Agriculture and climate change:
Socially optimal production and land use

Asta Ervola, Jussi Lankoski and Markku Ollikainen*

* Department of Economics and Management, University of Helsinki, Finland,
e-mail: asta.ervola@helsinki.fi, jussi.lankoski@helsinki.fi, markku.ollikainen@helsinki.fi

Paper prepared for presentation at the EAAE 2011 Congress
Change and Uncertainty
Challenges for Agriculture,
Food and Natural Resources

August 30 to September 2, 2011
ETH Zurich, Zurich, Switzerland

1 Introduction

Agriculture has a special role in climate change and climate policies. Agriculture is an important source of greenhouse gases (GHGs) and thereby an integral part of the climate change problem. At the same time, however, suitably designed agriculture may be a part of its solution, one of the corner stones of successful climate mitigation policies. These features make agriculture worth of detailed economic analysis that accounts for the life cycle impacts of agricultural sources and sinks of GHGs.

Starting with emissions, there are three main types of agricultural greenhouse gases. Agricultural carbon dioxide (CO_2) emissions are largely produced from decay of organic material and energy use, while nitrous dioxide (N_2O) emissions emerge from microbial transformation of nitrogen in soil and manure. Methane (CH_4) emissions come from manure management and fermentative digestion by ruminants. Agricultural soils are the largest source of agricultural GHG emissions; especially organic soils produce significant amounts of nitrous oxide and carbon dioxide emissions. Also, intensive cultivation methods and fertilization affect carbon and nitrogen cycles and boost GHG emissions to the atmosphere. (Paustian et al. 2006.) Cultivated mineral soils have however a capacity to store carbon dioxide (IPCC 2007, 514).

Agricultural croplands can contribute to climate mitigation policies via three channels (Lal et al. 1999). First, biofuels and bioenergy produced from crops can replace fossil fuels. Second, agriculture can enhance production efficiency on croplands and thereby reduce direct emissions of production. Third, land conversion and restoration can be changed so as to make cropland from a carbon source to sink. This last feature one is interesting. Continuous and intensive cultivation has resulted in a loss of soil organic matter and nutrients. The challenge is to reverse this dynamics (IPCC 2000). Carbon accumulates in vegetation residues and other organic material via photosynthesis and thus carbon content on soil can be increased by applying management practices that enhance carbon accumulation and soil organic matter content and decrease the decay rate. (Paustian et al. 2006, 7; Smith et al. 2007, 790.)

What complicates the assessment of agriculture’s role in climate policies is the heterogeneity of agricultural soils and land productivities. Emissions from mineral soils and peat lands differ in terms of GHG composition and amounts. Furthermore, emissions differ also in chosen cultivation technologies, such as conventional tillage and no-till, and crops under cultivation. For instance, cereal crops and grass lead to different emissions. Thus, the mitigation potential differs between soil textural classes, field parcels, technologies and crops.

These aspects may be the source to differences in the outcomes of different studies on the subject. While several studies argue that there is a considerable potential to decrease agricultural GHG emissions (Smith et al. 2007; Cannell 2003; Lal 2004), some other studies stress that the potential is somewhat overestimated or unclear (Smith 2004 and Smith et al. 2005). Also, environmental co-effects, such as impacts on agrobiodiversity and nutrient runoff, are said to support mitigation practices and thus policies; they can even create so called win-win situations (Lal et al. 1999). For instance, Antle et al. (2001) argue that using croplands for carbon sequestration without cease of cultivation can become a competitive mitigation measure compared to other, non-agricultural emission mitigation measures, if additional environmental and social impacts are taken into account. Zhao et al. (2003) in turn point out that attractiveness of emission mitigation practices, such as conservation tillage, depends on how society values different environmental benefits created.

In this paper we scrutinize agriculture’s role in mitigation of GHGs. We examine the life cycle climate impacts of agricultural practices, including green fallow, in different soil textural classes. We compare the social returns to agriculture to an alternative land use given by afforestation, a measure generally regarded beneficial to the climate. We focus on one crop cultivated in different soil types, different soil qualities/productivities and different tillage methods. We include emissions from cultivation practices and from soil, and allow for carbon sequestration.

2 Agricultural production and climate impacts: theoretical framework

Consider a parcel of land in three different soil textural classes, clay, organic and silt soil. The same crop is cultivated in these three soils under two alternative cultivation technologies, no-till and conventional tillage. Crop production under conventional mouldboard plough tillage turns the upper layer of soil around, crop residues are buried and soil is left bare. In no-till technology, the new crop seeds and fertilizers are incorporated through the crop residues, avoiding soil disturbance. No-till decreases soil disturbance and thereby potentially organic matter decay, and thus is suggested to be a potential way to decrease CO_2 emissions. (Paustian et al. 2000; Chatskikh et al. 2008).

In any soil type, the amount of crop produced depends on the soil quality q, fertilizer use l_t, and cultivation technology t, as follows,

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

In equation (1), f^t indicates the yields under the two technologies (in what follows t = 1 refers to conventional tillage and t = 2 to no-till). Market-based revenue (private profits) from crop production under technology t is defined by

$$\pi^t = pf^t(l; q) - cl - K_t, \tag{2}$$

where p refers the price of crop net of drying costs, $p = \hat{p} - \mu$ ($\hat{p}$ is the market price of the crop) and c is the price of fertilizer input. Technology specific and per parcel fixed cost K_t consists of labour, fuel, seed and capital costs.

We next add the GHG emissions to the model in terms of CO_2 equivalent emissions. They come from four sources: manufacturing and transporting of fertilizers, emissions from cultivation practices (ploughing, harrowing, planting, pesticide application, harvest etc.), emissions from grain drying and emissions from soil (due to fertilizer use and autonomously via decaying residuals). It is quite natural to postulate that emissions from manufacturing and transporting fertilizers to the field, E_m, are linear in fertilizer application, that is, $E_m = \varepsilon l$. These emissions are independent of cultivation technologies. Emissions from cultivation practices are constant per hectare but do depend on the chosen cultivation technology. We denote them by X^t. Emissions from grain drying are linear in the amount of cereal production and independent of the cultivation technology: $E_w = \sigma f(l; q)$. The most important component of agricultural emissions is the emissions from soil, denoted by E_s^t. They depend on the cultivation technology and fertilizer use. Moreover, a part of soil emissions can be called autonomous emissions from decaying residues. Thus, we express soil emissions as follows:

$$E_s^t = a_s^t + e_s^t(l), \tag{3}$$

where a_t refers to autonomous soil emissions and $e_s^t(l)$ denotes emissions from fertilizer use (the first and second derivatives are positive). Let ϕ denote the social costs of climate change due to emissions, then the social returns to the crop production can be expressed as a function of market revenue and climate impacts as follows:

$$W^{at} = \hat{p}f^t(l;q) - cl - K_t - \phi\left[E_m + X^t + E_w + E_s^t\right], \tag{4}$$

where *a* refers to agriculture and *t* to technology.

Besides crop production, agricultural land can be used for green fallow. Under green fallow, agricultural land may become a sink instead of source of emissions. Carbon sequestering process is finite both in the magnitude and duration, that is, the soil has a capacity to accumulate carbon only until certain point and if brought again to conventional cultivation carbon is released back to the atmosphere. The annualized present value of carbon benefits, *h*, are given in equation (5), where *T* presents the time when the soil carbon stock achieves its long term equilibrium level, and *r* is the real interest rate and α the carbon sequestration rate.

$$h = \frac{\sum_{t=1}^{T}(1+r)^{-t}\alpha\phi}{T} \tag{5}$$

Denote the costs of establishing green fallow by z, then the social returns to green fallow are,

$$W^g = h - z \tag{6}$$

As equation (6) suggests, the decision concerning to establish a long term green fallow is just a discontinuous technologically determined choice. Green fallowing provides also biodiversity benefits (IEEP 2008) and reduces nutrient runoff, but they are omitted here. Let π^g denote the private profits from green fallow. In the absence of support payments π^g may be zero.

3 Socially optimal cultivation when climate impacts count

The problem of a social planner is to choose for each soil type/textural class the combination of land use (crop production under chosen tillage method or green fallow) and input use intensity, which maximizes the social welfare. The planner compares the best agricultural choices - crop production under best tillage technology and green fallow. Our model is recursive, that is, the planner decides first the optimal input use intensity for the two agricultural land-use forms for all soil types, and then chooses the best agricultural alternative for each soil type.

$$\underset{l}{Max}\, W^{at} = \hat{p}f^t(l;q) - cl - K_t - \phi\left[E_m + X^t + E_w + E_s^t\right], \quad \text{t=1,2} \tag{7}$$

For each soil type and both cultivation technologies, the planner chooses the optimal fertilizer rate. For both technologies the optimal choice of fertilizer use is characterized by,

$$W_l^{at} = \hat{p}f_l^t(l;q) - c - \phi\left[E_m' + E_w' + E_s^t{}'\right] = 0 \tag{8}$$

Interpretation of the first-order condition is conventional: the value of marginal product equals fertilizer price adjusted by all relevant social costs (climate damages). Plugging next the optimal fertilizer intensity back to social welfare function (8) defines the maximum social welfare achievable under both technologies in each soil type given exogenous parameters. Thus, for each soil class the choice of technology is defined by,

$$t : \max\left\{W^{a1}(l^{1*},...), W^{a2}(l^{2*}...)\right\}. \quad (9)$$

Equation (9) simply states that for each soil type the land use form is chosen, which produces highest returns.

4 Parametric model

We examine production and land allocation choices and optimal policy instruments in a parametric model tailored to Finnish agriculture. We focus on barley cultivation on clay, silt and organic soils under the two tillage technologies. In accordance with the theoretical model, we determine also returns to green fallow and afforestation on the same soil types.

4.1 Crop production parameters

Farmers use fertilizer that contains nitrogen (N) and phosphorus (P) in fixed proportions. We employ Mitscherlich nitrogen response function: $f^t(N;q) = m^t(1-\sigma\exp(-\rho N))$, t=1,2. Experimental studies in Finland suggest that maximum yields for conventional tillage are slightly higher than for no-till. No-till's life cycle GHG emissions (excluding soil emissions) are lower than those of conventional tillage. Total emissions are slightly lower in no-till, as it has no ploughing and harrowing. Joint emissions for both technologies consist of manufacture, transportation, and application of fertilizers, lime and herbicides, cultivation practices (field work and grain drying), and soil emissions. (Mäkinen et al. 2006).

Climate emissions from nitrogen fertilizers are due to fertilizer manufacture and transportation, and from arable soils due to nitrogen fertilizer application. Application of nitrogen fertilizer increases soil N_2O emissions. Lime, which is used to address soil acidity through increase of soil pH-value, contains different carbonate compounds, mainly limestone ($CaCO_3$) and dolomite lime ($CaMg(CO_3)_2$). Lime application rate is assumed to be 4000 kg/ha once per 5 years and thus yearly emission rate is average annual figure. Carbonate in lime reacts in soil releasing carbon dioxide. In GHG inventory emissions from liming are calculated assuming that all lime is reacting (Pipatti et al. 2000, 13-14). Due to perennial weeds the use of herbicides is higher for no-till.

4.2 GHG emissions of arable soil

Emissions from agricultural soils cover the largest part of agricultural emissions all over the world, also in Finland (Statistics Finland 2009). Nitrous oxide is produced in soils through microbial process of denitrification in anaerobic conditions and nitrification in aerobic conditions. The processes behind carbon dioxide and nitrous oxide emission fluxes are highly complicated and strongly influenced by changes in environmental conditions and agricultural management practices, making the emissions fluctuating and difficult to predict. (Pihlatie et al. 2004; Maljanen et al. 2003.) N_2O emissions are divided into direct emissions from soils due to fertilizer application, biological nitrogen fixation, crop residues and cultivation of organic soils and indirect emissions from nitrogen runoff to water systems and atmospheric deposition of nitrogen (Statistics Finland 2009, 217). For carbon dioxide emissions, organic croplands are the largest source of emissions but mineral soils can work as carbon storage, although field parcels under intensive cultivation are generally sources of carbon rather than sinks. Carbon dioxide fluxes through ecosystems continuously due to photosynthesis and respiration by vegetation and animals and decomposition by microbes. Considering the climate change, distribution of input of CO_2 to the soil and its release back to atmosphere plays important role. The process of decomposition and erosion which are few reasons of CO_2 emissions may be affected by cultivation practices, such as soil tillage. (Paustian et al. 2000, 148.) In general organic arable soils have considerably higher carbon dioxide efflux than mineral soils, due to high soil organic matter content and decomposition rate.

There is no single experiment or study for emission fluxes of crop fields or green fallow in Finland on different soil types. The results of existing studies differ from each other among other things due to heterogeneity between locations, cultivation history and study method and duration. We collect the results from the most existing studies in Table 1. We provide not only CO_2-equivalents but also decompose them to carbon dioxide, nitrous oxide and methane. Due to great uncertainties, results for nitrous oxide and methane are given in ranges. Although there is also large uncertainty regarding carbon dioxide emission fluxes, we use the average values.

Starting with the comparison of conventional tillage and no-till, based on Regina et al. (2007b), results seem to follow the earlier studies in terms of N_2O emissions. They are higher in no-till than conventionally tilled soil. Results on carbon dioxide emissions are slightly surprising: emission rate is generally higher in no-till fields compared with conventionally tilled fields. This is clearly against what one would expect.

Although no-till technology has often argued to increase soil organic matter content and decrease CO_2 emissions, it seems that this argument does not necessarily hold. West and Post (2002) quantified potential carbon sequestration of no-till fields converted from conventional tillage fields. They conclude that global sequestration potential may be on average about 480 kg C/ha/year and continue for 15 to 20 years. This rate is close to one suggested by Lal et al. 1999 (500 kg C/ha/year). Six et al. (2004) suggest that there is a potential to sequester carbon via no-till technology, but the rate is considerably lower (97 kg C/ha/year). Moreover, sequestration is not dependent solely on technology, but is affected by climatic conditions indicating that sequestration rate may be higher on tropical than temperate zones. They also suggest that incorporating crop residues to soil (as in conventional tillage) has positive impact on soil organic carbon content. Also several other studies conducted recently have ended up with results that indicate that no-till may possibly increase carbon sequestration on upper parts of the soil, but does not have that effect or may even decrease the soil organic matter on the lower layers of the soil compared to conventional tillage. (Hermle et al. 2008; VandenBygaart et al. 2002; Oorts et al. 2007; Gál et al. 2007)

Carbon accumulated to crop vegetation is released rapidly back to atmosphere when the crop is consumed, which is presumably shortly after harvesting. Nevertheless, to keep consistency with crop production, fallowing and field afforestation, we use the measure of net ecosystem exchange (NEE) for each land use option which measures the total CO_2 exchange. In other words NEE tells how much carbon is entering and releasing from ecosystem, including soil and vegetation, thus also carbon accumulated to crop is taken into account.

Lower part of Table 1 focuses on green fallow and afforested fields. Conversion of cropland to (perennial) green fallow may have great potential to enhance carbon sequestration of degraded soils (Paustian et al. 2006). Green fallow systems are regarded more beneficial for environment compared to bare fallow, which leaves the soil uncovered. (Nieder & Benbi 2008, 205). Green fallow reduces erosion, increases soil carbon content (Hyytiäinen & Hiltunen 1992, 78) and reduces nutrient runoff to water systems (Heinonen et al. 1992, 314). Also, nitrous oxide emissions are smaller compared to croplands, as soil is not fertilized (Ruser, Flessa, Schilling, Beese & Munch 2001) though using legumes as green fallow vegetation may increase N_2O

emissions. (Nieder & Benbi 2008, 207). Bare fallow has higher rate of erosion, nutrient runoff and GHG emissions, even compared to crop fields, resulting from absence of vegetation (Heinonen et al. 1992, 314; Syväsalo et al. 2004; Regina, Syväsalo, Hannukkala & Esala 2004; Lohila et al. 2003). Thus, only green fallow is considered as an option for land allocation.

Table 1. Net emissions from experiment barley soils under conventional tillage, no-till, green fallow and afforestation. Average CO_2-eq. accounted using GWP of 298 (N_2O) and 25 (CH_4).

GHG gas	Clay Soil	Silt soil	Organic
Conventional tillage			
CO_2-eq.	2684	2008	12207
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]
No-till			
CO_2-eq.	8298	4263	12450
CO_2	1864[f]	536[f]	6723[f]
N_2O	19.7 – 23.5[g]	8.4 – 17[g]	7.9 – 30.6[g]
CH_4	-0.003 – (-0.22)[h]	-2.44 – (-2.18)[h]	-0.62 – (-0.15)[h]
Green fallow			
CO_2-eq.	>-1317	>-1317	5641
CO_2	-1317[b]	-1317[b]	3240[a]
N_2O	no data.	no data.	8.2[a]
CH_4	no data.	no data.	-1.7[a]
Afforested field			
CO_2-eq.	>-3631	>-3631	1516-3304
CO_2	-3631[c]	-3631[c]	500[d]
N_2O	no data.	no data.	3,5-9,5[e]
CH_4	no data.	no data.	-1,1[e]

Data sources: cultivation technologies
[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 (porpotion calculated from Syväsalo et al. 2004); [g] Regina et al. 2007b, Table 3 (porpotion calculated from Lohila et al. 2004); [h] Regina et al. 2007b Table 3 (proportion calculated from Regina et al. 2007a)
Data sources: fallow and afforestation
[a] Maljanen et al. 2007; [b]Lal et al. 1999; [c]Liski et al. (2006); [d]Lohila et al. 2007; [e]Mäkiranta et al. (2007)

Maljanen et al. (2007) measured greenhouse gas emission fluxes from abandoned organic cropland on five field parcels in western Finland during years 2003-2004. Fields were set aside from cultivation about 30 to 40 years ago and left undisturbed to grow grass. Emission flux measurements were performed using chamber method. The net ecosystem exchange (NEE), covering soil respiration and plants gross photosynthesis was measured to be on average 3 240 kg CO_2 /ha/year. The results in terms of CO_2 are similar with study of Lohila et al. (2004), where emission flux from one year old perennial fallow was about 2900 kg CO_2/ha/year (with uncertainty of $\pm$91 kg CO_2/ha/year). Lohila et al. (2004) suggest that organic peat soils are decomposing rapidly even if the intensive crop cultivation is ended. Thus green fallow does not make the soil a sink of carbon. In addition methane and nitrous oxide emissions are similar from abandoned field than from field under barley cultivation (Maljanen et al. 2004).

For green fallow on mineral soil we follow Freibauer et al. (2004) and assume that carbon sequestration rate for set aside field is the same as for no-till. Lal et al. (1999) estimated that converting soil from conventional tillage to no-till would sequester carbon of 500 kg C/ha/year which is equivalent to yearly emission reduction of 1835 kg CO_2/ha. We have expected that the sequestration is continued for 25 years, diminishing towards the soil carbon balance.

5 Production and land use options under climate change

We now use the data to solve the parametric model for socially optimal input use and land allocation. Reflecting the current carbon policies of the EU, we solve the socially optimal solution when only CO_2 emissions count and then expand the analysis to cover all emissions through CO_2-equivalents. We then compare the social returns of each land use form to see which brings highest returns on each soil type.

5.1 Social returns

Table 3a presents the socially optimal solutions when only CO_2 emissions or all climate emissions are considered. Starting with optimal nitrogen fertilizer use, the intensity is 90 kg/ha or below, the highest intensity being on clay soil under conventional tillage and the lowest on silt soil under no-till. In general no-till fields are fertilized less. When only CO_2 emissions are accounted for, optimal fertilizer levels are close to private solution, but allowing for CO_2-eq. emissions, fertilizer intensity reduces considerably in contrast to privately optimal levels. The impact of accounting for all climate effects is rather intense and average fertilizer application rate reduces about 5 kg/ha relative to the case where only CO_2 emissions are taken into account. As a consequence, crop yields decrease. Climate emissions from production differ between the soil types not only in terms of fertilizer use but also in terms of other constant emissions. Net climate emissions (CO_2-eq.) are higher from no-till fields compared to conventional tillage fields, regardless of soil type. On organic soil the difference is nevertheless marginal.

Table 3b presents the monetary estimates of environmental impacts and the social welfare for each case. It presents the social welfare regarding only those emissions that the policy design is targeting (Part I) but the lower part of the table (Part II) accounts for all emissions regardless what emissions the policy is targeting. Landscape valuation is included to the social returns.

Table 3a. Input use, production, and environmental effects from barley cultivation on different soil types and under different policy scenarios.

Soil type	**Clay**		**Silt**		**Organic**	
Tillage technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Fertilizer use, kg/ha						
CO_2	90.00	87.67	84.33	82.00	86.83	84.49
CO_2-eq.	85.28	82.94	79.61	77.27	82.11	79.77
Production, kg/ha						
CO_2	4269	4068	3794	3611	3998	3807
CO_2-eq.	4190	3989	3715	3532	3919	3728
GHG emissions, kg CO_2-eq./ha considered in social welfare (CO_2/CO_2-eq.)						
CO_2	2375	2673	1247	1320	8592	7519
CO_2-eq.	3827	9337	3103	5255	13017	13166
GHG emissions when all emissions are accounted						
CO2	3893	9253	3169	5321	13066	13214
CO_2-eq. (same as above)	3827	9337	3103	5255	13017	13166

Table 3b. Net returns, damage from climate emissions and social welfare.

Soil type	Clay		Silt		Organic	
Tillage technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Net returns from production, €/ha						
CO2	98	99.29	55.34	58.62	73.55	75.95
CO2-eq.	97.38	98.67	54.72	57.99	72.93	75.32
Part I						
Damage from GHG emissions, €/ha						
CO2	47.50	53.47	24.93	26.41	171.83	150.39
CO2-eq.	76.54	186.75	62.07	105.10	260.35	263.31
Social welfare, €/ha						
CO2	**219.50**	214.78	199.41	**201.21**	70.72	**94.56**
CO2-eq.	**189.84**	80.92	**161.65**	121.89	**-24.54**	-24.93
Part II						
Damage from GHG emissions, when all emissions are accounted €/ha						
CO2	77.86	185.06	63.39	106.42	261.32	264.28
CO2-eq.	76.54	186.75	62.07	105.10	260.35	263.31
Social welfare when all GHG emissions are accounted						
CO2	**189.14**	83.23	**160.95**	121.20	**-25.24**	-25.63
CO2-eq.	**189.84**	80.92	**161.65**	121.89	**-24.53**	-24.93

Regardless of the accounting system or cultivation technology, organic soils give distinctively lowest welfare due to high soil GHG emissions. The emissions are actually so great that they make the social welfare negative. For mineral soils; silt and clay, social returns are positive and close to each other. When only carbon dioxide emissions are accounted for, no-till is more profitable on silt and organic soil, whereas conventional tillage performs best on clay soil. When all GHG emissions are considered, conventional tillage provides highest returns on every soil textural class; no-till is outperformed mainly because of its high nitrous oxide emissions. On organic soils the difference in returns between no-till and conventional tillage is very marginal, whereas it is greater on mineral soils.

The upper part of table 4 presents the social welfare of green fallow on different soil types in the presence of landscape valuation payment to the analysis. Due to lack of data about N_2O and CH_4 emissions from green fallowed mineral soils, we have generalized emission flux values from organic soils. We consider only GHG emissions from fallowed soil, although practices that maintain the area under green fallow (preventing natural afforestation) have some emissions, related to energy consumption (mainly fuel use). Presumably these emissions are not significant and due to lack of data, these emissions are not included to the analysis.

Green fallow has other environmental values, such as biodiversity benefits and reduced nutrient runoff. As regards risks in land use, fallowed fields are easier to bring back to cultivation than afforested lands, (this may increase farmers' willingness to accept fallow rather than afforestation as a land use option). On the other hand due to the same reason, long term emission reductions in the form of carbon sequestration are more uncertain. These additional environmental benefits or uncertainties are not considered in our study, although they could have an impact on the social welfare of land use comparison with crop production.

On lower part of table 4 we report the annual social returns to afforested agricultural lands calculated from the first forest rotation. The analysis is based on an empirical study on the profitability of afforestating birch stands in Finland (Ollikainen & Lankoski 2009). Also, we use several empirical studies about climate impacts of afforestation (Mäkiranta et al. 2007; Liski et al. 2006; Lohila et al. 2007; Berg & Lindholm 2005). Both carbon sequestration on the stand of trees and climate emissions from silvicultural practices are included in the analysis. Organic forest soils are a source of carbon dioxide whereas mineral soils are a sink.

Table 4. Environmental damage, profits and social welfare of green fallow and field afforestation.

Soil type	profit €/ha	Climate benefits/damage €/ha	Social welfare €/ha
		Green fallow	
Mineral soils	-44	-21.68	103.32
Organic soils	-44	-106.02	12.18
		Afforestation	
Mineral soils	47.8	32.98	80.78
Organic soil	47.8	-49.64	-1.84

Negative climate impact (€/ha) signify that land is a source of the emissions, when as positive that it is a sink and yield environmental benefits. Climate impact of afforestation includes also emissions from silvicultural practices of 72 kg CO_2/ha/year (Berg and Lindholm 2005)

Table 4 shows that the social returns to green fallow are lower in mineral soils compared to crop cultivation. On organic soils in contrast, social welfare is higher on fallowed land compared to crop cultivation. The ranking would be the same when only CO_2 emissions are taken into account. The social welfare for afforested site of organic soil is about -2 €/ha/year and on mineral soil about 81 €/ha/year, respectively. The result is, once again, negative on organic soils because of organic matter decomposition and high CO_2 emissions (Lohila et al. 2007). Negative climate impact is increased by nitrous oxide emissions. Generally forests' climate emissions are negative, indicating that mineral forest soils and vegetation store carbon. Afforested mineral soils are assumed to have same CH_4 and N_2O impact as organic soils.

The profit of afforested mineral soils can be somewhat underestimated as the timber price and thus profit from birch is lower than from e.g. spruce. Norway spruce is often most recommended tree species for afforestation on mineral soil due to higher stumpage price (Pahkasalo 2005; Valkonen 2008). On organic soils birch is on the other hand suggested to be more profitable than coniferous trees. The analysis is done based on the available data of afforested soils, which is at this point rather limited merely on data from afforested pine forest on organic soil. For mineral soil more generic data from Finland's forests is used.

5.2 Optimal land allocation

Table 5 provides a comprehensive comparison of social returns to allocate the land in socially optimal fashion. The social welfare of crop cultivation is higher for conventional tillage than no-till regardless of the soil type. Conventional tillage on mineral soils (silt and clay) is socially more profitable also when comparing it to alternative land use options, green fallow and afforestation. On organic soil the ranking is reversed due to high greenhouse gas fluxes and both of the alternative land allocation choices gives higher social returns from which the green fallow would be the most optimal.

Table 5. Social welfare of given land use options on distinctive soil types. All GHG emissions included.

	Clay	Silt	Organic
Conventional tillage	**189.84**	**161.65**	-24.53
No-till	80.93	121.89	-24.93
Green fallow	103.32	103.32	**12.18**
Afforestation	80.78	80.78	-1.84

The LFA subsidy (valuation of agricultural landscape) is high increasing profitability of crop cultivation and fallowing. In the absence of this landscape valuation component, afforestation would be the optimal land allocation on every soil type, because afforested field have considerably lower climate impact compared to arable land. We are tempted to argue that not all parts of agricultural landscape are as equally valuable, so that land allocation of marginal organic lands may cover in addition to green fallow also afforestation.

Our results are in a sharp contrast with the arguments which suggest that no-till has global potential to sequester carbon and mitigate climate change (Lal et al. 1999). In the light of empirical findings for Finland and many other countries, the climate impact of no-till is uncertain, and depending on the soil type no-till may even increase GHG emissions. There is no doubt that other than soil emissions related to crop production, are lower under no-till than conventional tillage. West and Marland (2002) suggest that cuts from energy consumption related emissions are more permanent and easier to verify compared to emission reductions with carbon sequestration. Lewandrowski et al. (2004) suggest that sequestrated carbon should be stored in soil for up to 100 years before it can be accounted as permanent emission reduction and comparable with other, more unequivocal emission reductions.

6 Conclusions

We developed a theoretical and parametric model to assess the social welfare of different land use options, with objective to assess the optimal agricultural land allocation in terms of climate change mitigation.

According to our results, cultivation practices suggested for climate change mitigation are not unequivocally profitable for society. Organic soils are significant source of emissions, possibly several times larger than mineral soils. Thus, emission mitigation practices are also most efficient when targeted to organic soils. On cultivated mineral soils the emission mitigation practices have a minor, possibly even negative, effect on emissions. Lack of data hinders especially analysis regarding no-till and green fallow, although both of them are suggested to be possible options for climate change mitigation.

Our study gives an outline how to assess the profitability of land use when climate emissions are considered and how to allocate land to environmentally more efficient use. For further assessment about the agricultural mitigation options, important would be to cover thoroughly issues, such as uncertainty of emission reductions, problems with accurate estimates of regional and global soil emissions, or sequestration potential and its permanence.

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.

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

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.

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.

FAO 2001. Soil carbon sequestration for improved land management. Food and Agriculture Organization of the United Nations. World Soil resources Reports 96. Rome.

IPCC 2000. Land Use, Land-Use Change and Forestry. Watson, R., Noble, I., Bolin, B., Ravindranath, N.H., Verardo, D. and Dokken, D. (Eds.) Carmbridge University Press, UK.

IPCC 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Reference Manual, Vol 3.

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.

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., 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.

Lohila, A., Regina, K., Aurela, M., Tuovinen, J-P. and Laurila, T. 2009. CO2 balances on different boreal arable sois (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.

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.

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. 2003. 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.

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.

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. & Tuhkanen, S., Mälkiä, P. and Pietilä, R. 2000. Maatalouden kasvihuonekaasupäästöt sekä päästöjen vähentämisen mahdollisuudet ja kustannustehokkuus. VTT Julkaisuja 841.

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

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

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.

Smith, P. 2004. Carbon sequestration in croplands: the potential in Europe and the globval context. European Journal of Agronomy 2, 229-236.

Smith, P., Andrén, O., Karlsson, T., Perälä, P., Regina, K., Rounsevell, M. and Van Wesemael, B. 2005. Carbon sequestration potential in European croplands has been overestimated. Global Change Biology 11, 2153-2163.

Statistics Finland 2009. Greenhouse gas emissions in Finland 1990-2007. National Inventory

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.

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.

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

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.