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# How to measure greenhouse gas emissions by fuel type for binary sustainability standards: Average or Marginal emissions? An example of fertilizer use and corn ethanol

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## Abstract

This study proposed a modelling framework which addresses various issues such as decreasing marginal yield of corn with respect to fertilizer use in biofuel production and the resulting greenhouse gas emissions. Particularly, the framework considered exogenous changes including oil price development and biofuel policy through market interactions of different inputs and outputs in biofuel production. We applied the modelling framework numerically in an example of corn ethanol production in the United States to illustrate how the economics of fertilizer use could impact the GHG emissions based on both average and marginal emissions. The results show that higher oil prices increase the prices of gasoline, natural gas, ethanol, and corn, which stimulates corn-based ethanol production and increases corn yields by encouraging profit-maximizing farmers to increase their application rate of nitrogen fertilizers slightly. The effect is that, on average, GHG emissions per unit of produced corn ethanol remain almost constant if oil price increases from 60 to 120 $/barrel.

However, the marginal emissions per additional unit of ethanol production increase by 2.2% or10%, depending on whether the Volumetric Ethanol Excise Tax Credit is implemented or not. More important is that the marginal emissions of corn ethanol are much higher than those of conventional gasoline. Although on average there are GHG emission savings of corn ethanol compared to conventional gasoline, the savings are negative when based on the marginal emissions of corn ethanol. An interesting implication is that the effectiveness of biofuel policies aimed at reducing GHG emissions might be questionable.

**Key words:** oil price, ethanol, corn, nitrogen fertilizer, greenhouse gas emissions, ethanol tax credit.

JEL: Q16, Q42, Q43, Q48

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## 1. Introduction

More than 50 countries have implemented legislative instruments to promote the use of biofuels, such as the mandatory use of biofuels and tax exemptions for them, and many more countries are considering introducing similar policies (Sorda *et al.* 2010, OECD *et al.* 2011, Le et al. 2013a, 2013b ). As a result, the use of biofuels has increased rapidly in recent years: Biofuels currently account for about 3.4% of worldwide energy use in road transport (REN 21 2013).

The United States is one of the countries with an ambitious biofuel policy, which started with the implementation of the Energy Policy Act in 2005 (US Congress 2005). The Energy Policy Act included targets for the mandatory use of biofuels in the transportation fuel supply in the US. The Energy Independence and Security Act of 2007 expanded the biofuel blend mandates to 9 billion US gallons of biofuels in 2008, and to 36 billion gallons in 2022 (US Congress 2007). This legislation is referred to as the Renewable Fuel Standard 2 (RFS 2). In the RFS 2, the use of corn ethanol is capped at 15 billion gallons. These policies resulted in an increase in the use of biofuels from 4.2 billion gallons in 2005 to 13.8 billion gallons in 2013. A key objective of the RFS 2 is to reduce the country's dependency on fossil oil imports, to increase energy security, and to increase resilience against price fluctuations of fossil oil. The prerequisite for the use of biofuels is that their use contributes to reducing greenhouse gas (GHG) emissions, i.e. a 20% threshold reduction of GHG emissions (compared to conventional gasoline produced from fossil oil) for biofuel-producing facilities whose construction was started after December 2007. Similarly in Europe, a GHG saving of 35% is proposed for implementation of biofuels by the Renewable Energy Directive (EC, 2010).

In this context, how to evaluate the GHG emissions from biofuel production becomes an important task. According to the annotated example of a GHG calculation (Alberici and Hamelinck, 2010), a comprehensive assessment of environmental impacts over the life cycle of a biofuel, i.e. a life cycle analysis (LCA) is involved to calculate the average emissions of GHG per unit of biofuel (e.g. kg CO2-eq/MJ ethanol). LCAs have been used for evaluating the effectiveness of biofuel policies in reducing GHG emissions, i.e. the GHG savings of a biofuel by comparing its GHG emissions with those of gasoline (e.g. Le et al., 2013b). LCAs take into account the emissions from the production chain of a biofuel measured across the entire life cycle, i.e., including biomass production, processing, and distribution and calculate the emission for a functional unit such as one MJ or one tonne of a biofuel. The final conclusion on the emission saving is thus based on the average emissions of a biofuel. In the conventional LCAs, a linear relationship between emissions and direct inputs is assumed without considering the external effects of the use of biofuels. Particularly, indirect effects, diminishing marginal productivity of a biomass (e.g. corn) with respect to fertilizer input and interrelations in the energy and agricultural markets are not well considered. Examples of these indirect effects are the impact of biofuel production on indirect land use change (ILUC) and on energy use (Hochman *et al.* 2010, Laborde 2011, Rajagopal *et al.* 2011, Le *et al.* 2013b, Kavallari *et al.* 2014, Smeets *et al.* 2014). These effects may have a large impact on the overall GHG savings of biofuels (Plevin *et al.* 2014).

Apart from the increase in the cultivated area, the increase in biomass production for biofuels is usually realized through higher corn yields per unit of area. Higher crop yields are often proposed as a promising strategy to avoid undesirable ILUC effects of biofuel production and thereby undesirable effects on GHG emissions and biodiversity. These higher yields are partially realized by higher fertilizer application rates. However, higher application rates are probably related to higher GHG emissions per unit of corn, because of a concave yield response function. Kim and Dale (2008) investigated the *economically and environmentally optimal nitrogen application rates* of corn production in the US. Their results show that the GHG emissions associated with per unit of corn production decrease as the nitrogen application rates increases, until a minimum GHG emission level is reached. Further increasing the nitrogen application rate increases the GHG emissions, due to decreasing marginal productivity gains of fertilizer use. That is, there is a U-shaped relation between the nitrogen application rate and the GHG emission intensity of corn production. Their results also indicate that the economically optimal application rates of fertilizers are higher than those at which the GHG emissions per unit of corn are the lowest. Stehfest *et al.* (2010) suggest that merely increasing the quantity of nitrogen fertilizer – probably the simplest way to produce higher yields – could lead to additional emissions of up to 150 kg $CO_2$ eq. per GJ biofuel, which is more than the 91 kg $CO_2$ eq. per GJ of the conventional gasoline. This shows that higher crop yields may have similar GHG emissions effects as ILUC, if higher corn yields are realized through higher application rates of fertilizers under conditions of decreasing marginal productivity gains of fertilizer use. Therefore, there is a need to calculate the marginal emissions of a biofuel (e.g. the emissions from the last unit of biofuel produced from the last unit of corn) for evaluation of emission savings.

Furthermore, the biofuel sector is closely connected with other economic sectors. There is a close economic linkage between the inputs of corn ethanol (e.g., natural gas) through commodity markets and government policies (Tyner *et al.* 2012, Babcock 2013). Price changes in the oil market have a direct impact on the demand for ethanol and the price of gasoline through energy markets (e.g., Tyner and Taheripour 2007; Serra *et al.* 2011), which influences the use of inputs for ethanol production (corn and fertilizers) and therefore the GHG emissions. Current biofuel policies – such as tax for fossil fuels and tax credits for biofuels – change the economic incentives of economic agents to choose their energy products, which have impacts on the GHG emissions.

The aim of this paper is to present a modeling framework for evaluating the impact of the economics of nitrogen fertilizer use on GHG emissions, based on average and marginal GHG emissions, considering the interactions of energy and agricultural markets. The model is applied to the case of corn-ethanol production in the US, and it particularly concerns the impacts of oil price developments and ethanol policies, especially the Volumetric Ethanol Excise Tax Credit (VEETC), on the average and marginal GHG emissions. The novelty of this paper is that we are able to calculate both average and marginal GHG emissions of biofuels which can be compared to those of fossil fuels, and provide useful insights on the actual emission savings of biofuels.

The paper is structured as follows. Section 2 presents an analytical framework for calculating the average and marginal GHG emissions of corn ethanol, taking into account energy and agricultural market interactions. The framework consists of an economic model that links the oil price to the prices of gasoline, corn ethanol, and corn, the price of fertilizers used for the production of corn, and the price of natural gas for the production of corn ethanol. GHG emissions from corn production depend, among others, on the application rate of fertilizers. Economic-maximized rate was recommended in the Corn-Belt in the US (Sawyer et al., 2006). Therefore we determine the economically optimal nitrogen application rate based on profit maximization. To calculate the average and marginal emissions of corn ethanol, the economic model was combined with the data on the GHG balance of corn ethanol from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) LCA model (CARB 2009). In section 3, we take the corn-ethanol production in the US as an example to illustrate how the model can be applied. We report the data for the model parameters and the range of the oil prices we use in the calculations, as well as information on GHG emissions from the production of conventional gasoline from oil sands. The main results concerning the GHG emissions from corn ethanol production under different oil prices are presented for two scenarios, namely with and without VEETC. Sensitivity analyses are presented for the yield–fertilizer response curve and the fertilizer type. Finally, in section 4 we present our conclusions and discuss implications for policy and research.

## 2. The Analytical Framework

To calculate the GHG emissions, we developed an analytical framework based on the four main stages of a corn ethanol production chain, namely: corn cultivation, corn transportation, ethanol production (corn to ethanol conversion), and ethanol distribution (including transport of ethanol and blending with gasoline). The framework consists of two parts: an economic analysis and the calculation of GHG emissions. The economic analysis deals with the interactions between inputs and outputs in different stages, particularly the market interactions between oil, natural gas, gasoline, ethanol, and fertilizers, which impact the use of fertilizers in corn cultivation. The emission part calculates the particular outputs, i.e., the emissions of $CO_2$ and $N_2O$ from the ethanol chain, based on an environmental LCA. In this way, the framework combines the economic analysis of the inputs and outputs with the LCA to calculate the GHG emissions from the corn ethanol production. It thus allows capturing the impact of external changes – such as changes in oil price or a biofuel policy – on the GHG emissions from the corn ethanol production through the market interactions of inputs and outputs, particularly the change in fertilizer use in corn cultivation (see Figure 1).

GHGs are emitted in all stages of the ethanol production chain. In the corn cultivation stage, we use the economically optimal nitrogen application rate to achieve the maximum economic return from the corn production. This economically optimal nitrogen application rate is based on profit maximization, despite the possible overuse of fertilizers by farmers due to risk aversion in most developed countries. It depends on the relative price of nitrogen fertilizers to corn and the corn yield response function. Any change in inputs or outputs in this stage will influence the nitrogen application rate, which will definitely impact the GHG emissions from corn cultivation. In the stage of ethanol production where corn is converted to ethanol, natural gas is the second important input after corn. Therefore, any exogenous forces such as a change in oil price, which influences the price of natural gas and thus the cost of production of corn, will impact the price of ethanol. This will have a feedback effect on the corn production and the fertilizer use in the first stage, and therefore result in changes in GHG emissions. In the stage of blending with gasoline, exogenous changes such as oil price changes will have implications for the price of gasoline and ethanol through the energy market. This again will have a feedback effect on the production of corn as well as the fertilizer use, and influence the final GHG emissions. Below we present the quantitative relations that describe the optimal application rate of nitrogen and the market interactions of inputs and outputs, which finally determine the GHG emissions of corn ethanol.

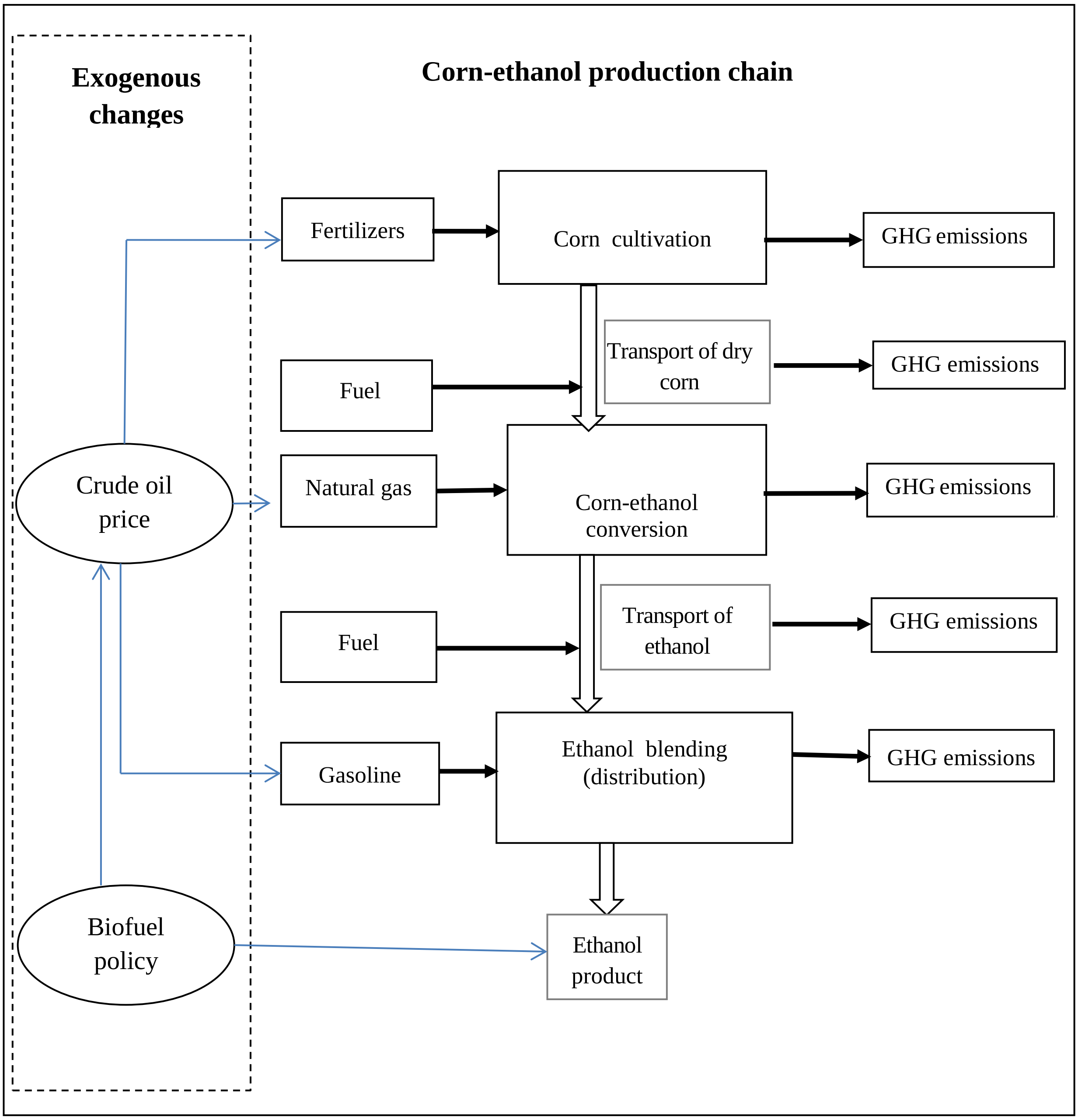

**Figure 1: The analytical framework for calculating GHG emissions from corn-ethanol production**

## 2.1 The economic analysis

In this section, we elaborate in a mathematical model the optimal application rate of nitrogen fertilizer in corn cultivation, the price relation of inputs and outputs in ethanol production, and the price relation between ethanol and gasoline under biofuel policies. The optimal application rate of nitrogen fertilizers is determined by the profit maximization of corn farmers, taking into account the yield response to the nitrogen input. The price relation of corn, natural gas as an input, and ethanol as an output in ethanol production is determined by the equilibrium condition where no positive profit of ethanol production is made under constant return to scale technology. As for the price relation of ethanol and gasoline, the energy efficiency is considered in the vehicle engines for the same distance travelled. Biofuel policies such as a gasoline tax or a biofuel subsidy influence the consumer prices of ethanol and gasoline.

### *Economically optimal application rate of nitrogen in corn cultivation*

We pay special attention to the economically maximized application rate based on the yield response function, which is currently recommended by agronomists. The problem can be represented as follows. A corn farmer maximizes his profit by choosing the application rate of nitrogen fertilizers, subject to the yield–nitrogen response function. Since the response function is based on the nitrogen content, the application rate and the price of fertilizers in the following calculations are also in terms of nitrogen content (kgN/ha or \$/kgN, respectively). The unit-area profit function can be written as:

$$\pi_{corn} = Q_{corn}\, P_{corn} - NP_{nitrogen} - C_{other} \tag{1}$$

where $Q_{corn}$ is the corn yield or the corn output per unit of land (kg/ha), $P_{corn}$ and $P_{nitrogen}$ are the price of corn (\$/kg) and nitrogen (\$/kgN), respectively, $N$ is the application rate of fertilizer in nitrogen content (kgN/ha), and $C_{other}$ are the costs of other inputs per unit of land for corn production (\$/ha). The price of nitrogen is based on the price of nitrogen fertilizers (ammonia is used as a reference fertilizer) and the nitrogen content. Following Cerrato and Blackmer (1990), the yield response function can be expressed as a quadratic function of the application rate of nitrogen, indicating a positive relation between nitrogen input and corn output with diminishing marginal productivity. That is:

$$Q_{corn} = m + n * N - kN^2, \tag{2}$$

where *m*, *n* and *k* are parameters and *N* is the same as above. Plugging (2) in (1) gives:

$$\pi_{corn} = mP_{corn} + \left(nP_{corn} - P_{nitrogen}\right) * N - kP_{corn}N^2 - C_{other} \tag{3}$$

Similar to Sawyer *et al.* (2006), assuming the costs of other inputs are fixed, we take the derivative of (3) with respect to *N* and set it to zero to obtain the *economically optimal application rate* of nitrogen and corn yield:

$$N = \left[\left(\frac{P_{nitrogen}}{P_{corn}}\right) - n\right]/(-2k)\ , \tag{4}$$

$$Q_{corn} = \left[4mk + \left(\frac{P_{nitrogen}}{P_{corn}}\right)^2 - n^2\right]/(-4k)\ . \tag{5}$$

### *Price relation between corn, ethanol, and natural gas in ethanol production*

Ethanol production (see Fig. 1) needs corn and natural gas as inputs. Following Tyner and Taheripour (2007), the production technology of ethanol production based on the dry mill process follows a linear relation between inputs and outputs including the co-product of dried distillers' grains with solubles (DDGS). The profit derived from ethanol production includes the revenue from selling ethanol and the DDGS, minus the various costs including those of corn and natural gas and other costs. Due to fixed technical coefficients of inputs and outputs (i.e., a constant return to scale production technology), the unit profit of the ethanol producer ($/m$^3$) can be expressed as:

$$\pi_{ethanol} = \beta P_{ethanol} - \alpha P_{corn} - \gamma P_{natural\,gas} + \delta P_{DDGS} - c_0, \tag{6}$$

where $P_{ethanol}$ is the price of ethanol ($/m$^3$), $P_{corn}$ is the price of corn ($/kg), $P_{natural\ gas}$ is the price of natural gas ($/m$^3$), $P_{DDGS}$ is the price of DDGS ($/kg), and $c_0$ are the other costs including the capital costs per unit of ethanol production. Parameters β, α, γ, and δ are the technical coefficients, i.e., γ m$^3$ of natural gas and α kg of corn can produce β m$^3$ of ethanol and δ kg of DDGS for one m$^3$ of ethanol production (CARB 2009). Since the co-product DDGS can be used as a substitute for corn and soybean meal in animal feed, its price is correlated with the corn price (Tyner *et al.* 2007). This can be expressed as $P_{DDGS} = xP_{corn}$, where $x$ is the price ratio of DDGS to corn. As a result, the unit profit function can be written as:

$$\pi_{ethanol} = \beta P_{ethanol} - (\alpha - \delta x)P_{corn} - \gamma P_{natural\ gas} - c_0. \tag{7}$$

In a competitive market, if the profit under constant return to scale technology is positive, the producer will continue to increase his production by demanding more corn inputs. This results in a higher price of corn and a lower price of ethanol. The producer will continue to increase his production until the profit becomes zero or an equilibrium is reached. Therefore, at the equilibrium, the following price relation exists:

$$P_{corn} = (\beta P_{ethanol} - \gamma P_{natural\ gas} - c_0)/(\alpha - \delta x). \tag{8}$$

It can be seen that equation (8) is consistent with equation (2.1) of de Gorter et al. (2015) when α=1, which is the case for Leontief technology.

### Ethanol and gasoline prices under biofuel policies

We follow de Gorter et al (2015) to derive the ethanol and gasoline price relations under the volume tax and volume tax credit policies. For fuel users, the willingness to pay (WTP) for a certain fuel depends not only on the fuel price, but also on the energy efficiency of the fuel for travelling a given distance. Due to its lower energy content, one unit (e.g. one m$^3$) of ethanol will power a vehicle over a shorter distance than the same amount of gasoline, assuming the combustion efficiency of the two fuels is equal. Assuming that for fuel users gasoline and ethanol are perfect substitutes, the WTP for ethanol and gasoline for travelling the same distance should be equal. If the ratio of distance (e.g., km) made by 1 $m^3$ of ethanol to that of gasoline is denoted as $\lambda$ ($0< \lambda< 1$), the price relation between ethanol and gasoline in a competitive market is: $P_{ethanol} = \lambda\, P_{gasoline}$ (de Gorter and Just, 2010a). If a volumetric consumption tax for any fuel is used, the price relation between gasoline and ethanol becomes:

$$P_{ethanol} = \lambda\,(P_{gasoline} + t) - t \tag{9}$$

where $P_{ethanol}$ and $P_{gasoline}$ are the prices of ethanol ($\$/m^3$) and gasoline ($\$/m^3$), respectively, $\lambda$ is the ratio of kilometers made by one $m^3$ of ethanol relative to the same amount of gasoline, and $t$ is the volumetric fuel tax ($\$/m^3$).

Furthermore, the VEETC (i.e., a subsidy to ethanol blenders) was implemented in the US to promote the blending of ethanol with gasoline. For each unit of ethanol blended with gasoline, the ethanol blender obtains a certain credit, which changes the price relation as follows:

$$P_{ethanol} = \lambda\, P_{gasoline} - (1-\lambda)t + t_c, \tag{10}$$

where $t_c$ is the tax credit including state and federal subsidies for each unit of ethanol blended ($\$/m^3$).

### *Price relation of fossil fuels and nitrogen fertilizers*

The prices of crude oil, natural gas, and gasoline are closely related (Serra and Zilberman, 2013). Based on some historical data on these prices, the following correlations[1] were identified using a linear regression analysis by Tyner and Taheripour (2007):

$$P_{natural\,gas} = a_1 + a_2 P_{crude\,oil} \tag{11}$$

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[1] It needs to be cautious for the use of the price correlation between natural gas and crude oil because after 2005 they are not always strongly correlated.

$$P_{gasoline} = b_1 + b_2 P_{crude\ oil} \tag{12}$$

where $P_{natural\ gas}$, $P_{gasoline}$, and $P_{crude\ oil}$ are the prices of natural gas, gasoline, and crude oil (\$/m$^3$), respectively, and $a_1$, $a_2$, $b_1$, and $b_2$ are the estimated parameters.

For the production of nitrogen fertilizers, around 80% of the production cost is attributed to the use of natural gas (GAO 2003). Due to the close relation between the prices of natural gas and crude oil, a statistically evident price relation between fertilizer and crude oil can also be established (Chen 2013), i.e.:

$$P_{fertilizer} = c_1 + c_2 P_{crude\ oil}, \tag{13}$$

where $c_1$ and $c_2$ are estimated parameters (EIA 2013, USDA 2013).

Equations 1–13 form the economic part of the framework for determining the optimal application rate of nitrogen and yield in corn production as well as the price relations between corn, ethanol, gasoline, natural gas, fertilizers and crude oil. In what follows, we explain how we calculated the GHG emissions from corn ethanol.

## 2.2 Calculation of greenhouse gas emissions

The GHG emissions of corn ethanol production were calculated using data from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (CARB 2009). The GREET model provides data on inputs and outputs in different stages of the production chain of corn ethanol: corn cultivation, corn transportation, corn to ethanol conversion, and ethanol distribution including transportation and blending (see Figure 1 and Table 1). Estimated emissions of nitrous oxide from nitrogen fertilizer use in the GREET model are based on the national greenhouse gas inventories by the International Panel on Climate Change (IPCC 2006). They include both direct emissions from the field on which fertilizers are applied, and indirect emissions from nitrogen lost through runoff and leaching. They are converted into $CO_2$ equivalent. Table 1 also shows the average GHG emissions per MJ of ethanol production and the marginal emissions per additional MJ in terms of $CO_2$ equivalent based on the GREET model.

We used the GREET model to calculate the GHG emissions of corn ethanol production under different application rates of nitrogen. The dry corn milling of ethanol conversion was used in the calculations, because it accounts for 85% of the ethanol production (CARB 2009). This assumption resulted in a conservative estimate of the GHG emissions, since wet milling results in 10% higher emissions (CARB 2009). Also note that emissions from indirect land use change (ILUC), which can be substantial, were not considered in this study. For example, Hertel *et al.* (2010) estimated the GHG emissions of corn ethanol produced in the US at 27 $gCO_2$ eq./MJ due to ILUC. Also the impact of biofuel use on energy markets can greatly reduce the GHG saving effect of biofuels (Smeets *et al.* 2014).

**Table 1: GHG emissions of dry mill corn ethanol production**

| **Stages** | **Main activities and inputs** | **GHG ($gCO_2$ eq/MJ)** |
|---|---|---|
| *Corn cultivation* | Corn farming | 5.65 |
| | Agricultural chemicals excluding nitrogen fertilizers | 7.88 |
| | Nitrogen fertilizer N2O in field | 15.91 |
| | Production of nitrogen fertilizers | 6.40 |
| *Corn transportation* | | 2.22 |
| *Corn to ethanol conversion* | Corn to ethanol conversion, excluding DDGS | 38.30 |

|  |  |  |
|---|---|---|
|  | DDGS | -11.51 |
| *Ethanol distribution* | Ethanol transportation and blending | 2.70 |
| ***Total*** |  | 67.55 |

Source: CARB 2009.

### *Average GHG emissions of corn ethanol*

The GHG emissions of corn ethanol were calculated based on the emissions from each phase of the production chain: $E_{cc}$ in the cultivation stage, $E_{ct}$ for the corn transport, $E_{ep}$ for the corn to ethanol conversion, and $E_{et}$ for the ethanol transport. The units for calculation were modified to the SI units. As indicated, α kg of corn can produce β $m^3$ of ethanol. The following equation gives the relation between the corn yield in kg/ha and ethanol in $m^3$/ha:

$$Q_{corn} = \frac{\alpha}{\beta} Q_{ethanol} \qquad (17)$$

The total GHG emissions from ethanol production per unit area (ha) can be written as:

$$TE(N, Q_{ethanol}) = E_{cc}(N, \frac{\alpha}{\beta} Q_{ethanol}) + E_{ct}(\frac{\alpha}{\beta} Q_{ethanol}) + E_{ep}(Q_{ethanol}) + E_{et}(Q_{ethanol}) \qquad (18)$$

The average GHG emissions per $m^3$ of ethanol production ($E_{average}$) is calculated as:

$$E_{average} = \frac{TE(N, Q_{ethanol})}{Q_{ethanol}} \qquad (19)$$

In order to calculate the GHG savings of corn ethanol, we took the difference between the average GHG emissions of corn ethanol and those of conventional gasoline. In order to compare the environmental impact of corn ethanol with that of fossil fuels, we further converted $m^3$ to MJ in calculating the average and marginal emissions for consistency with the literature.

***Marginal GHG emissions of corn ethanol***

The marginal GHG emissions are defined as the change in emissions for an additional unit of ethanol production. According to the relationship between the total GHG emissions (TE) and production quantity ($Q_{ethanol}$) in (18), marginal emissions are mathematically the derivative of TE with respect to $Q_{ethanol}$. However, we do not have an explicit function for TE as a function of $Q_{ethanol}$ in (18). Therefore the marginal emissions will be dealt with numerically. Consider that the last unit of ethanol production can be achieved by using more fertilizers and there exists a non-linear yield response function. If the nitrogen application rate increases by a small amount ΔN, i.e. from N to $N^*$ (= N + ΔN), and the corn yield increases to $Q^*_{corn}$ (= $Q_{corn}$ + Δ $Q_{corn}$), then the production of ethanol increases to $Q^*_{ethanol}$ (= $Q_{ethanol} + \Delta Q_{ethanol}$). This leads to the total GHG emissions TE*, a function of $N^*$ and $Q^*_{ethanol}$ (see (17) and (18) ). The marginal GHG emissions of ethanol or the emissions of the last unit of ethanol ($E_{margainl}$) can then be calculated as:

$$E_{marginal} = \frac{\Delta TE(N, Q_{ethanol})}{\Delta Q_{ethanol}} \approx \frac{TE^*(N^*, Q^*_{ethanol}) - TE(N, Q_{ethanol})}{Q^*_{ethanol} - Q_{ethanol}} \tag{20}$$

## 3. A Numerical Example

### 3.1 Input Data

This section summarizes the data needed for calculation. The parameter values used in the economic analysis are presented in Table 2. *The base year is 2007* with an application rate of 136 lb. nitrogen per acre or 152 kg nitrogen from ammonia per hectare.

For the price of crude oil ($P_{crude\ oil}$), we considered a plausible increase range from 30 to 120 S/barrel, because corn ethanol becomes attractive only above this level when it can compete with gasoline under the scenarios with poor weather (low yields) and good weather (high yields) (Good *et* *al.* 2011). An upper limit of 120$ per barrel was considered to account for the variability in the near future (IEA 2013).

To calculate emission savings, we used the average GHG emissions 91.0 $gCO_2$ eq. per MJ (or 4.31 GJ per $m^3$) for gasoline sold in the US provided by Lattanzio (2014). About 9% of the oil products consumed in the US are currently made from oil sands (Lattanzio 2014). The use of oil sands from Canada will increase as a result of the Keystone pipeline system. We therefore considered the GHG emissions from the gasoline produced from Canadian oil sands, which are on average 14–20% higher than the average of 91.0 $gCO_2$ eq. per MJ, or 104–109 $gCO_2$ eq. per MJ, which is equal to 4.93–5.31 GJ per $m^3$ (Lattanzio 2014). In this study, we therefore used 106.5 $gCO_2$ eq. per MJ, or 5.05 GJ per $m^3$ for the marginal emissions of gasoline produced from oil sands.

**Table 2: Parameter values used in calculations based on the analytical framework**

| **Parameter** | **Value** | **Units** | **Sources** |
|---|---|---|---|
| $m$ | 93.739 | Not applicable | Vanotti and Bundy (1994) and Havlin and Benson (2006) |
| $n$ | 0.58443 | Not applicable | Vanotti and Bundy (1994) and Havlin and Benson (2006) |
| $k$ | 0.0014954 | Not applicable | Vanotti and Bundy (1994) and Havlin and Benson (2006) |
| $\gamma$ | 87937.6 | Btu | CARB (2009) |
| $\alpha$ | 1 | bushel | CARB (2009) |
| $\beta$ | 2.72 | gallon | CARB (2009) |
| $\delta$ | 14.52 | lb. | CARB (2009) |
| $c_0$ | 1.22 | $/bushel | Mallory *et al.* (2012) |

|  |  |  |  |
|---|---|---|---|
| $x$ | 91 | % | Anderson *et al.* (2008) |
| $\lambda$ | 0.7 | Not applicable | de Gorter and Just (2010) |
| $t$ | 0.48 | \$/gallon | API (2013) |
| $t_c$ | 0.52 | \$/gallon | Koplow (2006) |
| $a_1$ | 2.1748 | Not applicable | USDA ERS (2013) |
| $a_2$ | 0.0400 | Not applicable | USDA ERS (2013) |
| $b_1$ | 0.3693 | Not applicable | USDA ERS (2013) |
| $b_2$ | 0.0278 | Not applicable | USDA ERS (2013) |
| $c_1$ | 0.0826 | Not applicable | USDA ERS (2013) and EIA (2013) |
| $c_2$ | 0.0030 | Not applicable | USDA ERS (2013) and EIA (2013) |

Note: Units in the table are given according to the original sources.

### 3.2. Numerical Results

We used the framework developed in section 2 and the data in section 3.1 to calculate how changes in oil prices and tax credits influence the economic variables and GHG emissions. We then calculated the emission savings compared to conventional gasoline from oil sands. We also conducted sensitivity analyses particularly for the parameter values in the yield response function and the type of fertilizers.

Table 3 shows the impacts of changes in the price of crude oil and of the Volumetric Ethanol Excise Tax Credit (VEETC) on the price of ethanol, corn, and nitrogen, the yield of corn, the nitrogen application rate and the economic return to nitrogen, and the ethanol production per ha. The impacts on the average and marginal GHG emissions of corn ethanol are also shown in Table 3.

**Table 3: Impacts of oil prices on economic variables and emissions, with and without VEETC**

| | With VEETC | | | | Without VEETC | | | |
|---|---|---|---|---|---|---|---|---|
| | **Crude oil price ($/barrel)** | | | | **Crude oil price ($/barrel)** | | | |
| | 30 | 60 | 90 | 120 | 30 | 60 | 90 | 120 |
| ***Prices*** | | | | | | | | |
| Ethanol ($/m$^3$) | 322 | 476 | 630 | 785 | 184 | 339 | 493 | 647 |
| Corn ($/kg) | 0.09 | 0.17 | 0.25 | 0.32 | 0.02 | 0.1 | 0.17 | 0.25 |
| Nitrogen ($/kg N) | 0.46 | 0.71 | 0.95 | 1.19 | 0.46 | 0.71 | 0.95 | 1.19 |
| ***Corn and ethanol production*** | | | | | | | | |
| Nitrogen application rate (kg N/ha) | 186 | 191 | 193 | 194 | 61 | 170 | 182 | 187 |
| Corn yield (kg/ha) | 9384 | 9410 | 9418 | 9423 | 7605 | 9288 | 9367 | 9392 |
| Economic return to nitrogen ($/ha) | 782 | 1455 | 2129 | 2802 | 121 | 773 | 1444 | 2116 |
| Ethanol yield (MJ/ha) | 80384 | 80604 | 80677 | 80713 | 65147 | 79558 | 80239 | 80450 |
| ***Emissions*** | | | | | | | | |
| Average emission (g $CO_2$eq./MJ) | 69.20 | 69.57 | 69.72 | 69.79 | 61.03 | 68.17 | 68.98 | 69.30 |
| Marginal emission (g $CO_2$eq./MJ) | 148.54 | 154.06 | 156.31 | 157.53 | 96.97 | 135.98 | 145.65 | 150.03 |

### 3.2.1 Price and production effects

We first examined the price and production effect of an increase in oil price, i.e., from 60 $/barrel to 120$/barrel, which partially reflects the past and future expected development of oil prices. An increase in oil price results in an increase in the price of gasoline (see equation 12; not shown in Table

3) and ethanol (equation 10). The increase in oil price from 60 to 120$/barrel increases the price of ethanol from 476 to 785 $/m$^3$ if VEETC is implemented, or from 339 to 647 $/m$^3$ if VEETC is not implemented.

The price of nitrogen fertilizers is strongly correlated with the price of natural gas and oil, because the price of natural gas is strongly correlated with the price of oil (see equation 11) and because of the high share of natural gas in the production costs of nitrogen fertilizers. The increase in oil price from 60 to 120$/barrel leads to a 68 % increase in the fertilizer price, i.e., from 00.71 to 1.19 $/kg, which is the same in both scenarios (see equation 13).

An increase in the price of ethanol induces an increase in the production of ethanol, which depends on the price of corn and the costs of other inputs (equations 6–8). Especially important is the price of natural gas, which is used for distilling the corn ethanol and is correlated with the price of oil, and the price of DDGS, which is correlated with the price of corn. The net effect is an increase in the price of corn. The increase in the price of corn is greater if the price of ethanol is higher. The price of corn increases from 0.17 to 0.32 $/kg (i.e. by 88%) in the case that VEETC is considered and from 0.1 to 0.25 $/kg (by 150%) without VEETC.

The increasing corn price provokes an increase in the production of corn as a result of the profit maximizing behavior of farmers (equations 1–5). An increase in corn production is partially realized via an increase in fertilizer use, despite the higher costs of nitrogen fertilizer (which follows from the assumed increase in oil prices).

As a result of the higher prices of corn and ethanol, the nitrogen application rate and corn production effects are greater in the case that the VEETC is implemented. Consequently, the economic returns to nitrogen fertilizers are higher in the case with VEETC (i.e.,1455–2802 $/ha) than in the case without VEETC (i.e.,773–2116 $/ha).

The net effect of an increase in oil price is that both the corn yield per hectare and the yield of corn ethanol per hectare increase. However, the impact on yields and on the nitrogen application rate is limited. Corn yields per additional kilogram of nitrogen fertilizers decline with the increase in the oil price. This shows that the marginal productivity of fertilizer use is declining (see equation 2 and Figure 2).

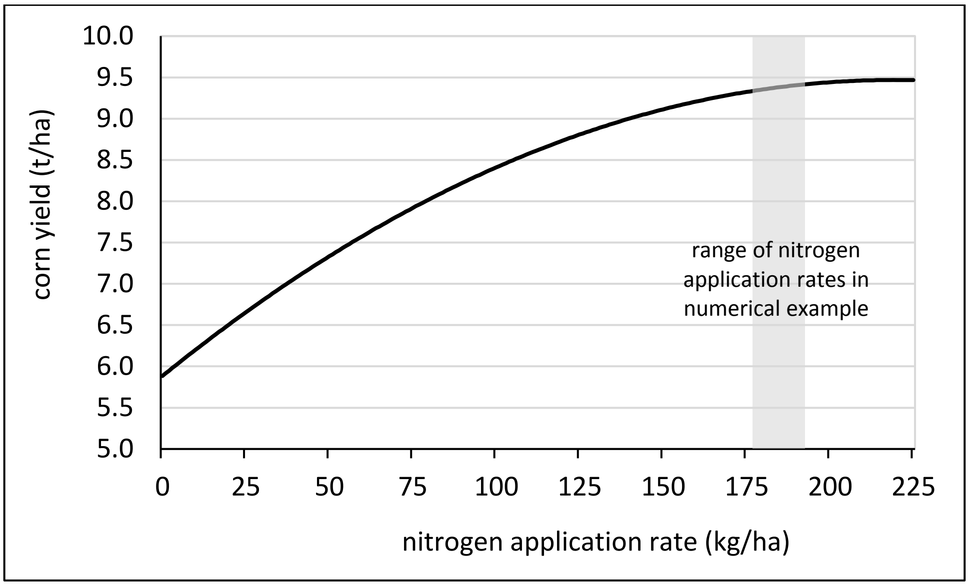

**Figure 2: Correlation between fertilizer use and corn yield.**

Figure 2 shows the link between nitrogen application rates and the corn yield response curve, which is concave. Important to note is the relatively limited response of corn yields for the range of nitrogen application rates of 186–194 kg nitrogen per hectare considered in this study (see Table 3). It suggests that the yield of corn in the US is currently close to the maximum yield. For a comparison, the average nitrogen fertilizer use in the US in 2010, when the oil price was 80 $ per barrel, was 157 kg per hectare (USDA, 2013).

The results presented above also show that the nitrogen application rate is determined by the price of nitrogen fertilizers and especially by the price of corn. The results also show that the price of corn is significantly influenced by the oil and ethanol markets and indirectly through the RFS 2 biofuel policy (i.e., the blender tax credit).

Table 3 also shows the relation between the price of oil and the application rate of nitrogen, which is positive but at a decreasing rate with the oil price. This relationship is graphically represented in a stylized form in Figure 3. The vertical axis shows the price ratio of nitrogen to corn. A higher oil price reduces the nitrogen to corn price ratio. This means that the increase in the price of nitrogen is less than the increase in the price of corn. This effect is reduced when the price of oil increases. According to equation 4, the price ratio has a negative and linear relationship with the (economically optimal) nitrogen application rate. The relations were examined by a series of continuous calculations in the application of the analytical framework. We show the outcomes of our calculations for the range of oil prices between 30 and 120 $/barrel in Figure 3.

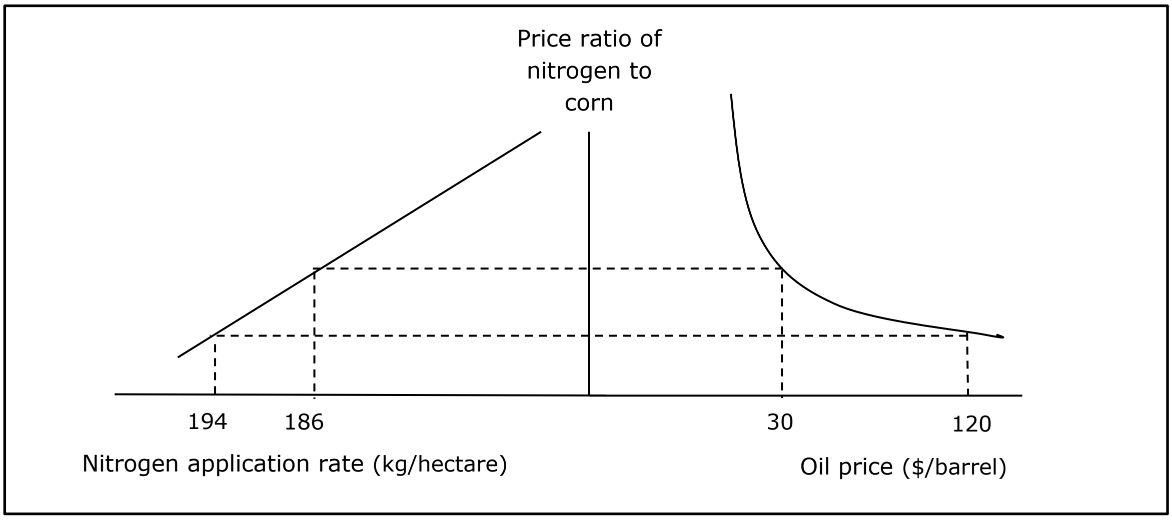

**Figure 3: Relations between oil price and nitrogen application rate**

The results in Table 3 show that both the average and the marginal emissions of corn ethanol increase with the oil price. The increase in average emissions is negligible, whereas the increase in the marginal emissions is 3.5% or 10% for oil price increases from 60 to 120$/barrel, depending on whether the VEETC is implemented or not.

Furthermore, we also analyze the impacts of a price fall in crude oil e.g. from 60 to 30 $/barrel, which reflects the recent oil market development. Under lower oil price (e.g. oil decreases from 60 to 30 $/barrel), marginal emissions decrease by 3.5% or 29%, while the average emissions decrease by 0.5% or 10%, depending on whether the VEETC is implemented or not. This result shows a stronger impact of oil price change on the marginal emissions than the average emissions of ethanol production.

### 3.2.2 Savings of greenhouse gas emissions of corn ethanol compared to gasoline

The results presented in the previous section show that it is profitable for farmers to increase their production of corn through higher fertilizer application rates, when the oil price increases. These changes also influence the GHG emissions of corn and corn ethanol. In this paper a distinction is made between the effect on the average emissions and the marginal emissions of corn ethanol. The GHG emission savings are defined as the percentage reduction in GHG emissions from the production of corn ethanol compared to conventional gasoline. For example, a 24% GHG emission saving of ethanol means that the substitution of one energetic unit of ethanol for gasoline reduces the GHG emissions by 24%.

The results in terms of emission savings are presented in Figure 4, showing the average and marginal GHG emission saving effect of substituting ethanol for gasoline under the range of oil prices considered for the scenarios of with and without tax credits. The average emissions are hardly affected by the change in oil price, and thus also the GHG emission saving based on the average GHG emission saving of corn ethanol and gasoline are nearly constant at 25.2% to 26.9%.

However, our calculation of the marginal GHG emissions from ethanol production is much higher than the marginal emissions of conventional gasoline. The comparison of the two along the range of oil prices considered shows that the marginal GHG saving is negative, and becomes more negative as oil prices increase. This means that each unit of additional ethanol production results in an increase in emissions above the marginal emissions of gasoline produced from oil sands, which are 106.5 $gCO_2$ eq. per MJ. The increase in marginal GHG emissions of corn ethanol is the result of the higher application rate of fertilizers and the decreasing marginal productivity of fertilizer use. It is also interesting that the blender tax credits lead to higher (average and marginal) emissions, but also reduce the emission increasing effect of higher oil prices.

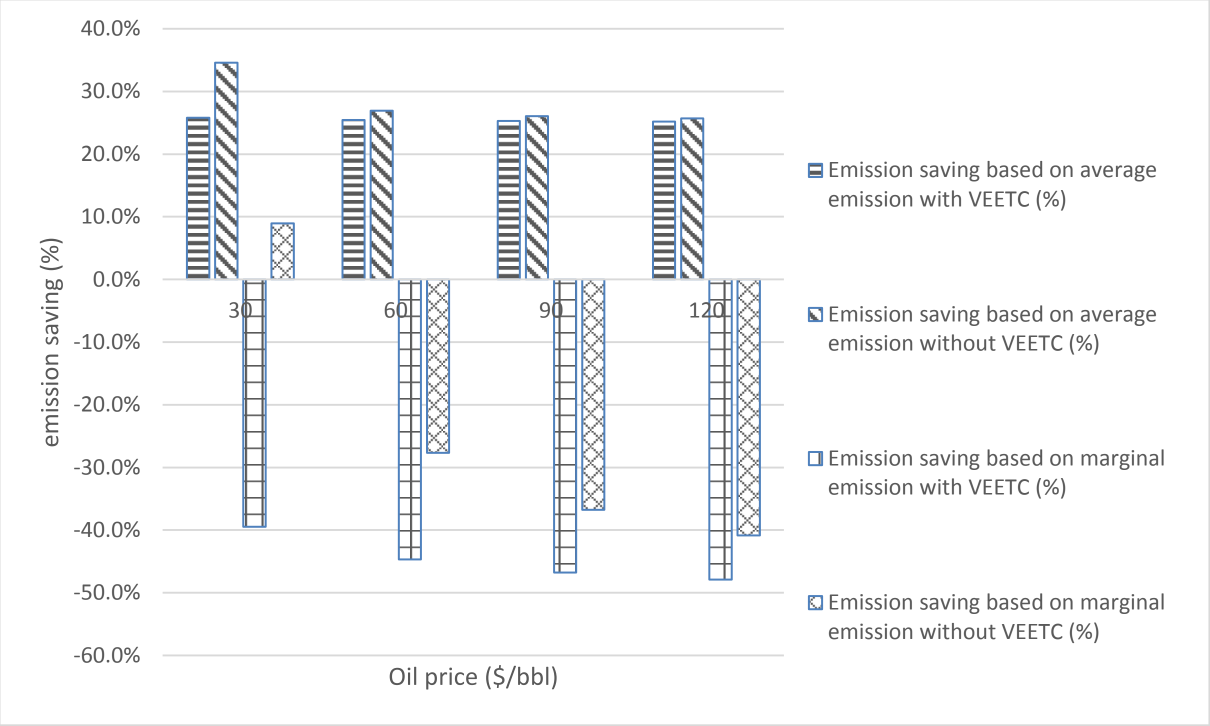

**Figure 4: Average and marginal emission savings of corn ethanol with and without VEETC.**

## 3.3 Sensitivity analyses

The analytical framework presented in Section 2 is based on a set of assumptions concerning the dynamics of energy markets and the agricultural production of corn. In this section, the robustness of the model results is illustrated by sensitivity analyses in which two key sets of parameters were adjusted: The corn yield response function (equation 2) – which determines the decreasing marginal yields of fertilizer use – and the type of fertilizers (equation 13), which is an important factor for determining the optimal application rate. The sensitivity analyses were carried out under the 'with a blender tax credit' scenario. The results are presented in Table 4.

### Sensitivity analysis 1: yield response curve

Together with the price of corn and nitrogen, the yield response function determines the economically optimal application rate of nitrogen at a given oil price level. The reference results presented in Table 3 are based on an empirical yield response function (see section 3 for the values of the relevant parameters). However, Vanotti and Bundy (1994) refer to a lower yield function variant that depends on soil quality, crop management, and cultivation technology. We therefore took their (lower) values for an alternative yield function (equation 2): 61.265, 0.50653, and 0.0012038 for parameters *m*, *n*, and *k*, respectively. Our calculation (see Table 4) shows that this alternative yield function is less responsive to the oil price changes and the optimal nitrogen application rates are around 5.5% higher, while corn yields are about 24% lower compared to the results in Table 3. This leads to about 8% higher average emissions per unit of corn ethanol, and slightly lower marginal emissions per additional unit of corn ethanol. We conclude that the results are rather robust for changes in the fertilizer yield response curve.

### Sensitivity analysis 2: fertilizer type

The most important types of nitrogen fertilizer used in corn cultivation are ammonia, urea and ammonium nitrate. In the calculations above, we used ammonia as a reference. However, different types of fertilizers have different prices, which have implications for their use. For urea fertilizer, different correlations between the oil price and fertilizer price have been identified. According to EIA (2013) and USDA (2013), parameters $c_1$ and $c_2$ are lower for urea than for ammonia, which are 0.0754 and 0.0021, respectively. We used these values for the sensitivity analysis of the fertilizer type.

The use of urea leads to higher nitrogen prices and thus lower optimal application rates. Compared to ammonia, the production of urea requires more energy. In addition, urea contains carbon that can be released in the soil as $CO_2$. Therefore, the average emissions are higher when urea is used as a fertilizer for corn cultivation than when ammonia is used. However, the marginal emissions per additional unit of ethanol are lower compared to ammonia fertilizer. A lower nitrogen application rate corresponds to a higher corn production level, which indicates a higher ethanol production with fewer emissions. The marginal emissions of corn ethanol are, however, still well above the marginal emissions of gasoline produced from oil sands.

**Table 4: Sensitivity of the yield response function and the fertilizer type to the results**

| | Yield response function | | | | Fertilizer type | | | |
|---|---|---|---|---|---|---|---|---|
| | **Crude oil price ($/barrel)** | | | | **Crude oil price ($/barrel)** | | | |
| | 30 | 60 | 90 | 120 | 30 | 60 | 90 | 120 |
| ***Prices*** | | | | | | | | |
| Ethanol ($/m$^3$) | 322 | 476 | 630 | 785 | 322 | 476 | 630 | 785 |
| Corn ($/kg) | 0.09 | 0.17 | 0.25 | 0.32 | 0.09 | 0.17 | 0.25 | 0.32 |
| Nitrogen ($/kg N) | 0.46 | 0.71 | 0.95 | 1.19 | 0.46 | 0.71 | 0.95 | 1.19 |
| ***Corn and ethanol production*** | | | | | | | | |
| Nitrogen application rate (kg N/ha) | 194 | 201 | 204 | 205 | 171 | 181 | 185 | 186 |
| Corn yield (kg/ha) | 7086 | 7118 | 7128 | 7133 | 9296 | 9359 | 9379 | 9389 |
| Ethanol yield (MJ/ha) | 60696 | 60969 | 61060 | 61104 | 79632 | 80169 | 80340 | 80423 |
| ***Emissions*** | | | | | | | | |
| Average emissions (g $CO_2$eq./MJ) | 74.52 | 75.11 | 75.34 | 75.46 | 68.25 | 68.89 | 69.13 | 69.26 |
| Emission savings based on average emissions (%) | 20.13 | 19.50 | 19.25 | 19.12 | 26.85 | 26.17 | 25.91 | 25.77 |
| Marginal emissions (g $CO_2$eq./MJ) | 235.7 | 233.06 | 232.9 | 233.0 | 136.8 | 144.4 | 147.6 | 149.4 |
| Emission savings based on marginal emissions (%) | -121.3 | -118.8 | -118.7 | -118.8 | -28.48 | -35.58 | -38.62 | -40.30 |

## 4. Discussion and conclusions

This paper attempted to provide a modeling framework to evaluate the greenhouse emissions from biofuel production. Particular attention has been paid to how diminishing productivity of corn with respect to the fertilizer inputs, and the market interactions of energy and agricultural products may impact the GHG emissions of biofuels under oil price development and the Volumetric Ethanol Excise Tax Credit (VEETC).

The use of biofuels leads to fundamental changes in the economic linkages between energy and agricultural markets. Especially important for the greenhouse gas (GHG) emission saving potential of biofuels is the economics of fertilizer use. For example, the production and use of nitrogen fertilizers accounts for one third or more of the GHG emissions of corn ethanol production in the US. Changes in fertilizer use can thus have a large impact on the GHG saving potential of corn ethanol. Therefore, we applied the modelling framework to evaluate the impact of the correlation between oil markets and the markets for ethanol and corn in the US on nitrogen fertilizer use and on the GHG emissions of corn ethanol.

The results show that a higher oil price results in higher gasoline, ethanol, and corn prices. The profit maximizing behavior of farmers results in an increase in the use of fertilizers to increase the production of corn. The effect is that the average GHG emissions per unit of corn ethanol remain fairly constant, but that the marginal emissions increase somewhat (5%), mainly as a result of decreasing marginal yield with respect to fertilizer use. The conclusion is that although higher corn yields result in higher GHG emissions, on average increasing corn ethanol production for fuel reduces GHG emissions compared to the alternative of increasing gasoline production.

It should be noted that our analysis is based on an economically-optimal applicate rate of fertilizers. In reality, risk-averse farmers may overuse fertilizers due to lack of knowledge on decreasing marginal yields with respect to nitrogen fertilizers. Therefore our calculation based on economically optimal application rate may underestimate the real emissions. Next, we have not included the other indirect effects of ethanol production such as land use change. Out numerical results on the marginal emissions thus only reflect the lower bound of the real emissions related to the last unit of the ethanol production. Furthermore, the use of the linear relation for the market interactions of energy and agricultural products based on historical data before 2007 without considering the recent development of shale gas may also overestimate the economic response of higher oil prices. The objective of the exercise presented in this paper is not to produce a thorough calculation of GHG emissions of corn ethanol production in the US, which requires estimating the actual application rate in different regions. The modelling framework presented in this paper aims to illustrate how different effects could be taken into account when calculating emissions. The novelty is that the diminishing productivity of corn with respect to nitrogen fertilizers can have profound impacts on the marginal emissions of biofuels. The results show that the marginal emissions of corn ethanol production in the US can be substantially higher than the average one, implying that the efficiency and effectiveness of biofuel policies to reduce GHG emissions might be questionable.

An important limitation of the modeling framework applied in this study is that it represents only short-term economic correlations. Our numerical example took the relation between oil price and natural gas based on the historical data before 2007. Therefore we should be aware that the huge increase in shale gas supplies in recent years may have changed this quantitative relation. Increasing the use of fertilizers is, in the short term, a logical and simple way to increase yields and to optimize economic returns in response to higher corn prices. In the long run, higher corn prices may also induce higher corn yields through technological changes, such as the development and use of improved seeds and the increased use of irrigation and agricultural machinery. In that case, the increase in GHG emissions will be reduced as a result of the use of improved corn production technologies and of the higher corn yields.

Another limitation of this paper is that the numerical example for applying the modelling framework does not include the other indirect effects although the market interactions of inputs and outputs are considered. However, we are able to calculate the marginal emissions of the corn-ethanol, which provides useful insights for environmental management. Economic instruments such as emission tax are based on the marginal emissions in order to determine the optimal production level. Therefore, identifying the marginal emissions also creates the basis for policy intervention.

Moreover, the prices of oil, natural gas, and agricultural commodities (including corn) have fluctuated substantially during this timeframe. This means that the empirically observed correlations and parameter values considered in this study are partially uncertain. More detailed analyses that take into account longer timeframes are needed to improve the accuracy of the parameters used in our modeling framework. Further research is also encouraged to model the economic interactions between oil, ethanol, and corn markets in more details. This study should therefore be seen as a first-order assessment that, despite the uncertainties, clearly shows the potential impact of the economic correlations between energy and agricultural markets on the average and the marginal GHG emissions of corn ethanol. To include other indirect effects of GHG emissions from ethanol production is an interesting future research direction.

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