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Ethanol production under endogenous crop prices: Theoretical analysis and application to barley

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Abstract:

We examine the social desirability of ethanol production from agricultural crops when its effects on the greenhouse gas balance, land competition and crop prices are taken into account. The model comprises two land use forms: bioenergy crop and conventional feed crop. Industry demands crops for both ethanol and feed production. We characterize theoretically the private and social optima and apply the framework to barley production in Finland. In particular, we focus on various parts of the production chain and examine how the life cycle CO_2 –eq emissions associated in each part and the endogenous prices impact social benefits from ethanol production. We find ethanol production socially desirable under current ethanol price if, in addition to ethanol itself, it is possible to produce the side products: grain residue for animal feed, and the straw for energy. If either these side products cannot be produced, social returns to ethanol production either vanish or become very small. Moreover, we show that emissions from soil belong to critical key variables; if the existing uncertain proxies underestimate emissions from soil, social returns to ethanol production may vanish altogether. In all above cases, the outcomes result from changes in emissions offset, fertilizer intensity and land-use that are guided by endogenous crop prices.

Keywords: biofuels, life cycle impacts, CO_2 –equivalent emissions, emission offsets

1 INTRODUCTION

The European Union’s Emission Trading Scheme (EU-ETS) and the current renewable resource program have changed production incentives in favour of renewable energy production. The goal of renewable energy production is to reduce CO_2 -eq emissions and promote the production and use of bioenergy and biofuels. However, the net greenhouse gas (GHG) impacts of alternative biofuel production pathways remain disputable. It is possible that instead of net CO_2 -eq emission offsets, production and use of biofuels creates more CO_2 -eq emissions than the production and use of fossil fuels (Farrell et al. 2006, Mäkinen et al. 2006, Edwards et al. 2006).

The determination of life cycle GHG profiles of biofuel and fossil fuel production chains requires life cycle assessment (LCA). Most LCA studies have focused on the energy and GHG balances of biofuels and fossil fuels. These studies have demonstrated that in comparison to conventional fuels, biofuel pathways may provide GHG emission reductions (e.g. Mäkinen et al. 2006, Edwards et al. 2006). However, as von Blottnitz and Curran (2007) observed in their review of ethanol production pathways, GHG emission reductions provided by different biofuel chains may vary significantly. This variation is mainly driven by differences in the treatment of co-products (protein meal from oilseed crops and feed from distiller grains) and how impacts are allocated to them. Also the quantity and type of process energy used has significant impact on the results. (Rajagopal & Zilberman 2007.)

Accounting for the direct greenhouse gas balance of the whole life cycle is not enough, however. Changes in economic behavior must be accounted for, because these changes are reflected on the greenhouse gas balance as well. Promoting bioenergy and biofuel production leads to increased competition on agricultural land. Even if substituting biofuels for gasoline reduces direct GHG emissions and thus provides carbon benefits of using that land for biofuels, it is possible that their production involves indirect carbon costs through land use change (see e.g. Searchinger et al. 2008). Moreover, cropland diverted from feed and food production in Europe and the U.S. could provide strong incentives for taking additional land into cultivation of feed and food crops in other parts of the world (such as Brazil, China and India). This indirect land use change could lead to very high land-use change related emissions (Searchinger et al. 2008).

Ethanol can be produced from barley or wheat under existing cultivation methods. The higher the amount of land allocated outside of food and feed production, the higher the prices of cereals one can expect to be. OECD (2006 & 2008a) and Mitchell (2008) assessed bioenergy production and its impact on agricultural commodity prices. Prices, according to these studies, may rise 5-15% due to increased biofuel and bioenergy production.

As Rajagopal and Zilberman (2007) suggest, price changes of agricultural commodities depend on several regional factors, such as intensity of bioenergy crop cultivation and the extent of trade in food-related commodities. Furthermore, they point out that food industry may be negatively affected by the resulting higher input costs. However, socially optimal amount of biofuel production does not only depend on the price of cereals and on the effects of rising prices on different industries, but also on the climate impacts of biofuel production. Thus, examination of social desirability of ethanol production must therefore be rooted in an analysis that endogenizes crop prices. Then, endogenous crop prices allow for the analysis of the trade-off between climate benefits from bioenergy crop production (either for heat and electricity or biofuel) and consumers' valuation of food and feed production.

In this paper we examine the social desirability of ethanol produced from agricultural crops. To endogenize the competition on land use, we employ a Ricardian model of heterogeneous land quality, where land is allocated to alternative crops on the basis of their relative profitability. This land-use model captures nicely the fact that profits from crop cultivation depend on the land productivity as well as on the relative prices of alternative crops. The model comprises two land use types: bioenergy crop and conventional feed crop. Effects on the GHG balance are explicitly taken into account. To endogenize the bioenergy crop price we assume that industry demands the crop for both ethanol and feed production, and thus, competes on the crop. We apply the theoretical framework to ethanol produced from barley in Finnish agricultural conditions.[1]

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[1] There is currently no ethanol industry in Finland. However, there are plans to open one or two ethanol plants, and our empirical section uses this information. While our study aims to provide insight into the social desirability of ethanol production in Finland, our approach itself is more general. Besides general theoretical analysis, we suggest here a systematic economic and LCA treatment of the whole production chain to reveal the key variables impacting ethanol production.

Our model integrates both the economic aspects as well as the climate impacts of agriculture and biofuel production. Integrating comprehensive GHG balances with consistent economic framework is vital in assessing the social desirability of biofuel production. Furthermore, agricultural production is described in detail in our model. This allows us to analyze the impacts of privately and socially optimal biofuel production on agriculture. This orientation is usually ignored in macroeconomic models of biofuel production. Finally, we make a major effort to trace out the key parts of the life cycle chain and economics variables that impact the desirability of biofuel production.

The rest of the paper is organized as follows. In section 2 we develop the theoretical framework and compare the privately and socially optimal solutions. Section 3 builds the parametric version of the model, presents the baseline results and examines key factors impacting the social returns to biofuel production. Concluding section 4 ends the paper.

2 ETHANOL PRODUCTION AND COMMODITY MARKETS: A FRAMEWORK AND MARKET EQUILIBRIUM

In this section we develop a framework to determine the private and social optimum for bioenergy crop production. We integrate the LCA aspects to conventional economic analysis. We assume that bioenergy crop is used in the production of both biofuels and animal feed; thus, there is competition for bioenergy crop produced by farmers that will affect the endogenous price of bioenergy crop and alternative crop.

2.1 Privately optimal ethanol production

Ethanol and animal feed production

Consider an ethanol firm that manufactures animal feed and ethanol. Ethanol is the primary product and it is produced from bioenergy crop grains. These grains go first through ethanol production process. Production technology defines a concave production function $g(\hat{h},e)$, where $\hat{h}$ denotes bioenergy crop and e energy used in production process, with $g_{\hat{h}} > 0$, $g_e > 0$, but $g_{\hat{h}\hat{h}} < 0$ and $g_{ee} < 0$. Production process does not exhaust the grain inputs but the amount of residues (distiller grains) is used in a secondary production process to provide animal feed. We denote the amount of these residues by ϕ, which is a technical coefficient expressing the ratio of residues to input intensity of the primary process. The production of animal feed is described by a production function $a(\phi\hat{h},e)$. This production process requires energy, which is denoted with e. Let P be the price of ethanol, R the price of animal feed, p_H the price of bioenergy crop and θ the price of energy. Then, the profits of the ethanol firm is given by

$$\pi_E = \lfloor Pg(\hat{h},e) + Ra(\phi\hat{h},e) - p_H\hat{h} - \theta e \rfloor \tag{1}$$

The first order conditions from equation (1) are

$$\frac{\partial \pi_E}{\partial \hat{h}} = P\frac{\partial g(\hat{h},e)}{\partial \hat{h}} + R\frac{\partial a(\phi\hat{h},e)}{\partial \hat{h}} - p_H = 0 \tag{2a}$$

$$\frac{\partial \pi_E}{\partial e} = P\frac{\partial g(\hat{h},e)}{\partial e} + R\frac{\partial a(\phi\hat{h},e)}{\partial e} - \theta = 0 \tag{2b}$$

Equations (2a) and (2b) describe the privately optimal ethanol production. The former implies that ethanol producer increases the production of ethanol to a point where the marginal revenue of using bioenergy crop in the production is equal with the marginal costs. The latter equation imposes the same condition for energy use. The factor demand of bioenergy crop can be implicitly derived from above equations and is given as $d_{\hat{h}} = d_{\hat{h}}(\underset{-}{p_H}, \underset{+}{P}, \underset{+}{R}, \underset{-}{\theta})$. The effects are intuitive.

In addition, a conventional animal feed producer manufactures animal feed with a production function $y(\tilde{h})$ and profits

$$\pi_F = Ry(\tilde{h}) - p_H\tilde{h} \tag{3}$$

The first order condition from equation (3) is

$$\frac{\partial \pi_F}{\partial \tilde{h}} = R\frac{\partial y(\tilde{h})}{\partial \tilde{h}} - p_H = 0\,. \tag{4}$$

From (4), the animal feed producer increases the production to the point where the marginal revenue of the production equals the marginal costs. The factor demand for bioenergy crop can be implicitly derived from the above condition and is expressed as $d_{\tilde{h}} = d_{\tilde{h}}(\underset{-}{p_H}, \underset{+}{R})$.

Agriculture

Let the total amount of arable land in the economy be *G*, which is assumed to be constant. This agricultural land is divided into parcels, production units. The land quality in each production unit is uniform but differs between production units. The quality depends on physical, chemical and biological factors, such as soil textural class, organic content, and soil acidity. It is assumed that the land quality can be ranked according to a scalar measure *q*. The scalar varies between zero and one, $0 \le q \le 1$ so that zero is the minimal and one maximal land quality. The cumulative distribution of *q* can be written as $G(q)$ and the density is $\delta(q)$ which is assumed to be continuous and differentiable for analytical convenience:

$$G = \int_0^1 \delta(q)dq \tag{5}$$

Each production unit can be allocated to two different cereal crops, bioenergy crop and alternative crop. It is assumed that the alternative crop (crop W) is more profitable than the bioenergy crop (crop H) at higher quality parcels and more responsive to changes in land quality. The respective shares of land allocated to crops are denoted by L_W and L_H. The latter can be expressed as a function of L_W, $L_H = (1 - L_W)$. The profit function of crop cultivation for crops *i=H,W* is $\pi_i(p_i, c, q) = \hat{p}_i f_i(l_i, q) - cl_i$ where $\hat{p}_i$ denotes the net price of crop, l_i the fertilizer intensity, $f_i(l_i, q)$ the fertilizer response function of crop *i* (derivatives $\frac{\partial f_i}{\partial l_i} > 0, \frac{\partial^2 f_i}{\partial l_i^2} < 0$), *c* fertilizer input cost and *q* land quality. The optimal fertilizer intensity $l_i^* = l_i(p_i, c, q)$ for crops *i= H,W* is derived from the respective profit functions. Optimal fertilizer intensity is first chosen for both crops over all land qualities. Then each production unit is allocated to the crop which produces highest profits given land quality of the parcel. The total profits from all production units can be defined as [2]

$$\max_{L_W} PV = \int_0^1 \left[\pi_H^*(p_H, c, q)(1 - L_W) + \pi_W^*(p_W, c, q)L_W\right]\delta(q)dq \tag{6}$$

The first order condition of equation (6) is

$$\frac{\partial PV}{\partial L_W} = \pi_W^*(p_W, c, q^*) - \pi_H^*(p_H, c, q^*) = 0 \tag{7}$$

According to (7), the critical value of q^* is defined by the equality of profits from both crops, that is, $q^* : \pi_W^*(p_W, c, q^*) = \pi_H^*(p_H, c, q^*)$. Crop *H* is the optimal choice when $0 \le q \le q^*$ and crop *W* when $q^* < q \le 1$. The resulting land areas devoted to crop *H* and crop *W*, respectively, are

$$A_H = \int_0^{q^*} \delta(q)dq = G(q^*) \tag{8}$$

$$A_W = \int_{q^*}^1 \delta(q)dq = G(1) - G(q^*) \tag{9}$$

Market equilibrium

Assume there are *j=1...n* identical producers of ethanol and *s=1...m* identical animal feed producers and that markets in which they operate are competitive. The individual demand curves are aggregated resulting in market demand curve for bioenergy crop. The aggregate ethanol demand for bioenergy crop can be defined as $D_{\hat{h}} = \sum_{j=1}^{n} d_{\hat{h}}^{j}$ and the aggregate animal feed demand as $D_{\tilde{h}} = \sum_{s=1}^{m} d_{\tilde{h}}^{s}$. Thus the market aggregate demand for bioenergy crop is

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[2] In the empirical application, the straw from bioenergy crop is assumed to replace peat in combined heat and power production following Mäkinen et al. (2006). However, the production and use of straw is not included in the theoretical model.

$\overline{D}_H = D_{\hat{h}} + D_{\tilde{h}}$. Furthermore, the supply of bioenergy crop is expressed as $S_H = f_H(l_H^*, q)A_H$ and the aggregate supply of alternative crop as $S_W = f_W(l_W^*, q)A_W$.

Agricultural markets (of both bioenergy and the alternative crop) are assumed to be competitive. The exogenous demand for alternative crop is denoted by $\overline{D}_W$. The equilibrium prices for crops are determined from the market equilibrium conditions and are denoted by $p_H^* : \overline{D}_H = S_H$ for bioenergy crop and $p_W^* : \overline{D}_W = S_W$.

2.2 Socially optimal ethanol production

Society accounts for the climate impacts of production. Let $\tau = \tau(l_W)$ represent the climate damages from alternative crop production which are a function of fertilizer intensity of alternative crop. Let $b = b(\hat{h}, e, l_H)$ denote the net climate benefits of the ethanol production. These benefits are defined as $b = \lambda g(\hat{h}, e) - \chi$, where $\lambda = \lambda(l_H)$ represents the CO$_2$-eq emission offsets if ethanol is used to replace conventional gasoline production. Furthermore, $\chi = \chi(l_H)$ denotes the climate damages from bioenergy crop production. Let

$$Z = \int_0^1 [\tau L_W - b(1 - L_W)]\delta(q)dq \qquad (10)$$

denote the aggregate climate impacts of ethanol production. Let *D(Z)* denote the damage function of climate impacts of ethanol production, with $D'(\cdot) > 0$ and $D''(\cdot) > 0$.

The social planner maximizes social welfare defined as a sum of consumers' and producers' surpluses, comprising the sum of relevant market actors' net profits and the climate benefits and damages of ethanol production chain. The bioenergy crop production is used by the two industries. Let z $(0 \le z \le 1)$ denote the (endogenous) share of production used in ethanol firm and (1-*z*) by the animal feed firm. Then $\hat{h} = z\int_0^1 (f_H(l_H, q))(1 - L_W)\delta(q)dq$ and $\tilde{h} = (1 - z)\int_0^1 (f_H(l_H, q))(1 - L_W)\delta(q)dq$ exhaust the production. We define the social welfare function as:

$$\begin{aligned} SW &= \left[Pg\left(\hat{h},e\right)+Ra\left(\phi\hat{h},e\right)-p_H\hat{h}-\theta e\right]+\left[Ry\left(\tilde{h}\right)-p_H\tilde{h}\right] \\ &+\int_0^1\left[\left(\hat{p}_H f_H\left(l_H,q\right)-cl_H\right)(1-L_W)+\left(\hat{p}_W f_W\left(l_W,q\right)-cl_W\right)L_W\right]\delta(q)dq \\ &-D(Z) \end{aligned} \tag{11}$$

The problem of the planner is to choose fertilizer intensity for both crops, the use of bioenergy crop in both firms, use of energy input and land allocation between the three land use forms. This results in five simultaneous equations:

$$\frac{\partial SW}{\partial e}=P\frac{\partial g(\hat{h},e)}{\partial e}+R\frac{\partial a(\phi\hat{h},e)}{\partial e}-\theta-D'(\cdot)\lambda\frac{\partial g(\hat{h},e)}{\partial e}=0 \tag{12a}$$

$$\frac{\partial SW}{\partial z}=P\frac{\partial g(\hat{h},e)}{\partial\hat{h}}+R\left(\frac{a(\phi\hat{h},e)}{\partial\hat{h}}-\frac{\partial y(\tilde{h})}{\partial\tilde{h}}\right)+D'(\cdot)\lambda\frac{\partial g(\hat{h},e)}{\partial\hat{h}}=0 \tag{12b}$$

$$\begin{aligned} \frac{\partial SW}{\partial l_H} &= \left[\left(P\frac{\partial g(\hat{h},e)}{\partial\hat{h}}+R\frac{a(\phi\hat{h},e)}{\partial\hat{h}}\right)z+(1-z)R\frac{\partial y(\tilde{h})}{\partial\tilde{h}}\right]\frac{\partial f_H(l_H,q)}{\partial l_H} \\ &-c+D'(\cdot)\lambda\frac{\partial g(\hat{h},e)}{\partial\hat{h}}\frac{\partial f_H(l_H,q)}{\partial l_H}=0 \end{aligned} \tag{12c}$$

$$\frac{\partial SW}{\partial l_W}=p_W\frac{\partial f_W(l_W,q)}{\partial l_W}-c-D'(\cdot)\frac{\partial f_W(l_W,q)}{\partial l_W}=0 \tag{12d}$$

$$\frac{\partial SW}{\partial L_W}=\pi_W^*(p_W,c,q)-\pi_H^*(p_H,c,q)-D'(\cdot)(\tau+b)=0 \tag{12e}$$

Equation (12a) is conventional; energy input is used up to the point where the value of marginal product equals the effective input price comprising also the climate impacts. From (12b), bioenergy crop yield is allocated between the two industries so that the value of its marginal product is the same from both of them, taking into account also the climate impacts associated with ethanol production. Equation (12c) characterizes the input use intensity for bioenergy crop in any parcel. Fertilizer intensity is increased to the point where its marginal contribution to the value of marginal product of bioenergy crop in both industries is equal to the sum of its input cost (comprising also the cost of CO_2-eq emissions) and marginal climate impacts. The rest two are familiar from standard heterogeneous land quality models (see e.g. Lichtenberg 2002). Equation (12d) defines input intensity for the alternative crop and (12e) determine the land allocation between the two crops at critical land quality, where bioenergy crop becomes as profitable as alternative crop. In equation (12e), the net climate benefits are taken into account as well.

3 EMPIRICAL APPLICATION AND RESULTS

We next apply the theoretical framework to Finnish agriculture. Barley (crop H) is cultivated in whole country whereas the climate conditions restrict wheat (crop W) cultivation to the southern and western parts of Finland.

3.1 Parametric functions and greenhouse gas emissions

A Cobb-Douglas production function is calibrated for barley ethanol production in Finland. Here we focus on the feedstock-to-ethanol conversion process in which following stages are taken into account: harvest of starchy parts of barley (straw/stalks used in combined heat and power production), feedstock conversion to sugar (including starch separation, milling, and conversion to sugars via enzyme application), process heat, sugar conversion to alcohol (including fermentation and distillation of alcohol), and co-products (distillers grains). The production function of ethanol is:

$$g\left(\hat{h},e\right)=T\hat{h}^{\alpha}e^{\beta} \tag{13}$$

Parameter values for α, β and T are given in appendix 1. Furthermore, animal feed is produced from distiller grains. It is assumed that the production of animal feed depends linearly from the use of barley in the ethanol production process.

We use Mitscherlich specification of nitrogen response function for barley (i = H) and wheat (i = W) defined as:

$$f_i(l_i,q)=m_i\left[1-\gamma_i\exp\left(-\rho_i l_i\right)\right] \tag{14}$$

Where m_i, γ_i and ρ_i are parameters and l_i is nitrogen fertilizer intensity. The parameters of Mitscherlich response function have been estimated on the basis of Finnish field trials by Bäckman et al. (1997). In order to calibrate the response function to actual yield levels corresponding to given nitrogen fertilizer use in Finland land quality is incorporated through parameter m_i which is assumed to be linear in land quality, i.e. $m_i = m_i^0 + m_i^1 q$. The total amount of arable land is divided into 19 different land qualities. Each of these qualities is represented by a field parcel of one hectare. Parameters of Mitscherlich nitrogen response function, prices, cultivation costs and support payments are provided in appendix 1.

An exogenous constant elasticity functions are used to determine demand for wheat (alternative crop) and animal feed demand for barley. The function for wheat is expressed as $\overline{D}_W = C_W p^{-\varepsilon_w}$, where C_W is shift parameter and ε_W denote the elasticity of demand for wheat. Animal feed demand for barley is expressed as $D_{\tilde{h}} = C_H p^{-\varepsilon_H}$, where C_H is shift parameter and ε_H denote the elasticity of demand for barley.

We use greenhouse gas balance between conventional gasoline and ethanol as an indicator of climate impacts of production in the economy. Mäkinen et al. (2006) provide life cycle GHG emission estimates for biofuels used in transportation (see appendix 2). They estimated CO_2-equivalent emissions for the whole chain from the production of inputs to the final use of bioenergy and biofuels. In this application, as presented in appendix 3, the following aspects are included in the agricultural phase: (i) CO_2-eq emissions related to the transportation of crops, denoted with parameter ψ (kg CO_2-eq/kg crop); (ii) CO_2-eq emissions related to the manufacturing, transportation and application of fertilizers, denoted with parameter η (kg CO_2-eq/kg nitrogen fertilizer); (iii) CO_2-eq emissions from soil, tillage practices and harvest as well as pesticides and lime manufacturing, transportation and application, denoted with parameter μ (kg CO_2-eq/hectare); and (iv) CO_2-eq emissions from grain drying, denoted with parameter ξ (kg CO_2-eq/kg crop). Moreover, following Mäkinen et al. (2006) we assume that barley straw is used in combined heat and power production, where it replaces peat.

As regards ethanol conversion process we take the following aspects into account: (i) CO_2-eq emissions from process energy and (ii) CO_2-eq emissions from storage and distribution of ethanol. Furthermore, following Mäkinen et al. (2006), we assume that distillers dried grain replaces imported soybean meal in feed production. As our focus is on climate policy, we consider ethanol to be carbon neutral. Thus, the end-use of ethanol does not increase the total amount of carbon in the atmosphere.

The valuation of climate impacts is incorporated into social welfare function through equation (11). Parametric version of the equation (11) can be written as,

$$Z = \int_0^1 \left[\tau L_W - \left(\lambda\left(T\hat{h}^{\alpha} e^{\beta}\right) - \chi\right)(1 - L_W)\right]\delta(q)dq \,. \tag{15}$$

In equation (15), the CO$_2$-eq emissions from wheat cultivation, τ, is defined as $\tau = \eta l_W + (\xi + \psi)\left(m_W\left[1 - \gamma_W \exp\left(-\rho_W l_W\right)\right]\right) + \mu A_W$ and, in similar vein, the CO$_2$-eq emissions from barley cultivation, χ is defined as $\chi = \eta l_H + (\xi + \psi)\left(m_H\left[1 - \gamma_H \exp\left(-\rho_H l_H\right)\right]\right) + \mu A_H$. The value for λ, which represents the difference in GHG emissions between conventional gasoline production and use and ethanol production and use, is calculated from emissions presented in appendix 2.

Combining profit functions derived from equations (13) and (14) as well as parametric representation of climate impacts in equation (15) results in a parametric form of social welfare function.

3.2 The baseline scenario

We start reporting the market level results of the baseline in table 1. Ethanol production in the private optimum (68 702 tonnes) is higher than in the social optimum (66 413 tonnes); this is somewhat against intuition. Given the exogenous price of ethanol, this difference emerges from the equilibrium of agricultural markets. At the social optimum, the equilibrium production of barley and wheat is lower than in private solution because of the net climate impacts of agriculture. The reduction of output for barley is 1.94% and 0.17% for wheat. Thus, at the social optimum the equilibrium prices of wheat and barley become higher than in the private optimum (the price of barley is 1.36% and price of wheat is 2.12% higher in the social optimum). Therefore, barley input price is higher in the social optimum and ethanol production is lower in social optimum than in the private optimum.

Note finally that the ethanol demand is more price responsive than animal feed demand. Consequently, ethanol demand for barley decreases 5.06% in social optimum whereas animal feed demand decreases only 0.14%.

Table 1 Market equilibrium

	Private optimum	Social optimum	Change %
PRICES (eur/t)			
Barley	155.60	157.72	1.36
Wheat	172.08	175.72	2.12
ETHANOL INDUSTRY (t)			
Ethanol production	68 702	66 413	-3.33
Animal feed production (from DDGS)	89 988	85 433	-5.06
BARLEY MARKETS (t)			
Production in market equilibrium	791 978	776 606	-1.94
Animal feed demand of barley	501 694	501 015	-0.14
Ethanol demand of barley	290 284	275 591	-5.06
WHEAT MARKETS (t)			
Production in market equilibrium	523 576	522 674	-0.17

Turning to agricultural details of the two equilibria (table 2), the social optimum favors wheat cultivation relative to the private optimum. In the private optimum, 10 out of 19 quality parcels are allocated to barley and rest to wheat, whereas in the social optimum the allocation is reversed. The socially optimal fertilizer intensity for both crops is lower than the privately optimal (8.23% for barley and 9.06% for wheat); this is because of the net life cycle climate impacts of fertilizer application. Consequently, the total amount of fertilizer application in agricultural production decreases 8.40% in the social optimum compared with private optimum. The average yield for both crops decrease in the social optimum due to the lower input use intensity. Finally, per hectare profits increase for both crops in the social optimum because the crop prices are higher and input intensities lower for both crops.

Table 2 Agriculture

	Private optimum	Social optimum	Change %
AGRICULTURE			
Total amount of nitrogen fertilizer applied (t)	17 188	15 746	-8.40
BARLEY CULTIVATION			
Fertilizer intensity (average) (kg/ha)	97.24	89.13	-8.23
Yield (average) (kg/ha)	3 385	3 284	-2.93
Profits (average) (eur/ha)	58.78	64.15	10.16
Lower bound of profits (eur/ha)	34.22	39.91	18.79
Upper bound of profits (eur/ha)	83.52	88.54	6.69
WHEAT CULTIVATION			
Fertilizer intensity (average) (kg/ha)	132.34	120.26	-9.06
Yield (average) (kg/ha)	3 933	3 801	-3.30
Profits (average) (eur/ha)	112.98	124.77	11.09
Lower bound of profits(eur/ha)	84.09	94.07	12.73
Upper bound of profits (eur/ha)	142.09	155.72	10.11
LAND ALLOCATION			
Barley	10	9	
Wheat	9	10	

Table 3 CO_2-eq emissions in private and social optimum

	Private optimum	Social optimum	Change %
CO_2-eq emissions (t)			
Fertilizer (production and use)	184 172	168 721	-8.40
Soil	214 340	214 340	0.00
Grain drying	35 939	34 875	-2.96
Transportation (inputs and outputs)	6 443	6 252	-2.96
Pesticides (production and use)	2 494	2 494	0.00
Tillage practices (plowing, harrowing, lime, etc.)	37 632	37 632	0.00
CO_2-eq emission offsets (t)			
Ethanol replacing fossil fuel	20 894	20 582	-1.49
Total CO_2-eq emissions	460 126	443 732	-3.56

CO_2-eq emissions in the private and social optima are presented in table 3. The greatest source of CO_2-eq emissions in both private and social optimum is soil. The emissions, however, remain the same in both optima because per hectare emissions from soil are same for barley and wheat. The other main source of CO_2-eq emissions in both optima is manufacturing and application of fertilizer. Due to reduced fertilizer application intensity the total CO_2-eq emissions from manufacturing and application of fertilizer decrease by 8.40%. There are no reductions in emissions from tillage practices, because they are the same for barley and wheat. However, the emissions from grain drying and transportation are 2.96% lower in the social optimum.

Finally, CO_2-eq emission offstes are slightly lower in the social optimum because the total amount of ethanol produced in the social optimum is lower. Overall the total CO_2-eq emissions are 3.56% lower in the social optimum than in the private optimum.

Table 4 presents the welfare of market agents and climate impacts of biofuel production. In the empirical application the animal feed industry demand for barley is exogenous and thus it is not included in the profits.

Table 4 Social welfare

	Private optimum	Social optimum	Change %
PROFITS (million eur)			
Ethanol industry			
Ethanol production	0.491	0.970	97.39
Animal feed production	7.842	7.355	-6.21
Ethanol industry total	8.333	8.325	-0.10
Agriculture			
Barley cultivation	4.400	4.145	-5.79
Wheat cultivation	8.457	8.568	1.29
Total	21.190	21.036	-0.73
SOCIAL VALUATION OF THE CLIMATE IMPACTS (million eur)			
Ethanol production (benefits)	0.418	0.412	-1.49
Barley cultivation (damages)	-4.496	-4.217	-6.21
Wheat cultivation (damages)	-5.124	-5.069	-1.07
Net impact (damages)	-9.203	-8.875	-3.56
SOCIAL WELFARE (million eur)	11.987	12.161	1.45

Profits from animal feed production dominate over the profits from ethanol production and, consequently, the total profits of ethanol industry are lower in social optimum than in the private optimum. Total profits from agriculture are lower in social optimum as well, however, profits from wheat cultivation increase in social optimum whereas profits from barley cultivation decrease. In total, the profits of all market agents decrease by 0.73%. Social benefits from ethanol production are 1.49% lower in social optimum than in private optimum because the amount of ethanol produced decreases in the social optimum. Social costs from agriculture, which represents climate damages from crop cultivation, decrease as well. The decrease is greater in barley cultivation (6.21%) than in wheat cultivation (1.07%). In total, the valuation of net climate impacts are 3.56% lower in social optimum than in private optimum. Consequently, the social welfare increases by 1.45%.

3.3 Key factors impacting social desirability of ethanol production

The baseline scenario was built on a set of assumptions concerning the production chain and associate life cycle impacts. We now turn to examine one by one the impacts of the most critical assumptions of the production chain, as well as the impact of ethanol price. We want especially to find the key factors that may question the desirability of ethanol production.

Impact of ethanol price

The baseline scenario uses the market price of ethanol in the EU. We now let ethanol price change (±20%). Lower ethanol price results in lower ethanol production and crop prices (table

Table 5 Alternative ethanol price and alternative soil emissions

	Price of ethanol -20%				CO_2-eq emissions from soil +20%			
	Private optimum		Social optimum		Private optimum		Social optimum	
Variable		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Price (eur/t)								
Price of barley	140.19	*-9.90*	142.11	*-9.90*	155.60	*0.00*	156.65	*-0.68*
Price of wheat	157.06	*-8.73*	160.37	*-8.74*	172.08	*0.00*	174.66	*-0.60*
Production (t)								
Total production of ethanol	60 953	*-11.28*	58 713	*-11.59*	68 702	*0.00*	66 090	*-0.49*
Total production of barley	771 546	*-2.58*	755 990	*-2.65*	791 978	*0.00*	776 250	*-0.05*
Total production of wheat	529 713	*1.17*	526 786	*0.79*	523 576	*0.00*	522 091	*-0.11*
Emissions (t)								
Total CO_2-eq emissions	448 072	*-2.62*	431 856	*-2.68*	524 926	*14.08*	507447	*14.36*
CO_2-eq offsets from ethanol production	18 647	*-10.75*	17 609	*-14.44*	-1 038	*-104.97*	-1 284	*-106.24*
Total profits (million eur)								
Ethanol industry	5.915	*-29.02*	5.907	*-29.05*	8.333	*0.00*	8.325	*0.00*
Agriculture	10.551	*-17.94*	10.394	*-18.24*	12.856	*-0.01*	12.692	*-0.17*
Social benefits & damages (million eur)								
Social benefits from ethanol production	0.373	*-10.77*	0.352	*-14.56*	-0.021	*-105.02*	-0.026	*-106.31*
Social damages from agriculture	-9.335	*-2.96*	-8.990	*-3.19*	-10.478	*8.92*	-10.123	*9.01*
Social welfare	1.589	*-86.74*	1.757	*-85.55*	10.691	*-10.81*	10.869	*-10.62*

5), and land is allocated from barley to wheat production. The total CO_2 -eq emissions are now lower thanks to lower fertilizer intensity. However, now the CO_2 -eq emission offsets decrease as well. The effect of a lower ethanol price on private profits is drastic: ethanol production itself becomes unprofitable; industry makes profit only if it produces animal feed from distillers' dried grains with solubles (DDGS) (see appendix 4). Farmers are worse-off due to lowered profits from both barley and wheat cultivation. The social welfare is lowered by almost 90%. (For a 20% increase in ethanol price, just the opposite happens, more ethanol is produced, crops prices are higher and more land is allocated to barley and total emissions increase, and social welfare more than doubles, see appendix 4).

Role of soil CO_2 -eq emissions

The emissions from soil are highly uncertain and difficult to measure. Moreover, they depend on spatial aspects as well as soil texture and composition. Thus, we let the soil CO_2 -eq to vary by 20%. We report the results for higher emissions in table 5 (see appendix 4 for more details and the case where emissions from soil are 20% lower than estimated and the case for ethanol becomes much stronger). We find that in the private optimum, the prices, production, and profits remain unchanged, because no climate impacts are considered there. Moreover, the respective changes in the social optimum are marginal.

If the CO_2 -eq emissions from soil are higher than in the baseline, total emissions become roughly 14% higher in private and social optima. Moreover, there are no longer climate benefits from ethanol production; the climate policy basis for biofuel promotion programs has vanished. Thus, the uncertainty of estimated soil emissions has important implications on social desirability of ethanol production. Furthermore, the emissions from soil can, in fact, be much higher than presented in this alternative scenario, which would probably imply even greater climate damages from ethanol production.

Table 6 No CO_2 -eq emission offsets from straw; no feed production from DDGS

	No straw benefit				No feed production from DDGS			
	Private optimum		Social optimum		Private optimum		Social optimum	
Variable		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Price (eur/t)								
Price of barley	155.60	*0.00*	151.45	*-3.98*	88.49	*-43.13*	92.26	*-41.50*
Price of wheat	172.08	*0.00*	169.57	*-3.50*	106.27	*-38.24*	111.00	*-36.83*
Production (t)								
Total production of ethanol	68 702	*0.00*	63 397	*-4.54*	38 413	*-44.09*	33 777	*-49.14*
Total production of barley	791 978	*0.00*	768 512	*-1.04*	658 537	*-16.85*	635 423	*-18.18*
Total production of wheat	523 576	*0.00*	524 683	*0.38*	548 044	*4.67*	545 680	*4.40*
Emissions (t)								
Total CO_2-eq emissions	601 900	*30.81*	569 960	*28.45*	400 794	*-12.89*	388 925	*-12.35*
CO_2-eq offsets from ethanol production	-120 880	*-678.54*	-111 336	*-640.94*	-3 912	*-118.72*	-7 309	*-135.51*
Total profits (million eur)								
Ethanol industry	8.333	*0.00*	8.291	*-0.41*	4.659	*-44.09*	4.612	*-44.60*
Agriculture	12.856	*-0.01*	12.587	*-0.99*	-20.692	*-260.94*	-20.793	*-263.56*
Social benefits & damages (million eur)								
Social benefits from ethanol production	-2.418	*-678.47*	-2.227	*-640.53*	-0.078	*-118.66*	-0.146	*-135.44*
Social damages from agriculture	-9.620	*0.00*	-9.173	*-1.22*	-7.938	*-17.48*	-7.632	*-17.81*
Social welfare	9.152	*-23.65*	9.479	*-22.05*	-24.049	*-300.63*	-23.960	*-297.02*

The impact of CO_2 -eq emission offsets from straw

The baseline assumed that barley straw is used in the combined heat and power production to generate CO_2 -eq emission offsets. This hardly is possible at a larger scale in the economy. Results for the case of CO_2 -eq emission offsets from straw use are presented in table 6. In the private optimum, prices, production and profits remain the same in the baseline. The great difference relative to the baseline is in the emission offsets. They vanish altogether and net emissions are produced.

Hence, if barley straw is not used in energy production, ethanol production is not socially desirable, as it causes climate damages. Private profits are still positive, and this keeps the production still going on but at much lower level than in the baseline. This has the obvious implication for crop prices and land allocation.

The role of animal feed production from DDGS

We examine next the role of animal feed production for desirability of ethanol production. When animal feed production is not feasible, the ethanol industry sells only ethanol and the CO_2 -eq emission offsets from DDGS replacing imported soybean meal vanish. The results differ radically from the baseline scenario (table 6). Ethanol production is almost 50% and crops prices over 40% lower than in the baseline and more land is allocated to wheat. The total CO_2 -eq emissions decrease due to reduced fertilizer application, even though there are no CO_2 -eq emission offsets from ethanol production. As offsets from DDGS are absent, ethanol production causes more emission than it offsets. In the absence of animal feed production from DDGS, the total profits of the ethanol industry and agriculture negative. Furthermore, social valuation of ethanol production is now negative making the social welfare negative as well. Thus, with no animal feed production from DDGS, mitigation of climate change does not support ethanol production from barley in Finland.

4 CONCLUDING REMARKS AND POLICY IMPLICATIONS

We examined the social desirability of ethanol production from agricultural crops in market equilibrium model with endogenous land use between bioenergy crop and conventional feed crop that are demanded by ethanol and feed industry. Drawing on the GHG balance, we particularly examine the key factors of social desirability of biofuel production.

Starting with price impacts, our baseline scenario results show that the socially optimal demand for barley is 1.92% lower than demand obtained in the private optimum. Even though the use of ethanol as transportation fuel offsets some CO_2-eq emissions relative to conventional gasoline production and use, the optimal ethanol production is 3.68% lower in social optimum than in private optimum. This is due to the fact that the social costs of CO_2-eq emissions in agriculture are greater than the social benefits obtained from ethanol production and use. Thus, it is socially favorable to reduce the input use intensity in agriculture even though this reduces the supply of barley and, consequently, the amount of ethanol produced.

Our results show that in the baseline scenario, producing socially optimal amount of ethanol increases the price of barley by 1.44% and price of wheat by 2.20%. This impact is small, much less than, for instance, the recent price changes of agricultural markets in 2007-2008 in agricultural markets (in Finland 75% for wheat and over 65% for barley). Previous studies (e.g. OECD 2006, 2008a & 2008b, Mitchell 2008) predicted that crop prices would increase 5-15% due to increased production of biofuels. However, in our baseline scenario, the crop prices increase merely, because the social costs in agriculture are taken in account, not because the production of biofuels increase. Actually, the amount of biofuel produced in the social optimum is lower than in private optimum and barley demand for ethanol is lower as well. This suggests that greenhouse gas mitigation is a questionable argument for promoting ethanol production when the life cycle impacts of the whole production chain are carefully accounted for.

The results of our baseline scenario depend highly on the definition of the production chain of ethanol. In more detail, the assumptions made on the CO_2 -eq emissions of barley cultivation have a considerable impact on the results. Moreover, the changes in relative prices of inputs and outputs have an impact on the results as well. Sensitivity analysis shows that a 20% lower ethanol price makes ethanol production unprofitable. Consequently, the profitability of ethanol industry would depend only on the production of animal feed from DDGS. Furthermore, lower ethanol price would decrease the total social welfare considerably.

Uncertainties of CO_2 -eq emissions from soil are large. If the soil related CO_2 -eq emissions are 20% higher than in our baseline scenario, there are no climate benefits from ethanol production. Again, we are in a situation, where ethanol production creates more CO_2 -eq emissions than the use of ethanol offsets in transportation. Thus, it would be crucial to get accurate data on soil-related emissions to be able to analyze the social desirability of ethanol prodcution. Furthermore, if straw does not replace peat in combined heat and power production, which was a key assumption of baseline, there are no CO_2 -eq emission offsets in energy production. Consequently, ethanol production would not create CO_2 -eq emission offsets, but net emissions. Finally, if it would not be possible to produce animal feed from residues of ethanol production process, both the profits from agriculture and the total social welfare are negative. Thus, ethanol production would only be socially desireable if the residues of production process are further processed to animal feed.

The findings of this paper have a larger bearing. We demonstrated that accounting for just the direct life cycle effects or just the price effects of ethanol production is not enough. Joining them in an integrated analysis is the right approach to assessing the social desirablity of biofuel production. We observed that in the baseline and alternative scenarios ethanol production was lower in social optimum than in private optimum. This calls for a modification of biofuel programs on environmental grounds; many key variables may even argue against any biofuel policies. Thus, mitigating climate change with production of ethanol does not seem especially viable policy option. As recently emphasized, reserving arable land for food production may be in a longer term much wiser option in the face of expected food crisis.

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Appendix 1 Parameter values in the empirical application

Parameter	**Symbol**	**Value**	
PRICES*			
Market price of ethanol	p^e	0.51615	€ / kg
Price of animal feed	p^r	0.202	€ / kg
Price of energy	$\tilde{w}$	0.007175	€ / MJ
Price of nitrogen fertilizer	c	1.44	€ / kg
Price of EU-ETS emission allowance	d	0.020	€ / kg CO_2
AREA PAYMENTS*	S^i		
LFA support		169	€ / ha
EXPENDITURE IN AGRICULTURE FOR OTHER VARIABLE INPUTS THAN FERTILIZER*	$\hat{K}$		
Fixed machinery cost /both		242.00	€ / ha
Seed / barley		53.00	€ / ha
Seed / wheat		73.00	€ / ha
Lime / both		9.00	€ / ha
Pesticides & herbicides / barley		60.00	€ / ha
Pesticides & herbicides / wheat		72.00	€ / ha
Fuel, tractor & harvester / both		51.00	€ / ha
Grain drying	φ	0.0145	€ / kg
Transportation	ω	0.0097	€ / kg
PARAMETERS			
Ethanol production function	α	0.57	
	β	0.195	
	A	100	
Technical coefficient of animal feed production	ϕ	0.31	
Mitscherlich nitrogen response function of barley	m^1	3813–4713	
	γ^1	0.828	
	ρ^1	0.0168	
Mitscherlich nitrogen response function of wheat	m^2	4136–5112	
	γ^2	0.7623	
	ρ^2	0.0104	
Elasticity of demand for wheat	ε_W	-0.10	
Elasticity of demand for barley	ε_H	-0.10	
CLIMATE IMPACTS (CO_2-eq emissions)			
Nitrogen fertilizer	η	10.715	kg CO_2-eq / kg N
Soil + tillage practices / cereals	$\mu^{1,2}$	1701.356	kg CO_2-eq / ha
Transportation	ψ	0.058811	kg CO_2-eq / kg
Grain drying	ξ	0.06561	kg CO_2-eq / kg
Ethanol production, storage and distribution	λ	35.00	g CO_2-eq / MJ
OTHER PARAMETERS*			
Exogenous supply of barley (from other areas than Southern Finland)		538 652	t
Exogenous supply of wheat (from other areas than Southern Finland)		229 180	t
Total arable land in feed barley and wheat cultivation (in Southern Finland)		149 700	ha

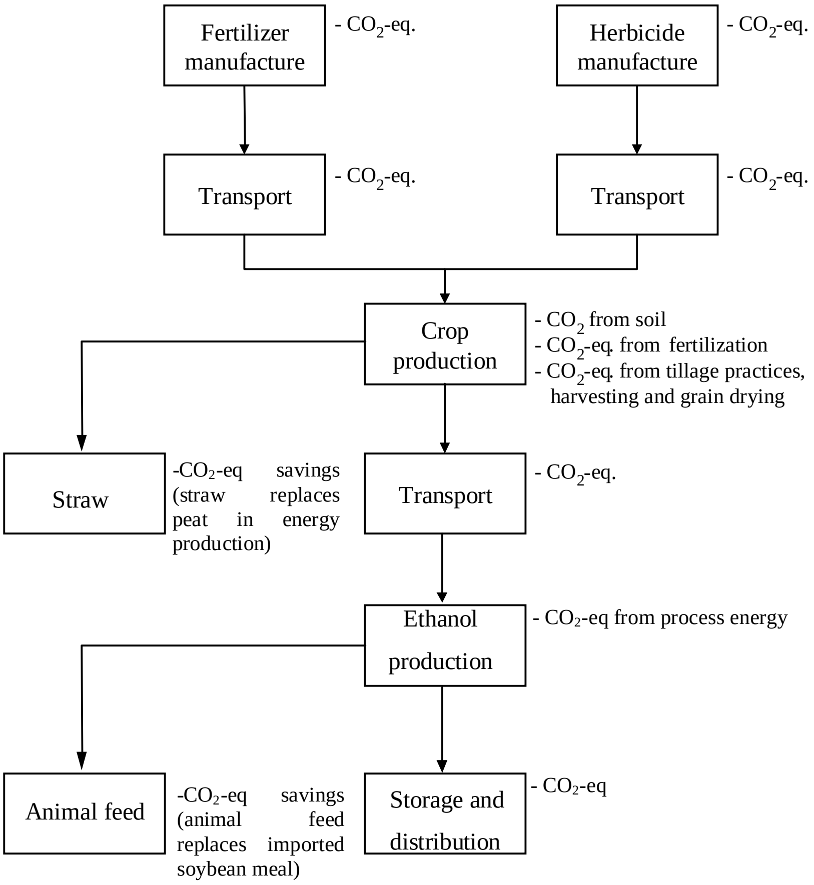
*) All prices, costs, area payments and other parameters are from 2007.

Appendix 2 Greenhouse gas emissions from ethanol production chain and reference fuel

Emissions	**Value**	
ETHANOL PRODUCTION		
Production and use of nitrogen fertilizer*	10.715	kg CO_2-eq / kg N
Soil*	1 430	kg CO_2-eq / ha / a
Pesticides production and use*	16.7	kg CO_2-eq / kg pesticides
Tillage practices (and lime)*	251.38	kg CO_2-eq / ha
Transportation*	0.05881	kg CO_2-eq / ton / km
Grain drying*	0.06561	kg CO_2-eq / kg
Ethanol production, storage and distribution*	0.035	kg CO_2-eq / MJ
End-use of ethanol	0	kg CO_2-eq
CO_2-eq SAVINGS IN ETHANOL PRODUCTION		
DDGS replaces imported soybean meal*	-0.007	kg CO_2-eq / MJ
Straw replaces peat in energy production*	-0.077	kg CO_2-eq / MJ
REFERENCE FUEL (GASOLINE)		
Production of conventional gasoline**	0.011727	kg CO_2-eq / MJ
End-use of gasoline*	0.075559	kg CO_2-eq / MJ

*) Mäkinen et al. 2006
**) Edwards et al. 2006

Appendix 3 Production chain and LCA impacts



Appendix 4 Sensitivity analysis, alternative scenarios

	Price of ethanol -20%				Price of ethanol +20%			
	Private optimum		Social optimum		Private optimum		Social optimum	
PRICES (eur/kg)		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Barley	140.19	*-9.90*	142.11	*-9.90*	171.48	*10.21*	173.74	*10.16*
Wheat	157.06	*-8.73*	160.37	*-8.74*	187.50	*8.96*	191.39	*8.92*
ETHANOL INDUSTRY (t)								
Ethanol production	60 953	*-11.28*	58 713	*-11.59*	75 565	*9.99*	73 256	*10.30*
Animal feed production (From DDGS)	82 024	*-8.85*	77 415	*-9.39*	96 716	*7.48*	92 255	*7.99*
BARLEY MARKETS (t)								
Production in market equilibrium	771 546	*-2.58*	755 990	*-2.65*	808 830	*2.13*	793 789	*2.21*
Animal feed demand	506 953	*1.05*	506 264	*1.05*	496 842	*-0.97*	496 192	*-0.96*
Ethanol demand	264 593	*-8.85*	249 725	*-9.39*	311 988	*7.48*	297 597	*7.99*
WHEAT MARKETS (t)								
Production in market equilibrium	529 713	*1.17*	526 786	*0.79*	518 260	*-1.02*	518 891	*-0.72*
AGRICULTURE (t)								
Total amount of nitrogen fertilizer applied	15 955	*-7.17*	14 480	*-8.04*	18 317	*6.57*	16 898	*7.32*
BARLEY CULTIVATION								
Fertilizer intensity (average) (kg/ha)	89.64	*-7.82*	81.47	*-8.59*	104.16	*7.12*	96.09	*7.81*
Yield (average) (kg/ha)	3 287	*-2.90*	3 172	*-3.41*	3 465	*2.36*	3 374	*2.74*
Profits (average) (eur/ha)	6.13	*-89.57*	10.71	*-83.30*	109.32	*85.98*	115.24	*79.64*
Lower bound of profits (eur/ha)	-13.86	*-140.50*	-8.98	*-122.50*	80.00	*133.78*	86.31	*116.26*
Upper bound of profits (eur/ha)	26.26	*-68.56*	30.56	*-65.48*	138.83	*66.22*	144.34	*63.02*
WHEAT CULTIVATION								
Fertilizer intensity (average) (kg/ha)	121.84	*-7.93*	109.61	*-8.86*	142.14	*7.41*	130.02	*8.12*
Yield (average) (kg/ha)	3 814	*-3.03*	3 667	*-3.53*	4 032	*2.52*	3 912	*2.92*
Profits (average) (eur/ha)	53.33	*-52.80*	63.52	*-49.09*	170.72	*51.11*	183.78	*47.30*
Lower bound of profits(eur/ha)	26.77	*-68.17*	35.31	*-62.46*	139.46	*65.85*	150.55	*60.04*
Upper bound of profits (eur/ha)	80.14	*-43.60*	92.01	*-40.91*	202.19	*42.30*	217.22	*39.49*
LAND ALLOCATION								
Barley	9		9		10		10	
Wheat	10		10		9		9	

	Price of ethanol -20%				Price of ethanol +20%			
	Private optimum		Social optimum		Private optimum		Social optimum	
CO$_2$ -eq EMISSIONS (t)		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Fertilizer (production and use)	170 969	*-7.17*	155 149	*-8.04*	196 261	*6.56*	181 057	*7.31*
Soil	214 340	*0.00*	214 340	*0.00*	214 340	*0.00*	214 340	*0.00*
Grain drying	35 008	*-2.59*	33 792	*-3.11*	36 699	*2.11*	35 754	*2.52*
Transportation (inputs and outputs)	6 276	*-2.59*	6 058	*-3.10*	6 579	*2.11*	6 410	*2.53*
Pesticides (production and use)	2 494	*0.00*	2 494	*0.00*	2 494	*0.00*	2 494	*0.00*
Tillage practices (plowing. harrowing. lime. etc.)	37 632	*0.00*	37 632	*0.00*	37 632	*0.00*	37 632	*0.00*
CO$_2$ -eq emission savings								
Ethanol replacing fossil fuel	18 647	*-10.75*	17 609	*-14.44*	22 194	*6.22*	22 575	*9.68*
Total CO$_2$ -eq	*448 072*	*-2.62*	*431 856*	*-2.68*	*471 812*	*2.54*	*455 111*	*2.56*
PROFITS (million eur)								
Ethanol industry								
Ethanol production	-3.125	*-736.46*	-2.550	*-362.89*	4.869	*891.65*	5.247	*440.93*
Animal feed production	9.040	*15.28*	8.458	*15.00*	6.130	*-21.83*	5.743	*-21.92*
Ethanol industry total	*5.915*	*-29.02*	*5.907*	*-29.05*	*10.999*	*31.99*	*10.990*	*32.01*
Agriculture								
Barley cultivation	0.434	*-90.14*	0.317	*-92.35*	8.917	*102.66*	8.518	*105.50*
Wheat cultivation	4.202	*-50.31*	4.170	*-51.33*	12.599	*48.98*	12.854	*50.02*
Total	*10.551*	*-50.21*	*10.394*	*-50.59*	*32.515*	*53.45*	*32.362*	*53.84*
SOCIAL VALUATION OF THE CLIMATE IMPACTS (million eur)								
Ethanol production (benefits)	0.373	*-10.77*	0.352	*-14.56*	0.444	*6.22*	0.452	*9.71*
Barley cultivation (damages)	-4.134	*-8.05*	-3.864	*-8.37*	-4.811	*7.01*	-4.524	*7.28*
Wheat cultivation (damages)	-5.201	*1.50*	-5.126	*1.12*	-5.069	*-1.07*	-5.030	*-0.77*
Net impact (damages)	-8.961	*-2.63*	-8.637	*-2.68*	-9.436	*2.53*	-9.102	*2.56*
SOCIAL WELFARE (million eur)	*1.589*	*-86.74*	*1.757*	*-85.55*	*23.079*	*92.53*	*23.260*	*91.27*

	Emissions from soil -20%				Emissions from soil +20%			
	Private optimum		Social optimum		Private optimum		Social optimum	
PRICES (eur/kg)		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Barley	155.60	*0.00*	158.78	*0.67*	155.60	*0.00*	156.65	*-0.68*
Wheat	172.08	*0.00*	176.77	*0.60*	172.08	*0.00*	174.66	*-0.60*
ETHANOL INDUSTRY (t)								
Ethanol production	68 702	*0.00*	66 750	*0.51*	68 702	*0.00*	66 090	*-0.49*
Animal feed production (From DDGS)	89 988	*0.00*	85 680	*0.29*	89 988	*0.00*	85 217	*-0.25*
BARLEY MARKETS (t)								
Production in market equilibrium	791 978	*0.00*	777 068	*0.06*	791 978	*0.00*	776 250	*-0.05*
Animal feed demand	501 694	*0.00*	500 680	*-0.07*	501 694	*0.00*	501 357	*0.07*
Ethanol demand	290 284	*0.00*	276 388	*0.29*	290 284	*0.00*	274 894	*-0.25*
WHEAT MARKETS (t)								
Production in market equilibrium	523 576	*0.00*	523 244	*0.11*	523 576	*0.00*	522 091	*-0.11*
AGRICULTURE (t)								
Total amount of nitrogen fertilizer applied	17 188	*0.00*	15 833	*0.55*	17 188	*0.00*	15 658	*-0.56*
BARLEY CULTIVATION								
Fertilizer intensity (average) (kg/ha)	97.24	*0.00*	89.61	*0.54*	97.24	*0.00*	88.65	*-0.54*
Yield (average) (kg/ha)	3 385	*0.00*	3 290	*0.18*	3 385	*0.00*	3 278	*-0.18*
Profits (average) (eur/ha)	58.78	*0.00*	67.74	*5.60*	58.78	*0.00*	60.52	*-5.66*
Lower bound of profits (eur/ha)	34.22	*0.00*	43.28	*8.44*	34.22	*0.00*	36.52	*-8.49*
Upper bound of profits (eur/ha)	83.52	*0.00*	92.36	*4.31*	83.52	*0.00*	84.68	*-4.36*
WHEAT CULTIVATION								
Fertilizer intensity (average) (kg/ha)	132.34	*0.00*	120.93	*0.56*	132.34	*0.00*	119.57	*-0.57*
Yield (average) (kg/ha)	3 933	*0.00*	3 808	*0.18*	3 933	*0.00*	3 794	*-0.18*
Profits (average) (eur/ha)	112.98	*0.00*	128.92	*3.33*	112.98	*0.00*	120.59	*-3.35*
Lower bound of profits(eur/ha)	84.09	*0.00*	97.95	*4.12*	84.09	*0.00*	90.15	*-4.17*
Upper bound of profits (eur/ha)	142.09	*0.00*	160.13	*2.83*	142.09	*0.00*	151.27	*-2.86*
LAND ALLOCATION								
Barley	10		9		10		9	
Wheat	9		10		9		10	

	Emissions from soil -20%				Emissions from soil +20%			
	Private optimum		Social optimum		Private optimum		Social optimum	
CO$_2$ -eq EMISSIONS (t)		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Fertilizer (production and use)	184 172	*0.00*	169 646	*0.55*	184 172	*0.00*	167 780	*-0.56*
Soil	171 472	*-20.00*	171 472	*-20.00*	257 209	*20.00*	257 209	*20.00*
Grain drying	35 939	*0.00*	34 941	*0.19*	35 939	*0.00*	34 808	*-0.19*
Transportation (inputs and outputs)	6 443	*0.00*	6 264	*0.19*	6 443	*0.00*	6 240	*-0.19*
Pesticides (production and use)	2 494	*0.00*	2 494	*0.00*	2 494	*0.00*	2 494	*0.00*
Tillage practices (plowing. harrowing. lime. etc.)	37 632	*0.00*	37 632	*0.00*	37 632	*0.00*	37 632	*0.00*
CO$_2$ -eq emission savings								
Ethanol replacing fossil fuel	42 825	*104.96*	42 588	*106.92*	-1 038	*-104.97*	-1 284	*-106.24*
Total CO$_2$ -eq	*395 327*	*-14.08*	*379 860*	*-14.39*	*524 926*	*14.08*	*507 447*	*14.36*
PROFITS (million eur)								
Ethanol industry								
Ethanol production	0.491	*0.00*	0.993	*2.37*	0.491	*0.00*	0.943	*-2.78*
Animal feed production	7.842	*0.00*	7.331	*-0.33*	7.842	*0.00*	7.382	*0.37*
Ethanol industry total	*8.333*	*0.00*	*8.324*	*-0.01*	*8.333*	*0.00*	*8.325*	*0.00*
Agriculture								
Barley cultivation	4.400	*0.00*	4.152	*0.17*	4.400	*0.00*	4.137	*-0.19*
Wheat cultivation	8.456	*-0.01*	8.575	*0.08*	8.456	*-0.01*	8.555	*-0.15*
Total	*21.190*	*0.00*	*21.051*	*0.07*	*21.190*	*0.00*	*21.018*	*-0.09*
SOCIAL VALUATION OF THE CLIMATE IMPACTS (million eur)								
Ethanol production (benefits)	0.856	*104.78*	0.852	*106.80*	-0.021	*-105.02*	-0.026	*-106.31*
Barley cultivation (damages)	-4.068	*-9.52*	-3.810	*-9.65*	-4.925	*9.54*	-4.624	*9.65*
Wheat cultivation (damages)	-4.695	*-8.37*	-4.639	*-8.48*	-5.553	*8.37*	-5.499	*8.48*
Net impact (damages)	-7.907	*-14.08*	-7.597	*-14.40*	-10.499	*14.08*	-10.149	*14.35*
SOCIAL WELFARE (million eur)	*13.283*	*10.81*	*13.454*	*10.63*	*10.691*	*-10.81*	*10.869*	*-10.62*

	No straw benefit				No feed production from DDGS			
	Private optimum		Social optimum		Private optimum		Social optimum	
PRICES (eur/kg)		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Barley	155.60	*0.00*	151.45	*-3.98*	88.49	*-43.13*	92.26	*-41.50*
Wheat	172.08	*0.00*	169.57	*-3.50*	106.27	*-38.24*	111.00	*-36.83*
ETHANOL INDUSTRY (t)								
Ethanol production	68 702	*0.00*	63 397	*-4.54*	38 413	*-44.09*	33 777	*-49.14*
Animal feed production (From DDGS)	89 988	*0.00*	82 293	*-3.68*	0	*-100.00*	0	*-100.00*
BARLEY MARKETS (t)								
Production in market equilibrium	791 978	*0.00*	768 512	*-1.04*	658 537	*-16.85*	635 423	*-18.18*
Animal feed demand	501 694	*0.00*	503 052	*0.41*	530 824	*5.81*	528 614	*5.51*
Ethanol demand	290 284	*0.00*	265 460	*-3.68*	127 713	*-56.00*	106 809	*-61.24*
WHEAT MARKETS (t)								
Production in market equilibrium	523 576	*0.00*	524 683	*0.38*	548 044	*4.67*	545 680	*4.40*
AGRICULTURE (t)								
Total amount of nitrogen fertilizer applied	17 188	*0.00*	15 259	*-3.09*	10 110	*-41.18*	8 870	*-43.67*
BARLEY CULTIVATION								
Fertilizer intensity (average) (kg/ha)	97.24	*0.00*	86.17	*-3.32*	53.43	*-45.05*	46.91	*-47.37*
Yield (average) (kg/ha)	3 385	*0.00*	3 242	*-1.28*	2 618	*-22.66*	2 452	*-25.33*
Profits (average) (eur/ha)	58.78	*0.00*	42.48	*-33.78*	-154.59	*-363.00*	-146.65	*-328.60*
Lower bound of profits (eur/ha)	34.22	*0.00*	20.12	*-49.59*	-160.44	*-568.85*	-152.13	*-481.18*
Upper bound of profits (eur/ha)	83.52	*0.00*	65.01	*-26.58*	-148.68	*-278.02*	-141.12	*-259.39*
WHEAT CULTIVATION								
Fertilizer intensity (average) (kg/ha)	132.40	*0.05*	116.12	*-3.44*	73.89	*-44.17*	63.78	*-46.96*
Yield (average) (kg/ha)	3 933	*0.00*	3 751	*-1.32*	3 089	*-21.46*	2 890	*-23.97*
Profits (average) (eur/ha)	112.98	*0.00*	100.00	*-19.85*	-130.86	*-215.83*	-118.99	*-195.37*
Lower bound of profits(eur/ha)	84.09	*0.00*	70.24	*-25.33*	-148.44	*-276.53*	-139.28	*-248.06*
Upper bound of profits (eur/ha)	142.09	*0.00*	130.00	*-16.52*	-112.82	*-179.40*	-98.19	*-163.06*
LAND ALLOCATION								
Barley	10		9		6		5	
Wheat	9		10		13		14	

	No straw benefit				No feed production from DDGS			
	Private optimum		Social optimum		Private optimum		Social optimum	
CO$_2$ -eq EMISSIONS (t)		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*		*%-change relative to base-line*
Fertilizer (production and use)	184 172	*0.00*	163 506	*-3.09*	108 327	*-41.18*	95 038	*-43.67*
Soil	214 340	*0.00*	214 340	*0.00*	214 340	*0.00*	214 340	*0.00*
Grain drying	35 939	*0.00*	34 472	*-1.16*	28 907	*-19.57*	27 231	*-21.92*
Transportation (inputs and outputs)	6 443	*0.00*	6 180	*-1.15*	5 182	*-19.57*	4 882	*-21.91*
Pesticides (production and use)	2 494	*0.00*	2 494	*0.00*	2 494	*0.00*	2 494	*0.00*
Tillage practices (plowing. harrowing. lime. etc.)	37 632	*0.00*	37 632	*0.00*	37 632	*0.00*	37 632	*0.00*
CO$_2$ -eq emission savings								
Ethanol replacing fossil fuel	-120 880	*-678.54*	-111 336	*-640.94*	-3 912	*-118.72*	-7 309	*-135.51*
Total CO$_2$ -eq	*601 900*	*30.81*	*569 960*	*28.45*	*400 794*	*-12.89*	*388 925*	*-12.35*
PROFITS (million eur)								
Ethanol industry								
Ethanol production	0.491	*0.00*	0.951	*-1.96*	4.659	*848.88*	4.612	*375.46*
Animal feed production	7.842	*0.00*	7.341	*-0.19*	0.000	*-100.00*	0.000	*-100.00*
Ethanol industry total	*8.333*	*0.00*	*8.291*	*-0.41*	*4.659*	*-44.09*	*4.612*	*-44.60*
Agriculture								
Barley cultivation	4.400	*0.00*	3.967	*-4.29*	-7.186	*-263.32*	-6.264	*-251.12*
Wheat cultivation	8.456	*-0.01*	8.620	*0.61*	-13.506	*-259.70*	-14.529	*-269.57*
Total	*21.190*	*0.00*	*20.879*	*-0.75*	*-16.033*	*-175.66*	*-16.181*	*-176.92*
SOCIAL VALUATION OF THE CLIMATE IMPACTS (million eur)								
Ethanol production (benefits)	-2.418	*-678.47*	-2.227	*-640.53*	-0.078	*-118.66*	-0.146	*-135.44*
Barley cultivation (damages)	-4.496	*0.00*	-4.076	*-3.34*	-2.301	*-48.82*	-1.922	*-54.42*
Wheat cultivation (damages)	-5.124	*0.00*	-5.097	*0.55*	-5.637	*10.01*	-5.710	*12.65*
Net impact (damages)	-12.038	*30.81*	-11.399	*28.44*	-8.016	*-12.90*	-7.779	*-12.35*
SOCIAL WELFARE (million eur)	*9.152*	*-23.65*	*9.479*	*-22.05*	*-24.049*	*-300.63*	*-23.960*	*-297.02*

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