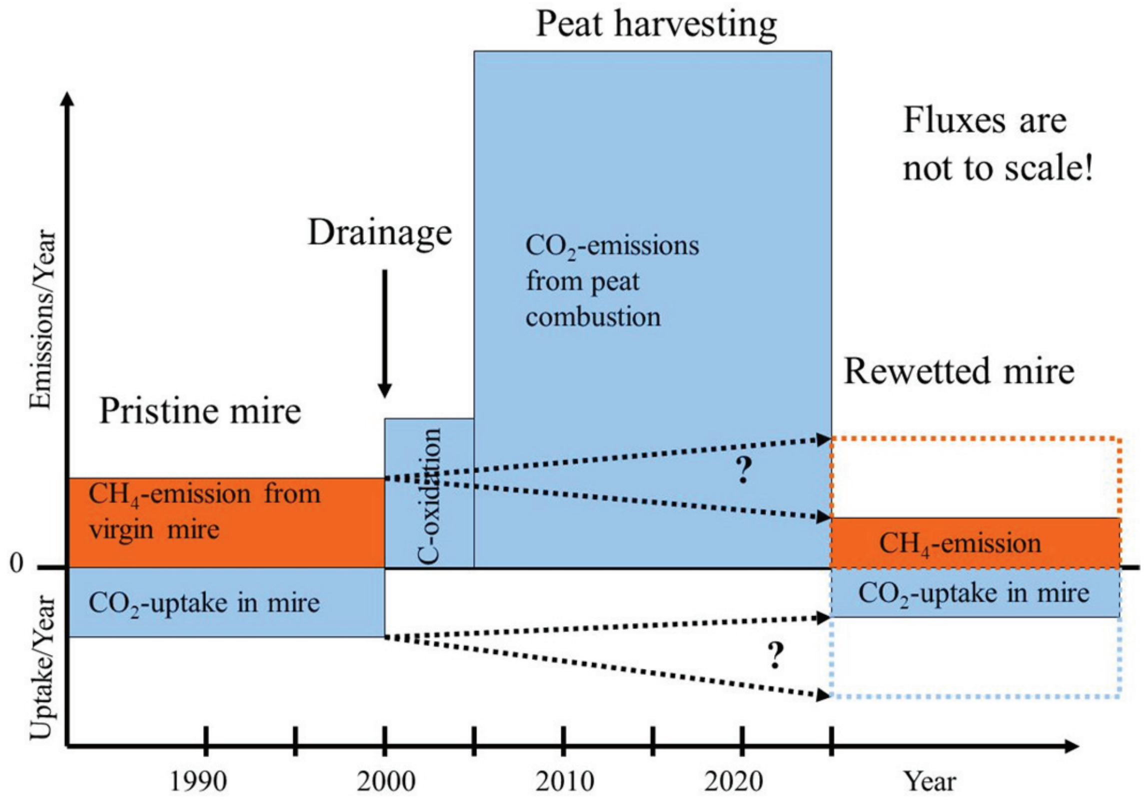

Figure 1. Schematic illustration of carbon dioxide (CO_2) and methane (CH_4) fluxes related to use of peat assuming a scenario where a pristine (virgin) mire is drained, harvested for peat and finally restored as wetland again.

From a policy point of view the use of peat is treated somewhat ambiguously. In the Swedish reporting to the EU ETS and to the climate convention, the emission factor for peat is 107.3 g CO_2/MJ fuel, which is higher than coal. In contrast, using peat for electricity production in Sweden renders green certificates just as bioenergy, wind and sustainable hydropower do. Moreover, there is no CO_2 tax on peat use in Sweden.

Several studies have investigated climate impacts from different peat extraction scenarios. Nilsson and Nilsson (2004) investigates climate impacts from four different peatland types (pristine peatland[3], forestry drained peatland[4], abandoned peatland[5] and agricultural peatland[6]) assuming

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[3] Pristine peatland is a natural mire which is drained and harvested for peat. The starting point is the natural mire.

[4] Forestry drained peatland is peatland that has been drained and used for forest production, a common land use form in Sweden and Finland. This scenario uses the already drained peatland as the starting point, which is a source of CO_2 due to the oxidation of peat. A forestry drained peatland scenario usually includes deforestation, peat harvest and then reforestation.

[5] Abandoned peatland has been drained for either forest or agricultural production, but has been abandoned. The starting point is the already drained peatland, which is usually a source of CO_2 due to the oxidation of peat.

two different after-treatment strategies (afforestation and wetland restoration). The estimated climate impacts vary considerably from being lower than forest residues to higher than coal over a 300 year perspective. Kirkinen et al. (2008) estimate the climate impacts from a forestry drained peatland–afforestation scenario to be higher than coal, while a cultivated peatland–afforestation scenario had a considerably lower climate impact over a 300 year time perspective, comparable to using forest residues. Hagberg and Holmgren (2008) estimate climate impacts from a forestry drained peatland–afforestation scenario to range from lower than natural gas to between natural gas and coal, while a cultivated peatland–afforestation scenario has a climate impact close to zero over a 300 year time perspective. Savolainen et al. (1994) find that the climate impacts from using peat can be comparable to coal. Rodhe and Svensson, (1995) estimate the climate impact from peat to be comparable to fossil oil. Åstrand et al. (1997) argues that using peatland can be comparable to using forest residues if the harvested peatland is forested and this forest is used for bioenergy in multiple generations.

Analysing climate impacts from peat use is complex since it involves uptake and emissions of several greenhouse gases over a long time period. Understanding of the factors that influence the climate impacts of peat provides guidance on choice of peatlands for exploitation and after-treatment strategies.

1.4 The EU Emission Trading System

The EU Emission Trading System, ETS, in operation since 2005 and covering almost 50 % of CO_2 emissions is described by the European Commission as the corner stone of EU's strategy to combat climate change (European Commission, 2008a). The EU emission trading system was launched with the purpose of reaching the EU reduction target according to the Kyoto protocol in a cost-effective way. It is now seen as the main policy instrument to reach the 20 % reduction target by the year 2020. The EU ETS is the first international trading system for carbon dioxide (CO_2) emissions in the world and applies to the 27 EU member states and Norway, Iceland and Lichtenstein. It covers some 11500 participating installations in the energy and industrial sectors which are collectively responsible for almost half of EU emissions of CO_2 and 40 % of its total greenhouse gas emissions (European Commission, 2009b).

In phases I and II, which concludes in 2012, the system only covers CO_2, but from phase III (2013-2020) it will also cover other greenhouse gases. The sectors covered are the energy sector including

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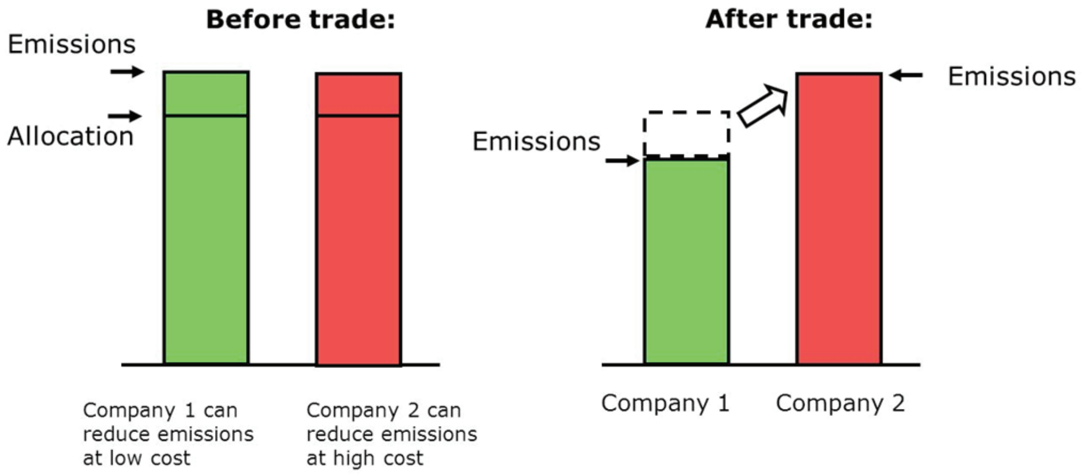
[6] Agricultural peatland or cultivated peatland has been drained for agricultural production, also a common land use form in Sweden and Finland. This scenario uses the already drained peatland as the starting point, which is a source of CO_2 due to the oxidation of peat. A 'cultivated peatland – afforestation' scenario usually includes peat extraction and afforestation.

refineries, production and processing of ferrous metals, the mineral industry and certain industrial facilities for the production of paper pulp, paper and cardboard. During phase III, the system will be expanded to cover the aluminium industry, some areas of the chemical industry, artificial fertiliser production and aviation, among others.

Figure 2 gives a schematic description of how emission trading works. Assume the trading system only involves two companies, the green one with inexpensive emissions reductions and the red one with expensive emissions reductions. Assume further that the regulator distributes emission allowances corresponding to 90 per cent of the company's current emissions to each company. Without trading, both companies would need to reduce their emissions by 10 per cent. With trading, however, the green company can reduce its emissions further and sell its surplus to the red company. The green company can sell the credits at a higher price than the reductions actually cost, whereas the red company can purchase at a lower price than its own reductions would have cost. Both companies benefit from this trade. The method is appreciated both by authorities and by industry. The authorities know in advance what the emissions will be, emission reductions are performed where it is cheapest and the companies are given the flexibility either to reduce their own emissions or to purchase emissions credits.



- Environmental benefit: A prescribed emission target is achieved
- Economical benefit: Reductions are performed where cheapest
- Flexibility for companies: reduce emissions or buy reductions by other company

Figure 2. How emission trading works.

For an emission trading system with many participating emissions sources, the regulator decides the level of emissions by issuing this amount of allowances to the participants, the cap. The shortage of allowances (in relation to actual emissions) creates a demand and subsequent price on allowances. In theory, if the market functions perfectly, the price of allowances will reflect the marginal costs for abatement for the participating sources. A company that can reduce emissions at a lower cost than the price of allowances will do so, while a company with abatement costs higher than the allowance price will buy allowances to cover their deficit. The incentives for emission reductions are created by the cap on emissions.

1.5 The role of allocation in the EU ETS

A central isuue in the design of an emissions trading program is how the emission allowances are initially distributed among participants. A fundamental question is whether firms should receive allowances for free or whether firms should be required to pay for them, for example through an auction. Since the value of this asset is considerable, the effects on firms' costs (and revenues) may be significant (Ellerman et al. 2007). This issue involves several considerations, for instance fairness, political feasibility and the efficiency[7] of the trading system. According to text book economics, allocation of emission allowances, once allocated, should not change the cost-effectiveness of the trading system (Montgomery, 1972). The allowance price, the environmental effectiveness, choice of abatement by firms and downstream price effects are all determined by the emissions reduction target (Zetterberg et al 2012). The opportunity cost of emissions is the same whether firms pay for allowances or not. However, this holds only under specific conditions, including an allocation process that does not affect the behaviour of the firm (Harrison et al. 2007).

In phases I and II of the EU ETS, emission allowances were to a large extent distributed free of charge based on historic emissions, often referred to as grandfathering. At the start of the program the EU supported grandfathering as a way to decrease the financial burden on participating firms, while attaining the emissions target. Grandfathering would offer a situation closer to the status quo, thus increasing the chances that participants would accept the trading system in the first place. In phases I and II, each Member State was responsible of developing a National Allocation Plan (NAP), defining the exact amount of allowances to be distributed to each participating installation. The plans were required to follow a set of criteria, listed in the Annex III of the Directive (European Commission, 2003) and be approved by the EU Commission. These criteria include, inter alia, that quantities of allowances to be allocated should be consistent with the potential to reduce emissions.

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[7] Efficiency in this context means minimizing the total costs of reaching an emission target

Although abatement incentives may be preserved; there are other potentially problematic features of grandfathering[8]. Over time, the data and circumstances upon which the allocation was originally based will become increasingly irrelevant. Production volumes change, old installations close, new installations enter, technologies, processes and products change. At some point the allocation needs to be updated, and this creates a dilemma to the regulator. If allocation in future trading periods is based on data that can be affected by industry, this may change the firms' incentives for action.

In the long term, auction is therefore the most efficient way to distribute allowances. Auction is also supported by the Polluter Pays Principle (PPP), thus increasing the perception of fairness in the system. Auction also ensures transparency and simplicity of the system. Moreover, revenue from auctions can be recycled in ways that reduce the overall cost of the regulation. But in spite of the theoretical advantages of auction, practical and political barriers to its implementation remain. Auctions have been opposed by important sectors of industry, as well as by some Member States. Industry argues that auctions would be economically detrimental to them, referring to the international competition that they face from firms outside the EU ETS. If these costs are not compensated, at least in part, this may lead to the relocation of economic activity and associated emissions to outside the trading region. This 'carbon leakage' could undermine the integrity of the GHG policy and, in fact, raise the cost of achieving environmental goals.

In preparation for phase III, the EU ETS was reviewed and the directive was updated (European Commission 2009b), drawing on lessons from the two first phases. In a transitional period, starting with the third phase in 2013, auctioning will be gradually phased in to reach 100 % in the year 2027. However, an exception will be made for installations in sectors judged to be at significant risk of carbon leakage, meaning that they could be forced by international competitive pressures to relocate production to countries outside the EU that do not impose comparable constraints on emissions (European Commission 2008b). For these sectors, the directive provides free allowances. The allocation of these free allowances is mainly to be based on production (output) and sector common benchmarks, referred to as *output based allocation* or *benchmarking* (European Commission 2009b, §18).

1.6 Objectives

The overall objective of this thesis is to increase the understanding of 'instruments' for reaching climate policy objectives, focusing on the role of bioenergy and peat and how climate efficient

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[8] For a review of arguments for and against grandfathering and other allocation options, refer to Zetterberg et al, 2012.

production can be incentivized by the EU Emissions Trading System. This general objective can be broken down into the following specific objectives:

Objective 1. What are the climate impacts and benefits from bioenergy focusing on how their use affects ecosystem carbon stocks and atmospheric CO_2 over time? Special attention is given to how fast combustion related carbon emissions are compensated by uptake of atmospheric carbon (or avoided emissions).

Objective 2. What are the climate impacts of using peat for energy and what is the importance of peatland characteristics and after-treatment strategies?

Objective 3. How should the EU Emissions Trading System be designed to incentivize CO_2 efficient production and reduce emissions in a cost effective way? Special attention is given to how different allocation rules affect firms' incentives to reduce emissions when allocation is adjusted in consecutive periods.

Objective 1 is addressed by Paper **I**. A set of fuel types representing different uptake rates is investigated, namely willow, branches and tops, stumps and coal. Objective 2 is investigated in Paper **II**, which evaluates the climate impact from using peat for energy in Sweden compared with alternative energy sources. Two different options for after-treatment are investigated: afforestation and restoration of wetland. Objective 3 is investigated in Papers **III-V**. Paper **III** investigates different rules for allocation of emissions allowances in the first phase of the EU ETS. Each allocation rule is tested against a set of criteria, i.e. consideration of early action and administrative costs related to implementing an allocation scheme in practice. Paper **IV** analyses how adjusting allocation affects the economic efficiency of cap and trade systems, using the treatment of closures and new entrants in the EU ETS as examples. Paper **V** investigates abatement incentives for free allowance allocation based on production and sector specific benchmarks, here called benchmarking.

2. Methods and System Boundaries

2.1 The climate impacts of bioenergy

A set of solid biofuels, representing different CO_2 uptake rates has been analysed, namely willow (fast uptake), branches and tops (medium uptake rate) and stumps (slow uptake) in traditionally managed forests. These alternatives are compared to coal (no CO_2 uptake). Only biogenic CO_2 fluxes are considered, i.e. uptake of atmospheric CO_2 in the forest ecosystem and emissions of CO_2 from combustion of the biofuel or from the decomposition of the forest residues, see Figure 3.

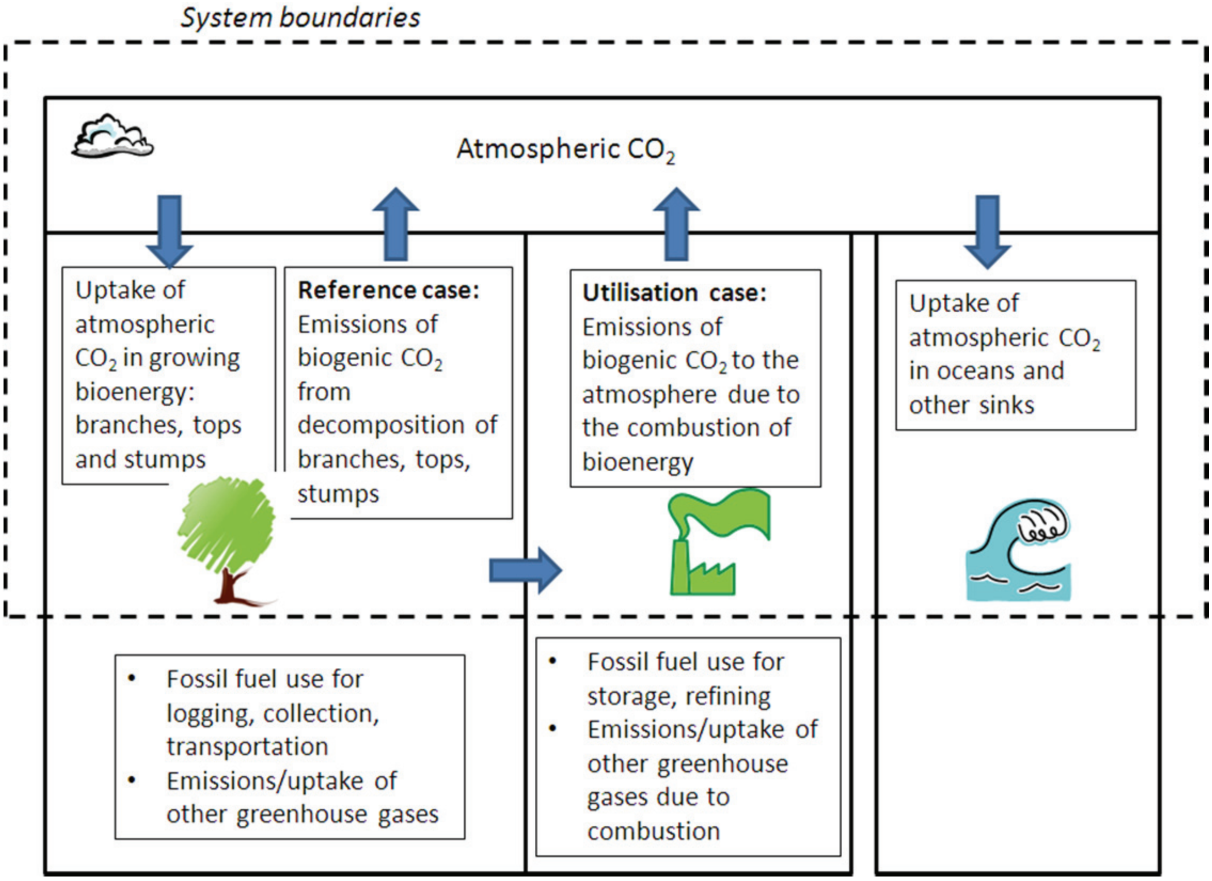


Figure 3. System boundaries for the investigated bioenergy.

The climate impacts have been calculated in four steps:

i) Emissions have been calculated based on biogenic carbon stock change data

ii) Atmospheric concentration changes have been calculated based on emissions

iii) Radiative forcing has been calculated based on atmospheric concentration changes

iv) Global surface temperature change has been calculated based on radiative forcing

The first three steps follow the same methodology as for instance Kirkinen (2010) and Holmgren et al. (2007), while the fourth step, global average surface temperature change, is estimated using an energy balance model. These methods and models are described below.

Emissions

The *net* emissions, E_{net}, as a function of time are defined as the emissions from the case of utilisation minus the emissions from a reference case:

$$E_{net}(t) = E_U(t)-E_{Ref}(t) \qquad (1)$$

The subscript *U* refers to the utilisation case and *Ref* to the reference case.

Expression (1) follows recommendations by Schlamadinger et al. (1997) and is applied by for instance Zetterberg and Hansén (1998), Lindholm et al. (2010), Kirkinen et al. (2008) and Hagberg and Holmgren (2008).

For forest residues, the reference case is to leave the residues in the forest to decompose. Estimates of CO_2 fluxes are based on information of how ecosystem carbon stocks develop over time assuming different management regimes; bioenergy extraction or leaving the forest residues in the forest. These data have been provided by Ågren et al. (2010) using a soil carbon model (Q-model) for Swedish conditions and Repo et al. (2010) using a soil carbon model (Yasso) representing Finnish conditions. Both models have been calibrated according to measured decomposition rates of branches, tops and stumps.

Atmospheric concentrations

The remaining mass $M_i(t)$ in the atmosphere for gas i at the time t is calculated as:

$$M_i(t) = \int_0^t E_{net,i}(\tau)\, f_i(t-\tau)d\tau \qquad (2)$$

where $f_i(\tau)$ is the pulse response function for greenhouse gas i, as presented by the IPCC (Forster et al. 2007). The pulse response functions for methane and nitrous oxide are described as a single exponential decay function, with average lifetime of 12 and 114 years respectively. The pulse response function for carbon dioxide is more complex and described by a combination of exponential decay functions:

$$f(t) = 0.217 + 0.259 \cdot e^{-t/172.9} + 0.338 \cdot e^{-t/18.51} + 0.186 \cdot e^{-t/1.186} \qquad (3)$$

Based on the remaining mass in the atmosphere, the concentration change $C_i(t)$ for gas i at the time t are calculated as:

$$C_i(t) = \frac{M_i(t) \cdot MV_{Atm}}{M_{Atm} \cdot MV_i} \qquad (4)$$

Where MV_{Atm} is the molecular weight of the atmosphere, M_{ATM} is the mass of the atmosphere and MV_i is the molecular weight of gas i.

Radiative Forcing

Radiative forcing is commonly used for assessing the expected climate impacts from global emission scenarios. The measure has also been used to assess the expected climate impacts from different energy carriers (Savolainen et al. 1994, Holmgren et al. 2006, Holmgren et al. 2007, Kirkinen et al. 2008, Kirkinen et al. 2010). Radiative forcing, expressed in W/m^2, is described as a change in average net radiation at the top of the troposphere, due to a change in either solar or infrared radiation

(IPCC, 1994). This can for instance be caused by changes in greenhouse gas concentrations, particles from volcanic eruptions or changes in solar intensity. A radiative forcing perturbs the balance between incoming and outgoing radiation of the global climate system. A positive radiative forcing tends to warm the surface; a negative radiative forcing tends to cool the surface. Increased concentrations of CO_2 lead to a positive radiative forcing. Ramaswamy et al. (2001) describes the relation between radiative forcing and increased concentrations of greenhouse gases in simple GHG specific functions, $RF_i(C_i)$, which are parameterisations of more complex radiative models. For instance, for CO_2, the radiative forcing, RF_{CO2} due to a concentration change $C_{CO2}(t)$ at the time t is calculated as:

$$RF_{CO2}(C_{CO2}) = 5.35 \ln (C_{CO2} / C_{CO2,0}) \quad (5)$$

Where $C_{CO2,0}$ is the reference atmospheric concentration for CO_2.

When several different greenhouse gases, for instance CO_2, CH_4 and N_2O are included in the emission scenario, the total radiative forcing is calculated as the sum of the radiative forcing of each gas, corrected for the overlapping of the infrared absorption bands of CH_4 and N_2O, which is given by Ramaswamy et al. (2001).

Often, derivatives of radiative forcing are used, such as:

AGWP, Absolute global warming potential is the time integration of radiative forcing from when the emission occurs to a prescribed time perspective, usually 20, 50 or 100 years (Ramaswamy et al. 2001).

$$AGWP(t) = \int_0^t RF(\tau)d\tau \quad (6)$$

AGWP is expressed in J/m^2 or $W \cdot year/m^2$. *Accumulated radiative forcing* is an alternative name for AGWP. The term *Instantaneous radiative forcing*, expressed in W/m^2, is sometimes used to distinguish radiative forcing from *accumulated radiative forcing*. The Relative Radiative Forcing Commitment, *RRFC(t)* is described by Kirkinen et al. (2008) as the ratio of the energy absorbed in the Earth system due to changes in greenhouse gas concentrations compared to the energy released at the combustion of the fuel. It is calculated as:

$$RRFC(t) = \frac{AGWP(t) \cdot A}{E_{fu}} \quad (7)$$

Where A is the surface of the Earth and E_{fu} is the energy of the fuel used.

Global surface temperature change

Based on the emission scenarios, global average temperature has been calculated using an energy balance model, IMAGES - Impact Model for Assessing Greenhouse Gas Emission Scenarios, which was developed in preparation for Paper **I**. Based on radiative forcing, the model calculates global average surface temperature using analytical functions. The model is presented in more detail in Paper **I**.

2.2 The climate impacts of peat

Climate impacts of using peat for energy and the importance of peatland characteristics and after-treatment strategies have been investigated (Paper **II**). This study assumes that a pristine (virgin) mire is drained and harvested for peat. Two different options for after-treatment are investigated: afforestation and restoration of the wetland. The methodology for calculating climate impacts follows the same methodology as for bioenergy, with three exceptions. First, global average temperature change has not been calculated for peat. Secondly, radiative forcing calculations use older expressions for estimating the relationships between increased concentrations and radiative forcing, presented in IPCC (1990). Thirdly, the emissions inventory for peat is more comprehensive than for bioenergy. An inventory of emissions and uptake of CO_2, CH_4 and N_2O is compiled for the different stages in the life cycle: before drainage, harvest, combustion and after-treatment. Fluxes from land-use, peat combustion and the use of fossil fuels are included. Net emissions are defined as emissions and uptake from using peat for energy (including drainage, harvest, combustion and after-treatment) compared to leaving the pristine mire as it is. Climate impacts are estimated by calculating the time dependent accumulated radiative forcing from using 1 PJ peat over a period of 20 years (years 6-25). In the peat-afforestation scenario, the area is assumed to be forested after the peat is extracted and the consequent uptake of CO_2 from the first generation of forest is credited to the peat. However, in contrast to Paper **II**, future production of biofuels on the land is not included in the calculations presented in this thesis. In the peat-afforestation scenario, we have assumed best estimates for forest growth rate and different rates for pristine wetland emissions. In the peat-restored wetland scenario, we have assumed different rates for pristine wetland methane emissions, restored wetland methane emissions and restored wetland carbon uptake rates.

2.3 The features of different allowance allocation rules

Four allocation rules for use in the EU ETS have been investigated (Paper **III**):

i) Emission-based allocation
ii) Output based allocation with sector specific benchmarks, based on historic performance
iii) Output based allocation based on data on Best Available Technology (BAT)
iv) Output based allocation with site specific benchmarks, based on historic performance

Each allocation rule is assessed with regard to how well they meet the criteria of the EU ETS Directive, listed in its Annex III and requirements of the Swedish FlexMex2-commission (SOU 2003). These criteria are presented in Paper **III**, pp. 601-602.

2.4 The effects of adjusting allocation on efficiency

The negative effects on efficiency of adjusting allocation have been demonstrated using the treatment of new entrants and closures in the EU ETS as examples (Paper **IV**). The analysis is based on literature studies and numerical examples of how the going forward operation costs depend on allocation rules and how this may affect firms' behaviour.

2.5 The effects of allocation rules on firms' abatement incentives

Abatement incentives are investigated by maximising the profit equation for a firm participating in the trading system (Paper **V**):

$$\Pi = Pq - c(q,a) - pe(q,a) + p\hat{e} \tag{8}$$

where *Π* is profit, *P* is output price, *c(q,a)* is the company's cost for output *q* and abatement *a*, *p* is the price of allowances which is assumed to be set exogenously, *e(q,a)* is the firm's emissions and *ê* is the amount of allowances issued freely. Calculating the first order conditions of the profit equation with respect to abatement, *a*, and output, *q*, gives us profit maximizing abatement levels and product price. For updated allocation, a two period model is developed. We set up two expressions for profit, representing two different trading periods, where the subscript 1 relates to the first period and subscript 2 the second trading period:

The profit for periods one and two, respectively are:

$$\Pi_1 = P_1 q_1 - c_1(q_1, a_1) - p_1 e_1(q_1, a_1) + p_1 \cdot \hat{e}_1 \tag{9}$$

$$\Pi_2 = P_2 q_2 - c_2(q_2, a_2) - p_2 e_2(q_2, a_2) + p_2 \cdot \hat{e}_2 \tag{10}$$

Optimal abatement levels and product price for a firm are derived by maximising the net present value of profit over two periods $\Pi_1 + \frac{1}{1+r}\Pi_2$ (11)

with respect to abatement, a_1, and output, q_1, in period 1. *r* is the discount rate between periods 1 and 2.

3. Results

3.1 Climate impacts from bioenergy focusing on the effect on carbon stocks over time

Climate impacts from bioenergy due to how fast combustion related emissions are compensated by uptake of atmospheric CO_2 (or avoided emissions) have been investigated (Paper **I**). A set of fuels, representing different uptake rates have been analysed, namely branches and tops, stumps and coal. 1 PJ fuel is assumed to be used as a single event at t=0. Net emissions (equivalent to net carbon stock change) have been calculated for each fuel and are presented in Figure 4a, expressed in kton CO_2/PJ fuel. Based on these net emissions, climate impacts, expressed in instant radiative forcing, accumulated radiative forcing and global average temperature change have been calculated and are presented in Figures 4b-4d respectively. Willow is analysed separately in the next section.

In Figure 4a the emission curves remind of exponential decay approaching zero in an asymptotic manner. For all forest residues (branches, tops and stumps), there is an initial emission pulse at t=0, due to combustion, which is reduced over time due to avoided emissions from decomposition in the reference case. For coal, there is no uptake or avoided emissions, so the emissions are constant over time. We can see that branches and tops are faster in compensating combustion related emissions than stumps, which in turn are faster than coal. The time to reach 50 % emissions reduction, $t_{50\%}$, is 6-9 years for branches and tops and 25-30 years for stumps. Figures 4b-d, show that branches and tops have the lowest climate impacts, followed by stumps, which in turn have a lower climate impact than coal.

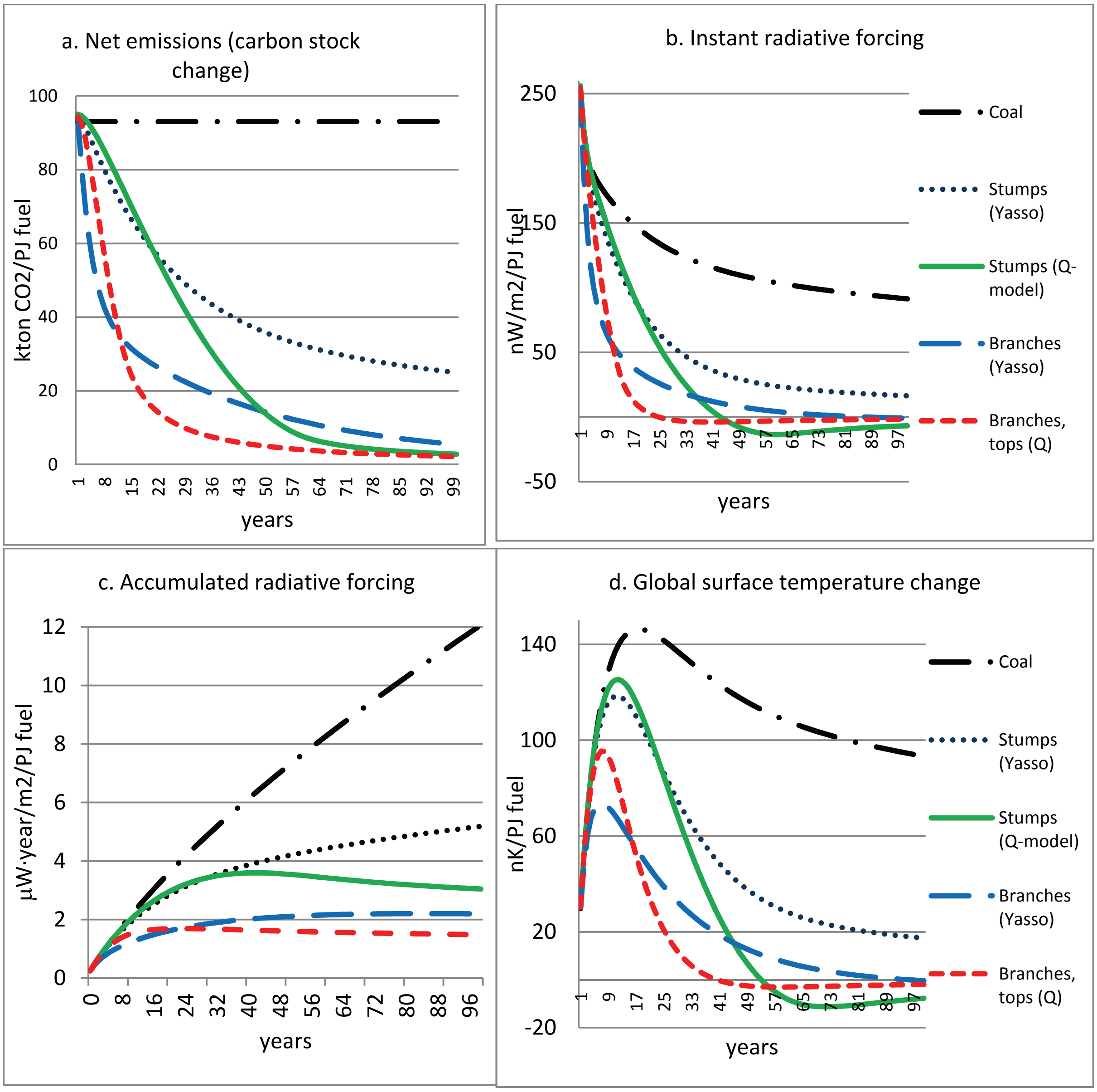


Figure 4. Climate impacts from bioenergy due to how fast combustion related CO_2 emissions are compensated compared to coal. We assume that 1 PJ fuel is used at t=0. Only biogenic CO_2 fluxes are considered. Emissions are based on numerical simulations by Ågren (2010) using a soil carbon model (Q-model) for Swedish conditions and Repo et al. (2010) using a soil carbon model (Yasso) representing Finnish conditions. Net emissions are defined as emissions from using the biomass for energy compared to leaving them in the forest to decompose. Climate impacts are expressed as instant radiative forcing, accumulated radiative forcing and global average surface temperature. Positive values correspond to warming and negative values to cooling. The unit µW·year is chosen to allow for comparison with other studies. The term ‘year’ refers to the number of seconds in one year. 1 µW·year is a measure of energy and approximately = 32 J.

Establishment of new energy crops – the example of willow

In addition to branches, tops and stumps, we have investigated the climate impacts from using willow for energy. Willow grown for energy is mature for harvest after 3-5 years and can therefore be considered a 'fast' biofuel compared to branches and tops ($t_{50\%}$ = 6-9 years) and stumps ($t_{50\%}$=25-30 years). However, willow differs from forest residues (branches, tops and stumps) in an important way. **Forest residues** are produced from land already established for forest production. The reference case is a scenario where the residues are left to decompose naturally. Therefore, using forest residues for energy results in net emission compared to the reference case. In contrast, willow is usually established on land that has previously been used for agricultural production. Simulations by Ågren et al. (2010) presented in Figure 5 show that the establishment of willow may increase the total carbon per unit area as compared to crops. So using willow for energy causes a *net carbon uptake* compared to the reference case. This puts willow at a significant advantage compared to forest residues, but requires additional land.

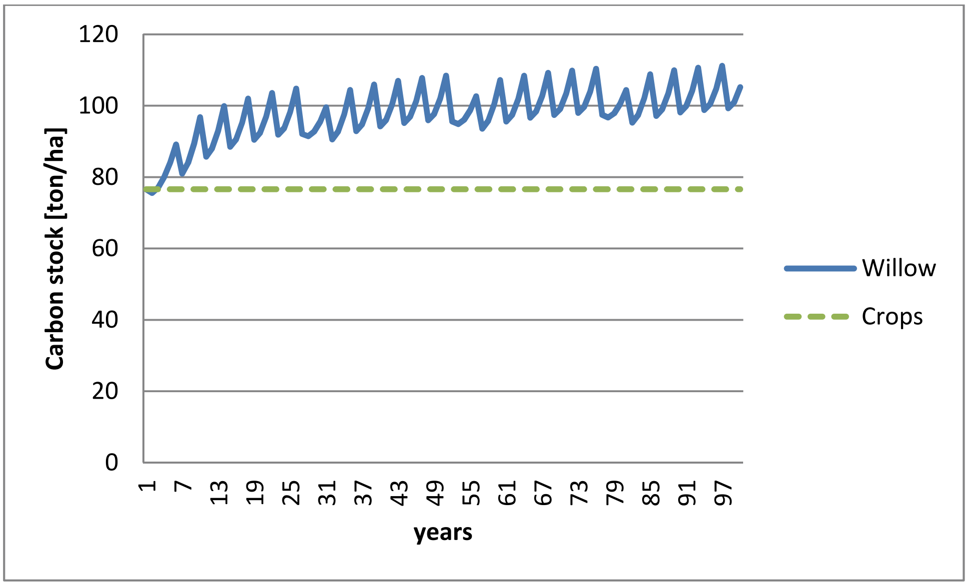
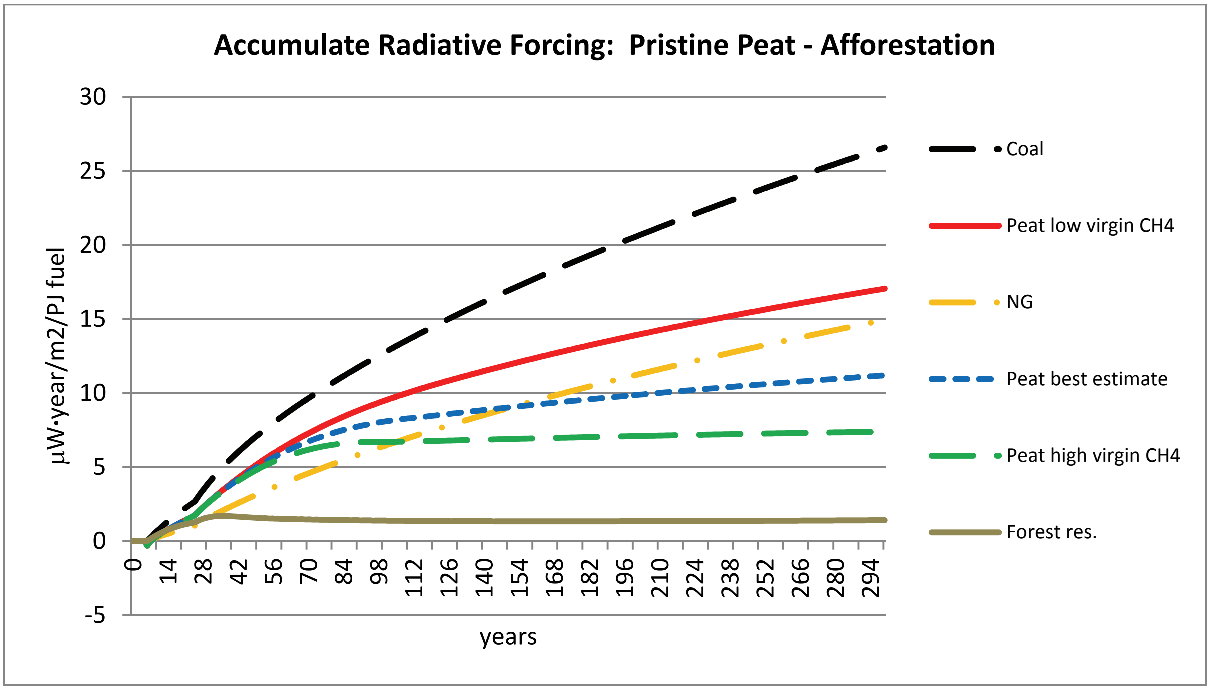


Figure 5. Carbon stock changes for two different options of land use, willow and crops, based on numerical simulations of carbon stock changes from the Q-model (Ågren et al. 2010).

3.2 Climate impacts from using peat for energy

The climate impact of using peat for energy has been investigated assuming different after-treatment strategies and different assumptions of wetland methane emissions, carbon uptake rates in the restored wetland and carbon uptake rates in afforested peat land (Paper **II**). The calculated climate impacts are presented in Figure 6.



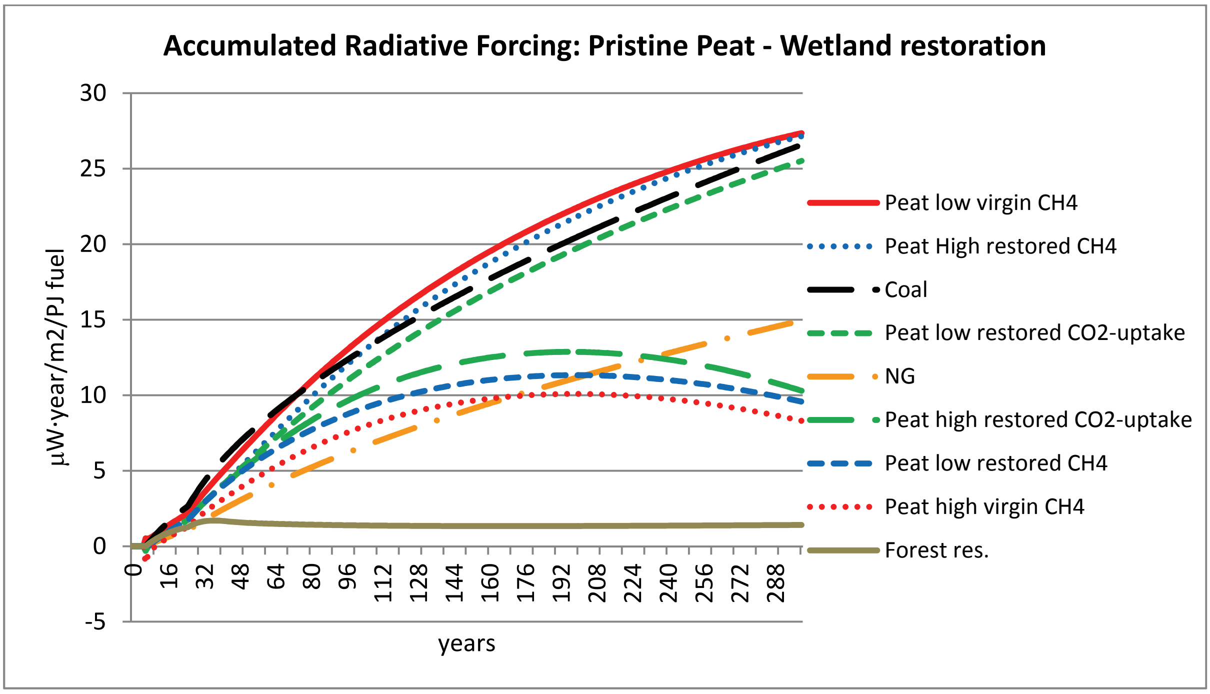


Figure 6. Climate impacts of using peat for energy and the importance of peatland characteristics and after-treatment strategies. A pristine mire is assumed to be drained and harvested for peat. Two different options for after-treatment are investigated: afforestation and restoration of the wetland. Fluxes of CO_2, CH_4 and N_2O from land-use, peat combustion and the use of fossil fuels are included. Net emissions are defined as the emissions and uptake from using peat for energy (including drainage, harvest, combustion and after-treatment) compared to leaving the pristine mire untouched. Climate impacts from using 1 PJ peat (0.05 PJ/year over 20 years, starting year 6) are calculated and expressed in accumulated radiative forcing. Data is based on Paper **II**, but recalculated as accumulated radiative forcing.

For the peat-afforestation scenario, we find that accumulated radiative forcing over 300 years range between 7-17 μW·year/m2/PJ produced peat, with a best estimate of 11 μW·year/m2/PJ. For the peat-wetland restoration scenario, we find that accumulated radiative forcing over 300 years range between 8-27 μW·year/m2/PJ produced peat, with a best estimate of 18 μW·year/m2/PJ. This can compared to 1.4, 15 and 27 μW·year/m2/PJ for forest residues, natural gas and coal respectively.

We find that for the peat-afforestation scenario, climate impacts are highly dependent on the methane emissions from the pristine mire, as well as the growth rate of the forest established after peat extraction. For the peat-wetland scenario, we find that climate impacts are highly dependent on methane emissions from the pristine mire and the methane emissions and carbon dioxide uptake from the restored wetland.

3.3 The effects of allocation rules on firms' abatement incentives

In phases I and II of the EU ETS, allowances were to a large extent allocated based on historic emissions, referred to as emission based allocation or *grandfathering*. However, in a transitional period, starting with the third phase in 2013, auctioning will be gradually phased in to reach 100 % in the year 2027. During this phase a limited amount of allowances will be based on production (output) and sector common benchmarks, referred to as output based allocation or *benchmarking*.

We have investigated the characteristics of emission based allocation and output based allocation (Papers **III-V**). We find that emission based allocation schemes are most straightforward, transparent and are easiest to implement. However, emission based allocation does not reward early action, nor does it take into consideration the potential to reduce emissions, which production-based allocation does. Production based allocation requires more data to implement (Paper **III**).

Special attention is given to understanding how allocation rules affect firms' incentives to reduce emissions. We demonstrate the negative effects of adjusting allocation using the treatment of new entrants and closures in the EU ETS as examples (Paper **IV**). Our analysis shows that adjusting allocation due to changes in firms' operations may severely reduce firms' incentives to become more CO_2 efficient. Concerning closures, in phase I of the EU ETS most Member States withheld or required transfers of allowances from closed installations. But there is a strong case to be made against withdrawing allocations after closures of installations. Paradoxically, the policy of withdrawal of allowances serves as a production subsidy because the allocation is received if and only if the installation continues to operate. This production subsidy for inefficient installations that otherwise would close has efficiency costs for the ETS and the economy.

The effects on abatement incentives of adjusting allocation have also been investigated using a two period analytical model where allocation to an installation in the second period is influenced by performance (emissions or output) in the first (Paper **V**). We find that updated emission based allocation may significantly reduce abatement incentives. Using the same two-period analytical model, we have investigated abatement incentives when allocation is based on output and sector specific benchmarks, here called benchmarking. Special attention is given to updated allocation. We confirm earlier studies where it was found that allocation based on updated output and prescribed benchmarks preserves abatement incentives, but constitutes an output subsidy. We find that allocation based on a prescribed cap that is distributed to firms based on their production in the previous period also preserves abatement incentives but involves an output subsidy.

4. Discussion

4.1 Climate impacts from bioenergy due to how they affect carbon stocks over time and carbon uptake rates

Using biomass for energy may affect ecosystem carbon pools over time and may therefore result in climate impacts that are not insignificant. Based on estimations of ecosystem carbon fluxes for a set of biofuels, we find that, assuming all other factors equal, the climate impacts from the use of biomass for energy depends on how fast the combustion related emissions are compensated by uptake of atmospheric CO_2 (or avoided emissions).

The analysis has focused on how the use of bioenergy affects carbon stocks and atmospheric CO_2 over time. The analysis does not consider the use of fossil fuels for harvest, collection, transportation and refining, emissions of other GHG than carbon dioxide, formation of tropospheric ozone or energy conversion losses. Impacts on albedo have not been considered. Substitution effects such as when bioenergy replaces other fuels are not included. Whether extraction of branches, tops and stumps may affect forest production in the next forest generation has not been analysed. We have not considered the absolute size of the carbon stocks associated with different bioenergy types, only how the carbon stocks change due to the use of biomass for energy.

Our analysis starts when the forest residues were extracted, not when the trees were planted. One may argue that the growth stage should be included in the analysis, since if there is no growth, there cannot be emissions. This is of course true, but not in conflict with our analysis. The typical situation in Sweden is that forests have long been used for the production of timber and cellulose for the pulp and paper industry. Forest residues from loggings are often collected and used as energy. The point of departure for our analysis is the decision to extract forest residues for energy instead of leaving them on the ground to decompose. Using the residues for energy will result in net emissions compared to leaving them on the ground and the consequent climate impacts have been analysed.

Our estimates of emissions and radiative forcing in large confirm other studies. We estimate **emissions** over a 100 year perspective to be 2 - 5 g CO_2/MJ for branches and 3 - 25 g CO_2/MJ for stumps (Paper **I**). According to Schlamadinger et al. (1995), Wihersaari (2005), Kujanpää et al. (2010) and Repo et al. (2010) emissions over a 100 year perspective for branches and tops range between 2 and 26 g CO_2/MJ. Repo et al. (2010) estimate emissions over a 100 year perspective to be 2 - 16 g CO_2/MJ for branches and 18 - 27 g CO_2/MJ for stumps. Lindholm et al. (2010) estimate **average** emissions over 100 years to be 20 g CO_2/MJ for branches and tops and 37 g CO_2/MJ for stumps.

We estimate the **accumulated radiative forcing** over 100 years for branches and tops to be 1.4 - 2.2 μW·year/m^2/PJ fuel (Papers **I** and **II**). Holmgren et al. (2007) estimate the accumulated radiative forcing over 100 years for branches and tops to be 1.6 - 2.6 μW·year/m^2/PJ fuel (values re-calculated from continuous fuel use). Kirkinen et al. (2008) estimate the *RRFC* for forest residues to be 20 - 40, which corresponds to an accumulated radiative forcing of approximately 1.2 - 5.0 μW·year/m^2/PJ fuel.

We find that the time perspective over which the analysis is done is crucial for the estimated climate impact of biofuels. Over a 100 year perspective branches and tops are significantly better for climate mitigation than stumps which in turn are significantly better than coal. This conclusion also holds over a 20 year time perspective, but the relative difference between biofuels and coal is smaller. This temporal dependency is confirmed by other scholars. Lindholm et al. (2010) find that using forest residues for energy is very beneficial for climate mitigation over long time scales. In a 20-year time scale however, the climate benefits are less since the residues are not completely decomposed after 20 years. Melin et al. (2010) find that in the long term, burning stumps is a more effective way to reduce emissions than coal. However, in the short term, using coal is slightly better than removing stumps from the forest carbon pool. Sathre and Gustavsson (2011) compare the climate impacts of forest residues and stumps with the climate impacts of using fossil fuels. The temporal dependency of biomass decomposition and atmospheric CO_2 is considered and climate impacts are assessed in terms of accumulated radiative forcing. The authors find that over a 240 year time perspective, forest residues are considerably better than oil, fossil gas and coal. Over a short time perspective, the differences are smaller. Over the first 10 - 25 years, oil and fossil gas have a lower climate impact than forest residues and stumps, but thereafter forest residues and stumps are increasingly superior to fossil alternatives for reducing climate impacts.

The temporal dependency of the climate benefits of bioenergy versus fossil fuels may have implications from a policy point of view. If environmental legislation, for instance the EU renewables directive, requires that climate impacts from biofuels be calculated over 20 years, this would put forest residues and especially stumps at a disadvantage vis-à-vis fossil alternatives. With respect to this, the IEA recommends that incentives should encourage the sustainable use of biomass to substitute fossil fuels instead of decaying unutilized (IEA 2011).

We find that establishing willow may result in a net accumulation of carbon in the soil and a *net uptake* of atmospheric carbon compared to the reference case of crops. This means that from a climate mitigation point of view, willow may have a significant advantage compared to forest residues, provided that new land is available. One could argue that if new land is acquired for willow production, there may be other ways to use this land that potentially could have an even better climate benefit. Paper **I** indicates that establishing spruce on new land may in the long term create larger carbon pools than willow, but produce biofuels much later.

A related issue is the question whether land, from a climate mitigation point of view, should be used for biofuel production or carbon sequestration. Olsson (2010) argues that in a managed[9] forest, trees accumulate carbon in stem wood, branches, stumps and roots. At thinning events and loggings, biomass is extracted from the forest, which reduces the carbon stock (g C/m^2) in living trees considerably. If a new forest is established a new carbon cycle starts. In contrast, in an unmanaged forest the carbon stock increases over time, but after some time at a slower rate, finally reaching a quasi-steady state where growth and decomposition is in balance. In Olsson's example, the unmanaged forest sequesters more carbon per m^2 than the managed forest, over all time scales. However, the managed forest also provides bioenergy which replaces fossil fuels and leads to a net reduction in CO_2 emissions. For each generation of bioenergy more fossil fuels can be replaced. Hereby the total emissions reduction accumulates over time (also illustrated by Eriksson 2006 and Soimakallio et al. 2009). Since sequestration reaches saturation, while bioenergy production is cumulative, bioenergy production is likely to be a better strategy in the long term for climate mitigation. Soimakallio et al. (2009) show that the relative benefits between carbon sequestration and substitution depends on the time-frame, the carbon sequestration rate and which fuel is substituted.

4.2 Climate impacts from peat utilisation in Sweden

Climate impacts from using peat for energy depend not only on combustion related emissions, but also to a large extent on CO_2 uptake and CH_4 emissions before and after peat extraction. The choice of peatland and after-treatment strategies therefore has great implications on the total impacts

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[9] The term 'managed forest' signifies here a forest that is used for the production of forest products such as timber, pulp- and paper and bioenergy. Over a life cycle, there are a number of thinning events and a final logging. The term 'unmanaged forest' signifies a forest which is allowed to grow without thinning events or logging.

from using energy peat. We have estimated the climate impacts from using pristine peatland for energy peat production, assuming different after-treatment scenarios, wetland restoration and afforestation, and different assumptions of wetland methane emissions, carbon uptake in the restored wetland and carbon uptake rates in afforested peatland.

For the pristine peatland–wetland restoration scenario, we find that the estimates of climate impacts, expressed in accumulated radiative forcing over 300 years, range from being lower than the impacts of natural gas to approximately equal to the impacts of coal. Nilsson and Nilsson (2004) estimate climate impacts from this scenario to range from a level equivalent to the impacts of natural gas to a level equivalent of the impacts of coal, while Hagberg and Holmgren (2008) estimate climate impacts from this scenario to be higher than coal. This wide range in results is mainly due to uncertainties in methane emissions and carbon dioxide uptake in restored wetlands (Hagberg and Holmgren, 2008). For the pristine peatland–afforestation scenario, we find that climate impacts, expressed in accumulated radiative forcing over 300 years, range from being lower than the impacts of natural gas to slightly higher than the impacts from natural gas. Nilsson and Nilsson (2004) estimate climate impacts from this scenario to range from being between the level of natural gas and the level of coal to being approximately equivalent to the impacts of coal. The difference in results is mainly due to Paper **II** applying higher values for pristine methane emissions and forest growth than Nilsson and Nilsson (2004).

In summary, our analysis shows that the climate impacts from the use of peat for energy can range from being lower than the impacts of natural gas or being comparable to the impacts coal. Other studies show that an even wider span in climate impacts is possible, ranging from being comparable to the impacts of forest residues to being higher than the impacts of coal. This wide range depends on the characteristics of the chosen peatland (i.e. pristine wetland methane emissions or drained peatland CO_2 emissions) and assumptions regarding after-treatment parameters (i.e. restored wetland methane emissions, CO_2 uptake in restored wetland, or CO_2 uptake in afforested peatland).

In addition to the parameters analysed in Paper **II**, other factors that could be important to consider include:

- A higher assumed extracted peat depth would increase the calculated climate impacts since, for a given area, the combustion related emissions increase while the avoided methane emissions are unchanged,
- As shown by for instance Kirkinen (2008) and Hagberg and Holmgren (2008) the choice of other types of peatland (forestry drained, abandoned or agricultural peatland) will have significant impacts on the results.

In our peat–afforestation scenario the CO_2 uptake in the established forest is credited to the peat. This follows the same convention as for instance Hagberg and Holmgren (2008) and Kirkinen et al. (2007), where the carbon sequestered in the growing forest is allocated to the biofuel, either as a temporally averaged value or a time dependent function, varying from zero just after harvest to a maximum value just before harvest. Most investigations of the climate impacts from peat apply a time scale of 300 years. However, in order to mitigate climate change, it's important to find alternatives to fossil fuels that are beneficial on a shorter time scale than 300 years. The analysis presented here addresses peatlands in the boreal zone, more specifically Sweden. The results are therefore only valid for this zone and not necessarily for other climate zones.

4.3 The effects of allocation rules on firms' abatement incentives

Allocating emission allowances to the participating firms in the EU ETS involves large values and is therefore an inherently contentious and political process. Adjusting allocation in response to changes in firm operations may affect firms' behaviour and reduce the cost-efficiency of the system. We have demonstrated that adjusting (updating) allocation may severely reduce the incentives for firms to become more CO_2 efficient (Paper **IV**). We show that benchmarking rewards operators that have taken early action and that benchmarking is more consistent with the Polluter Pays Principle (Paper **III**). Regarding incentives we find that allocation based on output and prescribed sector caps preserves abatement incentives, but constitutes an output subsidy (Paper **V**).

The negative effects on efficiency from updating allocations are confirmed by other studies. Neuhoff el al. (2006) point out that in contrast to most US allowance programs, where allocation is done only once as a lump sum, the EU ETS adopts a sequential approach. Allocation plans are decided for one commitment period at a time, with repeated negotiations about the allocation for the following period. The authors conclude that if power generators anticipate that their current behaviour will affect future allowance allocation, this can distort today's decisions. In a similar way, Sterner and Muller (2008) show that if allocation is regularly updated based on prior emissions, firms will have a financial incentive to pollute more. Harstad and Eskeland (2010) show that in a dynamic setting, anticipating the regulator's future desire to give more permits to firms that appear to need them, firms purchase permits to signal their need. This raises the price above marginal costs and thus results in an inefficient market outcome. In Paper **IV**, we argue that if the updating uses a sufficiently long time lag (10 years) discounting will reduce firms' incentives to increase current emissions for the purpose of gaining allocation profits. This is confirmed by Paper **V**. However, the analysis in Paper **V** also shows that this effect will be counteracted by an increase of allowance price. If the permit price increases at the same rate as the discount rate, the abatement incentives are reduced considerably.

Several studies have investigated how benchmarking (output based allocation) affects abatement incentives (Fischer 2001, Burtraw et al. 2001, Sterner and Muller 2008, Fischer and Fox 2007). These studies show that updated benchmarking can preserve abatement incentives, but it also serves as a output subsidy, increasing production past the optimum level. The result is a shifting of mitigation towards higher CO_2 efficiency and less output contraction, which leads to higher allowance prices, and lower product prices as compared to the social optimum. Lower product prices erode the efficiency of the system due to changed consumer incentives.

Egenhofer and Georgiev, (2010) report that some actors argue that updated benchmarks, based on the best performing companies in the previous period, will set the example for the other firms to follow, thus introducing a driver for continuous improvement in the sector. However, our analysis shows that updating the benchmark, based on performance in the same sector does not create incentives for continuous improvement of the CO_2 performance in the sector, but rather reduces these incentives.

5. Conclusions and further work

5.1 Conclusions

With respect to objective 1, we conclude that there is a climate impact from using bioenergy that depends on how fast the emission pulse is compensated by uptake of atmospheric carbon (or avoided emissions). Assuming all other factors equal, biofuels with slower uptake rates have a stronger negative climate impact than fuels with a faster uptake rate. The time perspective over which the analysis is done is crucial for the climate impact of biofuels. Over a 100 year perspective branches and tops are significantly better for climate mitigation than stumps which in turn are significantly better than coal. Over a 20 year time perspective this conclusion holds, but the relative difference between the investigated biofuels and coal is smaller. Establishing willow on agricultural land may reduce atmospheric carbon, provided new land is available.

With respect to objective 2, we conclude that climate impacts from using peat for energy can vary considerably depending on the characteristics of the peatland in question, the choice of after-treatment and assumptions regarding after-treatment parameters. Over 300 years, we estimate the climate impacts from peat to range from being lower than the impacts of natural gas to higher than those of coal.

With respect to objective 3, we find that benchmarking (allocation based on output and sector common benchmarks or a prescribed cap) rewards CO_2 efficiency and considers the technical potential to reduce emissions. We show that adjusting allocation may affect firms' behaviour and severely reduce their incentives to become more CO_2 efficient. Updated emission based allocation may significantly reduce abatement incentives. Updated benchmarking preserves incentives to reduce emissions, but involves an output subsidy.

5.2 Recommendations

Regarding bioenergy, results from this thesis can help decision makers to understand the climate impacts from different bioenergy types in order to prioritize between different bioenergy and land-use options. Results can also shed light on the importance of time scale. This may have implications from a policy point of view. If environmental legislation, for instance the EU directive on renewables, requires that climate impacts from solid biofuels are calculated over 20 years, this would put forest residues and stumps at a disadvantage vis-à-vis fossil alternatives.

The establishment of managed forests on fallow or agricultural land will both build up new carbon stocks and provide bioenergy and traditional forest products. Therefore, in the long term, from a climate mitigation point of view, there are strong arguments for establishing new managed forests. However, since bioenergy from newly established forests is not available until after several decades, in order to replace fossil fuels, there is also a need for energy carriers that can be produced earlier. In the short term, this can be achieved by increased use of forest residues, possibly stumps and the establishment of bioenergy crops like willow. An optimal land use strategy should consider both the short term benefits of replacing fossil fuels with energy crops (and forest residues and stumps) and the long term benefits of establishing new managed forests. Results from this study can also help understanding of the climate impacts from carbon neutral emission scenarios on a more general level, beyond bioenergy use. One application could for instance be to understand the climate effects of 'emissions compensation', i.e. when an emission from one activity is compensated by carbon uptake from another activity, for instance forestation.

Regarding peat, results from this and other studies show that the choice of peatland and after-treatment strategies has great importance for the climate impacts of using peat for energy. Therefore, if climate change is an important aspect to consider when planning peat utilization, the characteristics of the specific peat land and after-treatment options should be carefully assessed. Results indicate that the use of peat from cultivated peatland has the lowest climate impact, while using pristine mires for the extraction of peat has generally a high climate impact.

However, future use of agricultural land, forests and peatland is not merely an issue of reducing GHG emissions. These land types provide a wide set of services and functions, including biodiversity, habitats, water supply, food stocks, forest products, energy, recreation and culture. Decisions on future use of these land types need to consider the full set of services provided.

Benchmarking may offer a way to move from grandfathering in phase I and II of the EU ETS toward the long term goal of auctioning. This allocation rule allows for system adjustments such as new entrants, closures or other production changes without reducing firms' incentives for becoming more CO_2 efficient. Benchmarking rewards operators that have taken early action to reduce GHG emissions and is consistent with the Polluter Pays Principle. However, benchmarking involves an output subsidy that introduces inefficiency in the economy.

Climate efficient use of bioenergy and peat should be incentivized and include effects on carbon stocks, while considering other ecosystem services. This could for instance be accomplished by establishing a credit system for land-use related CO_2 reductions, which could be linked to the EU ETS.

5.3 Future research

This thesis has found that forest residues have a lower climate impact than stumps which in turn have a lower climate impact than coal. As discussed in the previous section, our results also indicate that the establishment of energy crops or forests on agricultural or fallow land may, in addition to providing bioenergy, build up new carbon pools. Fast growing energy crops, like willow have the advantage of producing bioenergy after a few years, while forests have the advantage of sequestering more carbon. What might an optimal land-use strategy, which considers both the short term benefits of replacing fossil fuels with energy crops (and forest residues and stumps) and the long term benefits of establishing new managed forests look like?

Another potential research task should address how efficient use of bioenergy and peat in the context of climate impacts can be incentivized, taking into consideration the effects on carbon stocks and land use related GHG fluxes. This could for instance be accomplished by establishing a credit system for land-use which could be linked to the EU ETS. Designing such a system needs to consider, inter alia:

- Metrics. How should climate impacts be calculated?
- Time frame. Such a system needs to establish a time frame for the calculation of credits that is probably longer than 20 years, but shorter than 300 years.
- Linking to other carbon markets. Linking means that credits produced in the land-use credit system can be traded with other markets, for instance the EU ETS.
- When the trees in a managed forest are mature they are felled and used for timber, paper and bioenergy etc. How should this be handled in a credit system?

- Long term responsibility. If carbon sequestration renders credits, who is responsible for safeguarding this stock in the future, for instance against forest fires?

This research could create an interesting linkage between natural science (optimal land-use and climate impacts over different time scales) and environmental economics (how climate policy instruments affect incentives for climate mitigation).

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7. References

Ågren, G., Svensson, M., Olsson, M. 2010. Carbon balances and biofuel production at land use changes, Swedish Energy Agency project 32273-1.

Ågren, G. 2011. Personal communication. SLU.

Åstrand, L., Ericson, S-E., Nyström, K. 1997. *Torvbränsle och växthuseffekten,* Report 1997/8, Vattenfall Support AB, Stockholm.

Berndes, G., Hansson, J. 2007. Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced redundancy on imported fuels. Energy Policy Vol 35, pp 5965-5979.

Berndes, G, Börjesson, P. 2003. Crediting of carbon accumulation arising from the establishment of bioenergy plantations: the case of Salix production in Sweden. In: Gale, J. and Kaya, Y. (Eds.) Greenhouse gas control technologies. Proceedings from the 6th International Conference on Greenhouse Gas Control Technologies (GHGT-6). Kyoto, Japan, 1-4 October 2002. Pergamon/Elsevier.

Burtraw, D., Palmer, K., Bharvirkar, R., Paul, A. 2001. The Effect of allowance allocation on the Cost of carbon Emission Trading. RFF Discussion paper. www.rff.org.

Byrne, K., Chojnicki, B., Christensen, T., Drösler, M, Freibauer, A., Friborg, T., Frolking, S., Lindroth, A., Mailhammer, J., Malmer, N., Seli, P., Turunen, J., Valentini, R, Zetterberg, L. 2004. EU Peatlands: Current Carbon Stocks and Trace Gas Fluxes. A contribution to the Concerted Action CarboEurope-GHG. Download available at www.bgc-jena.mpg.de/bgp/uploads/Teaching/Peatreport_final.pdf

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, A., Lucht, W., Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T., Pingoud., K. 2011: Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T. Eickemeier, P. Hansen, G., Schlömer, S., von Stechow, C. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Egenhofer, C., Georgiev, A., (rapporteurs). 2010. Benchmarking in the EU – Lessons from the EU Emissions Trading System for the Global Climate Change Agenda. Centre for European Policy Studies, Place du Congrès 1, B-1000 Brussels, Belgium. ISBN-978-92-9079-959-7.

Ellerman, D., Buchner, B.,K., Carraro, C. 2007. Allocation in the European Emissions Trading Scheme – Rights, Rents and Fairness, Cambridge University Press, ISBN 978-0-521-87568-4.

Eriksson, E. 2006. The potential for forestry to reduce Net CO_2 emissions. Doctoral thesis No. 2006:103. Swedish University of Agricultural Sciences, Faculty of Natural Resources and Agricultural Sciences, Department of bioenergy.

Eriksson, H. and Hallsby, G. 1992. Biomass fuels – effects on the carbon dioxide budget. NUTEK, R 1992:10. Stockholm.

European Commission. 2003. Directive 2003/87/EC of the European Union and of the Council of 13 October 2009 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.

———. 2008a. 20 20 by 2020 Europe's climate change opportunity. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. 23.1.2008 COM(2008) 30 Final.

———. 2008b. MEMO/08/35, Brussels, 23 January 2008. Questions and Answers on the Commission's proposal to revise the EU Emissions Trading System.

———. 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

———. 2009b. Directive 2009/29/EC of the European Union and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the community.

———. 2011. Fact sheet Climate Change. March 2011.

Fischer, C., 2001. Rebating Environmental Policy Revenues: Output based Allocations and Tradable Performance Standards. RFF Discussion paper. www.rff.org

Fischer, C., and Fox, A.K. 2007. Output based Allocation of Emissions Permits for Mitigation tax and Trade interactions. Land economics Vol 83, pp 575-599.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland. 2007. Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on ClimateChange [Solomon, S., D.

Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hagberg, L. and Holmgren, K. 2008. The climate Impact of future energy peat production. IVL report B1796. IVL Swedish Environmental Research institute Ltd.

Hansson, J., Berndes, G., Börjesson, P. 2006. The prospects of large-scale import of biomass and biofuels into Sweden – a review of critical issues. Energy for sustainable Development, 2006, Vol X(I), pp 82-94. Special issues in International bioenergy trade and development

Harrison, D., Klevnas, P., Radov, D., Foss, A. 2007. Complexities of allocation Choices in a Greenhouse Gas Emissions Trading Program. NERA Economic Consulting, 35th floor, 200 Clarendon St, Boston Massachusetts 02116, USA.

Harstad, B., Eskeland, G. 2010. Trading for the Future: Signalling in permit markets, J. of Public Economics Vol 94, pp 749-760.

Holmgren, K., Kirkinen, J., Savolainen, I. 2006**.** The climate impact of energy peat utilisation - comparison and sensitivity analysis of Finnish and Swedish results, IVL report B1681. IVL Swedish Environmental Research institute Ltd.

Holmgren, K., Eriksson, E., Olsson, O., Olsson, M., Hillring, B., Parikka, M. 2007. Biofuels and Climate Neutrality – System Analysis of Production and Utilisation. Elforsk report 07:35. www.elforsk.se

IEA, Bioenergy, Land Use Change and Climate Mitigation. 2010. IEA Bioenergy:ExCo:2010:03.

IPCC, 1990. Climate Change 1990: The Intergovernmental Panel on Climate Change Scientific Assessment [Houghton, J.T., Callander, B.A., and Varney, S.K. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC 2007a. Summary for Policy makers. In: Climate Change 2007: The Physical Science Base. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Climate Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007b. Climate Change 2007: Synthesis Report. Contribution of Working groups I, II and III to the Forth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri, R.K., Reisinger, A. (eds.). IPCC Geneva.

Kirkinen, J., Minkkinen, K., Penttilä, T., Kojola, S., Sievänen, R., Alm, J., Saarnio, S., Silvan, N., Laine, J., Savolainen, I. 2007. Greenhuse impact due to different peat fuel utilization chaines in Finland – a life-cycle approach.Boreal Environmental Research Vol 12, pp. 211-223.

Kirkinen J., Palosuo, T., Holmgren, K., Savolainen, I. 2008. Greenhouse Impact Due to the Use of Combustible Fuels: Life Cycle Viewpoint and Relative Radiative Forcing Commitment. Environmental Management Vol 42, pp 458-469

Kirkinen, J., 2010. Greenhouse impact assessment of some combustible fuels with a dynamic life cycle approach. PhD thesis. VTT Publications 733, VTT technical Research center of Finland, Vuorimiehentie 5, P.O. Box 1000, FI-02044 VTT, Finland.

Kujanpää, M., Eggers, J., Verkerk H., Helin, T., Lindmer M & H., W. 2010. Carbon balance of forest residue collection and combustion in Southern Finland. In Proceedings of the 18th European Biomass Conference, Lyon, France. 3-7.5.2010.

Lindborg, R., Stenseke, M., Cousins, S.A.O., Bengtsson, J., Berg, Å., Gustafsson, T., Sjödin, E., Eriksson, O. 2009. Investigating biodiversity trajectories using scenarios – Lesson from two contrasting agricultural landscapes. J. Environmental Management Vol 91, pp 499-508.

Lindholm, E.-L., Berg, S., Hansson, P.-A. 2010. Skörd av skogsbränslen i ett livscykelperspektiv. SLU report 023. ISSN 1654-9406. Swedish University of Agricultural Sciences

McKinsey & Company. 2009. Pathways to a Low-Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve. Available on solutions.mckinsey.com/ClimateDesk/default.aspx (2011-09-13)

Melin, Y., Petersson, H., Egnell, G. 2010. Assessing carbon balance trade-offs between bioenergy and carbon sequestration of stumps at varying time scales and harvest intensities. Forest Ecology and Management Vol 260, pp 536-542.

Montgomery, D.W. 1972. Markets in Licenses and Efficient Pollution Control Programs. J. of Economic Theory Vol 5, pp 395-.

Neuhoff, K., Martinez, K., K., Sato. M. 2006. Allocation, incentives and distortions: the impact of EU ETS emission allowance allocations to the electricity sector. Climate Policy Vol 6, pp 73-91.

Nilsson, K. and Nilsson, M. 2004. The Climate Impact of Energy Peat Utilisation in Sweden – the Effect of former Land-Use and After-treatment. IVL-report B1606. IVL Swedish Environmental Research institute Ltd.

Olsson, M., 2010. Kolets kretslopp och dess koppling till skog, skogsbruk samt samhällets användning av trä och fossila bränslen. In Skogsbrukets bidrag till ett bättre klimat, Kungl. Skogs- och Lantbruksakademins tidskrift nr 4. In Swedish.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G.Y., Solomon, S. 2001. Chaper 6 Radiative Forcing of Climate. 2001. In Climate Change 2001: The Scientific basis. Contribution of Working group I to the Assessment Report of The Intergovernmental Panel on Climate Change [Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Repo, A., Tuomi, M., Liski, J. 2010. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy, doi 10.1111/j.1757-1707.2010.01065.x

Rodhe, H. and Svensson, B. 1995. Impact on the Greenhouse Effect of Peat Mining and Combustion. Ambio Vol 24(4), pp 221-225.

Sathre, R., Gustavsson, L. 2011. Time-dependent climate benefits of using forest residues to substitute fossil fuels. Biomass and Bioenergy Vol 35, pp 2506-2516.

Savolainen, I., Hillebrand, K., Nousiainen, I., Sinisalo, J. 1994: Greenhouse impacts of the use of peat and wood for energy. Espoo, Finland. VTT Research Notes 1559. 65p.+app.

Schlamadinger, B., Spitzer, J., Kohlmaier, G.H., Ludeke, M. 1995. Carbon balance of bioenergy from logging residues. Biomass and Bioenergy Vol 8(4), pp 221-234.

Schlamadinger, B., Apps, M., Bohlin, F., Gustavsson, L., Jungmeier, G., Marland, G., Pingoud, K., Savolainen, I. 1997. Towards a Methodology for Greenhouse Gas Balances of bioenergy Systems in Comparison with Fossil Energy systems. Biomass and Bioenergy Vol 13 (6), pp 359-375.

Soimakallio, S., Savolainen, I., Pingoud, K., Sokka, L., Tsupari, E., Ekholm, T., Lindroos., T. J., Koponen, K. Climate Impacts relate to biomass utilization. 2009. Paper at symposium Life Cycle Assessment of Products and Technologies. VTT, Espoo, Finland. 6 October 2009.

SOU 2002:100. Uthållig användning av torv. Betänkande av Torvutredningen. Statens Offentliga utredningar. ISBN 91-38-21783-X. In Swedish.

SOU 2003:60. Handla för bättre klimat. Delbetänkande från FlexMex2-utredningen. Maj 2003. Statens offentliga utredningar.

Sterner, T., Muller, A. 2008, Output and Abatement Effects of Allocation Readjustment in Permit Trade, Climatic Change Vol 86(1), pp 33-49.

Swedish Energy Agency. 2006. Energiläget 2006. Report ET 2006:45. Download available at www.energimyndigheten.se. In Swedish.

Swedish Energy Agency. 2010. Energiläget 2010. Report ET 2010:45. Download available at www.energimyndigheten.se. In Swedish.

Swedish Environmental Protection Agency. 2011a. Emission factors for calculation of carbon dioxide emissions from fuel combustion, used for the Swedish reporting to the UNFCCC. www.naturvardsverket.se/sv/Start/Klimat/Utslappsminskning/Berakna-utslapp/Emissionsfaktorer-koldioxid/

Swedish Environmental Protection Agency. 2011b. Emissions of Greenhouse Gases in Sweden 2009. naturvardsverket.se/sv/Start/Statistik/Vaxthusgaser/Aktuell-utslappsstatistik/Utslapp-av-vaxthusgaser-i-Sverige/

Swedish Forest Agency 2008. Skogliga konsekvensanalyser 2008 – SKA-VB 08. Skogsstyrelsen rapport 25-2008. Skogsstyrelsen, Jönköping. Tables 3.22, 3.23, 3.24, 3.25. In Swedish.

Swedish Peat Producers Association. 2010. Torvåret 2009. Statistik över Sveriges torvproduktion. Torsgatan 12, 111 23 Stockholm. Download available at svensktorv.se. In Swedish.

Walmsley, J.D. and Godbold, D.L. 2010. Stump harvesting for Bioenergy – A review of the Environmental impacts. Forestry, Vol 83 (1). Doi 10.1093/forestry/cpp028.

Wihersaari, M. 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bionergy Vol 28(5), pp 435-443.

Wråke, M., Burtraw, D, Löfgren, Å., Zetterberg, L. 2012. What have we learnt from the European Union's Emissions Trading System? Accepted for publication in Ambio Special issue February 2012.

Zetterberg, L. and Hansén, O. 1998. Nettoemissioner av koldioxid till atmosfären vid användning av hyggesrester för el- och värmeproduktion, IVL report B 1298. In Swedish. IVL Swedish Environmental Research institute Ltd.

Zetterberg, L., Wråke, M., Sterner, T, Fischer, C., Burtraw, D. 2012. Short run allocation of emission allowances and long term Goals for climate policy. Accepted for publication in Ambio Special issue, February 2012.

Papers I-V