Climate change and agriculture:
theory and application of mitigation policies

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Tiivistelmä — Referat — Abstract
Agriculture's contribution to climate change is controversial as it is a significant source of greenhouse gases but also a sink of carbon. Hence its economic and technological potential to mitigate climate change have been argued to be noteworthy. However, social profitability of emission mitigation is a result from factors among emission reductions such as surface water quality impact or profit from production. Consequently, to value comprehensive results of agricultural climate emission mitigation practices, these co-effects to environment and economics should be taken into account.

The objective of this thesis was to develop an integrated economic and ecological model to analyse the social welfare of crop cultivation in Finland on distinctive cultivation technologies, conventional tillage and conservation tillage (no-till). Further, we ask whether it would be privately or socially profitable to allocate some of barley cultivation for alternative land use, such as green set-aside or afforestation, when production costs, GHG's and water quality impacts are taken into account.

In the theoretical framework we depict the optimal input use and land allocation choices in terms of environmental impacts and profit from production and derive the optimal tax and payment policies for climate and water quality friendly land allocation. The empirical application of the model uses Finnish data about production cost and profit structure and environmental impacts.

According to our results, given emission mitigation practices are not self-evidently beneficial for farmers or society. On the contrary, in some cases alternative land allocation could even reduce social welfare, profiting conventional crop cultivation. This is the case regarding mineral soils such as clay and silt soils. On organic agricultural soils, climate mitigation practices, in this case afforestation and green fallow give more promising results, decreasing climate emissions and nutrient runoff to water systems. No-till technology does not seem to profit climate mitigation although it does decrease other environmental impacts.

Nevertheless, the data behind climate emission mitigation practices impact to production and climate is limited and partly contradictory. More specific experiment studies on interaction of emission mitigation practices and environment would be needed. Further study would be important. Particularly area specific production and environmental factors and also food security and safety and socio-economic impacts should be taken into account.

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Tiivistelmä — Referat — Abstract

Maatalous vaikuttaa ilmastonmuutokseen eri tavoin. Kotieläin- ja kasvintuotannosta syntyy merkittäviä määriä kasvihuonekaasupäästöjä, mutta toisaalta maaperä ja kasvillisuus pystyvät sitomaan hiiltä ja vähentämään ilmakehän hiilidioksidipitoisuutta. Maataloudella on siten nähty olevan mahdollisuus osallistua ilmastonmuutoksen hillitsemiseen, joko lisäämällä hiilen sitoutumista tai vähentämällä tuotannosta syntyviä päästöjä. Ilmastopäästöjen vähentämisen yhteiskunnalliseen kannattavuuteen vaikuttavat kuitenkin päästövähennysten lisäksi myös muut tekijät, kuten päästöjä vähentävän teknologian vaikutus talouteen ja ympäristöön. Siten yhteiskuntataloudellisessa analyysissä maatalouden kasvihuonekaasupäästöjen lisäksi muut päästövähennystoimenpiteiden vaikutukset tulisi ottaa huomioon.

Tutkielman tavoite on tarkastella peltoviljelyn yhteiskunnallista ja yksityistä kannattavuutta teoreettisen yhteiskuntataloudellisen mallin avulla, joka ottaa huomioon viljelyn tuoton ja ympäristövaikutukset. Peltoviljelyn kannattavuutta arvioidaan kahdella erilaisella viljelyteknologialla (suorakylvö ja perinteinen) ja verrataan vaihtoehtoisiin maankäyttömuotoihin, viherkesannointiin ja pellon metsitykseen. Arvioimme olisiko osa viljelymaasta kannattavaa allokoida vaihtoehtoiselle viljelyteknologialle tai maankäyttömuodolle, jos maankäytön ilmasto- ja vesistöpäästöt sekä tuotto otetaan huomioon. Lopuksi tarkastelemme optimaalista ympäristöpolitiikkaa ja kannustinjärjestelmää.

Teoreettiseen viitekehykseen tukeutuva empiirinen analyysi hyödyntää suomalaista tutkimusaineistoa maatalouden ja pellonmetsityksen ympäristövaikutuksista sekä tuotanto- ja kustannusrakenteesta. Maatalouden heterogeenisyys huomioidaan analysoimalla maankäyttövaihtoehdot kolmella erilaisella maalaadulla. Analyysin tulosten perusteella mitigaatioteknologioiden vaikutus ilmastopäästöihin ja yhteiskunnan hyvinvointiin ei ole aivan yksiselitteinen. Savimailla mekaaniseen muokkaukseen perustuva muokkausteknologia tuottaisi yhteiskunnalle suuremman hyvinvoinnin kuin vaihtoehtoiset maankäyttömuodot. Toisaalta orgaanisilla mailla, jotka kattavat Suomen viljelypinta-alasta merkittävän osan, pellon metsitys tai viherkesannointi tuottaisi yhteiskunnallisesti arvioiden suurimman hyvinvoinnin. Suorakylvön edullisuus perustuu tulostemme perusteella pitkälle ravinnehuuhtouman vähentymiseen ja viljelykustannusten laskuun kuin ilmastohyötyihin.

Tutkimuksessa hyödynnetty tieto maankäytön vaikutuksista ilmastopäästöihin ja tuotantoon on osittain myös puutteellista, mikä saattaa vaikuttaa tuloksiin ja niiden soveltamiseen Suomen maatalouteen. Maatalouden tuotantorakenne ja maaperän ilmastopäästöt voivat vaihdella alueittain merkittävästi etenkin Suomessa, jossa tuotanto on jakautunut olosuhteiden osalta hyvin erilaisille alueille. Jatkotutkimustarve liittyykin maankäytön ilmastopäästöihin erilaisissa olosuhteissa ja päästöjen vähentämistoimenpiteiden sosio-ekonomisiin vaikutuksiin ja maataloustuotannon tulevaisuuteen.

Avainsanat — Nyckelord — Keywords

Maatalous, kasvihuonekaasupäästöt, ilmastonmuutos, peltoviljely

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List of Abbreviations and Units

CO_2-eq.	Carbon dioxide equivalent. Describes the amount of different greenhouse gases taking into account their global warming potential (GWP)
DRP	Dissolved reactive phosphorus.
GHG	Greenhouse gas. Gases that absorb heat in atmosphere and cause the greenhouse effect.
GWP	Global warming potential. Measure of how much a unit of one greenhouse gas has potential to contribute to global warming in comparison to carbon dioxide.
LFA	Less-favoured area. Term used in European Union for areas with natural weaknesses from water, climate, short crop season or for mountainous or hilly areas.
NEE	Net ecosystem CO_2 exchange. NEE defines the loss and gain of carbon dioxide between ecosystem and atmosphere.
NEP	Net ecosystem production, synonym to NEE.
NPP	Net primary production. NPP defines plant growth and biomass increment or in other words, the carbon uptake of ecosystem, and losses due to plant respiration (autotrophic respiration).
OM	Organic matter/material, see SOM.
PP	Particulate phosphorus.
R_h	Soil heterotrophic respiration indicates the decomposition of soil organic matter.
SOM	Organic matter in soil accumulated from plants and animals.
Mg	Megagram 10^6
Gg	Gigagram 10^9
Tg	Teragram 10^{12}

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1 Introduction

Agriculture's impact on the environment is not only limited to food production but it has also strong interaction with rural landscape and vitality, food security and safety and environmental problems such as nutrient runoff and erosion. A rather recently noted aspect in agriculture is its impact on climate change. Agriculture is a source of greenhouse gases (GHG's), such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Emissions are produced by farm animal and manure management, energy use, deforestation, fertilization and cultivated soils. Agricultural soils are one of the largest emission sources. Intensive agricultural land management and fertilization affect the carbon and nitrogen cycle and have increased the release of these gases to the atmosphere. (Paustian, Antle, Sheehan & Paul 2006.) Decrease of soil organic carbon begins when soil is taken under cultivation and continues as long as the soil is under intensive soil management practices. Nevertheless, agricultural soils still hold large amounts of carbon, which offsets the net emissions, making agriculture's role in climate change complex. (IPCC 2007b, 514.)

It is suggested that agriculture may have considerable potential to mitigate climate emissions. Thus it should be included in the emission mitigation policies along with other industries (Smith et al. 2007; Cannell 2003; Lal 2004). Agriculture's emission mitigation options can be divided into three categories based on the mechanism behind them; emission reductions in agricultural practices, emission avoidance or displacement with for example biofuel production, and uptake and storage of carbon dioxide by carbon sequestration. The first one is very self-explanatory and about reducing emission sources or causes by for example improving plant nitrogen uptake or increasing energy-efficiency. Avoiding or displacing emissions can be done by using agricultural products as a source of bioenergy to replace fossil fuel use or reducing uptake of new areas for agricultural use. Carbon sequestration has become one of the hottest options within climate change mitigation in agricultural sector. Although agricultural practices have reduced the carbon content of soils throughout centuries, the progress can be reversed (Watson, Noble, Bolin, Ravindranath, Verardo & Dokken 2000.) Carbon is accumulating to vegetation residues and other organic

material and thus the carbon content of soil can be increased by applying management practices that increase the plant residues and decrease the decay rate (Paustian et al. 2006, 7; Smith et al. 2007, 790).

Estimates on global agricultural emission mitigation potential range from minimal to highly optimistic values. The optimistic arguments suggest that the global potential of reductions is about 5500-6000 Tg CO_2-eq. per year by 2030 (Smith et al. 2007). Technical potential is however considerably higher than economic potential, which is why the GHG mitigation estimates have been under criticism. The economic potential is strongly related to the pricing of emission reductions (Smith et al. 2007; McCarl & Schneider 2000) but also to several socio-economic and environmental issues (Paustian et al. 2006, 34-39).

One reason that makes estimates about GHG mitigation potential so mixed is agriculture's heterogeneity regarding climate conditions, soil characteristics and agricultural history. They also create variability to social welfare from GHG mitigation practices. Environmental conditions and management decisions can create additional benefits or trade-offs which might affect the absolute emission mitigation and overall results of the policy. Generally these additional impacts are considered to be profitable for GHG mitigation practices and could even create a win-win situation (Lal & Bruce 1999). Antle, Capalbo, Mooney, Elliott and Paustian (2001) argue that if additional environmental and social impacts are also taken into account, it could increase the attractiveness of, for example, taking croplands under GHG mitigation practices. For example "economic efficiency of soil carbon sequestration depends on site-specific opportunity costs of changing production practices and rates of soil carbon sequestration and the policy design" (Antle et al. 2001). However, Zhao, Kling and Kurkalova (2003) point out that attractiveness of emission mitigation practice, such as conservation tillage, depends on how society values different additional environmental benefits.

The objective of this study is to focus on agriculture's potential to participate to climate change mitigation by examining the life cycle impacts of agricultural practices in different scenarios for crop cultivation. We develop an integrated ecological and economic model to

analyse the social welfare of crop cultivation taking into account different soil types common in Finland (clay, silt and organic soils) and tillage systems (mouldboard ploughing and no-till). Crop cultivation by given cultivation technologies are compared with alternative land allocation options, green fallow and afforestation in terms of social returns and private profits. We include in the analysis the environmental impacts confined to greenhouse gases from production life cycle including soil autonomous emissions and water system eutrophication increased by nutrient runoff. Also potential co-benefits are considered, such as carbon sequestration.

In the theoretical model we depict socially and privately optimal input use and land allocation choices which allow us to derive optimal tax and payments for climate and water quality friendly tillage practices and land allocation. The question introduced is, whether it would be privately or socially optimal to permanently allocate some of the barley fields to alternative land use, such as green set-aside or afforestation, when production costs, GHG emissions and water quality impacts are taken into account.

The empirical model uses Finnish agricultural and forestry data for environmental and economic factors to assess the impacts on production and environment. The crop species chosen is barley and the production is expected to focus on South of Finland. We use monetary values to estimate the damage or benefit of greenhouse gas emissions and nutrient runoff to society. Finally, the optimal level of environmental policy instrument for agriculture is defined. The economic basic default is that farmers are already applying the most profitable farmland allocation to maximise their profit. Incentives are needed to direct farmers to socially more profitable land use decisions. We suggest that the incentive is two phased, introducing first input tax for fertilizer and if necessary, a technology subsidy to establish a socially optimal solution.

To orientate to the characters of agriculture in terms of climate change, the first section of the thesis, chapter 2, reviews Finnish agricultural greenhouse gas sources and trends. Also emission mitigation is introduced in outline, including recent studies on potential and restrictions of the subject. The second section, chapters 3 and 4, introduce the theoretical

and empirical analysis. Theoretical framework depicts the production details of barley cultivation regarding optimal input use and environmental impacts (GHG's and surface water quality impact) under the two cultivation technologies and outlines the production characters related to green fallow and afforestation. In addition, we define the optimal policy instruments. In chapter 4 we introduce the data used for parametric model. Chapter 5 provides the results regarding optimal land use and chapter 6 concludes the thesis.

2 Agricultural greenhouse gas emissions and mitigation

In this chapter we view agriculture's impact on climate change in general and Finland's agricultural greenhouse gas emission rates and sources by introducing each important greenhouse gas separately (carbon dioxide, nitrous oxide and methane). The main focus is on cultivated agricultural soils, as they will be the object of the thesis in general. Thus for example emissions related to animal production are not discussed. Special attention is paid on organic soils as they are the largest singular GHG emission source within agriculture, but are also important emission source in their initial state as peatlands. Later agriculture's emission mitigation potential and emission mitigation characteristics are viewed focusing on earlier literature.

Agriculture's greenhouse gas emissions and participation in climate change mitigation

Although industrialisation is blamed to be the greatest source of greenhouse gases, Ruddiman (2003) claims, that human has contributed to climate change already much earlier. Atmospheric carbon dioxide concentration started to increase at the same time period when systematic crop cultivation started about 8 000 years ago. Later, about 5 000 years ago, when domestic animal production began, also methane emissions started to increase. (Ruddiman 2003.)

Parties who have ratified Kyoto Protocol, have agreed to reduce national GHG emissions, increase renewable share of final energy consumption and increase biofuel use in transportation (United Nations 1998). Agriculture is not yet bound to these targets in Europe, but in principle it could already be part of climate emission mitigation policies. According to Kyoto Protocol (Article 3.4), countries are allowed to account emission reductions done through different land use practices that reduce emissions from agricultural soils and forests (United Nations 1998).

Agriculture's possible role in GHG emission mitigation policies still contains several uncertainties, most of them relating to variation within agroecosystems and farming systems, which create challenges for policy designing, such as emission auditing.

Mixed results on agricultural emission fluxes are one of the most challenging issues. Agricultural, especially agricultural soil greenhouse gas emissions are in constant and strong interaction with environmental condition and agricultural practises. In other words, emission fluxes are sensitive to changes in biosphere or in agricultural management and makes emission flux rates difficult to predict or to measure. Temperature, water table level and precipitation, soil type and quality, may affect annual or even daily emission fluxes.

2.1 Agricultural emissions in Finland

By the Kyoto Protocol, Finland is committed to provide annual inventory on national anthropogenic GHG emissions by sources and removals by sinks. National Inventory Report (NIR) is compiled according to the reporting guidelines set by UNFCCC and Kyoto Protocol. Statistics Finland bears the overall responsibility to provide the information, but several expert organisations are participating in the reporting process. Inventory is divided to seven emission source categories; energy, industrial processes, solvent and other product use, agriculture, LULUCF (land use, land use change and forestry), waste and other. Annual inventory serve as a base for climate change policies and international comparison of greenhouse gas fluxes. (Statistics Finland 2009 2, 8, 194.) It should be noted that Finnish agricultural emission inventory is derived by using certain emission factors and is not depicting the emission fluxes affected by regional or site specific differences. Thus estimated national GHG emissions fluxes present more the approximation than accurate emission rate.

It is also characteristic for the inventory that a part of the emissions is reported in other sectors than they would appear to be caused by. CO_2 emissions from cultivated soils and

emissions from lime application are reported in LULUCF (land use, land use change and forestry) sector, although N_2O emissions from corresponding agricultural soils are included into agricultural sector. Also agriculture's emissions from energy consumption are accounted into energy sector instead of agricultural sector.

Accounting all the emission sources and sinks, Finland's net agricultural GHG emissions were in 2007 about 14,2 Tg CO_2-eq., which is about 18 % from the total emissions from Finland (Statistics Finland 2009, 195). We have compiled agricultural emissions sources by sectors in Table 1.

Table 1. Agricultural greenhouse gas emissions in Finland, year 2007. (Statistics Finland 2009) Nitrous oxide 310 GWP and methane 21 GWP.

	CO2 (Gg)	**N2O (Gg)**	**CH4 (Gg)**	**Total CO2-eq. (Gg)**
Enteric fermentation			74,30	1560,30
Manure Management		1,58	13,51	773,51
Energy use	1300,00			1300,00
Agricultural soils*	3083,40	10,30		6276,40
Liming/lime production	249,00			249,00
Grasslands	4057,13			4057,13
Total	**8689,53**	**11,88**	**87,81**	14216,34

* Organic croplands emit 4,6 Tg CO_2/year but mineral soils accumulate (carbon sequestration) -1,53 Tg CO_2

Finland's agricultural GHG emissions have decreased about 22 % from the level of 1990 to 2007 (Statistics Finland 2009, figure 6.1_2). This is primarily related to structural changes in agriculture. Milk and cattle production decreased during 90's because the efficiency of the production increased. Farm size has grown, but number of farms has decreased. (Pipatti, Tuhkanen, Mälkiä & Pietilä 2000, 59; Pipatti 2001, 41.) Also reduction in use of nitrogen fertilizers and measures taken to improve manure management to decrease the nutrient leaching to watercourses has declined agricultural greenhouse emissions (Statistics Finland 2009, 194). Globally agricultural CH_4 and N_2O emissions have increased from 1990 to 2005 and the trend is predicted to continue. Western Europe is the only region where agricultural emissions are proposed to continue to decrease. (US-EPA 2006, 66-76.)

Carbon dioxide

Most of the agricultural carbon dioxide emissions come from cultivated organic soils. CO_2 is also emitted directly and indirectly through different burning processes, like energy production (energy use for heating up buildings and fuel combustion) or straw burning on the fields. According to the emissions inventory, CO_2 net emissions in 2007 were about 8.7 Tg CO_2 (Statistics Finland 2009, 195, 261, Annex 1).

Characteristic for agricultural soils is that although they are a source of carbon dioxide, they work also as storage for carbon, which is accumulated to soil via photosynthesis. In general soils contain about three times more carbon than vegetation and twice as much as atmosphere. Soil organic carbon (SOC) is not nevertheless distributed equally throughout the soil, but the content varies between soil types and depth (Singh & Lal 2005, 161-162.) It is also characteristic that there is a constant influence of climatic conditions and land use systems to SOC, which can independently or combined affect the carbon accumulation and release (Singh, 2008). Carbon fluxes between soil and atmosphere continuously, but considering climate change, important is how much CO_2 is accumulated in soil due to photosynthesis and how much is released back to atmosphere due to decomposition or other burning process. This defines if soil is a net storage or source of carbon. (Paustian, Six, Elliott and Hunt 2000, 148.).

In 2007 cultivation of organic soils emitted 4.6Tg CO_2 in Finland but cultivated mineral soils offset the emission by 1.53 Tg CO_2 in the same year (Statistics Finland 2009, Annex 1). Soils can hold large quantities of carbon but agricultural practices can either increase the stock or decrease it. Carbon accumulation, also referred as carbon sequestration, can be enhanced by increasing residue inputs and reducing decomposition rates (Paustian et al. 2000, 148).

Carbon sequestration is probably the emission mitigation option that has raised most attention. Suggested management practices for carbon sequestration base in general on reduction of soil disturbance. Practices as decreasing soil ploughing or increasing cover

crops or crop rotation are noted to improve soil organic carbon content (SOC). (Singh & Lal 2005). Afforestation and permanent green fallow are efficient tools in increasing carbon sequestration but they are also more drastic actions than for example crop rotation, as agricultural land is withdrawn from cultivation. Other emission mitigation practices are generally related to energy consumption referring to energy efficiency, biofuels and the use of lime and fertilizers, the production and application of which are highly energy consuming.

Measuring carbon dioxide emission fluxes from agriculture often confronts several difficulties and uncertainties. For instance measured CO_2 emission rates from soils are typically more informative than exact values (Martikainen et al. 2002). Cultivation history and environmental conditions are only few of the reasons that affect the carbon dioxide emission fluxes and annual and seasonal changes in CO_2 emissions are very common. Although carbon sequestration is thought to be the most potential emission mitigation tool, it also seems to be the most uncertain. We discuss about emission mitigation utilizing agricultural soils further in chapter 2.3.

Nitrous oxide

Nitrous oxide is naturally produced in soils through microbial process of denitrification in anaerobic conditions and nitrification in aerobic conditions. Both processes are related to mineralisation of soil nitrogen. Nitrogen accumulates in soil through fertilization and plant and animal residues and is possible converted to ammonium (NH_4^+) in process of decay by decomposers such as bacteria and fungi. In nitrification ammonium is converted to nitrate (NO_3^-) by bacteria which is dependent on oxygen. Further, if the nitrate is on anaerobic conditions, it might be converted to NO_2^- and further to dinitrogen gas (N_2) and nitrous oxide (N_2O).

Processes of nitrification and denitrification are complex and strongly influenced by changes in environmental conditions and agricultural management practices (Pihlatie, Syväsalo, Simojoki, Esala & Regina 2004; Maljanen, Liikanen, Silvola & Martikainen

2003a) and soil chemical and physical properties. Anthropogenic nitrous oxide emissions are affected especially by nitrogen application. Emission rate depends on fertilization intensity and type, application method and timing (Perälä, Kapuinen, Esala, Tyynelä & Regina 2006).

Nitrous oxide emission fluxes during cultivation period are especially high just after fertilizer application (Maljanen et al. 2003a; Smith, McTaggert, Dobbie & Conen 1998) but considering annual emission fluxes, highest emissions from cultivated soils have been measured during spring time thawing, which can cover large part of the year's total emissions (Syväsalo, Regina, Pihlatie & Esala 2004). In general, nitrous oxide emissions rise in moisture conditions (Simojoki & Jaakkola 2000; Pihlatie et al. 2004) and in addition to moisture conditions due to precipitation and thawing, also irrigation might increase the emission rate (Simojoki & Jaakkola 2000).

Kaiser, Kohrs, Kücke, Schnug, Heinemeyer and Munch (1998) have estimated that solely nitrogen fertilizer application contribute approximately 0.7-4.1% of the annual N_2O emissions but the emission rate depends on different circumstances. Scottish in situ studies show that N_2O emission from the applied nitrogen fertilizer are on average 0.67 %, 0.63 % and 0.17% on spring barley, grass and winter wheat fields, respectively (Smith et al. 1998) but in general emission flux from nitrogen application is maybe somewhat higher (IPCC 1996).

It is characteristic for nitrogen application and N_2O emissions that although nitrogen fertilization is ended or decreased significantly, it does not reduce N_2O emissions in same proportion. Kaiser et al. (1998) discovered in their field experiments that if fertilization is stopped, N_2O emissions reduce to by half. They explain this by mineralisation of soil organic nitrogen. In general nitrous oxide emissions are very difficult to predict, although some generalisations in terms of climate, soil type and fertilisation rate has been done. It has been suggested that although for example decreasing soil disturbance would reduce nitrous oxide emissions, the amounts are hard to depict as the emission fluxes are dependent on various other factors.

Methane

Domestic animals are the largest source of agricultural methane emissions. Enteric fermentation, a process related to animal's digestion, emits methane as a by product. Smaller emission source is for example manure's anaerobic decomposition. (Statistics Finland 2009, Annex 1.)

This study focuses on agricultural soil emissions and does not review animal husbandry in any detail. Agricultural soil methane emissions are insignificant compared with N_2O or CO_2 emissions and are not even included in agricultural soil emissions in NIR. Generally arable soils in Finland work as a small sink of methane (Regina, Pihlatie, Esala & Alakukku 2007a).

What is interesting, and concerns agricultural soil management decisions, is that organic soils in their normal state are important sources of methane, but drainage of the soil reduces the emissions. Trade-off is that drainage of these soils increases carbon dioxide and nitrous oxide emissions. (Maljanen et al. 2007, 139.) This is discussed more in following chapter, 2.3.

2.2 Organic agricultural soils

Organic soils with high organic carbon content are a very typical feature of the Finnish agriculture. Finland has about 300 000 ha organic soils in cultivation (Myllys & Sinkkonen 2004, 56), of which 60 000 ha have been estimated to be peatlands (MMM 2001, 9). A large part of cultivated peatsoils is located to Northern Finland where in some municipalities the coverage of peatsoils of cultivated land can be up to half (Myllys & Sinkkonen 2004). Most of the cultivated peatsoils are under grass production (MMM 2001, 11).

Organic lands have an important and controversial role in the Finnish greenhouse gas emissions. Plants and animal residues have accumulated to organic soils during hundreds of years. The organic material does not decompose in anaerobic and moist conditions. Peat eventually forms when the decay rate is lower than biomass accumulation. Soil is classified to an organic soil or mull soil if the organic matter content (OM) is more than 20% in depth of more than 15,75 cm. Soils with higher OM content than 40 % are also classified as peatsoils. Soil organic material (SOM) can be either very well preserved plant and animal residues, or further degraded organic amorphous humus (Kasimir-Klemedtsson, Klemedtsson, Berglund, Martikainen, Silvola & Oenema 1997). As long as organic matter is not decomposing, the soil works as storage for the carbon. Soil drainage, which is done if peat soil is needed for cultivation, increases decomposition and carbon is released to atmosphere as carbon dioxide. (Maljanen et al. 2007, 139.) In Finland pristine peatlands have been developed for forestry, cultivation, pasture and peat extraction purposes throughout the centuries. These actions have released and still are releasing major quantities of carbon into the atmosphere.

Organic agricultural soils are also a significant source of nitrous oxide. (Maljanen et al. 2003a table 3). Yet cultivated organic soils cover only 13.6 % (Myllys & Sinkkonen 2004, 56) of the total agricultural land in Finland, they are responsible of 25 % of the total anthropogenic (human caused) N_2O emissions (Kasimir-Klemedtsson et al. 1997; Myllys & Sinkkonen 2004). In 2004 nitrous oxide emissions from cultivation of organic agricultural soils were 1.06 Tg CO_2 eq. and CO_2 emissions from organic grasslands and croplands 5 Tg CO_2. Totally the emissions in 2004 were 6.1 Tg CO_2 eq. (Lapveteläinen et al. 2007, 229).

Pristine peatlands

It would be easy to conclude that organic soils in agricultural use are a large source of GHG emissions compared with pristine organic soils, but organic soils in their natural state may emit large quantities of methane. When organic soil is drained, methane oxidation increases, lowering methane emissions. (Kasimir-Klemedtsson et al. 1997.) On the other hand pristine

peatland can work as a sink of N_2O but drainage affects the availability of oxygen and mineral nitrogen, increasing the emissions. In summary, organic soils are a source of methane, but under cultivation they release carbon dioxide and nitrous oxide emissions. Methane emissions from pristine peatlands are nevertheless argued not to be large enough to offset the benefits of carbon sequestration and lower nitrous oxide emissions. Table 2 presents results from few Finnish studies that support this assumption; soil emissions are significantly higher from cultivated soil compared with pristine peatsoil.

Turunen, Tomppo, Tolonen and Reinikainen (2002, table 3) estimated that carbon accumulation in mire type bogs and fens, can vary annually from 168 to 293 kg CO_2/ha. On the other hand they may emit methane of 2500-4900 kg CO_2-eq./ha (Nykänen et al. 1998 in accordance with Kasimir-Klemedtsson et al. 1997, table 5) Nitrous oxide emissions from pristine peat soils are trivial (Nykänen, Alm, Lång, Silvola & Martikainen 1995, 355).

After drainage, methane emissions are small or even turn negative but nitrous oxide and carbon dioxide emissions increase rapidly. Organic agricultural soils allocated to barley cultivation have been measured to accumulate methane at a rate of 27 to 33 kg CO_2-eq./ha but to release nitrous oxide of 1 600 to 3 367 kg CO_2-eq./ha and carbon dioxide on average 8 300 kg CO_2/ha (Maljanen, Komulainen, Hytönen, Martikainen & Laine 2004, table 3). Emission fluxes are converted to carbon dioxide equivalents with values of 25 for methane and 298 for nitrous oxide (IPCC 2007a, 210, table 2.14). Net emissions are compiled to Table 2.

Table 2. Soil greenhouse gas emissions from Finnish agricultural soils and pristine peatlands.

Climate emissions	**Pristine peatsoil kg/ha**	**Cultivated organic soil, CO_2-eq. kg/ha**
CO_2	-173 - (-261)[b]	8 300[c]
N_2O	0,2[a]	5,37-11,3[c]
CH_4	100 - 196 [a]	- 1,09 - (-1,33)[c]
Total CO_2-eq.	**2387 – 4699**	**9867 – 11640**

[a] Nykänen et al. 1998; [b]Turunen, Tomppo, Tolonen & Reinikainen 2002, table 3; [c] Maljanen et al. 2004, table 3

2.3 Agricultural emission mitigation features

Agriculture's participation to climate change mitigation is said to be justified, as agriculture is an important source of GHG emissions and has significant potential to decrease them (Smith et al. 2007; Cannell 2003; Lal 2004). Carbon sequestration is argued to have capacity to bring low cost emission reductions to mitigate climate change, and improve agricultural soil quality and soil productivity. The idea behind carbon sequestration is to increase soil organic carbon (SOC) content, which is reduced over years for example due to crop cultivation. Carbon accumulation can be promoted by increasing plant residues and reducing decay rate by limiting soil disturbance. Paustian et al. (2006, 7) summarise carbon sequestration practices on croplands as a use of high-residue crops and grasses, reduction or elimination of fallow periods between the crops (bare fallow), irrigation, use of low- or no-till practices and improving grazing land and hayland management. There are several suggested emission mitigation practices, but their potential to reduce greenhouse gases is variable and even unreliable due to diversity between agricultural and environmental conditions.

Potential of agricultural emission mitigation practices

GHG emission mitigation potential represents the potential decrease in atmospheric greenhouse gas concentration. Thus for carbon dioxide it is the amount of carbon accumulated to soil and vegetation, minus the amount released back to the atmosphere by decomposition. For CH_4 and N_2O gases mitigation potential represents the possible amount of emission reductions via for example manure management or reduced fertilizer application intensity. Emission mitigation potential for each mitigation practice varies between climates, regions, land use histories and social settings. Therefore none of the suggested emission mitigation practices are homogenous nor do give uniform quality results. (IPCC 2007b, 511-513.)

Cannell (2003) divides estimates on the emission mitigation potential to three groups from feasible to highly optimistic. According to the author the highest estimates "violate or ignore the ideals of sustainable development, encompassing economic, social and environmental goals". The potential of carbon sequestration depends on introduced technology, region where the emission mitigation practice is performed and the initial amount of carbon in the soil, or another words, the level of soil degradation. Economic potential accounts for different economic restrictions such as agricultural socio-economic characters. The economic potential to mitigate agricultural greenhouse gases is based on the opportunity cost principle. The actual level is affected by land owner's willingness and possibilities to adapt alternative land management systems. Farmers' age, education, experience, farm size and ownership status affect the adaptation (Paustian et al. 2006, 34-35) but also values and motivation may affect on decision making (Greiner, Patterson & Miller 2009).

Although economic constraints are not the only factors restricting agricultural emission mitigation, they are important ones. Agricultural emission reduction is claimed to bring low cost solution for climate change mitigation, but economic assumption is that farmers would already have introduced emission mitigation practices, if they would increase their profit. Farmers are supposed to maximise their economic profit which would indicate that emission mitigation practices would decrease farmer's profit. To enhance land owner's interest to adapt emission mitigation practices, should it be more profitable than not to.

Agricultural emission mitigation potential is often referred as a global or continent specific potential (Europe, U.S), although emission reductions are very climate and soil specific and thus variable. Estimates give nevertheless some idea about agriculture's capacity to mitigate emissions. Lal & Bruce (1999) estimate global potential for carbon sequestration with agricultural soils of 2 750-3 670 kg CO_2 Tg/year, or about half of the emissions agriculture is producing annually. Paustian et al. (2006, 5) have estimated that the technological potential in U.S by improving agricultural practices range from 102 to 270 Tg CO_2-eq. /year, covering carbon dioxide, nitrous oxide and methane. Carbon sequestration has by far the greatest emission mitigation potential and methane emission reductions the lowest. Estimate

is modest compared with several other estimates, but as agricultural emission mitigation contains various uncertainties, it is probably justified.

To get more detailed estimate about emission mitigation potential, West and Post (2002) reviewed multiple studies related to emission reductions from agricultural soils, limiting the focus on cultivation practices; no-till technology and improved crop rotation. According to their estimate, converting conventionally tilled crop fields to no-till fields would sequester carbon 480 ± 140 kg C/ha (1761 kg CO_2/ha). For improved crop rotation the rate is considerably lower (200 ± 120 kg C/ha). The estimate regarding no-till is consistent with estimate of West and Marland (2002) and Lal, Kimble, Follet and Cole (1999, 61). It should be noted that neither of the previously mentioned studies accounted the emissions from production, though it may be a significant part of the crop production due to high energy consuming production phases related to fertilizer and pesticide production and cultivation practices. They also do not consider other GHG emissions such as nitrous oxide, which might affect to the results. Although the estimates give an idea of the amount of emission reductions that could be reached by using agriculture as an emission mitigation option, they should be regarded carefully.

Value of agriculture's emission reductions

It is debated how emission reductions in agricultural sector, especially via carbon sequestration, are comparable with emission reductions done in other industrial sectors. Carbon emission reductions obtained by soil management are finite in magnitude and duration, which makes them distinctively different compared with reducing use of fossil fuels or improving energy efficiency of production machinery.

As noted before, carbon dioxide is easily released to atmosphere due to intensive soil management and disturbance, and the effect is the same before and after the emission mitigation practices. Thus gained emission reductions may be lost, if the land is again taken in cultivation after let's say, longer set aside period. This raises the question how long

should carbon be stored in soil, to make the reduction "permanent" and comparable. Carbon sequestered, even for a short period of time, is said to have value, as it has some influence on atmospheric CO_2 content (Watson et al. 2000, chapter 2.3.6.3.) and in theory it makes no difference whether the reduction is done with carbon sequestration or any other emission mitigation technology, as long as there is less carbon dioxide in the atmosphere (Feng, Zhao and Kling 2002, 144). But Lewandrowski et al. (2004) argue that in order to obtain the same value for unit of carbon sequestration than from permanent emission reductions, should carbon remain in soil for 100 years. WWF (2000) agrees that while carbon sequestration can be a cheap, short-term fix, preventing emission altogether produces better results for a long term problem. Nevertheless, general conclusion seems to be, that carbon dioxide mitigation would ease the emission mitigation pressure in the beginning, until more efficient mitigation practices are developed and atmospheric carbon concentration is in balance (Feng et al. 2002).

It is also characteristic for carbon sequestration that soil has a capacity to increase the carbon stocks rapidly in the beginning of the introduced emission mitigation practice, but the sequestration diminishes in time. The total potential of carbon sequestration depends on the initial amount of carbon in the soil and the sequestration capacity decreases until soil achieves new equilibrium when additional carbon is not stored anymore. (Batjes, 1999, 59-60.) IPCC (2007b, 514) estimates, that sequestration capacity is finite after 50-100 years but the carbon sequestration potential diminish during that time significantly and can be minimal only after 20 years. Batjes (1999) assumes that sequestration trend can be sustained just over 25 years. Presumably, timeframe for carbon sequestration is dependent on various factors, one of them being the technology. West and Post (2002) suggest that changing from conventional tillage to no-till increase the soil organic carbon content for about 10 to 15 years but if crop rotations are improved, the rate of sequestration may continue for 40 to 60 years. The sequestered amount is nevertheless the same.

Figure 1 depicts soil carbon balance when soil is under agriculture and later taken under carbon sequestration promoting practice. Before soil disturbance at time T_0, carbon stock is on steady-state but when land is taken under cultivation, carbon stock loose rapidly.

According to Watson et al. (2000), carbon stock never ends entirely but stays at certain lower level when the soil disturbance continues. When GHG emission mitigation practice is introduced at time T_1, soil starts to accumulate carbon again and reaches a new balance at time T_2.

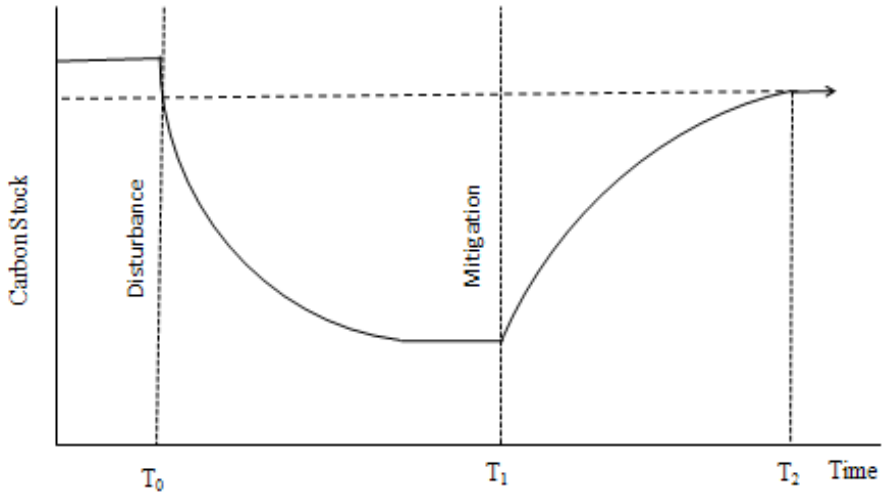

Figure 1. Carbon stocks following soil disturbance and carbon sequestration after the change in land management. Adapted from Watson et al. 2000, Figure 2-4.

Co-effects

It is characteristic for different emission mitigation technologies that any change in agricultural practices may impact multiple objects. As noted before, GHG fluxes are strongly dependent on environmental factors which are always difficult if not impossible to control. Changing initial management practice may decrease the emissions of any particular gas, but may at the same time change the soils gas balance so that net emission reduction is unreliable. Most common example is how no-till may decrease CO_2 emissions but increase N_2O emissions. Outcome of intended emission reductions depends on environmental conditions and applied technology. In addition to GHG fluxes, emission mitigation practices can affect various other environmental or socio-economic targets. (Feng, Kurkalova, Kling & Gassman 2007.)

These co-effects show up in the form of additional benefits and trade-offs. They may either increase or decrease the attractiveness of emission mitigation technologies. Additional benefits are positive impacts of action that was originally introduced to reduce atmospheric emissions. Trade-off is on the contrary a negative additional effect. Many of the suggested GHG mitigation practices that protect soil surface, may decrease erosion, improve crop yields and decrease or increase nutrient leaching. (Paustian et al. 2006, 23.) Because of additional benefits, GHG mitigation practices in agriculture, such as carbon sequestration, are often seen as a win-win strategy, as they may simultaneously increase economic and environmental benefits (Lal & Bruce 1999). For example, there is a strong interaction between soil quality and soil organic carbon content. In other words, increasing carbon sequestration improves soil quality, which again is beneficial for restoring degraded ecosystems, biomass production and crop yields. (Lal et al. 1999.) On the other hand, due to the complexity in soil physical and chemical interactions, introducing alternative management practice to increase carbon sequestration, can have impact to other greenhouse gas fluxes such as nitrous oxide emissions.

Several experiment studies have noticed that no-till has increased soil N_2O emissions to the extent where the net emissions are higher than before the emission reduction practice. In other words, if we account the global warming potential of all greenhouse gases, the emission reduction potential of no-till may be lower or even negative compared with if only carbon dioxide emissions are accounted. The eventual net result is nevertheless dependent on soil type and crop species as well as on other cultivation related practices such as fertilization. (Rochette, Angers, Chantigny & Bertrand 2008; Ball, Scott & Parker 1999.) Chatskikh, Olesen, Hansen, Elsgaard and Petersen (2008) have also found results that no-till would decrease N_2O emissions compared with conventional tillage, which reveal something about the complexity of the issue.

Emission mitigation practices are often originally designed and introduced for improving other environmental goals, giving GHG reductions as additional benefits. Kurkalova, Kling and Zhao (2003) noticed that policy that targets nitrogen runoff and wind and water erosion by using conservation tillage practices in Midwestern United States, improved also carbon

sequestration. Interestingly climate emission mitigation impact was greater with this policy implication than with policy that targeted only carbon sequestration. In developing countries practices that are now suggested as potential tools to mitigate climate emissions, are commonly introduced to secure farmers' livelihood. (Seeberg-Elverfeldt & Tapio-Biström 2010, 3).

As additional benefits from GHG mitigation often increase farmers' income, are they also promoted for farmers. Higher profitability is due to higher crop productivity, environmental benefits or lower management costs. It is nevertheless argued that these additional benefits are reached with a time lag, and would not affect farmers' decision making (Capalbo, Antle & Mooney. 2004). This would explain farmer's reluctance to introduce emission mitigation technologies although they would increase profit in long term.

Emission mitigation potential in recent literature

Agricultural GHG emission mitigation has been studied in Finland during recent years some. Studies have mostly concentrated either in biofuel production (Rinne 2007; Mäkinen, Soimakallio, Paappenen, Pahkala & Mikkola 2006), emission mitigation on organic soils or reducing nitrogen fertilization, targeting to decreased soil N_2O emissions (Bionova Engineering 2008). Not all of the suggested emission mitigation practices give promising results. For example biofuels are argued not to be a reliable way to reduce GHG emissions, nor would they give price competitive fuels to substitute fossil fuels (Rinne 2007; Mäkinen et al. 2006).

As noted before, reducing nitrogen fertilization may decrease soil nitrous oxide emissions and carbon dioxide emissions from fertilizer production. Nevertheless, limiting fertilization rate may also affect crop yields. Lower fertilization intensity does decrease per hectare emission rate, but may not decrease per crop kilogram emission rate. (Pipatti et al. 2000.) Although it is also estimated that there is potential to cut mineral fertilizer use without affecting the crop yields (Bionova Engineering 2008, 30), the optimization would need to

base on data on soil type, crop specie, other nutrients and climatic conditions. On the other hand, if succeeded, it would simultaneously decrease nutrient runoff and thus water system eutrophication. Similar problem appears regarding organic fertilizers, which are commonly used in organic farming. Use of organic fertilizers is considered to have lower N_2O emissions, but when the emissions are compared as kilograms N_2O per crop yield instead of kilograms N_2O per hectare, has organic and synthetic fertilizers emission rate been measured to have no difference. (Syväsalo et al 2004.)

From point of view of Finnish agricultural climate emission mitigation potential, organic soils seem to be one of the most interesting and prospective objects. Organic soils cover relatively large proportion of Finland's farmland area and are also important source of greenhouse gases. Restricting cultivation on organic soils or converting them to permanent grasslands or afforestation have been suggested to be potential options to balance Finnish agricultural GHG emissions without harming greatly agricultural production (Regina, Lehtonen, Nousiainen & Esala 2009; Bionova Engineering 2008; Pahkasalo 2005).

Published studies related to agricultural emission mitigation have increased rapidly during recent years. Large part of them focuses on general estimates about emission reduction potential, without concerning other related environmental or economic impacts. Pipatti et al. (2000) emphasise that as agricultural soil emissions are highly variable and insecure, and comprehensive impact of the emission mitigation practice is dependent on various factors, it would be important to base the estimates over the efficiency and cost-effictiveness of the practices on experiment studies. The weak point of the issue is that experiments over climate emission mitigation practices' impacts to economic and environment are at the moment partially inadequate. Nevertheless, the viewpoint of emission mitigation studies has been lately broadened. For example Sasaki (2010) performed a case study in Japan on optimal land use allocation and nitrogen application to fields, focusing especially on the socially optimal performance by using an environmental-economic model. As the conclusion he found that although converting wheat fields to rice paddy fields would decrease private profit, it has socially profitable outcome as it decrease GHG emissions and

nitrogen runoff. Nevertheless he points out that the results are more indicative than accurate due to limitation in available data.

In next chapter we introduce the theoretical framework of our study on climate mitigation potential regarding field cultivation and alternative land use options.

3 Theoretical framework: Agriculture and environmental impacts

The objective of this study is to evaluate the social welfare of given cultivation technologies and alternative land use forms in terms of environmental and economic issues. We develop an integrated economic and ecological model to analyse the profitability of conservation tillage and no-till and alternative land use systems, green fallow and afforestation. The social welfare of given land use options consist of private producers' surplus and value of environmental impacts as in here, climate emissions during the whole life cycle of production and nutrient runoff (nitrogen and phosphorus). Theoretical framework compares also the social and private optimum of cultivation practices in order to derive optimal carbon tax and payments regarding water quality impacts and climate emissions.

To begin with, we assess crop cultivation production under different cultivation technologies, no-till and conventional tillage. Later on the social profitability of green fallow and afforestation is analysed and finally we assess the optimal policy.

3.1 Crop production

Agricultural production, crop yield size, is defined through chosen soil management practice (conventional tillage or no-till) and quality of soil. Production function is thus:

$$y_t = f^t(l_t; q) \qquad t=1,2 \qquad (1)$$

where f^t indicates yields under each technology, l_t fertilizer input. t = 1 refers to conventional tilling and t = 2 to no-till. Yield size depends on the soil quality and fertilizer use. Thus crop yield increases in the soil quality q, $\frac{\partial f^t}{\partial q} > 0$. Soil quality consists of soil

characters and management history. Fertilizer l increases crop yield but in a decreasing fashion, $\frac{\partial f^t}{\partial l} > 0$, but $\frac{\partial^2 f^t}{\partial l^2} < 0$.

Farmers' profit from production is defined as revenue minus costs. Here revenue is determined by the amount of crop produced multiplied by its unit price. Costs consist of fertilizer price c and technology specific costs K_t, which consist of labour, fuel costs, seed price and investments and are specific for each technology. Conventional tillage has often higher management costs than no-till $K_1 > K_2$, which is generally result from less use of tractors and fewer needed work hours. On the other hand, often more herbicides are used on no-till, which balances the difference in total costs.

After harvesting grains are normally dried before selling. For example about 90 % of the barley crop yields in Finland is dried to maintain the seed quality after harvest (Hyytiäinen et al. 1995, 73-75). Drying creates additional production costs which reduce the effective crop price. Thus $\hat{p}$ depicts the crop price after drying where the drying costs are size of μ. Thus $p - \mu = \hat{p}$ and $\hat{p} < p$.

Farmers' profit under technology t is defined as:

$$\pi_t = \hat{p} f^t(l;q) - cl - K_t \qquad (2a)$$

Farmers' problem is to choose fertilizer application rate on the given technology so, that it maximises the crop yield with minimum costs. Conventional first order condition in terms of fertilization is thus:

$$\frac{\partial \pi^t}{\partial l} = \hat{p}\frac{\partial f^t}{\partial l} - c = 0 \qquad (2b)$$

and second order condition:

$$\frac{\partial^2 \pi^t}{\partial l^2} = \hat{p}\frac{\partial^2 \pi^t}{\partial l^2} < 0 \qquad (2c)$$

Equation (2b) shows that farmer increases fertilizer input to the point where the value of marginal revenue is equal to input unit costs. Fertilization intensity depends positively on crop prize and negatively on fertilizer prize and soil quality.

Climate impacts of crop cultivation

Field cultivation and agricultural practices cause greenhouse gas emissions that affect the social desirability of cultivation technology and land use option. Emissions are not accounted for in the farmers' management decisions, but they do affect the social welfare. GHG emissions *e*, are generated from the use of energy *w* and fertilization *l*. Nitrogen fertilizer increases soil N_2O emissions but also fertilizer production causes emissions.

Soil emissions from fertilizer application are a function of fertilization rate:

$$e^l = e_l^t(l) \qquad (3)$$

Fertilization intensity has direct impact on the nitrous oxide emissions from soil. Emission flux is also expected to be accelerating, as crops capability to use nitrogen is declining, thus $\frac{\partial e_l^t}{\partial l} > 0$ and $\frac{\partial^2 e_l^t}{\partial l^2} > 0$

In addition to emissions from fertilizer application, manufacture and transportation of fertilizers produce GHG emissions which are described by:

$$e^s = e_s^t(l) \qquad (4)$$

Emission rate increases along with manufacture, $\frac{\partial e_s^t}{\partial l} > 0$.

Seed drying is performed using either cold air dryers or warm air dryers to achieve wanted grain moisture level. The process demands energy which can be produced with fossil fuels or solar power. (Hyytiäinen et al. 1995, 73-75.) Emission function from drying is:

$$e^w = e_w^t f^t(l;q) \tag{5}$$

Emission rate depends on the yield, which is, again, determined by soil quality and fertilization rate. Emission rate grows linearly as the amount of crop to be dried grows, $\frac{\partial e^w}{\partial f^t(\cdot)} = e_w^t$.

Other life cycle emissions from field cultivation practices are described by term M_t. It represents emissions from field cultivation activities which are not included to soil emissions from fertilizer use, crop drying and fertilizer manufacture and transportation. Life cycle climate emissions from no-till are generally lower compared with conventional tillage due to lower energy use in different production phases (West and Marland 2002). Damages from GHG emissions are defined by multiplying the emissions with climate change costs ϕ which turn the emission impact to monetary value.

Surface water quality impact of crop production

Agriculture is the largest source of non-point nutrient runoff in Finland. Level of runoff from fields is affected by several environmental conditions such as steepness of the field, soil quality, and precipitation. Runoff rate is also affected by cultivation practices such as fertilizer input intensity, crop type, draining, buffer strips, soil tillage methods and timing.

Nitrogen and phosphorus load to water system has generally been the most concerning issue relating to agriculture's environmental effects. Nutrient load increases eutrophication in water systems and increased algal and aquatic plant growth causes oxygen loss and changes in biotope. Phosphorus is often the limiting factor on inland waters, but lack of nitrogen limits the over production on sea area coastal. No-till has been shown to decrease nutrient runoff and erosion compared with conventional tillage although no-till might increase dissolved phosphorus runoff (Lankoski, Ollikainen & Uusitalo 2006).

We follow the theoretical analysis of Lankoski et al. (2006) on nutrient surface runoff, excluding buffer strips. We also exclude herbicide use from the analysis. Fertilizer input is presumed to contain all necessary nutrients in fixed proportions, the main nutrients being nitrogen, phosphorus and potassium.

Nutrient runoff on fields is a function of applied fertilizer *l*:

$$z_t = g^t(l_t) \tag{6}$$

Nutrient runoff is increasing and concave in terms of fertilization and thus $\frac{\partial g^t(l_t)}{\partial l}>0$ and $\frac{\partial^2 g^t(l_t)}{\partial l^2} > 0$ (Lankoski & Ollikainen 2003, 56). Damage of nutrient runoff is D and damage increases as the amount of runoff increases. Thus, $D' > 0$ and $D'' > 0$.

Social welfare of crop cultivation

Our objective is to assess the fertilization intensity on both cultivation technologies and the choice of technology, which together maximises the social welfare when environmental costs are considered. Maximisation problem is presented via social welfare function:

$$\max_{l,q} SW^t = \hat{p} f^t(l;q) - cl - D(g^t(l_t)) - K_t - \phi\left[e_l^t(l) + e_s^t(l) + e_w^t f^t(l;q)\right] - \phi M_t \tag{7a}$$

Later we will leave subscript *t* out, to simplify the function notation. Technology will appear again in the empiric analyse. Derivation in terms of fertilization forms the first order condition for the problem:

$$\frac{\partial SW}{\partial l} = \hat{p}\frac{\partial f}{\partial l} - c - D'(\cdot)\frac{\partial g(l)}{\partial l} - \phi\left[\frac{\partial e^{l}(\cdot)}{\partial l} + \frac{\partial e^{s}(\cdot)}{\partial l} + e^{w}\frac{\partial f(\cdot)}{\partial l}\right] = 0 \qquad (7b)$$

and second order condition:

$$\frac{\partial^2 SW}{\partial l^2} = \hat{p}\frac{\partial^2 f}{\partial l^2} - D''(\cdot)\left(\frac{\partial g(l)}{\partial l}\right)^2 - D'(\cdot)\frac{\partial^2 g(l)}{\partial l^2} - \phi\left[\frac{\partial^2 e^{l}(\cdot)}{\partial l^2} + \frac{\partial^2 e^{s}(\cdot)}{\partial l^2} + e^{w}\frac{\partial^2 f(\cdot)}{\partial l^2}\right] < 0 \quad (7c)$$

The first order condition (7b) shows that the use of fertilizer input is increased to the point where the value of marginal product of fertilizer is equal to the sum of costs from the fertilizer and marginal environmental damage of nutrient runoff and GHG emissions. Emissions thus cause extra costs to the society and reduce the profitability of crop production. Equation 7c shows that it is a sufficient condition for the first order condition to represent a maximum.

Comparing equation (7b) to equation (2a) it can be seen that the privately optimal situation is same as in the socially optimal solution, excluding marginal damages of fertilization and greenhouse gases. This means that farmers produce more emissions than would be socially optimal.

Finally, the cultivation technology which brings the highest social welfare is chosen.

3.2 Green fallow and afforestation

Green fallow is expected to sequester carbon on limited amount of time before the soil has achieved a balance and additional carbon is not stored anymore. Carbon is also assumed to return into atmosphere if the land is again taken back to cultivation.

Reflecting Figure 1, equation (8) shows how the carbon is accumulated in the soil before the soil achieves the equilibrium:

$$h = \frac{\sum_{t=1}^{T}(1+r)^{-t}\phi u}{T} \tag{8}$$

where T is the time frame carbon is sequestered, r is the rate of interest and ϕ the price of sequestered carbon u. The annual present value of sequestered carbon is h. Equation (9) depict the social welfare from green fallow:

$$W^g = h^g - \gamma^g - R^g \tag{9}$$

where the annual costs and profits from establishment and maintenance of fallowed land are γ and nutrient runoff is R.

The decision on establishment of green fallow is a discontinuous technologically determined choice. Green fallow could also provide some biodiversity benefits (IEEP 2008) but they are not taken into account here. On the other hand in the parametric analysis, fallowed land is valued for its landscape likewise crop fields are.

Afforestation is suggested to be one of the most efficient technologies that improve soil carbon content and thus mitigate climate change. In addition to carbon sequestration, afforestation would decrease other climate emissions of crop production, although silvicultural practices demand also energy intensive practices.

Social welfare of afforestation follows similar function as is introduced for green fallow. Social returns consist of annual climate benefits or damages of afforested soil and biomass *h*, maintenance and establishment costs γ and nutrient runoff to water systems *R*.

$$W^a = h^a - \gamma^a - R^a \quad (10)$$

3.3 Emission mitigation policies

The basic assumption is that farmers are applying the land use practice that maximizes the private profit. In the absence of market failures private actors tendency to maximise their profit would maximise also the social profit and yield a Pareto efficient solution. Nevertheless, market failures, such as externalities, impact social welfare and create a need for climate policies. To attain the socially optimal solution for crop production, farmers should be motivated to take environmental effects into account in their decision making. Without government intervention, farmers are not willing to adapt climate mitigation practices (Smith et al. 2005). Economic incentives such as taxes, subsidies, marketable pollution permits and also technology support payment tools improve land owners environmental performance and minimize the total abatement costs by equating the marginal abatement costs across polluters. Incentive systems are somewhat different although their results are in theory similar; enhancing socially optimal decision making.

Emission trading as a baseline and credit system on agriculture would allow farmers to gain emission credits by reducing emissions and sell them to buyers. Although emission trading system is already used for climate change mitigation in other industry sectors[1], its administrative difficulties and uncertainties are suggested to be high especially in agriculture. Metcalf (2007) argues that emission tax would be more realistic policy for

[1] The most important economic incentive system on European scale is European Union Emission Trading Scheme (EU ETS) which is a trade system for CO_2 emissions for different energy and industrial sectors. For now, EU ETS covers only some sectors from industries and only carbon dioxide emissions. Agriculture and N_2O and CH_4 are not included to the cap.

agricultural climate change mitigation. Tax is widely used for environmental policies, fulfilling the Polluter Pays principle (Baldock 1992) as it makes the environmental damage visible for farmers and direct to optimal outcome. Carbon tax would be ideally set to maximise social welfare, taking into account the dynamic nature of the problem as well as the previously placed taxes. According to Metcalf (2007), there is no difference whether emission pricing is placed upstream (for example power production) or downstream to where the energy is consumed (in this case agriculture).

We assume that the tax is levied on fertilizer application, which would target the tax simultaneously to climate emissions and nutrient runoff. The optimal tax is solved to internalize the marginal damage of private solution that is, by solving a tax rate making social and private first order conditions equal.

Damage is related either to nutrient runoff or climate emissions as defined in equation (7b). Marginal damage $d\chi$ is thus:

$$SW_l - \pi_l = d\chi \tag{11a}$$

and the optimal tax is equal to the size of marginal damage.

$$d\chi = \tau^* \tag{11b}$$

Equation (11b) is described more specific in equations (11c) and (11d). To derive the optimal tax τ for fertilizer use on each given soil type and cultivation technology to guide farmers' fertilizer use, we assume that the tax is either placed for only climate emissions (11a) and also for nutrient runoff (11b).

$$\tau^* = \phi\left[\frac{\partial e^l}{\partial l} + \frac{\partial e^s}{\partial l} + e^w \frac{\partial f}{\partial l}\right] \tag{11c}$$

$$\tau^* = \phi\left[\frac{\partial e^l}{\partial l} + \frac{\partial e^s}{\partial l} + e^w \frac{\partial f}{\partial l}\right] + D'(\cdot)\frac{\partial g(l)}{\partial l} \qquad (11d)$$

Tax rate in equation (11d) is higher than in equation (11c) as it is directed both to climate impact and nutrient runoff.

It is possible that fertilizer tax is not sufficient policy for crop production as the farmer may choose a cultivation technology that is not socially optimal. This outcome is possible, as no-till and conventional tillage have different cost structure, often benefiting no-till. Therefore, society uses a lump sum payment T to make the socially optimal solution also optimal for farmers. Thus if socially optimal solution is technology 1, must the following relation hold: $\pi^{a1}(l_1^*,...) + T^* = \pi^{a2}(l_2^*,...)$ For alternative land use systems, here green fallow, a Pigouvian subsidy is placed for annual present value for climate benefits, when green fallowing or afforestation are expected to reduce climate emissions from soil compared with crop cultivation.

$$s^* = \phi h \qquad (11e)$$

Despite the simple structure of the subsidy, it is sufficient policy instrument for green fallow and afforestation. These technologies are expected to be technologically fixed, which means there is no variation within the technology.

In following chapter we provide an empirical model which is tailored for Finnish agricultural data to calculate the socially and privately optimal solutions and climate policies.

4 Empirical data and model

In the following chapter we examine crop production, land allocation choices and optimal policy instrument in a parametric model, which is applied to Finnish agricultural and forestry data. Three different soil types are considered on two different management technologies, no-till and conventional tillage and two alternative uses of the land, green fallow and afforestation. The crop in the application is barley.

4.1 Crop production

We choose barley for our parametric mode as it is one of the most common cereals cultivated in Finland distributing almost throughout the country (Hyytiäinen, Hedman-Partanen & Hiltunen, 1995, 62-63). Crop production cycle includes often soil tillage (mouldboard plough tillage) which prepares the soil for sowing or fertilization by turning it around on deepness of 20-25 cm, burying crop residues and leaving the soil bare. In alternative cultivation system, no-till, new crop is sowed through the crop residues, avoiding soil disturbance, thus in no-till soil is not ploughed. (Hyytiäinen & Hiltunen 1992, 115-116.)

Intensive tillage practices are noted to degrade soil quality and increase erosion and nutrient leaching. Thus, no-till has been developed and used for soils where erosion, nutrient runoff and drought are problems. [2] It is also suggested to be a potential way to decrease CO_2 emissions (Paustian et al. 2000; Chatskikh et al. 2008).

[2] No-till was introduced to Scandinavia in early 70's and its attractiveness was basically based on the possible economic benefits and reduced erosion, but today only small amount of cultivated soils are under no-till technology in Europe (Rasmussen 1999, 4). In countries where soil degradation and erosion are bigger problems as in some parts of United States and South America, no-till is a largely established technology.

Socially optimal crop cultivation

Barley yields depend on various factors from climate to soil conditions, but it is also strongly dependent on the fertilization intensity. Mitscherlich nitrogen response function defines the optimal fertilizer intensity on each cultivation technology:

$$f^t(N;q) = m^t(1-\sigma\exp(-\rho N)),\ \mathrm{t}=1,\ 2 \qquad (12)$$

where $f^t(N;q)$ is yield per hectare, N is the fertilizer use per hectare and m, σ and ρ are parameters for maximum yield and nitrogen proportion from fertilizer. Field studies have shown that barley maximum yields in Finland are somewhat higher on conventional tillage than on no-till fields[3] as reported in Table A1 in Appendix I.

Farmers choose the optimal nitrogen fertilizer rate which maximises their profit. Factors that affect the decision making are crop price and fertilizer price. Other costs from cultivation are expected not to vary in terms of cultivation decisions otherwise than between the given cultivation technology. These costs consist of capital costs and variable costs. Table A2 in Appendix I is reporting the cost structure of barley cultivation where costs are evaluated for crop yield of 4 000 kg/ha and are expected to be equal to all soil types (Lankoski et al. 2006). No-till has on average slightly smaller cultivation costs than conventional tillage. The difference is basically due to distinctive management practices. Due to ploughing and harrowing the total costs of conventional tillage are higher than in no-till, although no-till has higher costs due to herbicide use.

To evaluate the social returns to barley cultivation, we consider the climate impact of the whole life cycle of barley production and nutrient runoff created by nitrogen and phosphorus runoff. We start with the climate impacts of different agricultural practices and autonomous emissions from soil and also possible climate benefits of carbon sequestration

[3] In theory given soil management technologies (no-till and conventional tillage) do not impact the yields on longer term, though annual results vary by crop and region as well as climate and soil conditions (Rasmussen 1999; Kimble 2007; Mooney & Williams 2007).

and continue with phosphorus and nitrogen runoff. In both cases we account for different cultivation technologies.

Climate emissions

Life cycle climate emissions are net emissions from different steps of barley production. Emissions relate to lime, fertilizer and herbicide manufacture and application and cultivation practices, such as ploughing, harrowing, seeding, harvesting, transportation and grain drying. Also soils are either sources or sinks of greenhouse gases, depending on cultivation practices and environmental circumstances. Table 3 collects the GHG emissions from different sources in crop cultivation.

Life cycle GHG emissions from cultivation practices are modelled from research of Mäkinen et al. (2006) who studied energy and greenhouse gas balances in biofuel production and emission reduction costs for biomass-based fuels used in transportation and combined heat and power production compared with other fuels. Net emissions in terms of cultivation practices are in general lower on no-till management compared with conventional tillage for the same reasons as the costs are; emissions from tractor use are higher on conventional tillage although herbicide use and manufacture do raises net emissions of no-till. (Mäkinen et al. 2006.)

We expect that most of the GHG emissions are constant, but emissions related to crop drying and fertilization (soil and manufacture) change due to crop yield and fertilization intensity. Nitrous oxide emission factor for nitrogen applied to soil is defined by IPCC Guidelines for National Greenhouse gas Inventories (1996) and is 1.25 %. The factor is later changed to 1 % by IPCC Guidelines (2006) but as various studies have resulted higher emission rates from applied nitrogen (Ruser et al. 2001; Kaiser et al. 2001), we use the first factor.

Fields are generally limed using different carbonate compounds, mainly limestone ($CaCO_3$) and dolomite lime ($CaMg(CO_3)_2$) in order to increase soil pH-value and add important nutrients such as magnesium and calcium to the soil (Hyytiäinen et al. 1995). Lime application is assumed to take place every five years following Mäkinen et al. (2006). Carbonate in lime reacts in soil releasing carbon dioxide. In GHG inventory emissions from lime application is calculated assuming that all lime is reacting (Pipatti et al. 2000, 13-14.), which is also expected in emission factors defined for emissions from lime application. Basic crop cultivation practises include also different plant protection activities to secure proper yield from different additional factors that might diminish it. Weed, pest and plant disease control is done with proper cultivation practices, but also with chemicals or mechanical actions. Pesticide and herbicide use is kept minimal in general as chemicals are expensive, but the use is still a standard in crop cultivation. (Hyytiäinen & Hiltunen 1992, 115-118.) Control substances such as pesticides create environmental problems especially if they are inorganic. Microbes are able to degrade natural substances. Intensive or long term use of control substances might cause multiple problems depending on the quality of the substance (Heinonen et al. 1992, 329-330.) but so far there are not enough studies to define the exact environmental impact of control substances. Thus we have only included the climate emissions related to application and manufacture of control substances, leaving out other environmental impacts.

Table 3. Climate emissions created by barley production through life cycle (excluding soil autonomous emissions).

	Conventional tillage	No-till	Note
Mouldboard plough tillage	90		
Harrowing	54		
Grain seeds	151	161	
Nitrogen manufacturing	546[2]	546[2]	6.065 kg CO_2-eq./kg N (2.541 kg CO2/kg N)
Soil emissions due to N fertilizer application	335[2]	335[2]	0.0125 kg N_2O/kg N
Liming (production, transportation, and application)	111[1]	111[1]	139 kg CO_2-eq./ton of lime
Liming (soil emissions)	345[1]	345[1]	431 kg CO_2/ton of lime
Planting	13	27	
Herbicide manufacture and transportation	44	70	
Herbicide application	13	19	
Harvesting	54	54	
Transportation of harvest to grain dryer	1	1	325 g CO_2-eq./ton, km
Grain drying	119	113	
Transportation of output to processing industry	29	28	
Total kg CO_2eq./ha	**1905**	**1810**	

[1] Lime application is done once in five years with application rate of 4000 kg/ha.

[2] Emission rate is dependent on amount of nitrogen; rate is calculated for applied nitrogen of 90 kg/ha and converted to CO_2-eq. with GWP 298.

Soil emissions are affected by fertilization and cultivation practices, but some of the emissions are not directly connected to certain management practices, but are autonomous. To include these emissions into our study, we have collected data from annual soil emission fluxes of given soil types from several different studies performed in Finland on no-till and conventional tillage fields.

As there is no single experiment or study on emission flux of barley fields under no-till and conventional tillage on different soil types, the results and study methods differ from each other. The studies we utilize have measured soil emission fluxes with different methods, basically different static chamber and micrometeorogical methods. Static chamber method is generally used for all emissions fluxes (Martikainen et al. 2002; Regina et al. 2004; Maljanen et al. 2004; Mäkiranta et al. 2007) but CO_2 emission fluxes are also measured

using micrometeorological method called eddy covariance (EC) method (Lohila 2008). All measurements are based on following the flux of certain gas between soil and atmosphere but chamber method measures small fragment of the field, while micrometeorological methods consider larger, ecosystem level emission fluxes. The net flux in both systems represents the net emissions from or uptake by the soil. The results should be comparable with each other. Nevertheless, problems in comparability bring the length of study periods and the frequency of measurements. Emissions fluxes vary greatly due to changes in environmental circumstances and thus there can be significant variability in the emission rates on daily, seasonal and annual level. The results are most robust from long term experiments with frequent sampling. Difficulties in comparability bring also the fact that studies are done in different part of Finland which gives variability to climate and other environmental circumstances. Also the fact, that the parcels under research have different cultivation history, might affect the variability of results (VandenBygaart, Yang, Kay & Aspinall 2002). As we are not able to evaluate the environmental impact to the emission fluxes we have to take them as given. We have limited the sources to barley fields in Finland on three main soil types to keep the analysis as focused as possible.

There are only few studies carried out comparing climate emissions of conventional tillage fields and no-till fields on northern hemisphere. We use the results of study by Regina, Perälä and Alakukku (2007b) where emission fluxes from no-till and conventionally tillage fields are studied on parallel parcels. N_2O emission fluxes seem to follow the earlier theory. Fluxes are stronger from no-till than conventional tillage field. In terms of carbon dioxide the emissions are somewhat surprising. Many of the studies done in United States or South America have shown that no-till increase soil carbon content (Ussiri & Lal 2009; Spargo, Alley, Follett & Wallace 2008) and global estimate is that mineral soil under no-till sequester carbon at rate of 900 kg/ha (West & Post 2002) but according to Regina et al. (2007b) some no-till fields have even larger CO_2 emissions than conventional tillage land. From recent studies Hermle, Anken, Leifeld and Weisskopf (2008) from Switzerland, VandenBygaart et al. (2002) from Canada and Gál, Vyn, Michéli, Kladiviko and McFee (2007) from U.S. have also claimed that no-till might not improve soil organic matter content as assumed. It is suggested that no-till would increase SOC on upper parts of the

soil but decrease it on lowers, thus making no difference between no-till and conventional tillage in terms of carbon accumulation. According to study of Regina et al. (2007b) especially sand and silty loam soils would have higher carbon dioxide emissions on no-till. On clay and silty clay soils the results are variable and on organic soils the emissions would decrease on no-till fields. Due to lack of comparable studies in Finland or other Nordic countries, we utilize the results from clay, loam and organic soils. According to author Kristiina Regina, results of the study are usable for comparison of the two technologies, but not to compare the annual fluxes from fields between other studies as the calculations are only performed during day and measure ecosystem precipitation (K. Regina, e-mail to author, October 10, 2009). Thus we compare no-till and conventional tillage fields via the proportional change between the emissions fluxes.

To estimate net emissions of clay, silt and organic soils under no-till and conventional tillage, nitrous oxide and methane emissions are converted to carbon dioxide equivalents. Table 4 reports the emission fluxes from each soil types and cultivation technologies.

Table 4. Greenhouse gas net emission fluxes from cultivated soil in Finland. Negative value denotes gas accumulation and positive emissions.

GHG gas	**Clay Soil**	**Silt soil**	**Organic soil**
	Conventional tillage		
CO_2	1468[c]	367[c]	7700[e]
N_2O	3.7 – 4.4[a]	3.7–7.5[a]	6.2 – 24.1[b]
CH_4	0.008 – 0.58[d]	-1.22 – (-1.09)[d]	-0.53 – (-0.13)[d]
CO_2-eq. (av.)	2684	2008	12207
	No-till		
CO_2	1864[g]	536[g]	6723[g]
N_2O	19.7 – 23.5[f]	8.4 – 17[f]	7.9 – 30.6[f]
CH_4	-0.003 – (-0.22)[h]	-2.44 – (-2.18)[h]	-0.62 – (-0.15)[h]
CO_2-eq. (av.)	8298	4263	12450

[a] Syväsalo et al. 2004; [b] Regina et al. 2004; [c] Lohila et al. 2009; [d] Regina et al. 2007a;
[e] Lohila et al. 2004; [f] Regina et al. 2007b, Table 3 (proportion calculated from Syväsalo et al. 2004); [g] Regina et al. 2007b, Table 3 (proportion calculated from Lohila et al. 2004); [h] Regina et al. 2007b Table 3 (proportion calculated from Regina et al. 2007a)

Climate emissions in policy scenarios

As Kyoto Protocol applies at the moment emission policies only on CO_2 emissions, we perform SW analysis also for a case where N_2O and CH_4 emissions are absent. Thus we need to estimate emission fluxes from different production life cycle phases also considering only carbon dioxide. Table A3 in Appendix presents the values for different parameters used in the empirical analysis, differentiating the emissions of CO_2 and CO_2-eq.

GHG emissions from energy consumption are assumed to be entirely carbon dioxide emissions, as other than CO_2 emissions count only few percents of the total emissions (Mäkinen et al. 2006, 32-33). Thus we expect that for example the accounted emissions from crop drying are entirely carbon dioxide. Similar assumption is also done for control substances (Mäkinen et al. 2006, table 7) and other energy consuming cultivation practices. Fertilizer application creates mostly nitrous oxide emissions from soil, but manufacture and transportation causes CO_2 emissions. Emission factor used for fertilizer manufacture when only carbon dioxide emissions are accounted is 2,541 kg CO_2 /kg N. When all emissions are accounted, the factor is 6,065 kg CO_2-eq./kg N.

The applied lime is limestone (90%) and dolomite (10%) for which the emission factors slightly differs; 0,427 kg CO_2/kg limestone and 0,463 kg CO_2/kg dolomite (Statistics Finland 2009, 80). Mäkinen et al. (2006) have chosen emission factors of 0,431 kg CO_2 for both of the lime types, which also we use.

Social welfare of crop cultivation is comprised from costs and profits as we described in theory;

$$SW_t = \pi - \phi\left[e_l - e_w * f(N;q) - e_s\right] - \phi M - D\left[Z_N^t - Z_{PP}^t - Z_{DRP}^t\right] \qquad (13)$$

where damage D of nutrient runoff is divided to nitrogen N, particulate phosphorus PP, and dissolved reactive phosphorus PP runoff .

Phosphorus runoff

Phosphorus runoff occurs as dissolved reactive phosphorus (DRP) and particulate phosphorus (PP). Annual phosphorus leaching has been estimated to be about 0,8-1,7 kg/ha from Finnish crop cultivated fields (Rekolainen, Pitkänen, Bleeker & Felix 1995, 69). Particulate phosphorus runoff is strongly affected by erosion but dissolved phosphorus depends also on the initial phosphorus rate on soil, which has accumulated to the soil in the course of time due to fertilization. Runoff rates are also affected directly by fertilization intensity and water leaching from fields. (Heinonen et al. 1992, 316-317.)

We use description of DRP and PP (potentially bioavailable phosphorus) runoff developed by Uusitalo and Jansson (2002). DRP runoff is described as follows: *water soluble phosphorus in runoff (mg/l)=0.021*soil phosphorus (mg/l)-0.015(mg/l) to which fertilizer application increases soil phosphorus 0.01mg/l*. Particulate phosphorus runoff is mainly result of the amount of phosphorus in eroded soil: *Potentially bioavailable particulate phosphorus (mg/kg/eroded soil)=250*ln[soil phosphorus (mg/l) soil]-150.* The previous equations are derived here as follows:

$$Z_{PP}^{t} = \alpha^{t}\left[\varsigma^{t} * \left\{\frac{250 * \ln(\theta + 0.01 * P_{t})150}{1000000}\right\}\right] \tag{14}$$

$$Z_{DRP}^{t} = \beta^{t}\left[\frac{\psi * 0.021(\theta + 0.01 * P_{t})}{100}\right] \tag{15}$$

In particulate phosphorus equation ζ^{t} is the volume of erosion from fields kg/ha, θ the amount of soil phosphorus mg/ha and ψ amount of water leaching from fields mm/ha. P_t is the phosphorus application rate. Water leaching and volume of erosion differs within no-till and conventional tillage but the amount of soil phosphorus is fixed to 10.6 mg/l. To differentiate no-till and conventional technology, we have also applied technology specific factors. α^{t} and β^{t} depict the distinctive characters of technology 1 (conventional tillage) and 2 (no-till). Parameters used in analysis are also introduced in Table A3 in Appendix I.

To express the social valuation of phosphorus runoff damages, phosphorus is changed into nitrogen equivalents using Redfield ratio, which multiplies net phosphorus with 7.2 to describe the optimum N/P ratio for the growth of phytoplankton, relevant for algal growth in coastal waters. (Lankoski et al. 2006, 14.)

Nitrogen runoff

Nitrogen runoff is dependent on nitrogen fertilization intensity. We use Simmelsgaard (1991) nitrogen runoff function described by Lankoski et al. (2006) to describe the runoff rate from conventional tillage and no-till:

$$Z_N^i = \omega * Exp\left[b_0 + b * \frac{N_i}{100} \right] \qquad (16)$$

where Z_N^i is the nitrogen runoff at fertilizer rate from given cultivation technology, N_t kg/ha, ω depicts the runoff from average fertilization intensity, N_i is the amount of nitrogen proportioned with parameters $b_0 > 0$ and $b > 0$ for average fertilization intensity (100 kg). In the parametric model the N comes from the optimal use of fertilizer chosen by the farmer or social decision maker. To simplify we do not consider the potential of field edges and buffer strips to restrain the nutrient runoff, though in reality it would have some effect on the real runoff rate.

4.2 Afforestation

Afforestation of agricultural lands has been a trend in Finnish agricultural policy since 1960 when government wanted to restrain over production of national agricultural products. Afforestation of fields with low productivity has been subsidised to improve Finnish agriculture's structure and wood production (Wall 1996, 28-33). Nowadays afforestation has not got similar goal in national policy, but due to climate change, afforestation has been taken under conversation again as an option to reduce GHG emissions especially from low productive organic fields.

Feasibility of field afforestation depends on different environmental and silvicultural factors, one of them being the selection of tree species. Generally Norway spruce (*Picea abies*) and silver birch (*Betula pendula*) are most profitable for field afforestation, but downy birch (*Betula pubescens*) succeeds better on peatsoils. Pine trees are often failed as the soils on old arable land are too nutritive. Moreover, failing in field afforestation is often caused by lack of silvicultural practices such as weeding, thinning and complementary planting. Also field's imbalanced nutrient content affects the results. Organic and mull soils cause most problems as long term agricultural practices have changed soils chemical and physical character. (Hynönen & Hytönen 1997, 112-114.)

Due to additional planning and silvicultural practices, costs in field afforestation are generally higher than in normal forest renewal after final felling. Old fields may need forceful tillage and fertilization with potassium to avoid deficiency diseases. On the other hand, high nutrient content benefit grasses, which may impede tree growth demanding herbicide use. One, maybe the most costly difference compared with normal forest renewal is that trees should be planted instead of sowing, because planting increases succeed rate considerably. (Hynönen & Hytönen 1997.) Failing with the seedlings causes again additional costs for the process.

Niskanen (1999) has studied the economic profitability of field afforestation in Finland and claims that silver birch would give the highest private returns compared with Norway

spruce or Scots pine. But when risks of additional costs from renewal planting are included, gives Norway spruce the best results as silver birch has the lowest surviving rate. Nevertheless, not only silvicultural practices or tree species secure the success of afforestation. Regional differences are distinct, comparing afforestation profitability in North and South of Finland (Niskanen 1999, Pahkasalo 2005).

Environmental impacts of afforestation

Trees and vegetation accumulate carbon dioxide through photosynthesis and store it as carbon to their biomass. Eventually, carbon is accumulated also to the soil via litter and plant and animal residues. In general forest vegetation and soils work as a net sink of carbon dioxide. In 2007 NIR, forests were reported to store about -32.8 Tg CO_2. Living biomass contributed the largest part of the total sink (-32.7 Tg CO_2), the rest was stored in harvested wood products (-3.3 Tg CO_2) and mineral soils (-3.6 Tg CO2). Only organic forest soils are net emitters of carbon dioxide (6.7 Tg CO2). (Statistics Finland 2009, Annex1.)

Liski et al. (2006) have measured forest carbon fluxes in general scale in Finland, estimating the average carbon flux through soil and vegetation including heterotrophic respiration[4], litter production and natural and industry based tree removals. Although the study covers all soil types, are soil, litter and ground vegetation studied only on upland forests, excluding for example peatlands which generally have lesser tree stand. According to the study, net primary production (NPP), which denotes the carbon accumulation and losses of forest biomass, would be 0.375 kg C/m^2/year, which would convert to about 13 760 kg CO_2/ha/year. NPP covers the carbon dioxide uptake of vegetation and also the autotrophic respiration which is an important part of plant metabolism where some of the fixed carbon is released back to atmosphere. In the carbon cycle, most of the accumulated carbon is also released back to atmosphere via heterotrophic respiration which refers to organic matter decomposition, and felling (10 130 + 2 200 kg CO_2/ha). The extraction between the emission fluxes indicate if the forest is a storage or source of emissions and is referred as

[4] carbon dioxide flux from decomposition of organic material

net ecosystem production (NEP) or net ecosystem exchange (NEE). According to Liski et al. (2007) Finnish forests store annually about 1 431 kg CO_2/ha from which forest soil and litter sequester 400 kg CO_2/ha and forest biomass about 1 031 kg CO_2/ha.

Figure 2 describes the initial storage and carbon fluctuation in forest. Carbon is sequestering to forest biomass via vegetation photosynthesis (NPP) and is accumulating to soil as organic carbon through vegetation litter production and natural losses and harvest residues from felling. The carbon is released back to atmosphere through natural heterotrophic respiration. The margin between accumulated and released carbon is the annual carbon sequestration rate. Removed timber could be considered as lost or stored carbon depending on the time frame considered suitable for carbon sequestration. Carbon sequestration continues as long as the tree is alive and thus cutting down the wood ends the process. How fast the carbon is released back to atmosphere after the felling depends on how the wood is used (burning, decay, building material, et cetera). Carbon sequestered to wood product is expected to release within five years, but for example with wooden building the time frame is longer. According to Liski (2000) carbon is stored in forest soil for 50 years and in tree stand for 15 years.

The study by Liski et al. (2006) does not consider N_2O or CH_4 emissions, nor assorts results from each forest types (coniferous and deciduous trees), but gives thorough estimates about the total average carbon fluxes and effluxes in Finland's forests. It should be noted that the presented carbon accumulation rate is an average for a forest of any age. On young forest the accumulation is much higher than on forest in the end of the cycle, where also natural loss of trees is higher increasing heterotrophic respiration (Mäkipää & Tomppo 1998).

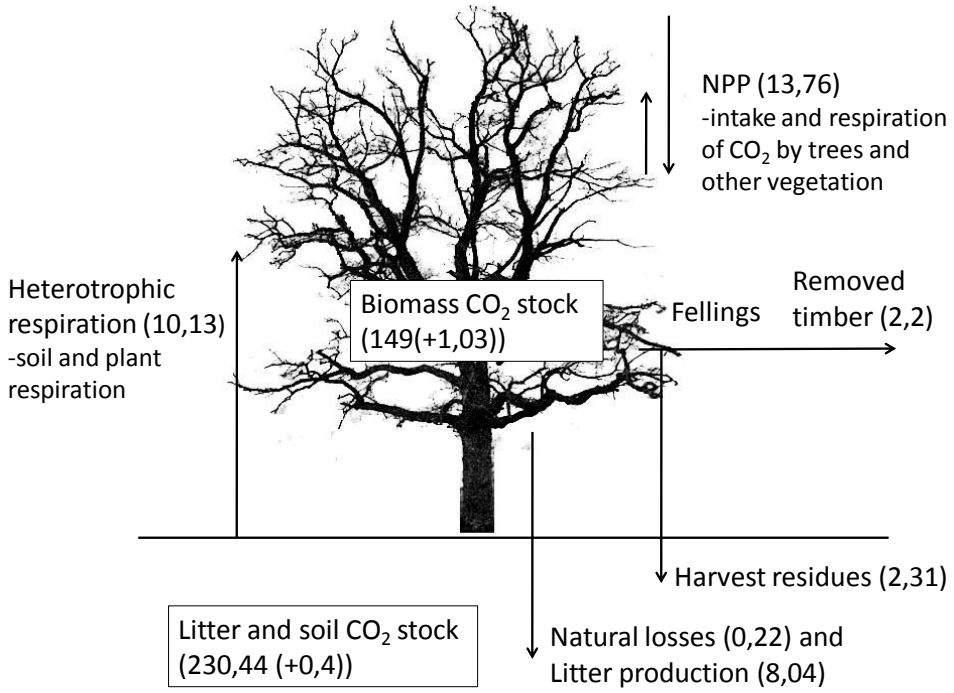

Figure 2. Average carbon dioxide budget of Finland's forests in 1990s. Carbon dioxide accumulation and emissions in CO_2 Mg/ha/year and stocks in CO_2 Mg/ha. Adapted from Liski et al. (2006, Figure 7). Carbon converted to CO_2 using rate 3.67 (US-EPA 2005, 6).

Studies on afforestation's impact to climate emissions are in general focused on organic soil, as it is the soil type afforestation is typically directed to in Finland due to their lower productivity. Field afforestation does not cease organic matter decomposition in organic soils, although the emissions decrease. According to Mäkiranta et al. (2007), soil heterotrophic respiration after afforestation varies from 2 070 to 5 390 kg CO_2/ha being higher in south than north, although region is not the only agent affecting to the emission fluxes. The study has concentrated to peat decomposition on different age and type of forests in Finland but does not dissect forest net emission fluxes more comprehensively, excluding carbon accumulation and carbon effluxes related to vegetation (root respiration, plant respiration). More complete study is done by Lohila et al. (2007), who have compiled the emission fluxes from 30 year old pine afforested organic field South of Finland. The soil respiration is estimated to be about 17 600 kg CO_2/ha, from study by Mäkiranta et al. (2007) measured in Western Finland (Alkkia). According to Lohila et al. (2007) net primary production of trees (NPP) would be about 8 700 CO_2 kg/ha/year (excluding fine roots) and

other forest biomass about 8 400 kg CO_2/ha, making the net accumulation 17 100 kg CO_2/ha, which is somewhat higher than estimated by Liski et al. (2006). The difference is likely due to heterogenic forest age and type. Due to the high peat decomposition rate, afforested organic soil is nevertheless a net source of carbon dioxide of 500 kg CO_2/ha. Lohila et al. (2007) notes that the carbon mineralisation rate and thus soil respiration is somewhat higher compared with other study parcels studied by Mäkiranta et al. (2007), which would suggest that the positive emission flux from the study site in question is higher than afforested organic fields generally have. The study of Lohila et al. (2007) is not taking into account the carbon released from trees after felling, which would indicate that the emission flux is higher than announced.

Nitrous oxide emissions from forest soils are generally low, but from afforested soil, which has been under cultivation for a long period of time, is the soils chemical and physical balance different to initial, thus creating also differing emission fluxes. Maljanen (2003b) suggest that the emission flux can be even higher from afforested organic soil compared with arable soil and Mäkiranta et al. (2007) have measured nitrous oxide emissions from afforested organic coniferous and deciduous forest soil of 9,5 kg N_2O/ha/year and 3,5 kg N_2O/ha/year, respectively. Methane emissions are an average negative, making the soil a sink of the gas of about -1,1 kg CH_4/ha per year.

Forest management practices such as seedling production, silvicultural practices, logging and transportations create climate emissions. Life cycle assessment (LCA) by Berg and Lindholm (2005) for forest industry in Sweden concludes that CO_2-eq. emissions per cubic meter of round wood from the whole life cycle of the wood production would be about 15 kg CO_2/m^3. Emissions are mainly created by energy use. Secondary haulage (transportation from forest) demands the greatest amount of fossil fuels and thus is the largest emission source covering about half of the total emissions. (Berg & Lindholm 2005, 40, table 4.) In addition stem removals at clear cutting reduce carbon content in ecosystem, possibly by one-third (Finér, Mannerkoski, Piirainen & Starr 2003).

Table 5 collects annual climate emissions from afforestation including emissions from silvicultural practices, and carbon accumulation or emissions from soil and vegetation. Forest climate impacts for mineral soil are derived from study by Liski et al. (2006) who have evaluated forest carbon fluxes in general. To make the emission fluxes comparable with afforested organic soils (Lohila et al. 2007), we have excluded the emissions resulting from timber removals. Nitrogen and phosphorus runoff rates are also provided only for organic soils by Lohila et al. (2007). As shown, mineral soils work as a sink of carbon dioxide but organic soils are a net source.

Table 5. Climate emissions of afforested soils. Negative value signify emission sink.

GHG gas	**Clay Soil**	**Silty soil**	**Organic**
CO_2	-3631[b]	-3631[b]	500[c]
N_2O[a]	3,5-9,5	3,5-9,5	3,5-9,5
CH_4[a]	-1,1	-1,1	-1,1
CO_2-eq.	-2616-(-831)	-2616-(-831)	1516-3304

[a]Mäkiranta et al. (2007); [b]Liski et al. (2006) (forest NEE in general excluding felling); [c]Lohila et al. (2007)

Forest soils have also a small nitrogen and phosphorus runoff rate to water systems, but compared with cultivated fields the impact is rather minimal on national and global scale. Different silvicultural practices increase the runoff rate which can create noteworthy impact on local level, for example by increasing the eutrophication of small lakes. The runoff rate is nevertheless dependent on the site characters and intensity and type of the silvicultural practice. Measured from different study parcels in Finland, phosphorus and nitrogen emissions from years 1991-1995 were and average 0,032 kg/ha and 2 kg/ha per year, respectively. (Vuorenmaa, Rekolainen, Lepistö, Kenttämies & Kauppila 2002.) The damage of nutrient runoff of regular forests might underestimate damage of afforested land as long term cultivation have increased soil nitrogen and phosphorus content, affecting also nitrogen cycle and nutrient runoff. As afforested fields are a larger source of nitrous oxide than normal forests, also nitrogen runoff rate is presumably higher.

We use the annual private returns in afforestation of 47.8€ /ha, estimated by Ollikainen and Lankoski (2009). The returns are estimated over one rotation for birch in South of Finland. It should be noted that most of the investments on afforested parcel are made in the beginning of the process and land owner gain incomes from wood thinning and final felling. The costs may also be lower on the next rotation.

To calculate the monetary values of environmental impacts, we have used the same parameters as for crop cultivation (Table A4, Appendix I). Forest land could also be valued for example for its biodiversity and recreation value. We nevertheless do not take into account these values referring to the abundance of forests in Finland. In other countries with more limited amount of forests the valuation of forests and agricultural land can be different.

4.3 Green fallow

Traditionally fallowing is a method to improve soil condition between cultivation periods. Decreased soil disturbance may decrease erosion, increase soil carbon sequestration and thus soil organic matter content, which profit cultivation. The climate benefit trend is sustained for the period of time the soil is fallowed. (Paustian et al. 2006). Thus, in the way fallowing is generally perceived, as a short term phase for cultivated soil, it is not suitable for long term GHG mitigation. For climate change mitigation fallowing is supposed to be more permanent solution for the land, as shorter fallow period is not expected to have difference for climate change. Thus also we expect that the fallowing is a permanent choice.

There are two distinctive ways to fallow the land. On bare fallow the soil is kept without vegetation either mechanically or chemically. On green fallow the soil is kept as undisturbed as possible and with vegetation cover. Vegetation on green fallow can either be annual or perennial. Perennial fallow is normally used if the fallowing is planned to continue several years. Fertilization is not normally needed especially if nitrogen binding vegetation such as legumes or clovers is sowed. (Hyytiäinen & Hiltunen 1992, 78-79.) Although the both systems are introduced as fallowing, they have very different

environmental performance, profiting green fallow. Thus when talking about climate mitigation in terms of fallowing or set aside, is green fallow generally in question.
Green fallow vegetation restrains erosion, decreasing nutrient runoff to water systems and increase soil carbon content (Hyytiäinen & Hiltunen 1992, 78; Heinonen, Hartikainen, Aura, Jaakkola & Kemppainen 1992, 314). It has also been noticed to decrease nitrous oxide emissions compared with croplands, which is probably due to absence of nitrogen fertilization (Ruser et al. 2001). On the other hand using legumes such as green fallow vegetation might increase N_2O emissions (Nieder & Benbi 2008, 207). Bare fallow has not the same capacity to decrease greenhouse gas emissions due to absence of vegetation and continuous mechanical or chemical soil disturbance (Heinonen et al. 1992, 314; Syväsalo et al. 2004; Regina, Syväsalo, Hannukkala & Esala 2004; Lohila, Aurela, Regina, & Laurila 2003).

Table 6 presents the emission fluxes from fallowed fields. Organic soil continue to be a source of carbon dioxide and the emission rate is expected here to be constant, although it is possible that the emission flux changes in the course of time. Maljanen et al. (2007) have studied abandoned organic crop fields (cultivation ended 30 to 40 years earlier) growing for example grasses and have ended up with results of annual net ecosystem exchange (NEE) of 3 200 kg CO_2/ha. As we are interested in the long term impact of green fallow, emissions fluxes are from abandoned fields probably more robust than congruent emissions from recently ceased crop field.

Similar experiment studies are not available for mineral soils but Freibauer, Rounsevell, Smith and Verhagen (2004) suggest that set-aside fields would sequester carbon similarly as no-till fields. Thus we have derived carbon dioxide emissions from this assumption using carbon sequestration rate provided by Lal et al. 1999 (500 kg C/ha/year, ~1835 kg CO_2/ha/year) for no-till fields. The sequestration rate is accounted from conventionally managed fields, making clay and silt soils a sink of carbon dioxide. To calculate the long term impact of fallowing, we expect that the carbon accumulation is maintained for 25 years. The accumulation decrease during time as described in equation (8). Due to lack of data

about nitrous oxide and methane emissions from mineral green fallowed soils, we assume later that the emission flux to be the same as for organic soils.

Table 6. Climate emissions of fallowed soils. Negative value signify emission sink.

GHG gas	Clay Soil	Silty soil	Organic
		Green fallow	
CO_2	-263[b]*	-1053[b]*	3240[a]
N_2O	nd.	nd.	8.2[a]
CH_4	nd.	nd.	-1.7[a]
CO_2-eq.	> -263	> -1053	5641
		Bare fallow	
CO_2	6100[c]	8700[c]	7900[d]
N_2O	5,5-7,8[e]	1,6-3,5[f]	6,5-7,1[f]
CH_4	0,19-0,29[g]	-1,94[g]	-0,34[g]
CO_2-eq.	8088	9436	9920

[a] Maljanen et al. (2007); [b]Lal et al. (1999); [c]Lohila (2008); [d]Maljanen et al. (2004); [e]Syväsalo et al. (2004); [f]Martikainen et al. (2002); [g]Maljanen (2003b)

* Sequestration rate estimated from 25 years following the principle of reducing sequestration capacity.

We analyse the social welfare of green fallow by including private returns and environmental costs or benefits from the fallowing period. We expect that the annual costs from establishment and maintenance are -44 €/ha, and private returns zero. Although fallowing is suggested to improve soil quality and thus possibly improve crop cultivation productivity in future, we assume that crop cultivation is not continued later but the land is on farmer's point of view permanently fallowed and productivity improvements indifferent.

For nutrient runoff we use estimates by Turtola (1993) who has studied different fallowed parcels in Finland during several years. Although fallowing decrease nitrogen and phosphorus runoff, are the rates nevertheless relatively high. Nitrogen runoff is measured to be an average 5 kg/ha and total phosphorus about 0,9 kg/ha (table 7).

In addition to climate and nutrient runoff, we also expect that fallowed field is valued for its landscape. To describe the value of rural landscape, we use the LFA (less favourable area)

payment. LFA is provided in European Union for farmers on areas where cultivation would not be otherwise profitable. Thus LFA describes the benefits of these creating from other reasons than effective crop production, such as rural area vitality and biotopes of rural environment. LFA payment was 169€/ha in 2007 for forage barley.

Green fallow or grass cultivation is suggested to be a better solutions for GHG mitigation than for example afforestation, which has additional impacts on biodiversity and landscape. But in any case, restricting cultivation has socio-economic impacts which would probably become unevenly distributed. According to Lehtonen, Peltonen and Sinkkonen (2006), restricting crop cultivation on peatlands in Finland, allowing only perennial crops, would have the strongest impact on Lapland, where 40 % of the peatland under cultivation are located. Nevertheless, climate policy directed on peatlands would reallocate crop and grass production to more productive soils and would affect agricultural income in Northern Finland only slightly. There is also a possibility that agricultural income would eventually increase compared with the base line. In addition another, environmental and economic benefits would create as a consequence. (Lehtonen et al. 2006.)

5 Comparison of farmland use options

In this chapter we compare the results in order to determine the socially optimal land allocation and production intensities. Later also optimal policies to obtain the socially optimal solutions are discussed. For crop cultivation we examine four different policy scenarios in terms of the environmental impacts. The policy schemes take into account either only carbon dioxide emissions or all CO_2-eq. emissions including nitrous oxide and methane emissions. Further these are treated with and without nutrient runoff. This is because the presumption is, that the policy should be directed so that all externalities are taken into account in order to obtain the maximum social welfare, but in reality this is not always possible to attain. Thus we view the solution in which the policy is considered to take into account all externalities and when it is not. Furthermore, we define the policy related social welfare and complement it by a welfare measure.

Although the main objective of the study is to analyse the social welfare, we do also view the privately optimal solution to compare the difference between input uses and land allocation in the privately and socially optimal solution and to derive the optimal policies.

5.1 Optimal farmland allocation and production

Private profitability

Table 7 presents the private production and profits from crop cultivation, green fallow and afforestation. Also it assess private solution in terms of environmental impacts.

In cultivated land, no-till cultivation gives higher private profits on all soil types than conventional tillage due to its lower production costs. The difference in profits is nevertheless rather small between the technologies, as conventionally tilled fields have higher crop yields. The results are calculated excluding taxes and subsidies, which would be

in reality rather large part of the farmers' returns. Finland's agriculture is operating in rather difficult surroundings due to harsh climatic conditions and thus production is strongly subsidised. Annual per hectare profit is according to our results varying on conventionally cultivated barley fields from 55 to 98 €/ha and on no-till from 59 to 99 €/ha. For both technologies higher profits are obtained in clay soil and lowest on silt soil, depending directly on crop yields.

When crop cultivation is compared with other land use options is barley privately optimal way to allocate the land to, regardless of the soil type. Neither afforestation nor green fallow gives high enough profit for farmers, so they are not realistic choices to allocate the land to. Farmers are expected not to take into account the additional factors which could affect to the decision making, such as environmental impacts.

As for the environmental impacts of each land use options, no-till has considerably lower nitrogen runoff impact compared with conventional tillage. Afforestation and green fallow have nevertheless considerably smaller impact on water systems but also on climate. In order to estimate the social welfare of private decision making deprived of environmental policies, we calculated the ex-post social welfare when only climate emissions are taken into account (Ex-Post welfare I) and when also nutrient damage is considered (Ex-Post welfare II). The results are later compared with the socially optimal welfare.

Table 7. Privately optimal production and profits from barley production, green fallow and afforestation and climate impacts. (Not including rural landscape valuation (LFA).

Soil type	**Clay**		**Silt**		**Organic**	
Crop production						
Technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Fertilization kg N/ha	92	90	86	84	89	87
Production kg/ha	4301	4100	3826	3643	4030	3839
Profits €/ha	98	**99**	55	**59**	74	**76**
External effects						
Nitrogen runoff kg/ha	14,19	6,98	13,64	6,71	13,88	6,83
DRP runoff kg/ha	0,41	0,64	0,41	0,64	0,41	0,64
PP runoff kg/ha	0,85	0,41	0,85	0,41	0,85	0,41
CO_2.eq. kg/ha	3923	9433	3170	5351	13419	13558
Ex post social welfare I	14	**-89**	-8	**-48**	**-195**	-195
Ex post social welfare II	-86	**-151**	-105	**-109**	-293	**-257**
Green fallow						
Establishment and maintenance €/ha	-44		-44		-44	
External effects:						
Nitrogen runoff kg/ha[1]	5		5		5	
DRP runoff kg/ha[1]	0,14		0,14		0,14	
PP runoff kg/ha[1]	0,76		0,76		0,76	
CO_2.eq. kg/ha[2]**	2138		1348		5641	
Ex post social welfare I	-87		-71		-157	
Ex post social welfare II	-136		-120		-206	
Afforestation						
Profits €/ha[4]	48		48		48	
External effects:						
Nitrogen runoff kg/ha[3]	2		2		2	
DRP runoff kg/ha[3]	0,026		0,026		0,026	
PP runoff kg/ha[3]	0,06		0,06		0,06	
CO_2.eq. kg/ha	-1649		-1649		2482	
Ex post social welfare I	81		81		-2	
Ex post social welfare II	70		70		-13	

[1] Turtola (1993) (average from two years measurement period from fallow field under perennial grass), [2]Maljanen (2003b), [3] Vuorenmaa et al. (2002) (average from years 1991-1995), [4] Ollikainen and Lankoski (2009)

* Soil and biomass. Negative figure means that forest is a sink of carbon, derived from Liski et al. (2007), Lohila et al. (2007) and Mäkiranta et al. (2007)

** Carbon sequestration estimated for 25 years.

Social returns

Table 8 presents the socially optimal fertilizer use, production and environmental impacts of both in no-till and conventional tillage technologies. Policy scenarios embody carbon dioxide emissions without (1) and with nutrient runoff (2) and CO_2-equivalents without (3) and with (4) nutrient runoff.

The socially optimal fertilizer use is in general less than 90 kg/ha and is lower the more environmental aspects are included in policy. When the policy is directed to carbon dioxide emissions, the fertilization rate is only few kilograms lower relative to the private optimum, but when the policy accounts all GHG emissions and nutrient runoff, the socially optimal fertilizer rate is an average 17,3 kg/ha less on conventional tillage and 12,8 kg/ha less on no-till. Decreased fertilizer intensity affects directly the crop yields. Considering the policy 4, the yields decrease an average 232 kg/ha, the reduction being nevertheless smaller on no-till fields.

Climate emissions decrease as the scope of the policy expands but the policy impact is rather small. As the policies target only emissions caused by fertilizer application and manufacturing, amount of climate emissions the policy does not reach, is rather great. These, so called autonomous emissions, cover large part of the total emissions but are not directly affected by the policy. Thus, although the policy optimises the emissions created by fertilization, it dismisses the other emissions created by arable land use. Table A5 in Appendix I describes the climate emission distribution between soil, fertilization and cultivation practices and shows that in some cases soil autonomous emissions cover significant part of the total climate emissions, culminating in organic soils. Emissions are described in initial situation without environmental policies and in situation when policy, which includes climate emissions and nutrient runoff, has been set. As shown, the emission reduction from the net climate emissions is relatively marginal.

Comparing the two cultivation technologies, policies which target also nutrient runoff, affect fertilization more on conventional tillage than no-till. This is due to the higher

nutrient runoff load from cultivation system in which the soil is ploughed. The difference between nitrogen load in no-till and conventional tillage is about 6 kg/ha on each soil type, favouring no-till. Also total phosphorus load is lower on no-till fields, although dissolved phosphorus runoff is about 30% higher from no-till, following the results of Lankoski et al. (2006). As table 8 shows, policies do not affect the phosphorus loading much, as fertilizer impacts negligibly runoff in contrast to soil phosphorus. Stronger the impact of fertilizer use is on nitrogen runoff. Decreased fertilizer application reduce nitrogen runoff rate up to 10 % on conventional tillage fields and 7 % on no-till fields. Our implicit assumption has been that the soil type itself does not affect nutrient runoff, and thus the difference in nitrogen and phosphorus load comes from different fertilizer intensities.

Table 8. Fertilizer application, crop yields, climate impacts and nutrient runoff of barley production on different soil types and policy scenarios.

Soil type	**Clay**		**Silt**		**Organic**	
Tillage technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Fertilizer use, kg/ha						
Policy 1	90,00	87,67	84,33	82,00	86,83	84,49
Policy 2	85,28	82,94	79,61	77,27	82,11	79,77
Policy 3	78,10	81,03	72,83	75,79	75,16	78,19
Policy 4	74,46	76,95	69,15	71,67	71,50	74,08
Production, kg/ha						
Policy 1	4269	4068	3794	3611	3998	3807
Policy 2	4190	3989	3715	3532	3919	3728
Policy 3	4058	3956	3591	3506	3792	3701
Policy 4	3985	3880	3517	3431	3718	3625
GHG emissions, kg CO_2-eq./ha						
Policy 1	3893	9403	3169	5321	13066	13214
Policy 2	3827	9337	3103	5255	13017	13166
Policy 3	3726	9310	3008	5209	12946	13149
Policy 4	3675	9253	2957	5177	12908	13107
Carbon dioxide emissions, kg CO_2/ha						
Policy 1	2375	2676	1247	1320	8592	7519
Policy 2	2361	2661	1244	1306	8577	7505
Policy 3	2339	2656	1212	1302	8556	7500
Policy 4	2328	2643	1253	1289	8545	7488
Surface water quality impact						
Nitrogen runoff, kg/ha						
Policy 1	13,99	6,88	13,44	6,61	13,68	6,73
Policy 2	13,53	6,66	13,00	6,40	13,23	6,51
Policy 3	12,87	6,57	12,40	6,33	12,61	6,44
Policy 4	12,54	6,38	12,09	6,15	12,29	6,26
DRP runoff, kg/ha						
All policies*	0,41	0,64	0,41	0,64	0,41	0,64
PP runoff, kg/ha						
All policies*	0,85	0,41	0,85	0,41	0,85	0,41

*Policies impact on P runoff is limited, e.g. on clay soil when only CO_2 emissions affect, are DRP runoff of conv. tillage 0.40595 kg/ha but when CO_2-eq. affect is DRP runoff 0.40569 kg/ha.

Table 9 and 10 present the social welfare from each land use options on each policy scenario derived from private returns and environmental damages on four scenarios. In table 9 we consider that only those emissions the policy is targeting, affect the social welfare, but

in table 10 emissions affect the social welfare weather they are included to the policy or not. The fourth policy scheme, which is directed both to nutrient runoff and all GHG emissions should nevertheless give the same social return regardless of the view point which explains the similar results described in the tables.

To evaluate the social welfare of each cultivation technologies on given soil types and policy scenarios, we define the social valuation of the environmental impacts. The climate emissions are valued to be 20 €/ton CO_2-eq, that is 0.02 €/kg CO_2-eq. Nitrogen equivalent load is valued to 4.27 €/kg N-eq. Moreover, cultivated and also fallowed fields are expected to be valued for their rural landscape, which is described by LFA payment of 169 €/ha.

In table 9 the higher social welfare between technologies on each soil type is marked with **bold.** The results reveal that the optimal land allocation differs depending on which environmental impacts are taken into account. On clay soil conventional tillage provides highest returns except when only carbon dioxide emissions and nutrient runoff are accounted. On organic soil no-till has highest social welfare, expect when all GHG emissions are accounted excluding nutrient runoff. On silt soil conventional tillage provides highest returns when all GHG's are accounted regardless of nutrient runoff. The variation in results is due to nitrous oxide emissions, which can have significant impact to the total climate emissions and thus to the optimal land allocation. The impact of nitrous oxide is especially strong on mineral soils under no-till, while on organic soils carbon dioxide emissions dominate regardless of tillage system. Damage from nutrient runoff varies only slightly between the soil types and the runoff creates difference only between the technologies in general. Damage of nutrient runoff is about one third smaller on no-till fields.

Table 9. Social welfare in different policy scenarios assuming, that only the emissions the policy targets are accounted for.

Soil type	**Clay**		**Silt**		**Organic**	
Tillage technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Net returns from production, €/ha						
Policy 1	98,00	99,29	55,34	58,62	73,55	75,95
Policy 2	97,38	98,67	54,72	57,99	72,93	75,32
Policy 3	95,05	98,22	52,62	57,65	70,69	74,96
Policy 4	93,17	96,84	50,71	56,32	68,83	73,62
Damage from GHG emissions, €/ha						
Policy 1	47,50	53,51	24,93	26,41	171,83	150,39
Policy 2	76,54	186,75	62,07	105,10	260,35	263,31
Policy 3	46,78	53,11	24,23	26,04	171,12	150,01
Policy 4	73,50	185,06	59,13	103,53	258,16	262,14
Damage from nutrient runoff, €/ha						
Policy 1	98,47	61,66	96,13	60,51	97,15	61,02
Policy 2	96,51	60,72	94,25	59,61	95,23	60,08
Policy 3	93,69	60,34	91,69	59,31	92,58	59,78
Policy 4	92,28	59,52	90,36	58,54	91,22	59,01
Social welfare, €/ha						
Policy 1*	**219,50**	214,78	199,41	**201,21**	70,72	**94,56**
Policy 2*	**189,84**	80,92	**161,65**	121,89	**-18,42**	-18,99
Policy 3	123,58	**153,77**	105,70	**141,30**	-24,01	**34,17**
Policy 4	**96,38**	21,25	**70,22**	63,25	-111,54	**-78,53**

*Damage from nutrient runoff is not accounted for

Table 10 present the social welfare comprising all emissions irrespective whether the policy targets them or not. From table 10, on mineral soils conventional tillage provide the highest social returns in every case, whereas no-till outperforms it on organic soils. On silt soil the difference between the technologies is only slight, but on clay soil conventional tillage is considerably more profitable. On organic soil the social welfare is again negative due to high soil greenhouse gas emissions. The difference in profitability between the technologies on organic soils is not caused by the climate emissions as the emission flux is higher on no-till fields (see table 4), but it is caused by lower nutrient runoff and production costs.

The difference between the social welfare of different policy scenarios is however very marginal within certain soil type and technology (for example policy 1-4 on conventionally

tilled clay soil). As environmental impacts are controlled by lower fertilizer use, it decreases crop yields and farmer's income. Thus the gained benefits from reduced climate emissions and nutrient runoff is offset by the decreased productivity, although lower fertilization intensity cuts production costs in part.

In addition comparing the ex-post welfare II (table 7) which depicts the social welfare with privately optimal production choices, the difference between the optimal social welfare and ex-post welfare is only marginal. The reason for the minimal increase in social welfare from the initial is again due to lower productivity as fertilization intensity is lower. (Note that table B1 in Appendix II does not include the landscape valuation, LFA.)

Depending on the accounting system (referring to different viewpoints on table 9 and 10), the optimal land allocation differs in terms of the cultivation technologies. When all emissions are included to the analysis (table 10), the results are more consistent compared with table 9.

Table 10. Valuation of environmental impacts and social welfare when all emissions affect the profit.

Soil type	**Clay**		**Silt**		**Organic**	
Technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Fertilization, production, net returns from cultivation, nutrient runoff impact and climate emissions, see table 8 and 9						
Damage from GHG emissions, €/ha						
Policy 1	77.86	188.07	63.39	106.42	261.32	264.28
Policy 2	76.54	186.75	62.07	105.10	260.35	263.31
Policy 3	74.53	186.21	60.17	104.19	258.92	262.99
Policy 4	73.50	185.06	59.13	103.53	258.16	262.14
Social welfare, €/ha						
Policy 1	**90.66**	18.57	**64.83**	60.69	-115.92	**-80.35**
Policy 2	**93.33**	20.21	**67.40**	62.28	-113.65	**-79.07**
Policy 3	**95.83**	20.68	**69.77**	63.15	-111.81	**-78.81**
Policy 4	**96.38**	21.25	**70.22**	63.25	-111.54	**-78.53**

Although no-till is suggested as a potential tool to mitigate climate change, our findings do not support it. The social welfare to no-till is not self-explanatory higher than social welfare

to conventional tillage. What is more, the increase in social welfare on no-till organic soils is not based on climate benefits, but more on reduction on nutrient runoff and production costs. As soil emission fluxes are seldom linked to cultivation technologies, the results should be regarded with caution. Although Singh and Lal (2005) argues that carbon sequestration potential would be especially high in cool and temperate regions and in conservation tillage technologies may give higher sequestration rates in Norway compared with other regions, referring to Europe or South and North America, this feature does not show in the studies performed in Finland. More indisputable benefit from no-till cultivation is reduced nitrogen and particulate phosphorus runoff compared with conventional tillage.

As the social welfare does not vary considerably whether the emissions are taken into account in the decision making about fertilizer intensity or not, the outcomes depend to a larger extend on the tillage systems and soil types. When all environmental impacts are taken into account, conventional tillage would be socially most attractive choice on mineral soils giving maximum social returns of 96 €/ha/year on clay and 70 €/ha/year on silt soil. Organic agricultural soils under no-till give negative social return of -79 €/ha/year (figure 3). Negative and significantly lower outcome compared with crop cultivation on mineral soils indicate that organic soils would be probably more profitable on alternative land use. Hence, crop cultivation could be allocated solely on mineral soils.

An important feature of the results is that emissions from production life cycle are generally lower from no-till compared with conventional tillage and these emissions are also easier to verify than the emissions from soils, which are affected by several external factors. More importantly, the reductions in production related emissions are permanent, while emissions reduced via carbon sequestration are more unreliable and unsteady, assuming that there will be some. West and Marland (2002) compared the environmental impact of no-till and conventional tillage in terms of carbon dioxide emissions from the whole life cycle of crop production and according to their results, even though no-till would not increase carbon sequestration, the net carbon dioxide emissions would be smaller from no-till compared with conventional tillage. They also suggest that as carbon sequestration is finite in magnitude, in other words, its capacity decreases during time, are other emission reductions

more stabile during the examined period of time. Thus their value could be regarded higher than more unstable and elusively verified soil emissions.

Table 11 presents the social welfare to alternative land use options; fallowing and afforestation, including monetary values of climate emissions and nutrient runoff. The social returns to green fallow include also rural landscape valuation.

Green fallow seems to be more profitable on mineral soil compared with organic soil (about 33 €/ha, 49 €/ha and -37 €/ha on clay, silt and organic soil respectively). As costsand damage from nutrient runoff are similar on each soil type, only climate emissions make the difference to social welfare. Nevertheless, on organic soils green fallow gives higher profit compared with crop cultivation, although the net profit is still negative. On mineral soil green fallow does not improve the profit compared with barley cultivation.

Afforestation yields negative welfare on organic and positive welfare on mineral soils (-13 €/ha and 70 €/ha respectively). Comparing to crop cultivation, organic soils give higher welfare from afforestation, but on mineral soils the difference between the profits from land use is not as clear. On clay soil barley cultivation gives higher welfare but on silt soil afforestation would be slightly better, although the margin between the land use options is minor.

Table 11. Environmental damage and social returns from green fallow and afforestation.

Soil type	Profits*	Climate benefit/damage*	Damage from nutrient runoff	Social welfare €/ha (fallow includes LFA)
Green fallow				
Clay	-44	-42.76[1,6]	-49.02[2]	33.22
Silt	-44	-26.96[1,6]	-49.02[2]	49.02
Organic	-44	-106.02[1]	-49.02[2]	-37.00
Afforestation				
Mineral, South Finland	47.80[3]	32.99[4]	-11.18[5]	69.61
Organic, South Finland	47.80[3]	-49.63[4]	-11.18[5]	-13.01

[1] Maljanen (2003b), Lohila et al. (2004); [2] Turtola (1993); [3] Ollikainen and Lankoski (2009); [4] Derived from Berg and Lindholm (2005), Mäkiranta et al. (2007), Liski et al. (2006), Lohila et al. (2007); [5] Vuorenmaa et al. (2002); [6] Lal et al. (1999)

*Returns from fallowing are negative

Considering alternative land allocation for cultivated soil, it seems that on mineral soil conventional barley cultivation gives generally higher social welfare when climate emissions, surface water quality impact and farmer's income are taken into account. As shown in Figure 3, alternative land allocation becomes considerably more profitable only on organic soils due to cultivation related high autonomous soil emissions. Afforestation gives also higher welfare than green fallow on organic soils, which would make afforestation in social profit point of view most attractive choice to allocate the land to.

Figure 3 also reveals the impact of nutrient runoff to the social returns to the land use and the affect to optimal land allocation. On mineral soils the absence of nutrient runoff only decreases the difference compared to other land use options, but on organic soils green fallowing becomes most profitable option, passing also afforestation.

What is not taken into account here is that considering risks (for example food security), green fallow fields are easier to convert back to cultivation than afforested land, if it is for some reason wanted to do. The impermanence of the green fallow could raise the attractiveness of the option. On the other hand the same reason makes fallowing a more risky solution considering climate emission reductions.

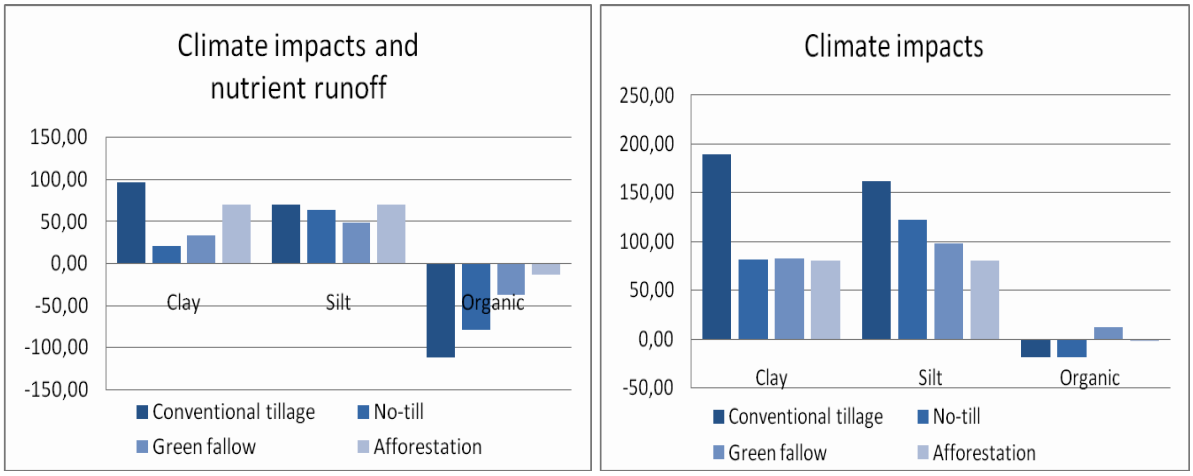

Figure 3. Social returns from land use on different soil types when environmental impacts are taken into account. Social return €/ha/year.

It should be noted that the valuation of agricultural landscape is expected to be relatively large compared with nutrient runoff or climate emissions. Without the LFA subsidy, afforestation would become most profitable on every soil type.

Restrictions to the results about field afforestation brings the fact that the private profit to afforestation is estimated for birch which is suggested to be a profitable tree species for organic soils, but due to higher stumpage price and rather good succeed rate, spruce is more often recommended especially for mineral soils (Pahkasalo 2005; Valkonen 2008). Thus the profit from afforestation on mineral soil could be higher, which we nevertheless have not been able to take into account.

In addition, due to lack of data about afforested mineral soil GHG fluxes and nutrient runoff rates, the results for environmental impacts are very suggestive. It seems again that also in case of social welfare of field afforestation, N_2O plays a significant role. Thus considering further studies, it would be important to have measured nitrous oxide emission fluxes also from afforested mineral soil.

5.2 Environmental policy

As landowners are expected to apply land management practices and allocation choices that yield the best economic return, they are willing to adapt the socially more optimal system only if it is made profitable to adapt. As shown above, the optimal policy requires possibly a combination of tax on fertilizer use and technology subsidy if the tax is not sufficient to provide the intended solution.

The optimal tax rate, cent per kilogram of nitrogen fertilizer, and possibly required subsidy for socially profitable land allocation option are reported in table 12. When emission tax is placed for fertilizer, it can be directed simultaneously on nutrient runoff and climate emissions. Presumably, the more environmental impacts the policy targets, the higher is the tax.

When the tax targets only climate emissions, that is nutrient runoff is excluded, the tax rate is similar for both tillage systems. When the tax is wanted to target also nutrient runoff, differences emerge between the cultivation technologies, making the tax higher for conventional tillage. The tax rate has also some variability between soil types, resulting from differences between the optimal fertilization intensity.

Table 12. Tax rate for nitrogen fertilizer on different policy scenarios and required technology subsidies.

Policy	**Fertilizer tax c/kg N**		**technology subsidy €/ha**
	Conv.	No-till	
Clay			
CO_2	0,06 (3.5)	0,06 (3.5)	1
CO_2-eq.	0,21 (12.4)	0,21 (12.4)	2
CO_2 + nutrient runoff	0,51 (30,0)	0,33 (17.6)	19
CO_2-eq. + nutrient runoff	0,58 (34.1)	0,40 (23.5)	19
Silt			
CO_2	0,06 (3.50)	0,06 (3.50)	6*
CO_2-eq.	0,21 (12.4)	0,21 (12.4)	-
CO2 + nutrient runoff	0,44 (25.9)	0,25 (14.7)	-
CO2-eq. + nutrient runoff	0,57 (33.5)	0,39 (22.9)	-
Organic			
CO_2	0,06 (3.50)	0,06 (3.50)	23*
CO_2-eq.	0,21 (12.4)	0,21 (12.4)	10*
CO_2 + nutrient runoff	0,44 (25.9)	0,26 (15.3)	6*
CO_2-eq. + nutrient runoff	0,58 (34.1)	0,40 (23.5)	-

*technology subsidy for conventional tillage on clay soil and for afforestation on organic and silt soil

The private profits after the emission tax are reported in table 13. They show that crop cultivation after the tax levied, is more profitable for a farmer using no-till than conventional tillage, regardless of soil type. On silt and organic soil afforestation becomes more profitable when the tax rate increase. (Policy schemes 2-4 on silt and policy scheme 4 on organic soil.) To attain the social optimum land allocation also when it does not meet with the private optimum, technology subsidy is required. The rates of the subsidies are reported in table 12, right column.

Technology payment is provided for conventional tillage on clay soil and for afforestation on organic and silt soil. The subsidy is required only down to the point when afforestation becomes an optimal solution for a farmer also without the technology payment.

Curiosity is that on lighter environmental policy, technology subsidy is high for organic soil to compensate the difference between private profit from afforestation and crop cultivation,

and lowers when the policy considers additional environmental impacts. On clay soil, where conventional tillage is subsidized, the payment lowers on lighter policy, increasing towards stronger policy scenario. The difference is due to the structure of the profit. On crop cultivation private returns decrease due to fertilizer taxation, but on afforestation the returns are constant.

Table 13. Private profit after tax levied (€/ha).

Soil type	**Clay**		**Silt**		**Organic**	
Technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
CO_2	93	**94**	50	**54**	68	**71**
CO_2 eq.	79	**81**	38	**41**	55	**58**
CO_2 + nutrient runoff	57	**75**	18	**37**	34	**54**
CO_2 eq. + nutrient runoff	44	**63**	6	**26**	22	**42**

6 Conclusions

Although there are numerous studies on agriculture's greenhouse gas emissions and their mitigation options, comprehensive studies with both economic and environmental aspects, basing on experiment studies and data are rare. This is probably due to the fact that the data about agricultural emissions is relatively new and region specific studies on agricultural soil emissions are still lacking, or being too broad-brushed to serve as a base for empirical analysis.

The objective of this thesis was to analyse the socially optimal agricultural land use when different environmental and economic issues are taken into account. We developed an integrated economic and ecological model to analyse the socially and privately optimal land use, which was further applied to empirical model with data of Finnish agriculture and forestry. Social returns from land use were expected to be dependent on climate emissions and nutrient runoff to water systems in addition to land owner's private returns. We included two different crop cultivation technologies, conventional tillage and no-till on three distinctive soil types; clay, silt and organic soil. Social welfare of crop cultivation was then compared with green fallow and afforestation on parallel soil types. In empirical study the chosen crop species was barley and cultivation expected to focus on South of Finland. We also considered the policy options for agricultural greenhouse gas mitigation, tax and subsidy payment system.

According to the analysis, no-till gives higher private returns for farmers than conventional tillage due to lower production costs, irrespective of the soil type. Crop cultivation is also expectedly more profitable for landowner than afforestation or green fallow. Socially optimal land allocation is nevertheless dependent also on externalities, in this case climate change and surface water quality impact. According to our results, socially optimal fertilizer application rate is lower when different environmental impacts are taken into account than what the private decision maker would choose. The decrease in fertilizer use is especially high when both nutrient runoff and climate emissions are taken into account. No-till system

demands generally lower fertilizer application intensity than conventional tillage, which affects the climate emissions and nutrient runoff. No-till technology has also somewhat lower GHG emissions from production life cycle due to absence of soil tillage and thus less intensive machinery use. It has also lower nitrogen and phosphorus runoff rates to water systems. However, considering the total climate impact is no-till not unequivocally superior compared with conventional tillage. No-till is showed to increase soil carbon dioxide and nitrous oxide emissions, which offset the gained emission reductions from other sources. Thus, according to our analysis, the benefits from no-till are not always sufficient to make it socially more profitable cultivation technology compared with conventional tillage.

There is nevertheless heterogeneity within cultivated lands, and socially optimal land allocation seems to depend on the soil type. Conventional crop cultivation gives the highest social returns on clay soil but on silt and organic soil the results are mixed making the difference between the profitability of the cultivation technologies less clear. In addition, on organic and silt soils also green fallow and afforestation becomes socially more profitable land allocation options, giving especially on organic soil considerably higher social returns compared with crop cultivation.

To attain socially optimal land allocation, we derived an input tax for fertilizer and technology subsidy payment for socially preferable land use option. The tax obtains socially optimal fertilizer intensity on both cultivation technologies and subsidy payment fixes possible distortion between social and private returns after the tax and directs to optimal land allocation. Autonomous soil emissions, which are caused indirectly by soil disturbance, are not covered by the given emission tax. As these emissions are relatively large part of the net climate emissions, cause the tax a distortion between the social and private profit, for which the subsidy payment is placed to direct farmers to the socially optimal land allocation. Thus on clay soil subsidy payment is directed on conventional tillage and on silt and organic soil on afforestation.

The difference between ex-post welfare and social optimum of crop cultivation is only slight, again due to the high rate of autonomous soil emissions. In other words, even if the

fertilizer application is at socially optimal level, it does not increase the social returns significantly from the initial or reduce the climate impact of crop cultivation. Greater increase to social welfare comes if organic soils are allocated to forest or green fallowed land. Decrease of GHG emissions would be large enough to offset the lost profit from crop production. No-till does not seem to decrease climate change impact but its profits are mainly related to reduced production costs and nutrient runoff. It should be noted that no-till has been also argued to decrease soil GHG emissions, which is not showing in available Finnish experiment studies. Thus the results may be dependent on study region and climatic zone. What should be also noted, considering the social welfare of land use, is that we have not been able to take into account all environmental circumstances such as field inclination, field edges and buffer strips. Field characters affect especially nutrient runoff rates. We have also excluded impact of climate change to agricultural production and soil emissions, although the temperature raise may affect crop yields and soil carbon content. The most restricting fact may nevertheless be the lack of complete studies of soil emissions on no-till, afforested and green fallowed lands, especially on mineral soils.

The developed model and the results of our study can be utilized in future discussion of social optimal land allocation and in development of further studies on the issue. The study results show that agricultural climate emission mitigation options do not always give socially optimal outcome, but climate emissions are possible to reduce and simultaneously increase social welfare if emission mitigation technology is optimally placed considering different environmental and production factors. On the other hand the impact of each mitigation technologies to GHG emissions should be more carefully dissected before any land use decisions are made.

There are still several issues for further study. As crop yields, production costs and soil specific climate emissions are important factors in social welfare of land use, optimal land allocation would be interesting to analyse with region specific parameters. For example production factors vary in terms of climate conditions and infrastructure. Our study parameters are derived from South of Finland agriculture, but considering that most of the organic agricultural soils are located on Northern part of Finland, any suggested policies

directed to organic soils may have larger impact on agriculture in North than in South. Lehtonen et al. (2006) studied the potential of decreasing agricultural GHG emissions by limiting cultivation on peatlands, and noted that it would not have significant socio-economic impact on national level, but the effect would be directed on local and municipal level. The results would suggest that restricting cultivation on organic soils would not necessarily affect the food production liability or safety. On the other hand, if afforestation would become socially optimal solution also on mineral soils, (as in our study on silt soil) it may have wider impact on crop production, Finnish agriculture and economics. Self-sufficiency of agricultural products is generally considered to be an important aspect and one of the goals in Finland's agricultural policies and thus crop production may have other values than those included here. Nevertheless, as climate change is a global problem, it is possible that also emission mitigation practices could be allocated worldwide in terms of their profitability. Thus also global valuation of optimal land allocation in terms of given environmental factors would be interesting.

References

Antle, J., Capalbo, S., Mooney, S., Elliott, E., Paustian, K. 2001. Economic Analysis of Agricultural Soil Carbon Sequestration: An Integrated Assessment Approach. Journal of Western Agricultural Economics Association 26/2, 344-367.

Baldock, D. 1992. The polluter pays principle and its relevance to agricultural policy in European countries. Sociologia Ruralis 32/1, 49-65. European Society for Rural Sociology.

Ball, B., Scott, A. and Parker, J. 1999. Field N_2O, CO_2 and CH_4 fluxes relation to tillage, compaction and soil quality in Scotland. Soil and Tillage Research 53, 29-39.

Batjes, N. 1999. Management options for reducing CO_2-concentration in the atmosphere by increasing carbon sequestration in the soil. ISRIC Technical paper 30. Internationational Soil Reference and Information Centre, Wageningen, The Netherlands. 144p.

Berg, S. and Lindholm E-L. 2005. Energy use and environmental impacts of forest operations in Sweden. Journal of Cleaner Production 13, 33-42.

Bionova Engineering. 2008. Maatalouden kasvihuonekaasupäästöjen kustannustehokas vähentäminen. Ministery of Agriculture and Forestry.
http://www.mmm.fi/attachments/ymparisto/5xYyNcvyN/MMM_CO2_raportti_v6.pdf
Cited 24.11.2009

Cannell, M. 2003. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally in Europe and the UK. Biomass and Bioenergy 24, 97–116.

Capalbo, S., Antle, J., Mooney, S. and Paustian, K. 2004. Sensitivity of Carbon Sequestration Costs to Economic and Biological Uncertainties. Environmental Management 33, 238-251.

Chatskikh, D., Olesen, J., Hansen, E., Elsgaard L. and Petersen, B. 2008. Effects of reduced tillage on net greenhouse gas fluxes from loamy sand soil under winter crops in Denmark. Agriculture, Ecosystems and Environment 128, 117-126.

Feng, H., Zhao, J. and Kling, C. 2002. The Time Path and Implementation of Carbon Sequestration. American Journal of Agricultural Economics 84/1, 134-149.

Feng, H., Kurkalova, A., Kling, C. and Gassman, W. 2007. Transfers and environmental co-benefits of carbon sequestration in agricultural soils: retiring agricultural land in teh Upper Mississippi River Basin. Climatic Change 80, 91-107.
Finér, L., Mannerkoski, H., Piirainen, H. and Starr, M. 2003. carbon and nitrogen pools in and old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting. Forest Ecology and Management 174, 51-63.

Freibauer, A., Rounsvell, M., Smith, P. and Verhagen J. 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122, 1-23.

Gál, A., Vyn, T., Michéli, E., Kladivko, E. and McFee, W. 2007. Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. Soil and Tillage Research 96, 42-51.

Greiner, R., Pattersson, L. and Miller, O. 2009. Motivations, risk perceptions and adoption of conservation practices by farmers. Agricultural systems 99, 86-104.

Heinonen, R., Hartikainen, H., Aura, E., Jaakkola, A. and Kemppainen, E. 1992. Maa, viljely ja ympäristö. First edition. WSOY.

Hermle, S., Anken, T., Leifeldt, J. and Weisskopf P. 2008. The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions. Soil and Tillage Research 98, 94-105.

Hynönen, T. and Hytönen J. 1997. Pellosta metsäksi. Pihlaja-sarja 1. Metsälehti Kustannus.

Hyytiäinen, T., Hedman-partanen, R. and Hiltunen, S. 1995. Kasvintuotanto 2. Helsinki. Kirjayhtymä Oy.

Hyytiäinen, T. and Hiltunen, S. 1992. Kasvintuotanto 1. Kirjayhtymä Oy.

IPCC 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Reference Manual, Vol 3.
http://www.ipcc-nggip.iges.or.jp/public/gl/invs6c.html
Cited 08.06.2010

IPCC 2006. IPCC Guidelines for National Greenhouse gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html
Cited 11.03.2010

IPCC 2007a. Intergovernmental Panel on Climate Change. Fourth Assessment Report: Working Group 1 Report. Climate Change 2007: The Physical Science Basis.
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm
Cited 15.6.2009

IPCC 2007b. Intergovernmental Panel on Climate Change. Fourth Assessment Report: Working Group III. Climate Change 2007: Mitigation of Climate Change.
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm
Cited 15.6.2009

Kaiser, E.-A., Kohrs, K., Kücke, M., Schnug, E., Heinemeyer, O. and Munch, J.C. 1998. Nitrous oxide release from arable soil: Importance of N-fertilization, crops and temporal variation. Soil Biology and Biochemistry 30/12, 1553-1563.

Kasimir-Klemedtsson, Å., Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J. and Oenema, O. 1997. Greenhouse gas emissions from farmed organic soils: a review. Soil Use and Management 13, 245-250.

Kimble, J. 2007. On-Farm Benefits of Carbon management: the Farmers' Perspectives. 45-65. In Kimble, J., Rice, C., Reed, D., Mooney, S., Follet, R. and Lal, R. (Ed.) Soil Carbon Management. Economic, Environmental and Societal Benefits. CRC Press

Kurkalova, L., Kling, C. and Zhao, J. 2003. Multiple Benefits of Carbon-Friendly Agricultural Practices: Empirical Assessment of Conservation Tillage. Environmental Management 33/4, 519-527.

United Nations 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations.
http://unfccc.int/resource/docs/convkp/kpeng.pdf
Cited 20.08.2009

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1-22.

Lal, R. and Bruce, J.P 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. Environmental Science & Policy 2, 177-185.

Lal, R., Kimble, J., Follett, R.F. and Cole, C.V. 1999. The potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press LLC. 1-57501-112-X.

Lankoski, J. and Ollikainen, M. 2003. Agri-environmental externalities: a framework for designing targeted policies. European Review of Agricultural Economics 30/1, 51-75.

Lankoski, J., Ollikainen, M. and Uusitalo P. 2006. No-till technology: benefits to farmers and the environment? Theoretical analysis and application to Finnish agriculture. European Review of Agricultural Economics 1-29.

Lapveteläinen, T., Regina, K. and Perälä, P. 2007. Peat-based emissions in Finland's national greenhouse gas inventory. Boreal environment research 12: 225-236.
Lehtonen, H., Peltonen, J. and Sinkkonen, M. 2006. Co-effects of climate policy and agricultural policy on regional agricultural viability in Finland. Agriculture Systems 88, 472-493.

Lewandrowski, J., Peters, M., Jones, C., House, R., Sperow, M., Eve, M. and Paustian, K. 2004. Economics of Sequestering Carbon in the U.S Agricultural Sector. United States Department of Agriculture, Technical Bulletin Number 1909.

Liski, J., Lehtonen, A., Palosuo, T., Peltoniemi, M., Eggers, T., Muukkonen, P. and Mäkipää, R. 2006. Carbon accumulation in Finland's forests 1922-2004 –an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. Annals of Forest Science 63, 687-697.

Lohila, A., Aurela, M., Regina, K. and Laurila, T. 2003. Soil and total ecosystem respiration in agricultural fields: effect of soil and crop type. Plant and Soil, 251, 303-317.

Lohila, A., Aurela, M., Tuovinen, J-P. and Laurila, T. 2004. Annual CO2 exchange of a peat field growing spring barley or perennial forage grass. Journal of Geophysical Research, 109.

Lohila, A., Laurila, T., Aro, L., Tuovinen, J.-P.m Laine, J., Kolari, P. and Minkkinen, K. 2007. Carbon dioxide exchange above a 30-year-old Scots pine plantation established on organic-soil cropland. Boreal Environment Research 12, 141-157.

Lohila, A. 2008. Carbon dioxide exchange on cultivated and afforested boreal peatlands. University of Kuopio. Department of Environmental Sciences. Finnish meteorogical institute. Contributions No 73. Academic Dissertation.

Lohila, A., Regina, K., Aurela, M., Tuovinen, J-P. and Laurila, T. 2009. CO2 balances on different boreal arable soils (In Finnish). In: Soinne, H., Helmisaari, H-S., Hänninen, P., Kähkönen, M., Rankinen, K. and Esala M. (Eds,) Maaperä muuttuvassa maailmasssa. V Maaperätieteiden päivien laajennetut abstraktit. Pro Terra 41, 67-68.

Mäkinen, T., Soimakallio, S., Paappanen, T., Pahkala, K. and Mikkola, H. 2006. Liikenteen biopolttoaineiden ja peltoenergian kasvihuonekaasutaseet ja uudet liiketoimintakonseptit. VTT tiedotteita- research notes 2357. Abstract in English.

Maljanen, M. 2003b. Greenhouse gas Dynamics of Farmed Forested Organic Soils in Finland. Kuopio university publications C. Natural and environmental sciences 156. Doctoral Dissertation.

Maljanen, M., Sigurdsson B.D., Guðmundsson, J., Óskarsson, H., Huttunen, J.T. and Martikainen, P.J. 2009. Land-Use and greenhouse gas balances of peatlands in the Nordic countries –present knowledge and gaps. Biogeoscience Discuss 6, 6271-6338.

Maljanen, M., Hytönen, J., Mäkiranta, P., Alm, J., Minkkinen, K., Laine, J. and Martikainen, J. 2007. Greenhouse gas emissions from cultivated and abandoned organic croplands in Finland. Boreal Environment Research 12, 133-140.

Maljanen, M., Komulainen, V.-M., Hytönen, J., Martikainen P.J. and Laine, J. 2004. Carbon dioxide, nitrous oxide and methane dynamics in boreal organic agricultural soils with different soil characteristis. Soil Biology and Biochemistry 36, 1801-1808.

Maljanen, M., Liikanen, A., Silvola, J. and Martikainen, P.J. 2003a. Nitrous oxide emissions from boreal organic soil under different land-use. Soil Biology & Biochemistry 35, 1-12.

Martikainen, P., Regina, K., Syväsalo, E., Laurila, T., Lohila, A., Aurela, M., Silvola, J., Kettunen, R., Saarnio, S., Koponen, H., Jaakkola, T., Pärnä, A., Silvennoinen, S., Lehtonen, H., Peltola, J., Sinkkonen, M. and Esala, M. 2002. Agricultural soils as a sink and source of greenhouse gases: A research consortium (AGROGAS) In: Käyhkö, J. and Talve, L. (Eds.) Understanding the Global System. The Finnish Perspective, 55-68. Finnish Global Change research Programme FIGARE, 2002.

McCarl, B. and Schneider, U. 2000. U.S. Agriculture's Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective. Review of Agricultural Economics 22, 134-159.

Metcalf, G. 2007. A Proposal for a U.S. Carbon Tax Swap. An Equitable Tax Reform to Address Global Climate Change. Discussion paper 2007-12.

MMM 2001 Maatalouden kehitysarvio kansallista ilmasto-ohjelmaa varten. Työryhmämuistio MMM 2001:2. Maa- ja metsätalousministeriö, helsinki 2001, 44. (In Finnish with an English abstract)

Mooney, S. and Williams, J. 2007. Private and Public Values from Soil Carbon Management. 67-96. In Kimble, J., Rice, C., Reed, D., Mooney, S., Follet, R. and Lal, R. (Ed.) Soil Carbon Management. Economic, Environmental and Societal Benefits. CRC Press

Myllys, M,. and Sinkkonen, M. 2004. Viljeltyjen turve- ja multamaiden pinta-ala ja alueellinen jakauma Suomessa. (Summary: The area and distribution of cultivated organic soils in Finland). Suo 55/3-4, 53-60.

Mäkipää, R. and Tomppo, E. 1998. Suomen metsät ovat hiilinielu – vaikka Kioton ilmastosopimuksen mukaan muulta näyttää. Metsätieteen aikakausikirja 2, 268-274.

Mäkiranta, P., Hytönen, J., Aro, L., Maljanen, M., Pihlajatie, M., Potila, H., Shurpali, N., Laine, J., Lohila, A., Martikainen, P. and Minkkinen, K. 2007. Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. Boreal environmental research 12, 159-175.
Nieder R. and Benbi D.K. 2008. Carbon and nitrogen in the terrestrial environment. Springer Science.

Niskanen, A. 1999. The financial and economic profitability of field afforestation in Finland. Silva Fennica 33/2m 145-157.

Nykänen, H., Alm, J., Lång, K., Silvola, J. and Martikainen P. 1995. Emissions of CH4, N2O and CO2 from a virgin fen and a fen drained for grassland in Finland. Journal of Biogeography 22, 351-357.

Ollikainen, M. and Lankoski J. 2009. Multifunctionality: Environment versus Rural Viability in Social Optima. Journal of Rural Development 32/2, 31-57.

Pahkasalo, T. 2005. Pellonmetsityksen yksityistaloudellinen ja yhteiskunnallinen kannattavuus. University of Helsinki. Department of Forest Economics. Master thesis.

Paustian, K., Antle, J., Sheehan, J and Paul, E. 2006. Agriculture's Role in Greenhouse Gas Mitigation. Prepared for the Pew Center on Global Climate Change.

Paustian, K., Six, J., Elliott, E.T. and Hunt, H.W. 2000. Management options for reducing CO2 emissions from agricultural soils. Biochemistry 48, 147-163.

Perälä, P., Kapuinen, P., Esala, M., Tyynelä, M. and Regina K. 2006. Influence of slurry and mineral fertiliser application techniques on N2O and CH4 fluxes from a barley field in southern Finland. Agriculture, Ecosystems and Environment 117, 71-78.

Pihlatie, M., Syväsalo, E., Simojoki, A., Esala, M. and Regina, K. 2004. Contribution of nitrification and denitrification to N2O production in peat clay and loamy sand soils under different soil moisture conditions. Nutrient Cycling in Agroecosystems 70, 135-141

Pipatti, R. 2001 Greenhouse gas emissions and removals in Finland. VTT Research notes. http://www.vtt.fi/inf/pdf/tiedotteet/2001/T2094.pdf
Cited 15.6.2009

Pipatti, R. & Tuhkanen, S., Mälkiä, P. and Pietilä, R. 2000. Maatalouden kasvihuonekaasupäästöt sekä päästöjen vähentämisen mahdollisuudet ja kustannustehokkuus. VTT Julkaisuja 841.
http://www.vtt.fi/inf/pdf/julkaisut/2000/J841.pdf

Rasmussen K.J. 1999. Impact of ploughless soil tillage on yield and soil quality: A Scandinavian review. Soil and Tillage research 53, 3-14.

Regina, K., Lehtonen, H., Nousiainen, J., Esala, M. 2009. Modeled impacts of mitigation measures on greenhouse gas emissions from Finnish agriculture up to 2020. Agricultural Food Science 18: 477-493.

Regina, K., Pihlatie, M., Esala and M., Alakukku, L. 2007a. Methane fluxes on boreal arable soils. Agriculture, Ecosystems and Environment 119, 346-352.

Regina, K., Perälä, P. and Alakukku, L. 2007b. Greenhouse gas fluxes in boreal agricultural soils under conventional tillage and no-till practice. In: Jandl, R., and Olsson, M (Ed.). European Cooperation in the Field of Scientific and Technical Research COST Action 639: Greenhouse-gas budget of soils under changing climate and land use (BurnOut). 53-56

Regina, K., Syväsalo. E., Hannukkala, A. and Esala, M. 2004. Fluxes of N2O from farmed peat soils in Finland. European Journal of Soil Science 55, 591-599.

Rekolainen, S., Pitkänen, H., Bleeker, A. and Felix, S. 1995. Nitrogen and Phosphorus Fluxes from Finnish agricultural Areas to the Baltic Sea. Nordic Hydrology 26, 55-72.

Rinne, J. 2007. Liikennepolttoaineeksi tarkoitettu ohraetanoli, Suomen ohramarkkinat ja ilmastonmuutos. University of Helsinki. Department of Economics and Management. Master thesis. Abstract in English.

Rochette, P., Angers, D., Chantigny, M. and Bertrand, N. 2008. Nitrous Oxide Emissions Respond Differently to No-Till in a Loam and Heavy Clay Soil. Soil Science Society of America Journal 72/5, 1363-1369.

Ruddiman, W. 2003. The anthropogenic greenhouse era began thousands of years ago. Climatic change 61, 261-293.

Ruser, R., Flessa, H., Schilling, R., Beese, F. and Munch J.C. 2001. Effect of crop-specific field management and N fertilization on N2O emissions from fine-loamy soil. Nutrient Cycling in Agriecosystems 59, 177-191.

Sasaki, H. 2010. Relationships between Agricultural Policies and Environmental Effects in Japan: And Environmental-Economic Integrated Model Approach. Seminar papers from 120th EAAE Seminar in Mediterranean Agronomic Institute of Chania 02-04 September, 2010.
http://eaae.maich.gr/eaae120/papers/Sasaki.pdf
Cited 29.9.2010

Schneider, U., and Smith, P. 2008. Greenhouse gas Emission Mitigation and Energy Intensities in Agriculture. Research unit Sustainability and Global Change, Hamburg University. Working Papers. FNU-164.

Seeberg-Elverfeldt, C. and Tapio-Biström M-L. Global survey of agricultural mitigation projects. Mitigation of climate change in agriculture, series 1. Food and Agriculture Organization of the United Nations (FAO). August 2010.
http://www.fao.org/docrep/012/al388e/al388e00.pdf
Cited 28.9.2010

Simojoki, A. and Jaakkola, A. 2000. Effect of nitrogen fertilization, cropping and irrigation on soil air composition and nitrous oxide emission in a loamy clay. European Journal of Soil Science. 51, 413-424.

Singh, B. 2008. Carbon sequestration in soils of cool temperate regions. Nutrient Cycling in Agroecosystems 81, 107-112.

Singh, B. and Lal, R. 2005. The potential of soil carbon sequestration through improved management practices in Norway. Environment, Development and Sustainability 7, 161-184.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar P., McCarl, B., Ogle, S., O'Mara F., Rice, C., Scholes, B., Sirotenko O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M. and Smith, J. 2007. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society, Biological Science 363, 789-813.

Smith, K., McTaggart, I., Dobbie, K., Conen, F. 1998. Emissions of N2O from Scottish agricultural soils, as a function of fertiliser N. Nutrient Cycling in Agroecosystems 52, 123-130.

Spargo, J., Alley, M., Follett, R. and Wallace, J. 2008. Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia coastal plain. Soil and Tillage Research 100, 133-140.

Statistics Finland 2009. Greenhouse gas emissions in Finland 1990-2007. National Inventory Report under the UNFCCC and the Kyoto Protocol. 8 April 2009. http://www.stat.fi/tup/khkinv/fi_nir_030409.pdf
Cited 05.06.2009

Syväsalo, E., Regina, K., Pihlatie, M. and Esala M. 2004. Emissions of nitrous oxide from boreal agricultural clay and loamy sand soils. Nutrient Cycling in Agroecosystems 69, 155-165.

Turunen, J., Tomppo, E., Tolonen, K. and Reinikainen, A. 2002. Estimating carbon accumulation rates of undrained mires in Finland - application to boreal and subarctic regions. The Holocene 12/1, 69-80.

US-EPA 2006. United States Environmental Protection Agency. Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020. EPA 430-R-06-003.
Uusitalo, R. and Jansson, H. 2002. Dissolved reactive phosphorus in runoff assessed by soil extraction with and acetate buffer. Agricultural and Food Science in Finland 11/4, 343-353

Ussiri, D. and Lal, R. 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil & tillage Research 104, 39-47.

Valkonen, S. 2008. Metsän uudistaminen. In Ed. Rantala, S. Tapion taskukirja, 25 edition. 145-163. Metsä kustannus. ISBN 978-952-5694-26-0.

VandenBygaart, A., Yang, X, Kay, B.D. and Aspinall, J. 2002. Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario. Soil and Tillage Research 65, 231-241.

Vuorenmaa, J., Rekolainen, S., Lepistö, A., Kenttämies, K. and Kauppila, P. 2002. Losses of Nitrogen and Phosphorus from Agricultural and Forest Areas in Finland During the 1980s and 1990s. Environmental Monitoring and Assessment 76, 213-248.

Watson, R., Noble, I., Bolin, B., Ravindranath, N.H., Verardo, D. and Dokken, D. 2000. IPCC Special Report on Land Use, Land-Use Change and Forestry. http://www.grida.no/publications/other/ipcc_sr/
Cited 25.5.2010

West, T. and Marland, G. 2002. A syntehis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture, Ecosystems and Environment 91, 217-232.

West, T. and Post, W. 2002. Soil organic Carbon Sequestration by Tillage and Crop Rotation: A Global Data Analysis. Soil Science Society of America Journal 66, 1930-1946.

WWF 2000. Critical Decisions Could Let Nations Keep Polluting and Still Reach Kyoto Targets. Posted on 04 May 2000
http://wwf.panda.org/about_our_earth/aboutcc/search_climate_news_resources/?2101/Critical-Decisions-Could-Let-Nations-Keep-Polluting-and-Still-Reach-Kyoto-Targets
Cited 15.07.2009

Zhao, J., Kling, C. and Kurkalova, L. 2003, Alternative Green Payment Policies under Heterogeneity When Multiple Benefits Matter. Working Paper. Center of Agricultural and Rural Development.

Appendix I: Parameter values

Table A1. Maximum barley yields on clay, silt and organic soils in South of Finland (kg/ha/year)

Technology	Clay	Silt	Organic
Conventional Tillage	5218	4743	4947
No-till	5017	4560	4756

Table A2. Annual barley production costs under no-till and conventional tillage.

	Symbol	Conv. Till.	No-till	Unit
Barley cultivation costs:				
seeds (own)		52	52	€/ha/year
seeds (bought)		18	18	€/ha/year
liming		9	9	€/ha/year
herbicides, pesticides	K	78	93	€/ha/year
machinery use (tractor)		53	19	€/ha/year
harvesting		9	9	€/ha/year
price of dry barley seed	$\hat{p}$	0.11	0.11	€/kg
price of nitrogen fertiliser	c	2.11	2.11	€/kg

Table A3. Parameters and parameter values for crop cultivation with no-till and conventional tillage

	Symbol	Conv. Till.	No-till	Unit
Nitrogen response function, Mitcherlich				
max. Barley yield (depends on soil type)	m	4743;5218	4560;5017	kg/ha/year
	σ	0,828	0,828	
	ρ	0,0168	0,0168	
Nutrient runoff				
constant	b_0	-0,7	-0,7	
constant	b	0,7	0,7	
average runoff from fertilization	ω	15	7,5	kg/ha/year from 100 kg N
Nitrogen fertilisation (depends on soil)	N_t	62;85	65;83	kg/ha/year
erosion	ζ	800	250	kg/ha/year
runoff volume	Ψ	234	234	mm/ha/year
soil phosphorus	θ	10,6	10,6	mg/l/year
phosphorus rate	P_i	0,143	0,143	mg/l/year
technology factor for PP	α_t	2,4	3,7	
technology factor for DRP	β_t	0,77	1,22	

Table A4. Annual production costs and parameter values and units for green fallow and afforestation.

	Symbol	Green fallow	Afforestation	Unit
Annual private profit	γ	-44	47.8	€/ha
Environmental impacts from afforestation and green fallow:				
climate damage	$Ø$	0.02	0.02	€/kg CO_2-eq.
nutrient runoff damage (nitrogen equivalent)	D	4.27	4.27	€/kg N-eq.
Carbon accumulation on mineral soil under green fallow				
Time frame for C sequestration	T	25	-	year
Rate of interest	r	3	-	%

Table A5. Greenhouse gases from crop cultivation when agricultural policies are not set and when policy is targeted to climate emissions and nutrient runoff.

	Clay		**Silt**		**Organic**	
Technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Climate emissions without environmental policies (initial situation)						
e^w (crop drying)	121	116	108	103	114	108
e^s (fertilizer manufacture etc.)	558	544	524	510	539	525
e^l (fertilization soil emissions)	343	334	322	313	331	322
other LCA	559	475	559	475	559	475
autonomous (soil)	2341	7964	1686	3950	11876	12128
Total	**3922**	**9433**	**3199**	**5351**	**13419**	**13558**
Policy targeting climate emissions (CO_2-eq.) and nutrient runoff of fertilizer application						
e^w	112	109	98	96	104	102
e^s	452	467	419	435	434	449
e^l	277	287	258	267	266	276
other LCA	559	475	559	475	559	475
autonomous (soil)	2276	7916	1622	3904	11811	12081
Total	**3675**	**9253**	**2957**	**5177**	**13174**	**13383**
Emission reduction kg CO2-eq./ha	247	180	243	174	245	175

***** Due to technical reasons within calculation, autonomous soil emissions are not same in initial situation and in environmental policy scheme, although emissions from fertilization are accounted separately.