Mitigation options and policies in agricultural sector: a theoretical model and application

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Summary

Agriculture's impact on climate change is unambiguous although its role is multifaceted as it is a source of greenhouse gases but also a sink. It's feasibility to mitigate climate change has raised interest, but thorough studies about the net benefits of the mitigation practices are needed. The aim of this paper is to analyse the social net benefits of barley cultivation on three different soil types in Finland (clay, silt and organic) by using an integrated economic and ecological model. We ask whether it would be privately or socially profitable to allocate some of barley cultivation permanently for alternative land uses or cultivation systems, when production costs, GHG emissions and surface water quality impacts are taken into account. We compare the profitability of barley cultivation under conventional tillage (mouldboard ploughing) to conservation tillage (no-till), green and bare fallow and afforestation. We develop a theoretical framework for climate policies in agriculture. A comparison of the socially and privately optimal input use and land allocation choices allows us to derive optimal carbon tax and payments for climate and water quality friendly tillage practices. The empirical application of the model uses Finnish data to define the social welfare created by alternative soil type and tillage combinations and optimal policy instruments. GHG emissions are assessed on the basis of the whole life cycle of the production comprising also CO_2 emission from soils. To assess the net social benefits related to alternative land use options monetary environmental valuation estimates are used in order to find the socially most profitable land allocation as regards soil type.

1 Introduction

Agriculture's impacts are not limited to food production only. Besides food security and safety, it modifies rural landscape and provides environmental benefits and damages. Traditionally, maintaining agrobiodiversity is regarded as one of the key environmental benefits, while nutrient runoff and soil erosion are the major negative externalities. Rather recently agriculture's impacts on climate and its possibilities to promote climate change mitigation have manifested in research agenda. Agriculture is a part of the climate change problem but, more importantly, agriculture can become an important part of solution as regards successful climate mitigation policies.

Agriculture is, indeed, a source of greenhouse gases (GHGs) due to carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) emissions. Agricultural CO_2 emissions are largely produced from decay of organic material and energy use, N_2O emissions from microbial transformation of nitrogen in soil and manure and CH_4 emissions 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, Antle, Sheehan & Paul 2006.) Interestingly, however, cultivated mineral soils have a capacity to store carbon dioxide (IPCC 2007b, 514).

Agriculture can contribute to mitigation policies via three channels: (i) reducing direct emissions from cultivation; (ii) enhancing GHG removal via carbon sequestration in soils; and (iii) replacing GHG from fossil fuels (Smith et al. 2007). The first channel is self-evident but the second one is interesting. Cultivation of arable land has reduced the carbon content on soils through centuries but this dynamics can be reversed (IPCC 2000). Carbon accumulates in vegetation residues and other organic material and thus carbon content on 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.) The third channel relates to bioenergy crop production and reducing the conversion of new, possibly forested areas for agricultural use.

What complicates the assessment of agriculture's role in climate policies is the heterogeneity of agricultural soils and land productivities. Thus, the mitigation potential differs between soil textural classes and field parcels, and so does other environmental impacts. 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 and it should be taken under mitigation policies (Smith et al. 2007; Cannell 2003; Lal 2004), some nevertheless argue that the potential is somewhat overestimated or unclear (Smith 2004 and Smith et al. 2005). Generally, the environmental co-effects, such as impacts on agrobiodiversity and nutrient runoff, are generally thought 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.

Given differing opinions on the agriculture's possible role in mitigation policies, we examine in the paper the life cycle impacts of agricultural practices in different soil textural classes and compare them to alternatives defined by green fallow and afforestation. 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. We allow for carbon sequestration and also take into account environmental co-benefits. We develop a theoretical model of agriculture, which integrates economic and ecological aspects of cultivation, as well as cultivation technologies (conventional tillage and no-till). A social planner allocates land to the best use and technology. In theoretical model, social returns to green and bare fallow and afforestation are given exogenously but in the empirical part they are analyzed in detail. We use the model to outline the mitigation policies for agriculture. More concretely, we derive the optimal tax rates (permit prices) and technology subsidies required to establish the socially optimal solution through the choices of farmers. We apply this general framework to the Finnish agricultural and forestry data and assess the expected impacts on production, environment as well as on optimal level of the climate instruments for agriculture.

In section 2 we develop the theoretical model of crop production under the two technologies and outline the features of green fallow. Section 3 is devoted to the analysis of socially optimal production intensities and land use, as well as socially optimal climate policies in agriculture. In section 4 we present the data to be used in a parametric model reflecting the theoretical framework. Section 5 provides the results and concluding section 6 ends the paper.

2 Agriculture 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 all 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 a given soil type, the amount of crop produced depends on the soil quality, q, fertilizer use, l_t, and cultivation technology, t, as follows,

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

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). Crop yield increases in soil quality ($f_q^t(l;q) > 0$), as well as in fertilizer application but in decreasing fashion ($f_l^t(l;q) > 0$ but $f_{ll}^t(l;q) < 0$). Crop yields under these two technologies differ slightly, which has to be taken into account. [1]

Market-based revenue (private profits) from crop production under technology t is defined by

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[1] Moreover, no-till reduces both labour and fuel costs and reduces both nitrogen and particulate phosphorus runoff compared to conventional tillage. Potential environmental trade-offs of no-till include increased dissolved phosphorus and herbicide runoff (due to increased use of herbicides to control perennial weeds). (see Lankoski et al. 2006 for a detailed economic and environmental analysis of both technologies).

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

where p refers the price of crop net of drying costs, $p = \hat{p} - \mu$ (thus, $\hat{p}$ 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 environmental dimensions in the framework. Sources of greenhouse gas emissions *e,* are energy use *w* and fertilizers. Emissions from fertilization consist of emissions from manufacturing and emissions from soil due to fertilization. We describe the soil emissions as a function of fertilizer intensity:

$$e^l = \varepsilon e_l^t(l), \tag{3}$$

where ε scales the emissions intensity. We set $\varepsilon = 1$ for the basic analysis. Emissions are increasing in fertilizer intensity, because soils and crops capability to use nitrogen is declining, thus $e_l^t{}' > 0$, and $e_l^t{}'' > 0$.

Manufacture and transportation of fertilizers produce GHG emissions which are depicted in:

$$e^s = e_s^t(l) \tag{4}$$

Again, emission rate is increasing in manufacture and transportation ($e_s^t{}' > 0$).

Finally, grain drying is performed using either cold air dryers or warm air dryers to achieve desired grain moisture level (e.g. 13%). Energy for grain drying usually comes from fuel oil, but also electricity or sun could be used. Emissions from grain drying depend linearly on the amount of yield/harvest,

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

The rest of life cycle emissions from cultivation practices are incorporated in the per parcel term M_t, and they include mostly emissions from fossil fuels and those emissions from soil, which are not dependent on fertilization. Total CO_2-eq. emissions from cultivation practices are slightly smaller from no-till than conventional tillage. The margin comes mainly from energy consumption. Also, agricultural land under conventional tillage have been argued to have higher GHG flux rate compared to no-till, due to stronger soil disturbance which increases the organic material decay rate.

Multiplying, finally, the GHG emissions with the social costs of climate change defines the social damages caused by agriculture. Given the minor role of agricultural emissions at global level, we employ constant marginal cost, ϕ, in the analysis.

As for the water quality impacts of cultivation, we follow Lankoski et al. (2006) and include nutrient runoff to surface waters. Nutrient runoff is a function of applied fertilizer l and chosen tillage technology. No-till technology and conventional tillage have differential effect on surface runoff due to the differences in soil management processes. Conventional tillage, leaving the soil bare for winter, exposes the land for stronger erosion than no-till. We denote nutrient runoff by $z_t = g^t(l_t)$. It is increasing and convex in fertilizer use: $g_l^t > 0$ and $g_{ll}^t > 0$. Nutrient damage function $D(g^t(l_t))$ exhibits conventional properties, $D' > 0$ and $D'' > 0$.

Collecting all parts together produces the social return to the crop production to be used in subsequent analysis:

$$W^{at} = \hat{p}f^{t}(l;q) - cl - K_t - \phi\left[\varepsilon e_l^t(l) + e_s^t(l) + e_w^t f^t(l;q)) - M_t\right] - D(g^t(l_t)) \quad (6)$$

Besides crop production, agricultural land can be used for green fallow. Under green fallow, agricultural land becomes a sink instead of being a source of emissions, that is, it sequesters carbon in soil over time. Notably, however, this 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. We illustrate this dynamic process in Figure C1 in the Appendix III and potential of carbon sequestration under fallowed field in equation 7. In equation 7, T presents the time frame before soil again attains the equilibrium, and r rate of interest. Carbon sequestration rate c is multiplied with price of CO$_2$, ϕ.

$$h = \frac{\sum_{t=1}^{T} (1+r)^{-t} \phi c}{T} \quad (7)$$

Let the sum of carbon sequestration per parcel under green fallow over time be H, so that the annualized present value of carbon benefits be h. Denote the costs of establishing green fallow be e. Then the social returns to green fallow are given by,

$$W^{g} = h - e - R \quad (7b)$$

As equation (7b) suggests, the decision concerning to establish a long term green fallow (conservation fallow) is just a discontinuous technologically determined choice. Nutrient runoff level R reduces compared to crop cultivation. Note also that green fallowing provides biodiversity benefits (IEEP 2008) but for parametric analysis only valuation of open landscape is included. Let π^{g} denote the private profits from green fallow. In the absence of support payments π^{g} may be zero[2].

We next combine agricultural equations (6) and (7b) with an additional land use alternative, afforestation, and derive the socially optimal solution, that is, land allocation and input use intensities that maximize the social welfare in each soil textural class and under differential land productivity.

3 Socially optimal production and policies 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 social welfare. The planner compares the best agricultural choices - crop production under best tillage technology and green fallow - with the social returns to afforestation, denoted W^{f} (and π^{f} being the private net harvest revenue from afforestation). Our model is recursive, that is, the planner decides first the

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[2] Note that it may be positive if green fallow is beneficial in terms of improved perennial weed control, soil structure etc.; our focus here is on a long term green fallow rather than the one used as a part of normal crop rotation.

optimal input use intensity for the two agricultural land-use forms for all soil types, and chooses the best agricultural alternative for each soil type. Finally, the planner compares the social returns from agricultural use to those from afforestation and allocates the land to the one that provides the highest social returns. We take the social and private returns to afforestation as exogenous in the theoretical part but it has an integral role in the empirical part of the paper (see Ervola et al. 2010 for detailed analysis of afforestation)

$$\max_{l} W^{at} = \hat{p}f^{t}(l;q) - cl - K_{t} - \phi\left[\varepsilon e_{l}^{t}(l) + e_{s}^{t}(l) + e_{w}^{t} f^{t}(l;q)) - M_{t}\right] - D(g^{t}(l_{t})), \text{ t=1,2} \quad (8)$$

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

$$W_{l}^{t} = \hat{p}f_{l}^{t}(l;q) - c - \phi\left[\varepsilon e_{l}'(l) + e_{s}'(l) + e_{w} f_{l}'(l;q)\right] - D'(g^{t}(l))g_{l}^{t} = 0 \quad (9)$$

The second order condition can be shown to hold, so that (9) defines maximum for both technologies. Interpretation is conventional: the value of marginal product equals fertilizer price adjusted by all relevant social costs (climate and runoff 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, $W^{a1}(l^{1*},...)$ and $W^{a2}(l^{2*},...)$. The agricultural choice for each soil type is the one which has higher social returns. Once the best tillage choice is known for each soil type, it is compared with social returns to green fallow and afforestation. For each soil type the land use form is chosen, which produces highest returns. This completes the choice of the socially optimal production.

Farmers' decisions differ from those of the planner, as they do not account for environmental impacts. Private decisions follow, however, a similar logic, so that we can deduct farmers' agricultural choices from (8) by setting marginal damages equal to zero to yield simply $\pi_{l}^{at} = \hat{p}f_{l}^{t}(l;q) - c = 0$. Hence, the farmers compare private profits, $\pi^{a1}(l^{1*},...)$ and $\pi^{a2}(l^{2*},...)$ from the two tillage technologies in each soil type and choose one providing highest profits and then they compare it with profits from green fallow and afforestation. Naturally, none of the choices need to coincide with those of the social planner.

The difference between privately and socially optimal fertilizer intensities and land use choices create needs and possibilities for climate policies in agriculture. Recall the aspects (i) and (ii) of mitigation policies in agriculture. As Smith (2005) rightly argues without the government intervening, farmers do not apply emission mitigation practices. Economic incentives can be created using taxes, subsidies and marketable pollution permits, and if needed, support payments that guide the choice of tillage technology. There has been some discussion on which instrument suits best to agriculture. Cap and trade has created interest because of existing emissions trading systems in the EU and U.S. and especially as regards carbon sequestration (McCarl and Schneider 2000; Weersink et al. 2003).[3] However, carbon tax is argued to have some advantages in agriculture. For instance, Metcalf (2007) stresses that if a tax is used there is no difference whether emission pricing is placed

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[3] The most important economic incentive system on European scale is European Union Emission Trading Scheme (EU ETS) which is a cap and 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 trading system.

upstream (i.e. power production) or downstream where energy is consumed (this case agriculture). We would like to add to this, that it is mostly likely easier to levy a tax on fuels and other sources of emissions associated with the everyday cultivation practices.

We now derive optimal policy instruments to guide farmer's input use and land allocation choices in the three soil textural classes. We start with crop production decisions. We denote the optimal tax targeting fertilizer application by τ (note though that τ can equally be interpreted as the price of carbon permits but for simplicity we think it as a tax) and negative tax by *s*. It is easy to show that when crop production is optimal, the optimal tax rate in cases where only climate impacts count (10a) and both climate impacts runoff damages count (10b) are,

$$\tau^* = \phi\left[\varepsilon e_l'(l) + e_s'(l) + e_w f_l'(l;q)\right] \qquad (10a)$$

$$\tau^* = \phi\left[\varepsilon e_l'(l) + e_s'(l) + e_w f_l'(l;q)\right] + D'(g(l))g'(l)\,. \qquad (10b)$$

Thus, the optimal carbon tax is an input tax on fertilizer application. From (10a), tax internalizes climate damages caused by the multiple chains through which fertilizer application affects emissions. Tax in equation (10b) is environmentally wider internalizing also runoff damages. Naturally, optimal tax rate is higher in (10b) than in (10a).

Carbon tax may not, however, be enough for efficient policies in crop production. Suppose first that technology 1 is socially preferable in a given soil type but farmer would choose technology 2. Given that cost structure between the technologies differs partly irrespective of environmental impacts, tax may not be enough to change the cost structure in favour of technology 1. Therefore, for such cases a lump sum payment *T* is needed to make the socially optimal cultivation technology preferable to farmers, that is, the following indifference relation must hold: $\pi^{a1}(l_1^*,...) + T^* = \pi^{a2}(l_2^*,...)$.

Furthermore, suppose green fallow is socially optimal on some soil type then a Pigouvian subsidy reflecting annualized present value of climate benefits would be simply

$$s^* = \phi h\,. \qquad (10c)$$

Subsidy payment has a simple structure since green fallow is technologically fixed. This subsidy is enough for shifting green fallow land to the socially optimal level. This completes our theoretical framework and policy design. We next use a parametric model calibrated to Finnish agronomic and environmental conditions to further examine the nature of climate policies.

4 Parametric model

We examine production and land allocation choices and optimal policy instruments in a parametric model tailored to Finnish agriculture.[4] We focus on barley cultivation in 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.

Farmers use fertilizer that contains nitrogen (N) and phosphorus (P) in fixed proportions. We employ Mitcherlich nitrogen response function,

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[4] Barley is most common cereal crop cultivated in Finland, covering almost half of the total cereal crop cultivation area in 2008. (Tike 2008 4.1.2). It is cultivated almost throughout Finland and succeeds on every soil type. It is mainly produced for forage, but also for malt and starch.

$$f^t(N;q) = m^t(1-\sigma \exp(-\rho N)),\ t=1,2 \qquad (11)$$

Experimental studies in Finland suggest that maximum yields for conventional tillage are slightly higher than for no-till, as reported in Table A1 in Appendix I.

Costs and prices are reported in Table A3 in Appendix I. It reveals that no-till technology has slightly lower cultivation costs than conventional tillage mainly because of less labour and fuel inputs (Lankoski et al 2006). We follow Lankoski et al. (20069 as regards description of nitrogen and phosphorus runoff and allocate equations describing nutrient runoff to Appendix II and focus here solely on GHG emissions in agriculture.

Life cycle emissions from barley production emerge from manufacture, transportation, and application of fertilizers, lime and herbicides, cultivation activities (field work and grain drying), and soil emissions. Life cycle GHG emissions are modelled on the basis of Mäkinen et al. (2006) and collected in Table A4 in Appendix I.

From Table A4, total emissions are slightly lower in no-till than conventional tillage. This owes to lesser cultivation activities (no ploughing and harrowing) in no-till. Emissions from nitrogen fertilizers are due to manufacture and transportation, and the N_2O emissions from soil due to the nitrogen application.[5] 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 ($CaMg(CO_3)_2$). Following Mäkinen et al. (2006), lime application is assumed to take place for barley with application rate of 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.

Emissions from agricultural soils - nitrous oxide and carbon dioxide - 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. These processes and emissions are strongly influenced by changes in environmental conditions and agricultural management practices. (Pihlatie et al. 2004; Maljanen et al. 2003a.) 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, though field parcels under intensive cultivation are generally sources of carbon rather than sinks. Carbon dioxide fluxes through soil continuously, but considering the climate change, important is input of CO_2 to the soil due to photosynthesis and how much is released due to decomposition, which is increased by e.g. soil moulding. (Paustian et al. 2000, 148.) As regards agricultural emissions, carbon dioxide emission factors have most uncertainties (Martikainen et al. 2002) which in turn make emissions rate estimations difficult.

There is no single experiment or study for emission fluxes from barley fields or green fallow in Finland on different soil types. The results of existing studies differ from each

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[5] Emission factor (0.0125 kg N_2O/kg N) is defined by IPCC Guidelines for National Greenhouse gas Inventories (1996). The factor is later changed to 1 % in IPCC Guidelines (2006) but as various studies have resulted higher emission rates from applied nitrogen, are we using the earlier factor (Kaiser et al. 1998; Ruser et al. 2001).

other among other things due to heterogeneity between locations, cultivation history and study method and duration.[6] 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. Also, we report the fluxes for open bare fallow. The numerous data sources used are reported at the lower part of the Table 1.

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: no-till produces more emissions than conventional tillage in sandy and clay soils and only slightly less than conventional in organic soils. This clearly is against what one would expect. According to authors of the study the results are useful for comparison of the two technologies, but not to compare the yearly fluxes from the experimental fields between other studies as the calculations are only performed during day and measure ecosystem precipitation. (K. Regina, personal communication, October 10, 2009). Therefore results of the studies are compared to other studies with proportion of the margin between the two technologies. West and Post (2002) have evaluated various studies from different regions concluding that average global carbon sequestration rate could be about 25 g C/m^2 on continuous wheat field under no-till system. As the conclusion of West and Post (2002) correspond to general assumptions, it is included in addition to Finnish studies to our analysis (in brackets in Table 1). Nevertheless net CO_2-eq. emissions are higher from no-till due to high nitrous oxide emissions.

Table 1. Net emission fluxes from experimental barley fields under conventional tillage, no-till, green fallow and bare fallow. Average CO_2-eq. accounted using GWP of 298 (N_2O) and 25 (CH_4).

GHG gas	Clay Soil	Silty soil	Organic
		Conventional tillage	
CO_2-eq.	2975	2010	12007
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 [5534]	4263 [2827]	12450
CO_2	1864[f] [-900[i]]	536[f] [-900[i]]	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	

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[6] Fluxes of methane, nitrous oxide and carbon dioxide are measured using different chamber techniques or micrometeorological methods. Static chamber method is generally used in the studies for N_2O, CH_4 (Martikainen et al. 2002; Regina, Syväsalo, Hannukkala & Esala 2004) and CO_2 emission fluxes (Maljanen, Komulainen, Hytönen, Martikainen & Laine 2004; Mäkiranta et al. 2007). CO_2 emission fluxes are also often measured using micrometeorological method called eddy covariance (EC) method (Lohila 2008). In principle the study method shouldn't bring inconsistencies to the results and they are comparable with each other. Comparability is challenged by the differing lengths of the study periods and the frequency of measurements. Emissions fluxes vary greatly due to changes in environment and thus there are variation between the time of day, week and year.

CO_2-eq.	-	-	5301
CO_2	-1835[c]	-1835[c]	2900[a]
N_2O	nd	nd	8.2[b]
CH_4	nd	nd	-1.7[b]
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 (porpotion calculated from Regina et al. 2007a) [i]West and Post 2002, continuous wheat, global estimation. Negative figure significates carbon sequestration			
Data sources: fallow [a] Lohila et al. 2004 [b] Maljanen et al. 2007 [c]Lal et al. 1999			

Lower part of Table 1 focuses on green fallow. Conversion of cropland to (perennial) green fallow or grasslands may have great potential to enhance carbon sequestration of degraded soils (Paustian et al. 2006).[7] 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 the soil is not fertilized with nitrogen (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.

Maljanen et al. (2007) have 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 and growing grasses and other vegetation. 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 3240 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. Lohila et al (2004) suggest that organic peat soils are decomposing rapidly even if the intensive crop cultivation is ended. Thus green fallow doesn't convert the soil into a sink of carbon during the first years. Study of Maljanen et al. (2007) suggests that the carbon flux never turns to negative or in other words the soil will always be a source of carbon dioxide, even though the emission rate would decrease. Methane and nitrous oxide emissions are similar from abandoned field than from field under barley cultivation (Maljanen et al. 2004).

Note that net ecosystem exchange includes also carbon accumulated to crop which is harvested from field. In real terms the crop releases the carbon back to the atmosphere relatively quickly. According to the results of Lohila et al. (2004), net ecosystem

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[7] Traditionally fallowing has been used to improve soil structure and control weeds between cultivation periods by withdrawing the land temporarily from active cultivation. Bare fallow is traditional method to control perennial weeds, but green fallow is from environmental viewpoint more recommended system.

production (NEP), which summarizes crop removed from field and soil emission fluxes, would give even higher emissions from green fallow (16 590 kg CO_2/ha/year) compared to barley cultivation (12 330 kg CO_2/ha/year). Due to lack of data about NEP from other cultivated soils, we are not able to compare the results on that part although it would be interesting. On the other hand, if land is converted to permanent green fallow where the crop is not removed from the field, the carbon accumulated to vegetation doesn't similarly release back to the atmosphere but is partly stored to the soil.

Social welfare of green fallow is compounding from establishment costs and possible environmental benefits or damages from emissions (Table 1 and A2 in Appendix). Equation 7a and 7b presented social welfare creating from green fallow and carbon sequestration during time T. Lal et al. (1999) have estimated that converting soil from conventional tillage to no-till would enhance carbon sequestration of 0.5 MT/ha/year[8] which is equivalent to yearly emission reduction of 1835 kg/ha. Freibauer et al. (2004) has evaluated that carbon sequestration rate for no-till could be the same as for set aside field. We are using the evaluated carbon sequestration rate only for mineral soils (here clay and silt) and for organic soils the research of Syväsalo et al. (2004). Nutrient runoff rates are clearly lower from green fallowed field compared to crop cultivation (Turtola 1993). Parameter values for empirical analysis are presented in Table A5 in Appendix I.

5 Comparison of the land use alternatives and policies

We now use the data to solve the parametric model for socially optimal input use and land allocation. We then outline the socially optimal policies under different cases. 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. Moreover, we add surface water quality impacts to both of above cases; thus we have four optimal solutions altogether. We then compare the social returns of each land use form to see which brings highest returns in each soil type. In a similar vein, we solve four set of optimal policy instruments to implement the socially optimal solution through farmers' private choices. We first report the results from privately optimal solution.

5.1 Optimal production and land allocation

Table A2 in Appendix conveys key results of the privately optimal solution under all land use forms. The upper part of Table A2 is devoted to crop production and green fallow and the lower part provides the annualized net present value of profits from afforestation. Furthermore, for each case we indicate the environmental impacts (external effects) and determine the ex-post social welfare.

Starting with crop production under conventional tillage and no-till technology, the privately optimal fertilizer application rates are close to each other and so are the yields. Thus, given that no-till has lower cultivation costs (labour and fuel), it is more profitable on every soil type. The difference is, however, marginal, so that basically either of the technologies can be chosen. Profits are small, indicating low productivity of agriculture in harsh climate. We also report in Table A2 the environmental impacts. Recall, in the absence of policies, farmers neglect these effects. Using the social valuation of climate and water damages, we also report the ex-post social welfare when CO_2-equivalents alone are

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[8] MT is an abbreviation for metric ton and equals 1000kg

taken into account (welfare I) and when also water pollution damages are taken into account (welfare II).

If the farmer decides to establish green fallow, the annualised costs from establishment and management would be about 44 €/ha and private returns will be zero. Nevertheless, the ex-post social welfare is XXX, because green fallow sequestrates carbon in soil. The private solution would in any case be crop cultivation in all soil types. The final stage is to compare private profits from best agricultural land use with profits from afforestation, presented in the lowest part of Table A2.

Table 2 present alternative socially optimal solutions depending on which environmental aspects are taken into account. As already mentioned the four analysed cases are: CO_2 without and with nutrient runoff, and CO_2-eq without and with nutrient runoff.

Table 2. Input use, production, and environmental effects under barley cultivation in 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 only	90	87,67	84,33	82	86,83	84,49
CO_2-eq. only	85,28	82,94	79,61	77,27	82,11	79,77
CO_2 + nutrient runoff	78,1	81,03	72,83	75,79	75,16	78,19
CO_2-eq. + nutrient runoff	74,46	76,95	69,15	71,67	71,5	74,08
Production, kg/ha						
CO_2 only	4269	4068	3794	3611	3998	3807
CO_2-eq. only	4190	3989	3715	3532	3919	3728
CO_2 + nutrient runoff	4058	3956	3591	3506	3792	3701
CO_2-eq. + nutrient runoff	3985	3880	3517	3431	3718	3625
GHG emissions, kg CO_2-eq./ha						
CO_2 only	2375	2673	1247	1320	8592	7519
CO_2-eq. only	4169	9388	3156	5306	13174	13513
CO_2 + nutrient runoff	2339	2656	1212	1302	8543	7500
CO_2-eq. + nutrient runoff	4097	9348	3087	5269	13091	13476
Nitrogen runoff, kg/ha						
CO_2	13,99	6,88	13,44	6,61	13,68	6,73
CO_2 -eq.	13,53	6,66	13	6,4	13,23	6,51
CO_2 + nutrient runoff	12,87	6,57	12,4	6,33	12,61	6,44
CO_2-eq. + nutrient runoff	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

*Change in phosphorus runoff between the policies is marginal, e.g. on clay soil when only CO_2 emissions are affecting to the decision making, are DRP emissions from conventional tillage 0.40595 kg/ha. When all GHG emissions are affecting, are DRP emissions 0.40569 kg/ha.

Starting with optimal nitrogen fertilizer use, it generally is clearly below 90 kg/ha, the highest rate being on clay soil under conventional tillage and the lowest on silt soil under no-till. When only CO_2 emissions are accounted for, optimal levels are close to private solution, but accounting for CO_2-eq. emissions reduces fertilizer use considerably relative to private levels. Taking into account nutrient runoff damage further reduces fertilizer use and changes relative fertilizer intensities between conventional and no-till cultivation. Now no-till has higher intensity. The impact of accounting for all environmental effects on fertilizer intensity is actually quite significant as average fertilizer application rate is reduced more than 10 kg/ha relative to the case where only CO_2 emissions are taken into account.

Life cycle emissions related to cultivation practices are assumed to be the same in all soil types so that the main differences are caused by fertilizer application from soil specific emissions, which are highest in organic soils.

Cultivation technologies differ greatly in their impacts on nutrient runoff. The difference in nitrogen runoff is about 6 kg/ha in favour of no-till. Also the particulate phosphorus runoff is about twofold less under no-till. In contrast, no-till increases the dissolved phosphorus runoff about 30%. Highest nitrogen runoff rate is on clay soil due to highest nitrogen application rate, although generally the nutrient runoff is fairly similar regardless of soil type.

In addition to agriculture's impact on climate change and surface water quality it also has an important role as regards traditional landscapes, agro-biodiversity, and viability of rural landscapes. As an estimate of social valuation of these aspects we use the LFA (less favorable area) payment of 169 €/ha as a social value of agriculture's contribution to rural landscape.

Tables 3, 4a and 4b present the monetary estimates of environmental impacts and define the social welfare under each case. In Table 3 we consider only those emissions the policy design is targeting.

Table 3. Social welfare in the case where only those emissions that are specifically addressed by policy are accounted for.

Soil type	Clay		Silt		Organic	
Tillage technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Net returns from production, €/ha						
CO2	98.00	99.29	55.34	58.62	73.55	75.95
CO2-eq.	97.38	98.67	54.72	57.99	72.93	75.32
CO2 + nutrient runoff	95.05	98.22	52.56	57.65	70.69	73.62
CO2-eq. + nutrient runoff	93.17	96.84	50.71	56.32	68.83	74.96
Damage from GHG emissions, €/ha						
CO2	47.50	53.47	24.93	26.41	171.83	150.39
CO2-eq.	83.37	187.75	63.12	106.11	263.47	270.26
CO2 + nutrient runoff	46.78	53.11	24.23	26.04	170.86	150.01
CO2-eq. + nutrient runoff	81.94	81.94	61.74	105.37	261.81	269.52
Damage from nutrient runoff, €/ha						
CO2	98.30	61.72	95.98	60.58	96.99	61.07
CO2-eq.	96.36	60.76	94.11	59.66	95.09	60.14

CO2 + nutrient runoff	93.54	60.40	91.54	59.38	92.41	59.83
CO2 eq. + nutrient runoff	92.13	59.59	90.20	58.61	91.05	59.06
Social welfare, €/ha						
CO2*	**219.5**	214.82	199.41	**201.21**	70.72	**94.56**
CO2-eq.*	**183.01**	79.91	**160.60**	120.88	**-21.55**	-25.94
CO2 + nutrient runoff	123.73	**153.71**	105.79	**141.24**	-23.58	**34.12**
CO2-eq. + nutrient runoff	**88.07**	19.29	**67.79**	61.34	-115.03	**-85.95**

*Damage from nutrient runoff is not accounted for

In Tables 4a and 4b we assume that all emissions affect social welfare regardless of which emissions the policy design is targeting. Furthermore, in Table 4b we keep the same assumption and assume that for clay and silt soil no-till cultivation can sequester carbon at rate of 900 kg CO_2/ha.

Table 4a. Social welfare when all emissions are accounted for.

Soil type	Clay		Silt		Organic	
Technology	Conv.	No-till	Conv.	No-till	Conv.	No-till
Fertilization, production, net returns from cultivation, nutrient runoff and damage, see Tables 2 and 3						
GHG emissions, kg/ha						
CO2	4199,38	9418,59	3186,69	5336,44	13204,58	13544,05
CO2-eq.	4168,52	9387,74	3155,86	5305,55	13173,72	13513,19
CO2 + nutrient runoff	4121,34	9375,21	3111,26	5295,84	13127,99	13502,85
CO2-eq. + nutrient runoff	4097,2	9348,31	3086,88	5268,74	13103,74	13475,81
Damage from GHG emissions, €/ha						
CO2	83.99	188.37	63.73	106.73	264.09	270.88
CO2-eq.	83.37	187.75	63.12	106.11	263.47	270.26
CO2 + nutrient runoff	82.43	187.50	62.23	105.92	262.56	270.06
CO2-eq. + nutrient runoff	81.94	186.97	61.74	105.37	262.07	269.52
Social welfare, €/ha						
CO2	**84.65**	18.18	**64.59**	60.30	-118.58	**-87.02**
CO2-eq.	**86.62**	19.14	**66.47**	61.24	-116.67	**-86.08**
CO2 + nutrient runoff	**88.06**	19.32	**67.80**	61.38	-115.67	**-85.92**
CO2-eq. + nutrient runoff	**88.07**	19.29	**67.79**	61.34	-115.03	**-85.95**

Table 4b. Social welfare and climate damage from no-till when no-till is assumed to sequester carbon at rate of 900 kg CO_2/ha/year. GHG emissions include all emissions during barley production life cycle and are expected to affect to the SW regardless whether they are included to the policy or not.

	Clay*	Silt*
Fertilization, production, net returns from cultivation, nutrient runoff and damage follows Tables 2 and 3		
GHG emissions kg CO2-eq./ha		
CO2	6654,59	3900,44
CO2-eq.	6623,74	3869,55
CO2 + nutrient runoff	6411,21	3859,84
CO2-eq. + nutrient runoff	6384,31	3832,74
Damage from climate emissions, €/ha		
CO2	133,09	78,01
CO2-eq.	132,47	77,39
CO2 + nutrient runoff	128,22	77,20
CO2-eq. + nutrient runoff	127,69	76,65
Social welfare, €/ha		
CO2*	77,46	89,02
CO2-eq.*	78,42	89,96
CO2 + nutrient runoff	78,60	90,10
CO2-eq. + nutrient runoff	76,81	90,09

Regardless of the accounting system or cultivation technology, organic soils give distinctively lowest outcome resulting from high GHG emission rate. In Table 4a organic soils differ from silt and clay soils as no-till technology seems to give higher SW compared to conventional tillage. This is due to lower production costs and nutrient runoff. Net climate emissions are nevertheless higher from no-till (Table 1). In Table 3 the result is partly the same in terms of clay and organic soils, but silt soil gives more diversified results. With all GHG emissions conventional tillage gives higher returns, but without nitrous oxide and methane emissions no-till would be more profitable.

Comparing the two technologies, no-till and conventional tillage, it seems that when all emissions are affecting to the SW regardless whether they are considered in the policy, conventional tillage is clearly more profitable cultivation system on clay soils and partly on silt soils. With lower field emission flux, no-till would be more profitable on silt soil, but does not change the result for clay soil. What is important to notice is that depending on the viewpoint (Table 3 and 4a) the order of most beneficial technology for each soil types may differ. In addition, when all emissions are accounted for in the SW, the difference between the policies is very marginal within the soil types. As climate policy would mean lower fertilizer application rate and thus lower yields it would affect farmers' income although it would simultaneously cut also the emissions and production costs. Without the landscape valuation payment (LFA compensation) the social welfare would be negative in many cases, but on organic soils when all emissions are accounted for the results are negative even with LFA payment.

Open landscape is also a feature affecting to the social valuation of green fallow. The results of ex-post social welfare with only GHG emissions (Ex-post social welfare I) and with impact to surface waters (Ex-post social welfare II) are presented in Table A2 in Appendix. For Table 5 we have estimated the social welfare of green fallow on different soil types using equation 7 and including also landscape valuation payment to the analysis. Due to lack of information about nutrient runoff on fallowed silt and organic soils, we are using the figures from clay soil, as the differences are not substantial on cultivated soil either. For N_2O and CH_4 emissions, values from organic soils are used.

Table 5. Social welfare creating from green fallow. €/ha/year

Soil type	Investments	Climate benefit/damage	Damage from nutrient runoff	Social welfare €/ha (including LFA)
Clay, Silt	-44	-21,69	-49,0196	54,30
Organic	-44	-106,02	-49,0196	-30,00

Negative value significant costs and positive incomes

To compare the social welfare of crop cultivation to afforestation, we are using the results of Ervola et al. (2010) for afforestation of old agricultural lands. In their analysis, social welfare of field afforestation is compounding from yearly net profit of the afforestation and environmental benefits or damages compounding from the afforestation during the first rotation in Finnish naturally regenerated downy birch forest. Environmental impacts are considered to be carbon sequestration to tree stand and climate emissions from silvicultural practices. Also nutrient runoff rates are considered. According to the study, average social welfare created by afforested site on organic soil is about 47 €/ha/year in South of Finland and 80 €/ha/year in North of Finland. Soil carbon decomposition is faster in South, which makes afforestation on organic soil in terms of carbon sequestration more profitable in North.

As organic soils have the lowest productivity as regards wood growth but highest soil emission fluxes, the results are likely to be higher on mineral soils. For example, profit from production in mineral soil in Southern Finland under spruce can be over three times more than on organic soil (Pahkasalo 2005). In general spruce is considered to be more productive than birch, as birch is often used as pulp but spruce is also used as timber, which has higher stumpage price. (Pahkasalo 2005; Valkonen 2008.)

What can be concluded from our findings is that although no-till has been considered as a potential tool to mitigate climate change, while lowering production costs, is the social welfare from fields under no-till slightly higher only on organic soils. From mineral soils conventional tillage gives higher social net profit. Our results suggest, that if policy is taking into account all environmental impacts included in our analysis, is the social welfare ranging from -115 to 88 €/ha/year on conventional tillage, the highest profit received from clay soils and the lowest from organic soils. As regards no-till the corresponding figures are from -86 to 61 €/ha/year, the highest profit received from silt soil and lowest again from organic soils. According to the studies used for comparing the climate impacts of different cultivation technologies, no-till wouldn't necessarily provide reductions for climate emissions, but depending on the soil type, would even increase them. The emission rate of no-till fields doesn't seem to follow the global estimate from carbon sequestration (Lal et al. 1999) which would indicate that our results would give lower welfare for no-till in Finland than what would be the case in global perspective. Indisputable benefit from no-till is lower nitrogen and particle phosphorus runoff, but then again, dissolved phosphorus runoff is about 35 % higher from no-till on every soil type.

According to our results, in social point of view, on mineral soils conventional crop cultivation seems to give the highest profit compared to no-tillage, or green fallow and possibly afforestation in South of Finland. Only on organic soils, where the soil emissions are significantly higher, is afforestation or green fallow more profitable. Also no-till gives higher social welfare, although the marginal benefit comes from lower nutrient runoff rates and cultivation costs rather than from lower climate impact.

5.2 Optimal climate and environmental policy design

Recall, optimal policy requires a combination of tax on fertilizer application and (possible) technology subsidy. We define this instrument combination for each four policies. Tax rates (cent per kilogram of nitrogen fertilizer) and required technology subsidies are reported in Table 7 is defined for different policy options. Not surprisingly, fertilizer tax rate is higher when the policy takes into account all GHGs and nutrient runoff, compared to policies that only account for example carbon dioxide.

Tax rate is generally very similar on both tillage systems. Difference becomes larger when also nutrient runoff is included, making the tax higher for conventional tillage and differing also between soil types. Tax ranges from 6 to 58 cent per kg nitrogen fertilizer which is about 3.5 to 34.1 per cent increase to nitrogen fertilizer price when the initial price is 1.7 €/kg N. When only carbon dioxide emissions are accounted for tax reduces profits only slightly. The impact becomes large when all tax rates reflect all emissions: farmers' profit decreases on average by 64 % under conventional tillage and 39 % under no-till. When all emissions are considered, is no-till most profitable for farmers on every soil type, yielding highest profits. In contrats, social welfare is highest under conventional tillage on clay and silt soil. Thus, optimal tax rate alone cannot establish the social optimum. (Only with organic soils the farmer's decision is parallel with social optimum.) Therefore a lump sum technology support payment for cultivation technology choice has to be introduced . Technology payment is defined as the minimum payment for conventional tillage to yield the same private profits as no-till. For organic soil the social optimal land allocation is field afforestation. Whether the policy is including GHG emissions and nutrient runoff, is privately optimal solution to afforest the soil, but with lighter policy a compensation needed.

Table 6. Tax rate (c/kg N) (per cent/€ N kg) for nitrogen fertilizer on different policy scenarios and lump sum substitution for technology.

Policy	**Fertilizer tax c/kg N**		**technology subsidy €/ha**
	Conv.	No-till	
	Clay		
CO2	0,06 (3.5)	0,06 (3.5)	1
CO2 eq.	0,21 (12.4)	0,21 (12.4)	2
CO2 + nutrient runoff	0,51 (30,0)	0,33 (17.6)	19
CO2 eq. + nutrient runoff	0,58 (34.1)	0,40 (23.5)	19
	Silt		
CO2	0,06 (3.50)	0,06 (3.50)	4
CO2 eq.	0,21 (12.4)	0,21 (12.4)	3
CO2 + nutrient runoff	0,44 (25.9)	0,25 (14.7)	20
CO2 eq. + nutrient runoff	0,57 (33.5)	0,39 (22.9)	20
	Organic		

CO2	0,06 (3.50)	0,06 (3.50)	20-23*
CO2 eq.	0,21 (12.4)	0,21 (12.4)	7-10*
CO2 + nutrient runoff	0,44 (25.9)	0,26 (15.3)	-
CO2 eq. + nutrient runoff	0,58 (34.1)	0,40 (23.5)	-
*technology subsidy for conventional tillage **technology subsidy for afforestation. Fields under no-till and conventional tillage have different base			

It is debated how those emission reductions done in agricultural sector are comparable with emission reductions done in other industrial sectors. The nature of carbon sequestration is distinctively different from e.g. reduction of use of fossil fuels or improving energy efficiency of production machinery. If agricultural emission reductions are considered as a potential way to mitigate national greenhouse gas emissions and include them to the emission reduction target, should the nature of agricultural emission reductions to be perceived. As mentioned before, carbon emission reductions done with soil management are finite in magnitude and duration. If the land is used for carbon sequestration e.g. shifting for conservation tillage but is later taken back for intensive agricultural cultivation, the carbon is easily and rapidly released back to atmosphere. The question is thus, how long should carbon be stored so that the reduction is to be valid as a “permanent” emission reduction. Lewandrowski et al. (2004) assess that to have the same value for unit of carbon sequestration than from permanent emission reductions, should carbon remain in soil for 100 years. Others argue that carbon sequestered even for a short period of time can be seen to have value, as it have had some influence to the atmospheric CO_2 content (IPCC 2000, chapter 2.3.6.3; Feng, Zhao and Kling 2002, 144). Although in general preventing the emission altogether gives better solution for long term problem, can carbon sequestration be seen as a inexpensive, short term fix and ease the emission mitigation pressure before more efficient solutions are developed (WWF 2000; Feng et al. 2002).

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, crop production and eutrophication of water systems. Social welfare consists of farmer’s private profits and environmental externalities resulting from the production. The analysis is performed using mainly Finnish data about environmental impacts and private profitability of different land use types and cultivation methods.

Land use options considered are two different cultivation methods; conventional tillage and no-till and green fallow and afforestation. According to our results, practices suggested for climate change mitigation, are not unequivocally profitable for society. From agricultural soils organic soils are significant source of emissions, possibly several times larger than mineral soils. Thus, emissions mitigation practices are also most efficient when directed on organic soils. On cultivated mineral soils the emission mitigation practices have minor effect on emissions, if not negative, and might give even lower net social welfare even though they would reduce other environmental impacts e.g. nutrient runoff to water systems.

On mineral soil conventional tillage produces socially and privately highest social profit on the basis of our data. To attain socially optimal solution, the tax is set for fertilizer and a lump sum payment is provided for socially preferable cultivation technology. For organic soil barley cultivation is both privately and socially optimal using no-till technology. In theory farmers would choose automatically the socially optimal technology and only fertilizing tax is needed to cut the fertilizing rate to the optimal level. In general organic soils would possibly be more profitable if afforested. Compared to crop cultivation on organic soils, also green fallow gives better social welfare, however still negative value.

Although field emissions are studied during past decades especially on organic soils, are further studies about different land use options needed. There seems to be lack of data especially from fields under no-till and green fallow, although both are suggested to be possible options for climate change mitigation. Also studies used here are generally not a long term experiments from soil emission fluxes, which might have an impact on the results. As several studies indicate, soil emission fluxes are not constant, but have significant variation due to changes in climate, environment and time elapsed from previous land use. Emission flux rates measured in Finnish no-till fields are not following the global estimation of carbon sequestration, which would suggest that more data would be needed.

For further assessment of the mitigation options, also comparative statics would be essential to estimate how higher value of emissions would affect to the profitability of land use. Important issues to be covered more thoroughly in future are issues such as uncertainty of emission reductions, problems with accurate estimates of regional and global soil emissions or sequestration potential, permanence, etc.

Appendix I

Table A1. Barley maximum yields on clay, silt and organic soils (kg/ha/year)

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

Table A2. Yearly private profits, input use and production impacts to environment on clay, silt and organic soils under barley production, green fallow and afforestation. Ex post social welfare €/ha/year. (Not including the LFA substitution of 169 €/ha for green fallow and crop fields.)

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	4 301	4 100	3 826	3 643	4 030	3 839
Profits €/ha	98	**99**	55	**59**	74	**76**
External effects						
Nitrogen runoff kg/ha	13,53	6,66	12,4	6,33	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
CO2.eq. kg/ha	4 214	9 433 (6437*)	3 172	5 351 (2827*)	13 219	13 558
Ex post social welfare I	14	**-89 (-30*)**	-8	**-48 (3*)**	**-190**	-195
Ex post social welfare II	-83	**-151 (-91*)**	-105	**-109 (-57*)**	-288	**-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	
CO2.eq. kg/ha[2]	566		566		5 301	
Ex post social welfare I	-55		-55		-150	
Ex post social welfare II	-104		-104		-199	
	Afforestation					
Profits €/ha[4]	47,8		47,8		47,8	
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	

$CO2.eq.$ kg/ha[4]	nd	nd	-2 268 — 1 181**
Ex post social welfare I	-	-	24-93
Ex post social welfare II	-	-	13-82
[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]Ervola et al. 2010, * International estimation for carbon sequestration of ~900 kg CO_2 /ha/year ** Soil and biomass. Negative figure means that forest is a sink of carbon			

Table A3. Barley cultivation under no-till and conventional tillage, parameter values and units

	Symbol	Conv.	No-till	Unit
Barley cultivation costs:				
seeds (own)	K	52	52	€/ha/year
seeds (bought)		18	18	€/ha/year
liming		9	9	€/ha/year
herbicides, pesticides		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/year
price of nitrogen fertiliser	c	2,11	2,11	€/kg/year
Environmental impacts:				
climate damage	$Ø$	0,02	0,02	€/kg CO_2-eq. /year
nitrogen runoff damage	D^N	4,27	4,27	€/kg N-eq./year
phosphorus runoff damage	D^P	7,2	7,2	€/kg CO_2-eq./year

Table A4. Life cycle GHG emissions from barley cultivation (kg CO_2-eq./ha/yr)

	Conventional tillage	No-till	Note
Mouldboard plough tillage	90		
Harrowing	54		
Grain seeds	151	161	
Nitrogen manufacturing	546**	546**	6.065 kg CO_2-eq./kg N 2.541 kg CO2/kg N
Soil emissions due to N fertilizer application	335**	335**	0.0125 kg N_2O/kg N
Liming (production, transportation, and	111*	111*	139 kg CO_2-eq./ton of

application)			lime
Liming (soil emissions)	345*	345*	431 kg CO_2/ton of lime
Planting	13	27	
Herbicide manufacture and transportation	44	70	
Herbicide application	13	19	
	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 GHG	**1905**	**1810**	

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

Table A5. Parameter values and units for green fallow

	Symbol	Value	Unit
Maintenance and establishment costs	e	44	€/ha
price of nitrogen fertiliser	c	2,11	€/kg
Environmental impacts:			
climate damage	$Ø$	0,02	€/kg CO_2-eq.
Time frame for C sequestration on mineral soil	T	1835	kg CO_2 /ha
Rate of interest	r	3	%
nitrogen runoff damage	D^N	4,27	€/kg N-eq.
phosphorus runoff damage	D^P	7,2	€/kg N-eq.

Appendix II. Phosphorus and nitrogen surface runoff

Phosphorus runoff occurs as dissolved reactive phosphorus (DRP) and particulate phosphorus (PP). Particle phosphorus runoff is strongly affected by the erosion rate but dissolved phosphorus depends also on initial phosphorus rate on soil, fertilizing and water leaching.

We use description of DRP and PP (potentially bioavailable phosphorus) runoff developed by Uusitalo and Jansson (2002; 2004) to where we add factors for no-till α^t and conventional tillage β^t. Equations that defines rate of PP and DRP are thus as follows:

$$Z_{PP}^{t} = \alpha^{t}\left[\varsigma^{t} * \left\{\frac{250 * \ln(\theta + 0.01 * P_t)150}{1000000}\right\}\right] \qquad \text{(xx)}$$

$$Z_{DRP}^{t} = \beta^{t}\left[\frac{\psi * 0.021(\theta + 0.01 * P_t)}{100}\right] \qquad \text{(xx)}$$

In equation XX 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 express the social valuation of phosphorus runoff damages, phosphorus is changed into nitrogen equivalents using a Redfield ratio of 7.2 to describe the optimum N/P ratio for the growth of phytoplankton, relevant for algal growth in coastal waters.

Nitrogen runoff depends on nitrogen runoff factor in addition to nitrogen fertilizing intensity. We are using Simmelsgaard (1991) nitrogen runoff function.

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

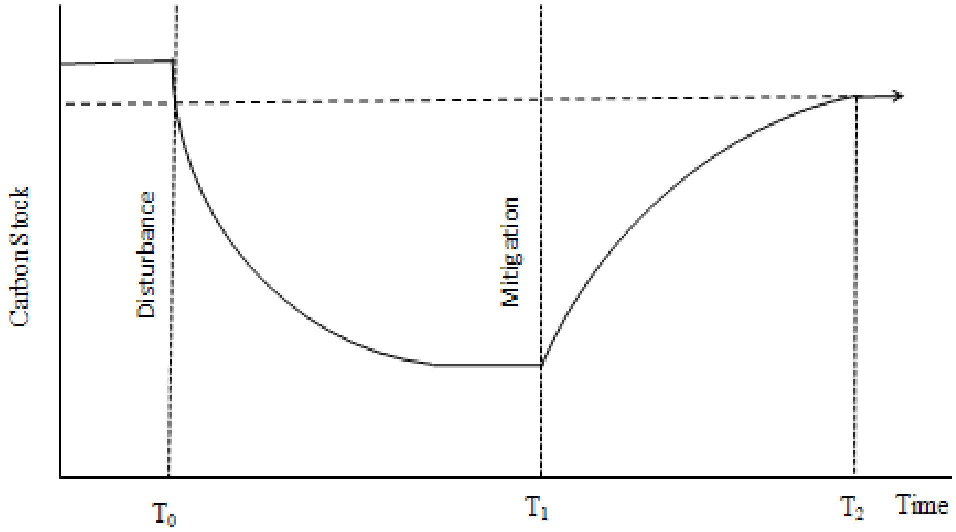
where Z_N^i is the nitrogen runoff at fertilizer rate N_t kg/ha, ω depicts the runoff from average fertilizing intensity, N_i is the amount of nitrogen proportioned with parameters $b_0 > 0$ and $b > 0$ for average fertilizing intensity (~100 kg).

Table B1. Parameter values in the numerical application

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

Appendix III

Figure C1. Carbon stocks following soil disturbance and change of tillage practice. Adapted from IPCC 2000, Figure 2-4.



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