BIOPRODUCTS AND ENVIRONMENTAL QUALITY: BIOFUELS, GREENHOUSE GASES, AND WATER QUALITY

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DISSERTATION

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ABSTRACT

Promoting bio-based products is one oft-proposed solution to reduce GHG emissions because the feedstocks capture carbon, offsetting at least partially the carbon discharges resulting from use of the products. However, several life cycle analyses point out that while biofuels may emit less life cycle net carbon emissions than fossil fuels, they may exacerbate other parts of biogeochemical cycles, notably nutrient loads in the aquatic environment. In three essays, this dissertation explores the tradeoff between GHG emissions and nitrogen leaching associated with biofuel production using general equilibrium models. The first essay develops a theoretical general equilibrium model to calculate the second-best GHG tax with the existence of a nitrogen leaching distortion. The results indicate that the second-best GHG tax could be higher or lower than the first-best tax rates depending largely on the elasticity of substitution between fossil fuel and biofuel. The second and third essays employ computable general equilibrium models to further explore the tradeoff between GHG emissions and nitrogen leaching. The computable general equilibrium models also incorporate multiple biofuel pathways, *i.e.*, biofuels made from different feedstocks using different processes, to identify the cost-effective combinations of biofuel pathways under different policies, and the corresponding economic and environmental impacts.

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CHAPTER 1

INTRODUCTION

1.1 Background

Measures to reduce in greenhouse gas emissions (GHG) are at the forefront of environmental policy debates worldwide. In the US, potential greenhouse gas reductions, together with reduced dependence on foreign oil, are fueling interest in ethanol and biodiesel as replacements for petroleum-based transportation fuels. Bio-based transportation fuels are part of an array of bio-based products proposed as substitutes for traditional fossil fuel commodities, including plastics, polymers, paints, solvents, lubricants, specialty chemicals, and electricity production.

While bioproducts comprise a relatively small market compared to petroleum-based products, the market is increasing. Ethanol and biodiesel make up the majority of the bioproduction market in the United States, with annual production of approximately 10 billion gallons and 0.7 million gallons of biodiesel in 2008 reported by Energy Information Administration (EIA 2009). More than 20% of the US corn crop is consumed for ethanol production (Sneller and Durante 2008). Ethanol is predominantly used as oxygenate in gasoline, but the amount used as a substitute for gasoline is climbing fast. Biofuels can be made from a variety of feedstocks using a number of different processes, *i.e.*, different biofuel pathways, and different biofuel pathways will have different effects on global agricultural activities, energy markets, and the environment. To determine which biofuels are best, we need to evaluate their economic and environmental impacts.

Many studies evaluating the economic and environmental impact of different biofuels have been undertaken and most of them are comparative life cycle analyses (e.g., Hill *et al*. 2006; Kim and Dale 2005; and Puppan 2002). They calculate life cycle inventories of costs, and environmental and energy flows to and from the environment, for both fossil fuels and their bioproduct counterparts. These analyses reveal advantages and disadvantages of biofuels in comparison to one another as well as to fossil fuels. Based on these life cycle studies, biofuels produced using different pathways differ in their environmental effects. Although most studies agree that biofuels may emit less life cycle net carbon emissions than fossil fuels[1], they also found out that biofuel feedstock production may exacerbate the nutrient loads in the aquatic environment (*e.g.*, Franke and Reinhardt 1998; Hill *et al*. 2006; and Puppan 2002). In the United States, several coastal areas suffer from hypoxia due to elevated nutrient loads. These areas include the Chesapeake Bay, Long Island Sound and the Gulf of Mexico (Environmental Protection Agency 2003). The effects of hypoxia to the watershed include but are not limited to (Environmental Protection Agency 2003):

1) More expensive water treatment
2) Kill fish and threaten commercial fisheries
3) Damage ecosystems and wildlife and cause “dead zones”.

For the United States, the most severe problem associated with excessive nutrients is hypoxia in the Gulf of Mexico. A report released by National Oceanic and Atmospheric Adiminstration (Rabalais *et al.* 1999), concluded that excess nitrogen from the Mississippi River combined with stratification of the Gulf’s water was the cause of the hypoxia. Added production of nitrogen-intensive feedstocks, especially corn, to support increasing use of biofuel would add to the problem. Policies that promote a mix of biofuel pathways that efficiently balances both economic and environmental impacts will be important in improving energy security and fighting climate change without exacerbating the problems of hypoxia.

In the absence of policy corrections for environmental externalities, for the case of biofuel and petro-fuel, the product with the least production cost would dominant the market given they are close substitutes. However, the externality generated from fossil fuel which is the least-cost product, CO_2 emissions, currently is the major driver of global warming for the whole world. In the US, several policies have been employed to address this externality. Among them are policies to encourage or mandate ethanol production as a substitute for gasoline due to the recognition that ethanol generates less GHG emissions. However, the increased production of this close substitute generates another type of externality, nitrogen leaching, which would exacerbate

[1] Some researchers argue that bioethanol may produce more life cycle greenhouse gases (GHG) than gasoline, mainly due to the emissions of nitrous oxide emissions from increases in fertilizer use (e.g., Crutzen *et al* 2007). However, most experts believe there are small net reductions of GHG emissions with corn ethanol and larger net reductions with sugar cane and cellulosic feedstocks (*e.g.*, Franke and Reinhardt 1998; Hill *et al.* 2006; Kim *et al.* 2004; Niven 2004; and Puppan 2002;).

hypoxia problems in the US (Environmental Protection Agency 2003; and Rabalais *et al.* 1999). Thus, policies designed to promote biofuel production and adjust one externality from fuel consumption might increase the emission level of another externality. The major objective of this dissertation is to examine: 1) theoretical general equilibrium interactions between policies for externality-generating products that are also close substitutes, using the biofuel-fossil fuel case as an example; and 2) empirical general equilibrium analysis of public policies as they influence multiple ethanol pathways, the mix of fuel consumption, and the corresponding economic and environmental effects.

1.2 Methods

General equilibrium models have no precise definition but they have certain specific features. General equilibrium models explicitly represent one or several national economies and account for the interactions between sectors and agencies (Bergman 2005). They aim to explain the behavior of supply, demand and prices in a whole economy as it responds to changes in public policies, consumer tastes, or production technologies. The foundation of general equilibrium models consists of the two fundamental theorems of welfare economics (Walras 1877). The flexible structure of general equilibrium models allows easy incorporation of environmental impacts alongside commercial considerations.

Since their first development by Walras (1877), general equilibrium models have shed lights on factors and mechanisms that determine relative prices and allocation of resources within market economies (Bergman 2005). The empirical manifestation of general equilibrium theory, computable general equilibrium models (CGE), have been widely used in sectoral analyses of policy changes or exogenous events (*e.g.*, Adelman and Robinson 1982; Alfsen *et al.* 1996; Bovenberg and Goulder 1997; and Shoven and Whalley 1984). Of particular interest for biofuels, CGE applications can assess different production pathways in a single model that captures competition and complementarities between those pathways. Impacts of current and potential policy instruments on the efficient mix of ethanol feedstocks can be evaluated by comparing the equilibrium from counterfactual cases to a benchmark equilibrium.

Prior to undertaking empirical examination of biofuel policies and technologies, we first develop and analyze a stylized theoretical general equilibrium model of the biofuel economy. The analysis sheds light on the key interactions between biofuel sectors and on the model parameters with particular importance for those interactions. Due to the complexity of the interactions, some of the interactions cannot be characterized analytically. We use numerical methods to gain further insight.

1.3 Contributions

This dissertation applies general equilibrium models to biofuel markets to evaluate the economic and environmental impacts of biofuels. As has been pointed out in several life cycle analyses, while biofuels may emit less life cycle net carbon emissions than fossil fuels, they may exacerbate other biogeochemical imbalances, notably nutrient loads in the aquatic environment. Without consideration of the water quality impacts, decisions about energy policies might be shortsighted. Yet, none of the CGE applications regarding biofuels to date have considered nutrient loads. Among the major nutrients that would cause eutrophication and hypoxia are phosphate and nitrate (Rabalais *et al.* 1999). Phosphate has very low mobility in soil, so its leaching rate is low. Soil conservation measures will also reduce phosphorus loads in surface water. These measures are not particular to specific crops, but are important for all annual crops that leave soils relatively expose for much of the year. On the other hand, nitrogen is soluable and moves easily in surface or subsurface drainage so it is a more dominant influence than phosphorus in estuarine and marine communities (*e.g.*, D'Elia *et al.* 1986; Harris 1986; and Valiela 1984). Not only is it the limiting nutrient in coastal waters, but nitrogen is needed by some crops more than others, so cropping patterns dictate its use. For these reasons, the effects of biofuel policies on nitrogen use are of considerable interest. In addition, none of the prior general equilibrium studies of biofuels explicitly incorporates competition among different biofuel pathways and the implications for markets and environmental quality. In this dissertation, we incorporate nitrogen discharges into the local watershed from biofuels production alongside the implications for Greenhouse Gases (GHGs) to evaluate the environmental and economic impacts of various biofuel pathways.

Using the interaction of fossil fuel and biofuel as an example, this dissertation starts with a theoretical general equilibrium model incorporating two environmental externalities which are connected from different sources that interact through market demands. This situation is unlike previous studies that consider simultaneous environmental externalities from a single externality-generating activity (*e.g.*, Caplan and Silva 2005; and Peterson 1999). The levels of the two externalities are determined not only by their individual production technology but also the interaction of their sources in the market. By explicitly modeling the production and market interaction of the two sources and using two policy instruments to control the two environmental externalities, this theoretical model evaluates how a policy intended to correct one externality affects the other and how the second-best policy for one externality is jointly determined by both distortions with the assumption that the other externality is not fully corrected. Although the market for fossil fuel and biofuel is used as a case study, this model can be applied in similar multi-product, multi-externality cases.

Following the theoretical analysis, we develop two computable general equilibrium models focusing on petroleum and ethanol market to evaluate how different policies affect the competition between these fuels, and between multiple biofuel feedstocks, in a world where greenhouse gases and nutrient pollution matter economically. The first of the two models artificially constrains trade in order to focus on domestic market interactions. The second model adds trade between the US and the rest of the world.

In summary, the contributions of this dissertation are:

1) Evaluating both analytically and empirically the interaction effects of multiple externalities and policies in a multi-product context such as with biofuels;
2) Assessing environmental and energy policies not only with respect to greenhouse gas production, but also for their implications for water quality; and
3) Incorporating multiple biofuel pathways in a single general equilibrium model.

1.4 Outline

Chapter 2 formulates and analytically solves a stylized general equilibrium model to evaluate the interaction effects of two externality taxes. We assess the effect of one tax on the emissions of the other externality and solve for a second best tax rate, given the existence of the other distortion. Chapter 3 develops a closed CGE model of the United States to identify the efficient mix of pathways under the influence of current and potential public policies. We solve the model under different policy regimes and analyze the corresponding economic and environmental effects. This one-country without trade model focuses on the economy of the United States without the extra data requirement and computational burdens introduced by trade between countries. Chapter 4 opens up the CGE model to trade with the rest of the world. Again, the analysis concentrates on the choice of biofuel pathways and the implications for environmental discharges.

CHAPTER 2

POLICY IMPLICATIONS OF INTERACTING EXTERNALITIES --- A THEORETICAL GENERAL EQUILIBRIUM ANALYSIS

2.1 Introduction

The theory of second best (Lipsey and Lancaster 1956) states that if one of the Paretian conditions cannot be fulfilled, an optimal solution is likely to require departures from all the other Paretian conditions. As a corollary, if multiple market failures exist in the economy, eliminating one doesn't necessarily improve welfare. As described in Bennear and Stavins (2007), multiple market failures can be jointly ameliorating (correction of one market failure ameliorates welfare loss from the other), jointly reinforcing (correction of one market failure exacerbates welfare loss from the other), or neutral (correction of one market failure doesn't affect welfare loss from the other). With multiple market failures, the interrelationships can grow complex, requiring explicit numerical examination to penetrate the web.

The theory of second best has been extensively studied in the analytical environmental policy literature. Most studies examine interactions between an environmental externality and pre-existing distortions from labor or capital taxes (*e.g.*, Bovenberg and Goulder 1996, 1997; Fullerton and Metcalf 2001; Oates and Schwab 1988; and Parry 1995, 1997). With varying assumptions about policy instruments and revenue recycling measures, their results differ substantially. For example, a second-best tax on the externality can be either higher or lower than the first-best Pigovian tax. The optimal tax is a function of multiple terms: (1) the Ramsey tax which represents the revenue-raising function of an environmental tax, and (2) the Pigouvian components that relate to each externality (*e.g*, Bovenberg and van der Ploeg 1994; and Samdmo 1975).

Unlike the literature on externality taxes in the presence of price distortions, very few studies consider corrective taxes regarding multiple simultaneous externalities. Caplan and Silva (2005) introduced the concept of "correlated externalities" to define multiple pollutants jointly produced by a single source that cause differentiated regional and global externalities. Within a multi-stage game theory framework, they found that non-cooperative, command-and-control environmental policies fail to achieve first-best optimality, but a joint permits mechanism can achieve a Pareto optimum. Such a policy scheme could face many political obstacles, especially market permits for a global externality. More typically, although not efficient, different externalities are regulated separately or the single source of the multiple externalities is regulated using a single instrument. For example, Peterson (1999) evaluated optimal agricultural land pricing policies considering pollution from agricultural land as well as non-market environmental benefits, such as open space. Thus, one source, land, generates both a public good and a public bad. He found the optimal land subsidy to correct the public goods would not equal the net extra-market regional values of the land amenities. Parry and Small (2005) evaluated the optimal gasoline tax considering traffic accidents, congestion and air pollution as externalities. In a similar spirit, Khanna *et al.* (2008) developed a stylized economic model to evaluate the first-best and second-best ethanol policies in the presence of greenhouse gas (GHG) emissions and traffic congestion resulting from transportation uses of fuel. In all three of these studies, a simple price-based policy instrument was applied to a single product (land, gasoline, or ethanol) to correct the corresponding externalities.

This chapter introduces a different way in which externalities arise and, thus, must be analyzed. In lieu of correlations arising through a single production process, we are interested in externalities that arise from multiple processes embedded within the economy. We refer to these as "connected externalities." They are connected through technical production processes, market relationships, or both. Our scenario generalizes the case of biofuel and fossil fuel production and the associated environmental externalities of greenhouse gases (GHG) and nitrogen leaching to surface waters. Both fossil fuel and biofuel production processes emit GHGs, but in different amounts per unit of output. The biofuel production process emits less carbon, but it also discharges nitrogen into the water environment.[2] The two environmental externalities are associated with two different products and the two products are substitutes in the market. The interaction between the two pollutants acts through the relative demands for the two products.

[2] In addition to increasing soluble forms of nitrogen into surface water, fertilizer used in crop production generates N_2O which is a GHG. Policies designed to reduce nitrogen would affect N_2O emissions as well as nitrogen runoff. In this paper, the N_2O emissions are omitted to simplify the analysis. Further study with a more complex model would be required to analyze the effects of a nitrogen policy on total GHG emissions.

In reality, policies for the two externalities are formulated one at a time since the two externalities affect two totally different environmental issues and are from two distict sources. Ideally, the tax rates for the externalities are set as their first-best levels. However, it is not always feasible to fully correct the environmental externality. For example, applying the first best tax for nitrogen leaching is infeasible. Nitrogen leaching is a non-point source pollutant and its accurate measurement is impossible. Although a fertilizer tax, command-and-control policies on fertilizer management strategies or generic engineered crops, etc, might be tried to correct this externality, many technical, economic or political obstacles stand in the way of efficient internalization. Given a suboptimal policy for nitrogen leaching, the optimal tax for GHG will depend in part on its effect on nitrogen leaching, which is mediated by the relationships between biofuel and fossil fuel.

This chapter develops a theoretical general equilibrium model incorporating two environmental externalities resulting from different sources that interact through market demands, in an economy with no government revenue requirement. The levels of the two externalities are determined not only by their individual production technologies, but also the interaction between their sources in the market. Two taxes are used to control the two environmental externalities and the resulting revenues are transferred to consumers in lump-sum. One tax is suboptimal, lower than the marginal environmental damage of the corresponding externality. By explicitly modeling the production and market interaction of the two sources, this paper evaluates:

1) the effects of a small change in one tax, whether or not the tax rates are optimal, and
2) the optimal tax for one externality given the existence of a distortion in the other externality.

This chapter is organized as follows. Section two describes the basic model. Section three describes the method used to solve the system. Section four develops the analytical solutions with a small increase of GHG tax and characterizes the optimal GHG tax. Section five offers a numerical example to illustrate the nature of the interactions between policies and uses sensitivity analysis to determine the most important parameters.

2.2 Model Structure

We continue the fossil fuel/biofuel metaphor in developing our analytical model. Consider an economy with *n* identical individuals who own one resources, a composite factor L. The individuals receive utility from two goods: a composite commodity *X* and energy *E*. Energy *E* is consumers' energy demand, and it can be achieved by consuming fossil fuel *F*, biofuel *B*, or both. The final demand ratio of biofuel to fossil fuel can be viewed as the blend percentage of biofuel in liquid fuel. We assume this ratio can be any value between zero and one. In this model, energy is treated as a production process with inputs of fossil fuel *F* and biofuel *B*. All the capital letters refer to per-capita amounts.

Production of X is assumed to require the composite factor L and energy *E*. Fossil fuel *F* is produced from *X*, and biofuel B is produced from the composite factor L. However, during the production and consumption processes, both fossil fuel and biofuel generate pollutants. Fossil fuel is a "dirty" product with pollutant emission *C*, representing CO_2 emissions. Biofuel is a substitute for fossil fuel. Combustion of biofuel also emits *C*, but the life cycle emissions from biofuel are less than those from fossil fuel. The emissions from fossil fuel are measured by the *net* emission compared to biofuel. At the same time, production of biofuel induces nitrogen leaching, N. In this paper the pollutant is treated as an input in the production process. The differential in inputs for *F* and *B* allows us to focus not only on the environmental effects but also the different input requirements. With the assumption of perfect competition and constant returns to scale, the production functions are assumed to be

$$X = X(L_X, E_X) \tag{2.1}$$

$$F = F(X_F, C) \tag{2.2}$$

$$B = B(L_B, N) \tag{2.3}$$

$$E = E(F, B) \tag{2.4}$$

The total emissions for each pollutant are summations across *n* identical individuals. Each consumer obtains utility from composite commodity X, direct consumption of energy E_U, and total emissions *nC* and *nN*:

$$U = U(X_U, E_U; nC, nN) \tag{2.5}$$

with $\partial U/\partial C < 0$ and $\partial U/\partial N < 0$.

In this static model, the overall factor constraint is:

$$L_X + L_B = \bar{L} \tag{2.6}$$

where $\bar{L}$ is the total fixed endowment of the composite factor in the economy.

For the system, the market clearing conditions are

$$E_X + E_U = E \tag{2.7}$$

$$X_F + X_U = X \tag{2.8}$$

By the choice of X_U and E_U, each individual maximizes utility subject to a budget constraint

$$I = P_X X_U + P_E E_U = T + P_L \bar{L} \tag{2.9}$$

where *T* is the lump-sum transfer to the consumer of the tax revenue, defined as $T = \tau_C C + \tau_N N$. The unit tax rates for GHG and nitrogen are represented by τ_C and τ_N, respectively. Market prices for the composite factor of production *L* and energy *E* are defined as P_L and P_E, respectively. The RHS of equation (2.9) is not chosen by the consumer, but endogenous to the economy. In this system, *X* is defined as numeraire. All the quantities and prices are endogenously determined except the tax rates for environmental externalities, τ_C and τ_N, which are exogenous.

2.3 Solution Strategy

The system is solved by totally differentiating relevant equations and solving the resulting system of differential equations. First, totally differentiating the production functions and imposing perfect competition conditions, we have

$$\hat{X} = \theta_{XL}\hat{L_X} + \theta_{XE}\hat{E_X} \tag{2.10}$$

$$\hat{F} = \theta_{FX}\hat{X_F} + \theta_{FC}\hat{C} \tag{2.11}$$

$$\hat{B} = \theta_{BL}\hat{L_B} + \theta_{BN}\hat{N} \tag{2.12}$$

$$\hat{E} = \theta_{EF}\hat{F} + \theta_{EB}\hat{B} \tag{2.13}$$

where a hat ($\hat{}$) denotes a proportional change, *e.g.*,$\hat{X} = dX/X$. Parameter θ_{XL} refers to the expenditure share of input L in the total production costs of X, mathematically defined as $\theta_{XL} = \frac{P_L L_X}{P_X X}$. Other θ_{IJ} parameters are defined analogously. The detailed definition of each parameter is listed in Table 2.1.

Totally differentiating the factor constraint yields

$$\beta_{LX}\hat{L_X} + \beta_{LB}\hat{L_B} = 0 \tag{2.14}$$

where β_{LX} is the quantity share of L used in the production of X in the total endowment, defined as $\beta_{LX} = L_X/\bar{L}$, with β_{LB} defined similarly.

The market clearing conditions in differentiated forms are written as:

$$\gamma_{EX}\hat{E_X} + \gamma_{EU}\hat{E_U} = \hat{E} \tag{2.15}$$

$$\gamma_{XF}\hat{X_F} + \gamma_{XU}\hat{X_U} = \hat{X} \tag{2.16}$$

where γ_{EX} is the quantity of E used in the production process of X relative to the total quantity of E in the market, and it is defined as $\gamma_{EX} = E_X/E$. All of the γ parameters refer to quantity shares and are defined analogously.

With perfect competition, the zero profit conditions for the four production sectors can be written as

$$P_X X - P_L L_X - P_E E_X = 0$$

$$P_F F - P_X X_F - \tau_C C = 0$$

$$P_B B - P_L L_B - \tau_N N = 0$$

$$P_E E - P_F F - P_B B = 0$$

Rearranging and totally differentiating these conditions yields

$$\hat{P_X} + \hat{X} = \theta_{XL}(\hat{L_X} + \hat{P_L}) + \theta_{XE}(\hat{E_X} + \hat{P_E}) \tag{2.17}$$

$$\hat{P_F} + \hat{F} = \theta_{FX}(\hat{X_F} + \hat{P_X}) + \theta_{FC}(\hat{C} + \hat{\tau_C}) \tag{2.18}$$

$$\hat{P_B} + \hat{B} = \theta_{BL}(\hat{L_B} + \hat{P_L}) + \theta_{BN}(\hat{N} + \hat{\tau_N}) \tag{2.19}$$

$$\hat{P_E} + \hat{E} = \theta_{EF}(\hat{F} + \hat{P_F}) + \theta_{EB}(\hat{B} + \hat{P_B}) \tag{2.20}$$

Producers of X can substitute between the factor input and energy, depending on the prices they face, P_L and P_E, according to the elasticity of substitution, σ_X, in the production technology. The producer's response to changes in prices can be obtained from the definition of σ_X:

$$\sigma_X = \frac{d\ln(L_X/E_X)}{d\ln(P_E/P_L)}$$

With no taxes on factor *L* or energy generally, converting the above equation to the hat form yields:

$$\hat{L_X} - \hat{E_X} = \sigma_X(\hat{P_E} - \hat{P_L}) \tag{2.21}$$

Pollutant emissions are assumed to be inputs in the production process. For fossil fuel production, both *X*, and GHG are required. The elasticity of substitution between the two inputs in fossil fuel production is denoted σ_F. The definition of σ_F in hat form analogous to equation (2.21), is written as

$$\hat{X_F} - \hat{C} = \sigma_F(\hat{\tau_C} - \hat{P_X}) \tag{2.22}$$

For biofuel feedstock production, nitrogen leaching might be reduced through improved fertilizer management strategies, genetic engineering that increases the nutrient conversion efficiency of crops, or substitution of cellulosic feedstocks for nutrient-intensive grains. We would expect substitutability between nitrogen leaching and capital (part of the composite input *L*). Several studies have estimated a nonzero elasticity of substitution between fertilizer and other inputs in corn productions, a major biofuel feedstock in the United States (*e.g.*, Hertel *et al.* 1996; and Thompson *et al.* 2006). From the definition of the elasticity of substitution (analogous to equations (2.21) and (2.22)), we have

$$\hat{L_B} - \hat{N} = \sigma_B(\hat{\tau_N} - \hat{P_L}). \tag{2.23}$$

Energy, in this paper, is yielded by a production process with inputs of fossil fuel and biofuel. Due to the different energy contents, the need for vehicle modifications when the ratio of biofuel (ethanol) to fossil fuel (gasoline) exceeds a certain level, and environmental considerations, we assume fossil fuel and biofuel are imperfect substitutes with elasticity of substitution σ_F. Analogous to equations (2.21), (2.22) and (2.23), we have

$$\hat{F} - \hat{B} = \sigma_E(\hat{P_B} - \hat{P_F}) \tag{2.24}$$

From the definition of the elasticity of substitution in utility, the relationship between consumption changes for X and F_U is:

$$\hat{X_U} - \hat{E_U} = \sigma_U(\hat{P_E} - \hat{P_X}) \tag{2.25}$$

By construction, $\sigma_U > 0$, so an increase in energy price index P_E will lead to more consumption of X, *i.e.*, a bigger X_U.

Totally differentiating the budget constraint yields:

$$\theta_{IX}\hat{X_U} + \theta_{IE}(\hat{P_E} + \hat{E_U}) = \frac{T}{I}\hat{T} + \frac{P_L\bar{L}}{I}\hat{P_L}$$

$$\hat{T} = \frac{\tau_C C}{T}(\hat{\tau_C} + \hat{C}) + \frac{\tau_N N}{T}(\hat{\tau_N} + \hat{N})$$

Combining the above two equations, we get

$$\begin{aligned}\theta_{IX}\hat{X_U} + \theta_{IE}(\hat{P_E} + \hat{E_U}) &= \frac{\tau_C C}{I}(\hat{\tau_C} + \hat{C}) + \frac{\tau_N N}{I}(\hat{\tau_N} + \hat{N}) + \frac{P_L\bar{L}}{I}\hat{P_L} \\ &= \theta_{IC}(\hat{\tau_C} + \hat{C}) + \theta_{IN}(\hat{\tau_N} + \hat{N}) + \theta_{IL}\hat{P_L} \qquad (2.26)\end{aligned}$$

Similar to previous definitions, θ_{IX} refers to the expenditure share of X in the consumer's total income, defined as $\theta_{IX} = P_X X/I$. And θ_{IE} is defined analogously. The mathematical definitions for θ_{IC}, θ_{IN}, and θ_{IL} are similar to θ_{IX} with different economic definitions. They refer to the income shares, rather than the expenditure shares. For example, θ_{IC} is the share of income from a GHG tax in the total income. The tax transfer is treated as income to consumer.

The numeraire is *X*. Thus $P_X = 1$ and $\hat{P_X} = 0$. In this system, we have $\hat{X}$, $\hat{X_F}$, $\hat{X_U}$, $\hat{E}$, $\hat{E_X}$, $\hat{E_U}$, $\hat{B}$, $\hat{F}$, $\hat{L_X}$, $\hat{L_B}$, $\hat{C}$, $\hat{N}$, $\hat{P_L}$, $\hat{P_E}$, $\hat{P_F}$, and $\hat{P_B}$, 16 variables, and equations (2.10) to (2.26), 17 equations. Based on Walras' law, if all markets but one are in equilibrium, the last market must also be in equilibrium. Thus one of the market clearing conditions can be dropped. In this study, the market clearing condition for energy is dropped, *i.e.*, equation (2.15). This leaves us with 16 variables and 16 equations. Now we can solve the system for the changes of prices and quantities with corresponding changes of τ_C or τ_N. Since *C* and *N* are modeled symmetrically in the system, the results are similar for the two cases with ($\hat{\tau_C} > 0$, $\hat{\tau_N} = 0$) and ($\hat{\tau_C} = 0$, $\hat{\tau_N} > 0$). Thus only the GHG tax case ($\hat{\tau_C} > 0$, $\hat{\tau_N} = 0$) is explored in the paper. Corresponding results for the nitrogen tax case ($\hat{\tau_C} = 0$, $\hat{\tau_N} > 0$) are provided in Appendix A

2.4 Policy Implication

2.4.1 Effects of GHG Tax

We start the analysis by introducing a small increase of the GHG tax, $\hat{\tau_C} > 0$, while keeping the nitrogen tax constant ($\hat{\tau_N} = 0$).

Solving the system of equations in the last section, the changes in the prices and quantities of interest, induced by the change in the carbon tax rate, are:

$$\hat{P}_F = \theta_{FC}\hat{\tau_C} \tag{2.27}$$

$$\hat{P}_B = -\frac{\theta_{XE}\theta_{EF}\theta_{FC}\theta_{BL}}{D_1}\hat{\tau_C} \tag{2.28}$$

$$\hat{P}_E = \frac{\theta_{XL}\theta_{EF}\theta_{FC}}{D_1}\hat{\tau_C} \tag{2.29}$$

$$\hat{C} = [-\frac{A_4}{D_1D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1D_2}\sigma_U - \frac{\theta_{FC}A_6(D_2-A_2)}{D_1D_2}\sigma_E - \frac{\beta_{LX}A_3+\theta_{FX}D_2}{D_2}\sigma_F - \frac{A_1A_4}{\beta_{LX}D_1D_2}\sigma_B]\hat{\tau_C} \tag{2.30}$$

$$\hat{F} = [-\frac{A_4}{D_1D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1D_2}\sigma_U - \frac{\theta_{FC}A_6(D_2-A_2)}{D_1D_2}\sigma_E - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{A_1A_4}{\beta_{LX}D_1D_2}\sigma_B]\hat{\tau_C} \tag{2.31}$$

$$\hat{N} = [-\frac{A_4}{D_1D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1D_2}\sigma_U + \frac{\theta_{FC}A_6A_2}{D_1D_2}\sigma_E - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{(A_1+\theta_{BL}D_2)A_4}{\beta_{LX}D_1D_2}\sigma_B]\hat{\tau_C} \tag{2.32}$$

$$\hat{B} = [-\frac{A_4}{D_1D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1D_2}\sigma_U + \frac{\theta_{FC}A_6A_2}{D_1D_2}\sigma_E - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{A_1A_4}{\beta_{LX}D_1D_2}\sigma_B]\hat{\tau_C} \tag{2.33}$$

$$\hat{E} = [-\frac{A_4}{D_1D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1D_2}\sigma_U + \frac{\theta_{FC}A_6(A_2-\theta_{EF}D_2)}{D_1D_2}\sigma_E - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{A_1A_4}{\beta_{LX}D_1D_2}\sigma_B]\hat{\tau_C} \tag{2.34}$$

where

$D_1 = \theta_{XL} + \theta_{XE}\theta_{EB}\theta_{BL}$

$D_2 = 1 - \beta_{LX}\gamma_{XU}\theta_{IL}$

$A_1 = \beta_{LB}\theta_{BN} - \beta_{LX}\gamma_{XU}\theta_{BL}\theta_{IN}$

$A_2 = \beta_{LX}\gamma_{XT} + \beta_{LX}\gamma_{XU}\theta_{IC}$

$A_3 = \gamma_{XT}\theta_{FC} - \gamma_{XU}\theta_{FX}\theta_{IC}$

$A_4 = \beta_{LX}\theta_{XE}\theta_{EF}\theta_{FC}$

$A_5 = \beta_{LX}\gamma_{XU}\theta_{XL}\theta_{IE}$

$A_6 = 1 - \theta_{XE}\theta_{BN}$

All of the parameters, βs and θs, are positive and less than one. Thus D_1, D_2, A_2, A_4, A_5, and A_6 are clearly positive. The signs for A_1 and A_3 are also positive as shown in Appendix B. Thus, for certain parameters, we may determine their signs, and so their effects on equilibrium quantities and prices. The results are summarized in Table 2.2.

Our model implies that the price change for each commodity is jointly determined by the price change of each of its inputs and the corresponding expenditure share of that input. For example, as shown in Equation (2.27), the percentage change of P_F is simply determined by the expenditure share of *C* in production of *F*, θ_{FC}, times the price change of *C*, $\hat{\tau_C}$, since the other input, *X*, is a numeraire. A positive $\hat{\tau_C}$ would unambiguously increase P_F since a positive $\hat{\tau_C}$ directly increases the production cost of *F*. Other prices are determined in the same manner except the mathematical expressions are more complex because the effects of $\hat{\tau_C}$ on their inputs are indirect.

Equation (2.28) shows the solution of $\hat{P_B}$. Since its denominator and nominator are both positive, $\hat{P_B}$ is negative. The price of fossil fuel increases in response to a higher carbon tax. Intuitively, we would expect an increase in the fossil fuel price would induce higher biofuel demand and thus a higher biofuel price. However, the demand for biofuel also depends on the change in total energy demand, for which the sign is ambiguous. We can explain the lower biofuel price due to a higher τ_C from the standpoint of input costs. Energy, whose price increases, is an input for *X*, the numeraire. Thus the price of *L*, the other input of *X*, has to fall for the producer of *X* to break even. An increase in τ_C reduces the relative price of *L* but has no effect on the price of nitrogen since the nitrogen tax rate is exogenous. Thus, the final price of biofuel has to decline for the producer of B to break even with an increase of τ_C.

The price of energy depends on the prices of both fossil fuel and biofuel, which change in opposite directions. The solution in equation (2.29) indicates that $\hat{P_E}$ is positive. Generally, in the current U.S. market, we would expect $\hat{P_E}$ to have the same sign as $\hat{P_F}$ because fossil fuel has a much larger market share than biofuel. However, without any assumption about the relative values of θ_{EF} and θ_{EB}, our result still indicates a positive $\hat{P_E}$ with a positive change of τ_C. The intuition behind this is that the negative change in P_B is a "feedback effect" to the increase of P_F and the increase of P_F is induced directly by the higher τ_C. Due to market adjustments, we would expect that $\hat{P_B}$ caused by the "feedback effect" is a much smaller than the $\hat{P_F}$ directly caused by $\hat{\tau_C}$. So $\hat{P_E}$ is positive even though $\hat{P_B}$ is negative.

The quantity values are much more complicated and difficult to interpret. However, we can get some insights if we separate the expressions based on elasticities. The signs for all elasticity coefficients with respect to $\hat{\tau_C}$ are listed in the second column in Table 2.2. As expected, a positive $\hat{\tau_C}$ yields a negative $\hat{F}$ and $\hat{C}$. The coefficients of all of the elasticities for the solutions of these two variables are negative, as shown in the second and third rows in Table 2.2. Since we assume *F* and *B* are substitutes ($\sigma_E > 0$), we would expect an increase in τ_C increases the demand for biofuel and the corresponding emissions, *N*. However, as shown in the fourth and fifth rows in Table 2.2, only the coefficient for σ_E is positive and all the rest are negative. Thus, without additional assumptions, the effect of $\hat{\tau_C}$ on *N* is ambiguous.

An increase in τ_C increases the energy price and this causes the producer of X to substitute factor L for energy based on their relative prices and the value of σ_X. This substitution directly reduces total energy demand and thus the equilibrium quantities of F and its associated externality *C*, and B and its associated externality *N*. Thus the first terms in equations (2.30) to (2.34) are all negative, as shown in the first columns of Table 2.2. The same logic applies to σ_U except that consumers substitute X for energy. Thus, with a positive change of τ_C, σ_U also has negative effects on F, *C*, B, *N* and E, as shown in the second columns of Table 2.2.

The elasticity of substitution between *F* and *B*, σ_E, governs the final "blending ratio" of biofuel to fossil fuel in the market. With an increase in τ_C, P_F increases and P_B decreases. This change in relative prices would shift the demand toward *B* and away from *F*. Thus, if τ_C increases, then a positive σ_E implies a negative $\hat{C}$ and a positive $\hat{N}$. Its effect on total energy demand *E* is ambiguous and would depend on the market share parameter of *F* and *B*, θ_{EF}.

The possibility to reduce GHG emissions with substitution of *X* is captured by σ_F. Increasing τ_C directly increases the price of *C*. As a result, the producer would reduce emissions of *C* (treated as an input in the production process). On the other hand, the elasticity of substitution between L and *N* in the biofuel production process, σ_B, implies a negative effect on *N* with an increase in τ_C. With an increase in τ_C, P_L would decrease. The producer of *B* would accordingly shift from *N* to more *L*.

With the elasticities that have definitive signs, an increase in τ_C would reduce production of *F* and emissions of *C*. For the rest of the variables, including *B* and *N*, the changes are ambiguous. However, with assumptions about the parameters, some definitive results could show up under special cases. Before proceeding with special cases, the optimal GHG tax rate (τ_C^*) is defined.

2.4.2 Optimal GHG Tax

To find the optimal GHG tax rate given a preexisting nitrogen tax, the following Langrangian equation needs to be solved:

$$max\ G = U(X_U, E_U; nC, nN) + \lambda(I - P_X X_U - P_E E_U) \qquad (2.35)$$

where $I = \tau_C C + \tau_N N + P_L \bar{L}$. Given $d\bar{L} = 0$, fixed τ_N, and exogenous prices for the consumer, the total derivative of equation (2.35) with respect to τ_C is written as

$$\frac{1}{\lambda}\frac{dG}{d\tau_C} = -\mu_C \frac{dC}{d\tau_C} - \mu_N \frac{dN}{d\tau_C} + \tau_C \frac{dC}{d\tau_C} + \tau_N \frac{dN}{d\tau_C}$$

where μ is the "marginal environmental damage" and the subscript refers to the pollutant (***e.g.***, μ_C is the dollar value of disutility for a consumer from a marginal increase of GHG emissions, defined as $-n\frac{\partial U}{\partial C}/\lambda$ where λ is the marginal utility of income). As defined before, $\partial U/\partial C < 0$ and $\partial U/\partial N < 0$, so both μ_C and μ_N are positive.

The change in consumer utility includes the changes in damages from the environmental externalities (the first two terms on the RHS) and the offsetting environmental tax revenues (the last two terms). The optimal GHG tax rate is achieved when $dG/d\tau_C = 0$:

$$\tau_C^* = \mu_C + (\mu_N - \tau_N)\frac{dN}{d\tau_C}/\frac{dC}{d\tau_C} \qquad (2.36)$$

If the nitrogen tax rate, τ_N, is set equal to μ_N, then τ_C^* would equal the marginal damage of GHG, μ_C, which would be the first-best policy. However, this is not the case for our example. More realistically, $\tau_N < \mu_N$, so τ_C^* would not be equal to μ_C (the marginal damages). The restriction on the size of τ_N precipitates a second-best policy problem.

To obtain the relationship between the second-best and the first-best tax rate, rewrite equation (2.36) to hat form as:

$$\tau_C^* = \mu_C + (\mu_N - \tau_N)\frac{N}{C}\frac{\hat{N}}{\hat{C}} \quad (2.37)$$

where *N* and *C* are the benchmark emission levels. Since μ_C, μ_N, C, and N all refer to the initial levels, and τ_N is exogenously defined, τ_C^* thus only depends on the ratio between percentage changes in nitrogen runoff and GHG emissions. As discussed before, the signs for $\hat{N}$ and $\hat{C}$ are ambiguous. To get some definitive results, we explore some special cases.

2.4.3 Policy Implications with Special Cases

Case 1*:* $\sigma_E \to \infty$, then $\tau_C^* < \mu_C$

When the blend ratio is unconstrained, we have practically perfect substitution between fossil fuel, *F*, and biofuel, *B*. With almost perfect substitution, σ_E is almost infinite. In each of the expressions, equations (2.30) to (2.34), compared to the term with σ_E, the terms with σ_X, σ_B, σ_F, and σ_U are numerically very small and accordingly inconsequential to the solution. Then an increase in τ_C, while keeping τ_N fixed, would definitely reduce *F* and *C*, and increase *B* and *N*. With this case, the two externalities are jointly reinforcing, *i.e.*, correction of one market failure exacerbates welfare loss from the other. Then τ_C^* can be written as

$$\tau_C^* = \mu_C - (\mu_N - \tau_N)\frac{N}{C}\frac{D_2}{M - D_2}$$

Along with the assumption that $\mu_N - \tau_N > 0,$, since $D_2 > 0$ and $M - D_2 > 0$, τ_C^* should be less than μ_C, the marginal environmental damage. A larger distortion in the nitrogen market implies a smaller τ_C^*.

Case 2*:* $\sigma_E \to 0$, then $\tau_C^* > \mu_C$

A very small value of σ_E represents the case with very low substitutability between fossil fuel and biofuel, such as when the mix ratio of ethanol reaches the “blend wall” and the consumer faces a very high cost to switch to alternative vehicles. Then the positive effects of σ_E in the corresponding production or emissions are negligible compared to the negative impacts from other elasticities of substitutions. The solutions become:

$$\hat{F} = [-\frac{A_4}{D_1 D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1 D_2}\sigma_U - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{A_1 A_4}{\beta_{LX}D_1 D_2}\sigma_B]\hat{\tau_C} < 0 \quad (2.38)$$

$$\hat{B} = [-\frac{A_4}{D_1 D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1 D_2}\sigma_U - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{A_1 A_4}{\beta_{LX}D_1 D_2}\sigma_B]\hat{\tau_C} < 0 \quad (2.39)$$

$$\hat{E} = [-\frac{A_4}{D_1 D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1 D_2}\sigma_U - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{A_1 A_4}{\beta_{LX}D_1 D_2}\sigma_B]\hat{\tau_C} < 0 \tag{2.40}$$

$$\hat{C} = [-\frac{A_4}{D_1 D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1 D_2}\sigma_U - \frac{\beta_{LX}A_3 + \theta_{FX}D_2}{D_2}\sigma_F - \frac{A_1 A_4}{\beta_{LX}D_1 D_2}\sigma_B]\hat{\tau_C} < 0 \tag{2.41}$$

$$\hat{N} = [-\frac{A_4}{D_1 D_2}\sigma_X - \frac{\theta_{EF}\theta_{FC}A_5}{D_1 D_2}\sigma_U - \frac{\beta_{LX}A_3}{D_2}\sigma_F - \frac{(A_1 + \theta_{BL}D_2)A_4}{\beta_{LX}D_1 D_2}\sigma_B]\hat{\tau_C} < 0 \tag{2.42}$$

Equations (2.38) to (2.40) indicate that $\hat{F} = \hat{B} = \hat{E}$. With no or very low substitution between *F* and *B*, a reduction in the production of *F* due to an increase in τ_C would also reduce *B* at the same rate because of the fixed "blending ratio" (the technology to produce *E*). Thus an increase in τ_C would reduce not only *C* but also *N*. Then the two externalities are jointly ameliorating, *i.e.*, correction of one market failure ameliorates welfare loss from the other. In this case, since both $\hat{C} < 0$ and $\hat{N} < 0$, the second term on the RHS in equation (2.37) is positive, so τ_C^* should be higher than the marginal environmental damage of GHG emissions. A larger distortion is in the nitrogen market implies a larger τ_C^*.

Case 3: $0 < \sigma_E < +\infty$ and $\sigma_X = \sigma_B = \sigma_F = \sigma_U = \sigma > 0$

In general, substitution between gasoline and ethanol is neither perfect nor zero since the consumers have easy access to flex fuel vehicles that significantly relax the "blend wall". Whether the value of σ_E is large or small corresponds to consumers' willingness to switch to the flex fuel vehicles. With a generalized σ_E, one special case is when all other production and utility functions have the same elasticity value, *i.e.*, $\sigma_X = \sigma_B = \sigma_F = \sigma_U = \sigma$. Then the corresponding solutions of interest are:

$$\hat{F} = [-\frac{\theta_{FC}A_2A_6 + \theta_{XE}\theta_{EF}\theta_{FC}\theta_{BN}D_2}{D_1 D_2}\sigma - \frac{\theta_{FC}A_6(D_2 - A_2)}{D_1 D_2}\sigma_E]\hat{\tau_C}$$

$$\hat{C} = [-\frac{\theta_{FC}A_2A_6 + \theta_{XE}\theta_{EF}\theta_{FC}\theta_{BN}D_2 + \theta_{FX}D_1D_2}{D_1 D_2}\sigma - \frac{\theta_{FC}A_6(D_2 - A_2)}{D_1 D_2}\sigma_E]\hat{\tau_C}$$

$$\hat{B} = [-\frac{\theta_{FC}A_2A_6 + \theta_{XE}\theta_{EF}\theta_{FC}\theta_{BN}D_2}{D_1 D_2}\sigma + \frac{\theta_{FC}A_6A_2}{D_1 D_2}\sigma_E]\hat{\tau_C}$$

$$\hat{N} = [-\frac{\theta_{FC}A_2A_6 + \theta_{XE}\theta_{EF}\theta_{FC}D_2}{D_1 D_2}\sigma + \frac{\theta_{FC}A_6A_2}{D_1 D_2}\sigma_E]\hat{\tau_C}$$

$$\hat{E} = [-\frac{\theta_{FC}A_2A_6 + \theta_{XE}\theta_{EF}\theta_{FC}\theta_{BN}D_2}{D_1 D_2}\sigma + \frac{\theta_{FC}A_6(A_2 - \theta_{EF}D_2)}{D_1 D_2}\sigma_E]\hat{\tau_C}$$

Under this special case, a positive $\hat{\tau_C}$, while keeping τ_N fixed, would reduce *F* and *C*. Its effects on *B* and *N* depend on the relative sizes of σ_E and σ. If $\sigma_E > (1 + \frac{\theta_{XE}\theta_{EF}M}{D_6 D_2})\sigma$, the positive effects of σ_E on nitrogen runoff with an increased τ_C overcome the negative effects of σ_X, σ_B, σ_F, and σ_U, so an increase in τ_C would increase the nitrogen runoff. Then $\tau_C^* < \mu_C$, like Case 1. On the other hand, if $\sigma_E < (1 + \frac{\theta_{XE}\theta_{EF}M}{D_6 D_2})\sigma$, an increase in τ_C reduces nitrogen runoff, so $\tau_C^* > \mu_C$, like Case 2. And, with a knife-edge situation when $\sigma_E = (1 + \frac{\theta_{XE}\theta_{EF}M}{D_6 D_2})\sigma$, then $\tau_C^* = \mu_C$.

The above three cases cover only a fraction of the possibilities. In general, the knife-edge value of σ_E that defines whether τ_C^* should be higher or lower than μ_C is in a much more complex expression and depends on the coefficients and the values of all of the elasticities. In the following section, plausible values are applied to the parameters to explore the likely size of the effects of a small change in τ_C on the economic equilibrium and the optimal value of τ_C^*.

2.5 Numerical Analysis

2.5.1 Parameter Impacts

The numerical analysis is based on US data for 2004. At that time, the major biofuel was corn ethanol, so we use data for gasoline and corn ethanol in this analysis. Our model is represented in the share forms, including the expenditure shares in production and consumption and the quantity shares in total demand. These values are calculated from a Social Accounting Matrix based on Global Trade and Analysis Program (GTAP) version 7.0 (Narayanan and Walmsley 2008).

Production data for the numeraire *X*, petrofuel *F*, and the factor costs for gasoline production are directly from GTAP 7.0 (Narayanan and Walmsley 2008). The numeraire X is the combination of all commodities produced apart from gasoline-related products. Factor inputs for ethanol production are from the GTAP_BIO developed by Taheripour *et al.* (2007). The environmental inputs (both GHG emissions and nitrogen leaching) for gasoline and corn ethanol are from a recent life cycle analysis (Khanna *et al.* 2009) which concludes that corn ethanol could reduce GHG emissions by 30% compared to gasoline. The benchmark GHG tax of \$24.9/tone of CO_2

equivalent is based on available carbon trading prices in European and East Asian markets (World Bank 2005)[3] and then transformed into a 2004 value. No nitrogen externality market or tax exists in the United States. Based on a 2002 case study in the Long Island Sound Watershed done by EPA, the benchmark nitrogen permit cost is set at $1.73 per pound (USEPA 2002)[4]. With these major data and related conversion factors, the required parameters can be calculated and are shown in Table 2.1.

The elasticity values are the most difficult to assign. Many studies have estimated elasticity of substitution values between different commodities or inputs in production processes. However, due to the extensive aggregation of sectors in our model, suitable elasticity values are not readily available in the literature. Instead of making assumptions about those values, the coefficients for these parameters in the model solutions are calculated and, based on those coefficients, the most important and sensitive elasticity values are determined. With the benchmark values documented in Table 2.1, the coefficients for the elasticities for each variable are listed in Table 2.3. Each cell shows the coefficient for each elasticity (indicated by each column) in the system solution for each variable (indicated by each row) with a shock in τ_C. A higher absolute value of the coefficient means a higher impact of this elasticity on that variable.

In Table 2.3, among all the coefficients for variable $\hat{C}$ shown in the third row, the coefficient of σ_F (column 5), -0.9350, departs from zero the most. This indicates that σ_F has the biggest impacts on *C* because τ_C directly increases the GHG price and σ_F allows the producer of *F* to shift away from *C*. The changes in biofuel production, $\hat{B}$ (row 4), and nitrogen leaching, $\hat{N}$ (row 5), are affected the most by σ_E (column 4). As τ_C changes, P_F changes correspondingly. The price change of fossil fuel causes a demand shift between *F* and *B*, which is governed by σ_E. With the shock of τ_C, all the effects of other eleasticites on $\hat{B}$ and $\hat{N}$ are relatively indirect compared to the effect of σ_E. In terms of the change in total consumption of energy, $\hat{E}$, σ_U has the biggest impact among all elasticity values although none of them are very big. Among all the elasticity values, σ_B, the elasticity of substitution between factor *L* and *N*, has the lowest impact

[3] The United State has no federal level GHG tax. Although a gasoline tax could correct the GHG externality, the tax burden on GHG emissions from the US gasoline tax is less than the value used in this numerical example.
[4] This nitrogen tax applies directly to the nitrogen leaching. It could be a burden to farmers but it might be an effective way to control the hypoxia problem.

on all the variables of concern because τ_C affects the price of *L* only remotely and has no impact on nitrogen price.

2.5.2 Policy Impact

In this section, we first discuss plausible elasticity values. Based on those values, we calculate the impacts of a change in τ_C on all of the variables and compute τ_C^* under the preexisting distortion in the nitrogen market.

In the production of biofuel, σ_B defines the elasticity of substitution between factor *L* and nitrogen leaching. No existing literature documents the substitutability between nitrogen runoff and other factors. However, nitrogen runoff is directly related to fertilizer usage in feedstock production. Thompson *et al.* (2006) estimate that the elasticity of substitution between fertilizer and other factors is nearly unity in U.S. corn production. Yasar and Uzunoz (2006) estimate the elasticity of substitution between fertilizer and other inputs is between 0.74 and 0.86 in sugar beet production in Turkey. In our model, ethanol producers can switch feedstocks so we would expect an even higher elasticity of substitution between the two inputs. As indicated in Table 2.3, the effects of σ_B on the system solutions are fairly low, so the result wouldn't be sensitive to its value. Thus, in this example, the Cobb-Douglas functional form is assumed for biofuel production, *i.e.*, $\sigma_B = 1$.

The elasticity of substitution between GHG and *X* in the production of fossil fuel, σ_F, can be fairly low. Most studies generally assume that GHG emissions are proportional to fossil fuel consumption. However, as more fuel-efficient technology/vehicles and carbon abatement technologies are developed, the substitution between X and GHG emissions becomes easier and we would expect a positive value of σ_F in this study. Since σ_F has the biggest impact on GHG emissions, the value of σ_F is very important. A small positive value of σ_F, 0.1, is assumed in the numerical example, and then sensitivity analysis is conducted on this value.

The value for the elasticity of substitution between energy and factor *L* in the production process of *X*, σ_X, is adopted from the value between capital and energy in the capital-energy composite in the GTAP_E model (Burniaux and Truong 2002). For elasticities of substitution between fossil fuel and biofuel, few studies have estimated σ_E due to inadequate data. In a modified GTAP_E model application by Birur *et al.* (2008), the elasticity of substitution between petroleum energy and biofuel for the US is defined as 3.75. With this value, they are able to reproduce the biofuel production in accordance with the historical evidence between 2001 and 2006 with a reasonable precision. We use the same value in this model.

Concerning the elasticity of substitution between *X* and energy for the consumer, σ_U, generally, transportation energy demand is fairly inelastic. Two meta-analysis (Espey 1996; and Goodwin *et al.* 2004) found that the average price-elasticity of demand for gasoline is around -0.25 in the short run. Based on the consumption ratio of energy, the elasticity of substitution between energy and other commodities is less than 0.2. A more recent study estimated the price elasticities of gasoline demand for two periods of time, ranging from -0.034 to -0.077 during 2001 to 2006, versus -0.21 to -0.34 for 1975 to 1980 (Hughes, *et al.* 2007), and concluded that demand for gasoline has become less elastic over time. We use a value of 0.2 for σ_U. Although the coefficients of σ_U for all the variables shown in Table 2.3 are not so small that they can be ignored, given the fact that the expected value of σ_U is generally fairly low, the effects of σ_U on the variables of concern should be relatively small comparing to other parameters. Thus even though value of σ_U is uncertain, sensitivity analysis is not essential. The elasticity values in the numerical example are summarized in Table 2.1.

With the assigned parameter values, the effects of a small change (1% increase) in τ_C are listed in Table 2.4. As expected, a positive increase in τ_C would reduces *F*, *C*, and *E* and increase *B*, and *N*. The percentage increase in *N* is about two times greater than the percentage reduction in *C*.

To evaluate the optimal GHG tax, τ_C^*, the marginal damage of both GHG emissions and nitrogen leaching are needed. Both are very difficult to estimate. In this paper, only a specific value of μ_N is assumed. The optimal GHG tax is then presented as a function of the marginal damage from GHG emissions, μ_C, and shows how much the second-best policy should differ from the first-best.

In a survey of environmental damage estimates, Smith (1992) suggests that the economic damages of nitrogen leaching to the water system probably lie within a range of 0.27% to 18.24% of total crop value. Abrahams and Shortle (2004) use 10% of total crop value in their study, which is about the mid-point of the range reported by Smith. In our model, the crop sector is not explicitly modeled. With the GTAP data, the assumption that the environmental damage of nitrogen runoff is about 10% of total crop value implies that μ_N is approximately \$5.70/lb. Accordingly, the optimal GHG tax (\$/ton) is:

$$\begin{aligned} \tau_C^* &= \mu_C + (\mu_N - \tau_N)\frac{N}{C}\frac{\hat{N}}{\hat{C}} \\ &= \mu_C - 12.0 \end{aligned}$$

This result indicates that the optimal GHG tax would be \$12/ton equivalent of CO_2 less than the marginal damage of GHG emissions given the benchmark values. If the nitrogen tax is less than the benchmark value of \$1.73/lb, or if μ_N is higher than \$5.70/lb, the optimal GHG tax, τ_C^*, would be even further below the marginal damage of GHG emissions.

2.5.3 Sensitivity Analysis

As shown in Table 2.3, the values of σ_F and σ_E are fairly important to the changes of environmental emissions which are our major concerns. In this section, ranges of values for these two parameters are tested to see the sensitivity of our results to these two parameters.

Ethanol and gasoline are highly substitutable commodities, and we would expect an elasticity of substitution greater than unity. In the numerical example, the value for σ_E is set to 3.75, as in Birur *et al.* (2008). In the sensitivity analysis, the alternative values tested range from 0 to 5 to represent all possible cases discussed before. The upper value represents nearly perfect substitution. For σ_F, most studies generally assume the GHG emissions are proportional to fossil energy consumption. However, with new technology for carbon abatement, the possibility of a positive σ_F should not be neglected. Since we would expect a relatively low substitution level, a range of σ_F from 0 to 0.5 is tested. Table 2.5a shows the percentage change of production levels with a 1% increase of τ_C with different values of σ_F, and Table 2.5b shows the optimal GHG tax. Table 2.6 documents the corresponding results with different σ_E.

Although other variables are not sensitive to the different values of σ_F as shown in Table 2.5a, GHG emissions respond significantly to it. Table 2.5b indicates that τ_C^* is also very sensitive to the value of σ_F, especially when σ_F is relatively low. Compare the values in the second column ($\sigma_F = 0$) and the third column ($\sigma_F = 0.1$) in both Table 2.5a and Table 2.5b. If σ_F is 0, a 1% increase of τ_C reduces GHG emissions by 0.03%, and τ_C^* is $55/ton lower than the marginal damages of GHG emissions ($\tau_C^* = \mu_C - 54.9$). However, if σ_F is 0.1, then a 1% increase of τ_C would reduce GHG emission by 0.12%, and τ_C^* should be $12/ton lower than the marginal damages ($\tau_C^* = \mu_C - 12.0$). Even higher values of σ_F mean more reduction of GHG emissions with an increase in τ_C, and τ_C^* is closer to its marginal damage. In another words, if the estimated value of σ_F is less than the true value, the effects of τ_C on GHG emissions would be underestimated, and the calculated τ_C^* would be less than optimal. The major concern regarding σ_F is that if σ_F is low, the optimal GHG tax is very sensitive to its value. A different of 0.1 in the value of σ_F, from its baseline of 0.1, could result in more than $40/ton difference in optimal GHG tax.

Concerning σ_E, none of the variables are as sensitive to σ_E as were GHG emissions to the size of σ_F. However, almost all outputs are responsive to σ_E to some extent. Among all the output values, *B* and *N* are the two most sensitive to the values of σ_E and their signs change from negative to positive as σ_E increases, as Table 2.6a implies. With a small σ_E, *i.e.*, low substitution between *F* and *B*, a positive change in τ_C would decrease *B* and *N*, as well as *F* and *C*. Correspondingly, the optimal τ_C would be greater than the first best tax. With a greater σ_E, an increase in τ_C would increase *B* and *N*. With a greater value of σ_E, a specific change in τ_C would yield more nitrogen leaching. If *F* and *B* are close substitutes, optimal τ_C would be smaller than the first best tax. A higher σ_E results in a lower τ_C^* but the effect is limited. If the estimated value of σ_E is lower than the true value, nitrogen leaching would be underestimated and the calculated τ_C^* would be higher than the optimal value.

2.6 Conclusion

This paper develops a general equilibrium model to address policy issues surrounding a special case of multiple externalities. Unlike previous studies, this paper incorporates two environmental externalities generated by different sources that also produce substitute goods. Two taxes are available to control the two externalities. Since the two externalites are connected through the fact that their sources are substitutes in the market, the two taxes interact. Emissions of both externalities are jointly determined by the two taxes. The direction of the effects of one tax on the emissions of the other externality is analytically ambiguous.

Using a general equilibrium model, we examine the second-best taxes in the presence of connected externalities. The individually-first-best policy scheme sets each tax equal to its marginal environmental damage. However, the first-best policy may not be feasible, as seems likely for nitrogen leaching. Given a suboptimal tax for one externality, the optimal tax for the other externality depends on the distortion arising from the other externality and tax. Our model results indicate that, with the existence of another closely correlated environmental externality, the second-best tax could be lower or higher than the first-best tax, depending on the nature of the distortion in the other externality and the interactions between the final goods. Only in the knife-edge case is the second-best tax rate equal to the first-best rate (marginal environmental damage).

Because of ambiguity in the analytical results, we develop a numerical general equilibrium model to explore plausible empirical relationships between fossil fuels and biofuels where greenhouse gases and nitrogen pollution are the externalities of concern. Our numerical results confirm that a GHG tax would increase nitrogen leaching with the assumption that gasoline and ethanol are close substitutes. Our analytical solutions suggest that under certain circumstances, the optimal GHG tax could be higher than the marginal damage of GHG emissions. However, if the benchmark nitrogen tax is lower than its marginal environmental damage, and other parameters are set at plausible levels, then the optimal GHG tax is lower, and could be much lower than the marginal environmental damage of GHG.

In our model, the emission levels of the two externalities are not affected solely by their individual production processes. The market interaction between the final goods also plays an important role in determining the emission levels. Our numerical example illustrates the relative importance of the technical production parameters relative to the market interaction. If τ_C

increases, the technical parameter associated with production of *F*, σ_F, has a significant impact on *C* but a small impact on *N*. On the other hand, the technical parameter associated with production of *B*, σ_B, has a very small impact on both externalities, because σ_B governs the substitution between *L* and *N* in production of *B* based on their relative price changes, and the change in τ_C has only a small impact on P_L and no impact on τ_N at all. Thus with a change in τ_C, the effect of the technical parameter of production *B* to the system is minimal. The elasticity of substitution between *F* and *B*, σ_E, partly represents the market interaction between *F* and *B*. It is the most important parameter in determining the level of *N* with an increase in τ_C.

Based on the sensitivity analyses, considering the impact of taxes on the externalities, for each production process, the technical production parameter plays the most important role in determining the emission level of the corresponding externality, and the parameter related to market interactions is the most important to the determine the emission level of the other externality. Since the second-best policies are jointly determined by both emission levels, parameters affecting either or both emission levels would matter to the policy design process. The second-best tax rate for one externality is most sensitive to the technical parameter in the production process associated with that externality, and the parameter that determines the substitution levels between the two final goods.

Tables

Table 2.1 Major Parameter Definitions and Baseline Values

Parameter	Definition	Baseline value
θ_{XL}	Expenditure share of *L* in *X* production, = $P_L L_X / P_X X$	98%
θ_{XE}	Expenditure share of fuel in *X* production, = $P_E E_X / P_X X$	2%
θ_{EF}	Expenditure Share of gasoline in total fuel consumption, =$P_F F / P_E E$	94%
θ_{EB}	Expenditure Share of ethanol in total fuel consumption, =$P_B B / P_E E$	6%
θ_{FX}	Expenditure share of *X* in gasoline production, =$P_X X_F / P_F F$	93%
θ_{FE}	Expenditure share of emissions cost in gasoline production, =$\tau_C C / P_F F$	7%
θ_{BL}	Expenditure share of *L* in ethanol production, =$P_L L_B / P_B B$	89%
θ_{BE}	Expenditure share of emissions cost in ethanol production, =$\tau_N N / P_B B$	11%
λ_{XL}	Share of *L* usage in *X* production in total endowment, = $L_X / \bar{L}$	99%
λ_{BL}	Share of *L* usage in *B* production in total endowment, = $L_B / \bar{L}$	1%
θ_{IX}	Expenditure share of *X* in consumer's consumption = $P_X X_U / I$	98%
θ_{IE}	Expenditure share of *E* in consumer's consumption = $P_E E_U / I$	2%
θ_{IL}	Income share of *L* in total income = $\tau_C C / I$	99.7%
θ_{IC}	Income share of *C* in total income = $\tau_N N / I$	0.2%
τ_C	GHG tax rate ($/tone)	24.9
τ_N	Nitrogen tax rate ($/lb)	1.73
σ_X	Elasticity of substitution between inputs in *X* production	0.1
σ_B	Elasticity of substitution between inputs in *B* production	1
σ_F	Elasticity of substitution between inputs in *F* production	0.1
σ_E	Elasticity of substitution between fossil fuel and biofuel	3.75
σ_U	Elasticity of substitution between *X* and *E* for consumers	0.2

Table 2.2 Signs of Elasticity Coefficients for Different Variables Given Positive $\hat{\tau_C}$*

Variables	σ_X	σ_U	σ_E	σ_F	σ_B
$\hat{F}$	−	−	−	−	−
$\hat{C}$	−	−	−	−	−
$\hat{B}$	−	−	+	−	−
$\hat{N}$	−	−	+	−	−
$\hat{E}$	−	−	Ambiguous	−	−
$\hat{P}_F$	+				
$\hat{P}_B$	−				
$\hat{P}_E$	+				

*: "+" indicates that σ has positive effects on the variable value with a positive change in the corresponding tax.
"-" indicates that σ has negative effects on the variable value with a positive change in the corresponding tax,
"Ambiguous" indicates that we cannot identify the effects of σ on the variable value with a positive change in the corresponding tax.

Table 2.3 Coefficients for Elasticities in Selected Variable Solutions

Variables	σ_X	σ_U	σ_E	σ_F	σ_B
$\hat{F}$	-0.0249	-0.0366	-0.0044	-0.0012	0.0000
$\hat{C}$	-0.0249	-0.0366	-0.0044	-0.9350	0.0000
$\hat{B}$	-0.0249	-0.0366	0.0626	-0.0012	0.0000
$\hat{N}$	-0.0249	-0.0366	0.0626	-0.0012	-0.0007
$\hat{E}$	-0.0249	--0.0366	-0.0006	-0.0012	0.0000

Table 2.4 Effects of GHG Tax Change for $\hat{\tau_C} = 1\%$

Variables	$\hat{\tau_C}$=1% (Unit: %)
$\hat{F}$	-0.0264
$\hat{C}$	-0.1198
$\hat{B}$	0.2247
$\hat{N}$	0.2240
$\hat{E}$	-0.0101
$\hat{X}$	-0.0005
$\hat{P_F}$	0.0662
$\hat{P_B}$	-0.0007
$\hat{P_L}$	-0.0008

Table 2.5a Percentage Change of Outputs with $\hat{\tau_C} = 1\%$, for Different σ_F

Variables	σ_F= 0	σ_F= 0.1	σ_F= 0.3	σ_F= 0.5
$\hat{F}$	-0.0263	-0.0264	-0.0266	-0.0269
$\hat{C}$	-0.0263	-0.1198	-0.3067	-0.4938
$\hat{B}$	0.2248	0.2247	0.2245	0.2243
$\hat{N}$	0.2241	0.2240	0.2237	0.2235
$\hat{E}$	-0.0100	-0.0101	-0.0103	-0.0106
$\hat{X}$	-0.0005	-0.0005	-0.0005	-0.0005

Table 2.5b Optimal GHG Tax for Different σ_F

	σ_F= 0	σ_F= 0.1	σ_F= 0.3	σ_F= 0.5
τ_C^*	$\mu_C - 54.9$	$\mu_C - 12.0$	$\mu_C - 4.8$	$\mu_C - 3.0$

Table 2.6a Percentage Change of Outputs with $\hat{\tau_C} = 1\%$, for Different σ_E

Variables	σ_E= 0	σ_E= 0.1	σ_E= 0.2	σ_E= 1	σ_E= 2.5	σ_E= 3.75	σ_E= 5
$\hat{F}$	-0.0099	-0.0104	-0.0108	-0.0143	-0.0209	-0.0264	-0.0319
$\hat{C}$	-0.1033	-0.1037	-0.1042	-0.1077	-0.1143	-0.1198	-0.1253
$\hat{B}$	-0.0099	-0.0037	0.0026	0.0526	0.1465	0.2247	0.3029
$\hat{N}$	-0.0107	-0.0044	0.0018	0.0519	0.1458	0.2240	0.3022
$\hat{E}$	-0.0099	-0.0099	-0.0099	-0.0099	-0.0100	-0.0101	-0.0102
$\hat{X}$	-0.0001	-0.0001	-0.0001	-0.0002	-0.0004	-0.0005	-0.0007

Table 2.6b Optimal GHG Tax for Different σ_E

	σ_E= 0	σ_E= 0.1	σ_E= 0.2	σ_E= 1	σ_E= 2.5	σ_E= 3.75	σ_E= 5
τ_C^*	$\mu_C + 0.7$	$\mu_C + 0.3$	$\mu_C - 0.1$	$\mu_C - 3.1$	$\mu_C - 8.3$	$\mu_C - 12.0$	$\mu_C - 15.6$

CHAPTER 3

ENVIRONMENTAL POLICIES AND BIOFUEL PATHWAYS IN THE UNITED STATES: CLOSED ECONOMY ANALYSIS

3.1 Introduction

Large scale production of biofuels could have significant effects on global agricultural activities, energy markets, and the environment. However, the precise nature of those effects is likely to vary depending on the mix of biofuels and feedstocks. Biofuels can be made from a variety of feedstocks using a number of different processes, *i.e.*, different biofuel pathways. The leading biofuel candidates are ethanol and biodiesel. Our focus is on ethanol. Ethanol derived from corn is the major biofuel under production currently in the United States. Second generation biofuels, cellulosic ethanols, are under intensive study now. The common belief is that cellulosic ethanol is better in terms of both greenhouse gas (GHG) emissions and competition with food crops for land (Groode and Heywood 2007; Khanna *et al.* 2009; Schmer *et al.* 2008; Wang *et al.* 1999; and Wang *et al.* 2007). However, current technology for cellulosic ethanol is not cost competitive compared to corn ethanol (Khanna *et al.* 2009; and Perrin *et al.*2008). With limited resources, especially for land used to grow the feedstocks, promoting an efficient mix of biofuel pathways is an important consideration in improving energy security and fighting climate change.

Several important policy questions surround markets for biofuels, including:

1) What is the most economically efficient mix of biofuel pathways under potential policies?
2) How do environmental policies influence the market for biofuels and thus the food market?

Because these questions involve interactions among different markets simultaneously, computable general equilibrium (CGE) modeling is well-suited to their analysis. CGE models have been widely used in sectoral analyses of policy changes or exogenous events, such as the introduction of innovative technologies. Several CGE applications have addressed bioenergy (*e.g.*, Cunha and Scaramucci 2006); Kancs *et al*. 2002; and Steininger and Voraberger 2003). Most of them focus on economic impact evaluation. Some recent CGE applications to biofuels consider greenhouse gas emissions (*e.g.*, Ignaciuk *et al*. 2006; and Korobeinikov *et al.* 2006). However, none of these studies have considered the potentials for water quality impacts from fertilizer use associated with feedstock production. Life cycle analyses have revealed that the production of some biofuel may exacerbate nutrient loads in the aquatic environment (*e.g.*, Franke and Reinhardt 1998; Hill *et al*. 2006; and Puppan 2002). Without consideration of the water quality impacts, decisions about energy policies could lead to unintended and unwanted outcomes for water quality.

This chapter assesses the economic and environmental impacts of the different biofuel pathways using a closed-economy CGE model of the United States. Closed-economy models are fairly common in evaluating bioenergy impacts (*e.g.*, Johansson and Azar 2007; and McDonald and Thierfelder 2005). Currently, a major issue motivating bioenergy analyses is the competition between food products and bioenergy feedstocks due to constraints on the availability of land. Since land is not internationally tradable, a closed-economy model can provide insights into the issues that are of most concern, especially for countries where internal markets dominate the economy. The US is such an economy.

The major differences between this chapter and other CGE applications on bienergy are that this work explicitly models the use of fertilizer and its contribution to both greenhouse gas (GHG) emissions and nitrogen (N) leaching, and that the model incorporates both first-generation and second-generation biofuels, with second generation biofuels (cellulosic ethanol) as an alternative technology to produce ethanol. The focus of this chapter is to anticipate the mix of pathways that most efficiently balances economic and environmental considerations under the influence of public policies.

The chapter is organized as follows. The next section discusses the environmental impacts of different biofuel pathways. Then, the essential elements of the general equilibrium model are described. The following section discusses the data sources and technology assumptions used in the model. Various model scenarios with results are presented later and followed by sensitivity analyses.

3.2 Environmental Impacts of Biofuel Pathways

Different biofuel pathways have different effects on global agricultural activities, energy markets, and most importantly for this study, the environment. For example, Miller *et al.* (2007) reports that while ethanol produced from corn can reduce greenhouse gas emissions by about 15%, that produced from cellulosic feedstocks can reduce them by 90%. Furthermore, cellulosic feedstocks from perennial grasses require little nitrogen and phosphorus as compared to corn and thus have the potential to substantially reduce nitrogen and phosphorus runoff from the cropland where they are grown. Figure 3.1 illustrates the tradeoff between improved climate change potential and water quality degradation resulting from different biofuel feedstocks (Miller *et al*, 2007).

With different assumptions and experimental conditions, the environmental emission values can vary dramatically. For corn ethanol, net GHG emissions are widely debated. Liska *et al.* (2009) used the Biofuel Energy Systems Simulator (BESS) to estimate that corn ethanol is responsible for approximately 50% less GHG emissions than gasoline per energy equivalent unit. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Wang *et al.* 2007) developed at Argonne National Laboratory estimates an 18% to 28% GHG reductions for corn ethanol versus gasoline. The Energy and Resources Group Biofuel Analysis Meta-Model (EBAMM) developed by Farrell *et al.* (2006) calculates a GHG reduction with corn ethanol of about 13%.

In all the models, N_2O from the application of nitrogen fertilizer is one of the major GHGs associated with corn production. Based on a study by the Intergovernmental Panel on Climate Change (Klein *et al.* 2006), most current studies of bioethanol assume that the conversion factor from N fertilizer to N_2O is about 1%. However, Crutzen *et al.* (2007) argued the conversion factor should be 3 ~ 5%. Based on the latter conversion factor, together with the high climate change potency of N_2O compared to CO_2, their results show a net increase of GHG emissions from corn ethanol compared to gasoline.

Compared to corn ethanol, cellulosic ethanol has an advantage with respect to GHG emissions. Studies on switchgrass ethanol show a relatively consistent result of GHG emissions 80% to 94% below those from gasoline (Adler *et al*. 2007; Schmer *et al.* 2008; and Wang *et al.* 1999).

Another perennial grass, *miscanthus*, has drawn a lot of attention as an ethanol feedstock because of its high yield, low inputs, and excellent carbon sequestration potential. Because *miscanthus* is a relatively "new" ethanol feedstock, few studies have explicitly studied its GHG emissions. A life cycle analysis conducted by Khanna *et al.* (2009) reports up to 94% GHG reduction from *miscanthus* ethanol compared to gasoline. The same study reports that switchgrass ethanol has a slightly lower global warming benefit -- up to 87% reduction in GHGs emissions compared to gasoline.

Another environmental concern associated with biofuel feedstock production is water pollution. Phosphate and nitrate are the major causes for eutrophication and hypoxia. However, when considering nutrient leaching from feedstock production, phosphate has the lowest leaching rate among the major plant nutrients due to its low mobility in soil -- 0 to 1.75 kg P/ha/year for mineral soils (Mengal and Kirkby 2001) and less for heavy arable soil (Cooke and Williams 1970). The leaching rate for nitrogen is much higher. Based on a study by Jaakkola (1984), leaching of nitrogen from clay soil is 17 kg N/ha/year on average for cereal crops. Other studies report even higher nitrogen leaching rates, especially for corn. Based on 57 nitrate leaching measurements in 15 field-scale studies, Miller *et al* (2006) calculated a mean leaching rate of 39.8±26.6 kg N/ha/year for corn production. Since the leaching rate of phosphate is quite low compared to nitrate, and the total application of P fertilizer is only about 35% of total N application (ERS/USDA: http://www.ers.usda.gov/Data/FertilizerUse/), in this study, only the N content of fertilizer is explicitly modeled. P and other nutrients are aggregated with other sectors.

It is generally believed that applying more fertilizer results in more nitrogen leaching. However, the leaching rate is affected by many other factors as well, such as the timing and method of fertilizer application, the use of stabilizers, irrigation rates, vegetative cover, and soil porosity (Canter 1996). Also, nitrate leaching can be an accumulative process. It is very hard to apply a single value to represent the nitrogen leaching rate for the production of a certain feedstock in different locations, and the functional relationship between fertilizer application and nitrogen leaching is debatable. Thus, in this study, the amount of fertilizer, instead of nitrogen leaching, is explicitly modeled. With the fertilizer application amount being explicitly modeled, the emissions of N_2O can be separated from other GHGs.

N fertilizer is a very important nutrient for corn production and the application amounts are well documented by USDA (ERS, http://www.ers.usda.gov/Data/FertilizerUse/). However, since switchgrass and *miscanthus* are not commercially produced, this study must rely on experimental data on nutrient use in their production. For switchgrass, although many studies have examined the relationship between nutrient additions and productivity, a consensus about nitrogen application has not emerged. The recommendations for nitrogen application range from minimal application up to a rate comparable to corn production (Parrish and Fike 2005). For *miscanthus*, studies have been done on several sites in Europe and the results show that production does not respond to N fertilizer from the second and third years onwards (Christian and Haase 2001). In the life cycle study by Khanna *et al.* (2009), based on previous studies and field trials, they assumed that the annualized N application for switchgrass is 50.4 kg/ha, and 25.3 kg/ha for *miscanthus* for an "optimistic" scenario, and 126 kg/ha for switchgrass and 50.7 kg/ha for *miscanthus* in a "pessimistic" scenario. This rates compared to the N fertilizer application rate for corn production of 146 kg/ha.

Clearly, with different production pathways, the same final product (ethanol) can have different environmental impacts. Since this study incorporates multiple biofuel pathways in one model, it is appropriate to use data for the different pathways from the same source if possible. In this analysis, the technology represented by the optimistic case from Khanna *et al.* (2009) for *miscanthus* and switchgrass production is used. Sensitivity analyses are conducted later to test how different assumptions affect the results.

3.3 Model Structure

This single region closed-economy model builds on the general equilibrium model of Arrow and Debreu (1954). The outcomes satisfy Walrasian equilibrium. The sectoral foci of this model are various ethanol pathways, petroleum-energy, and the food market. In order to focus on energy and food markets, other sectors are highly aggregated. This model assumes one representative consumer and one competitive producer for each production process. The detailed model specifications are discussed below.

3.3.1 Production

The major production sectors include grain (GRN), other crops (OCP) which includes all the other crop production, other food (OFD) which includes meat, dairy and all processed food, petroleum-energy (FUE), other energy (OEG) which includes coal, natural gas, and electricity, nitrogen fertilizer (FER), ethanol, which can be produced from grain, swithgrass, and miscanthus, and the rest of other consumptions goods (ROG). The definitions for all the sectors are defined in Table 3.1. All of the producers in the economy are assumed to be profit maximizers with zero profits. The major inputs to production include capital, labor, land, fertilizer, energy and other intermediate inputs.

Besides the traditional inputs, in this study, GHG emissions are also assumed to be inputs. Producers can be thought of as either using clean environmental resources to produce their products or buying permits to emit GHGs. At the margin, the price for an environmental input is its tax rate or permit price. In the model, only petroleum-fuel (FUE) and other energy (OEG) are the direct emitters of CO_2. The emissions from the other commodities, including various types of ethanol, are actually from their consumption of these two energy inputs. The CO_2 emissions from combustion of ethanol are assumed to be zero since the CO_2 embedded in these emissions were taken up from the atmosphere during biomass growth (Wang *et al.* 1999). The N_2O emissions from fertilizer, however, have no such offset. The N_2O emissions are calculated as a fixed percentage of the fertilizer applied and then are added into the total GHG emissions. GHG emissions, such as CH_4, generated from other production processes are not major concerns in this study and their emissions are excluded from our model.

The production processes for all final goods are assumed to follow nested Constant Elasticity of Substitution (CES) functions. With a CES production technology, inputs for production in the same "nest" have the same value of the elasticity of substitution. Each nest is defined as a standard CES functional form, which is written as

$$y = \phi(\sum_t \beta_t x_t^\rho)^{1/\rho} \qquad (3.1)$$

where y is the output, ϕ is the scale parameter, x_t is the amount of input t, β_t is the share parameter of that input, with $\sum_t \beta_t = 1$, and $\sigma = \frac{1}{1-\rho}$ is the constant elasticity of substitution between all x_t in the nest. The CES functional form is fairly flexible and can easily be transformed to represent common production technologies. If the elasticity of substitution $\sigma = 1$, then the production function reduces to a Cobb-Douglas technology. When σ approaches infinity, the inputs in the production process are perfect substitutes. When σ approaches zero, the production process follows a Leontief technology.

All production processes are separated into intermediate inputs and value-added. Energy inputs go into the value-added part at the same level as capital. Capital, land and labor are endowments in the system. We assume that their total quantities are fixed. By fixing the total amount of land, only the land harvested in the benchmark year (2004) is considered. This excludes the possibilities of planting energy crops on land not cropped in 2004. Although this is an artificially rigorous constraint, it avoids the need to address issues of the productivity of the land that might be brought into cultivation and the GHG emissions from disturbing fallow areas. Thus, we omit the land change possibilities and keep the focus on the policy implications. Ruling out the possibilities of increased total available acres of land is likely to overstate the competition between food and fuel crop production.

Producers have the ability to choose between petroleum-energy (FUE) and ethanol. Ethanol can be produced from three different feedstocks: grain, *miscanthus*, and switchgrass. The final products are all ethanol in the market. To simplify the exposition, we call the final products grain ethanol (CET), *miscanthus* ethanol (MET) and switchgrass ethanol (SET). Fertilizer is a value-added input and is substitutable with other factors. We assume carbon emissions from each energy product are proportional to the total demand for that commodity. As an example, the production process for grain can be represented by a production tree as shown in Figure 3.2. Other production processes follow similar structures with different inputs.

3.3.2 Consumption

The representative consumer maximizes utility by choosing consumption levels for each commodity subject to a budget constraint. The consumption goods include food, energy, and nonfood. Food is a composite commodity encompassing grain (GRN), other crops (OCP), and other food (OFD). As with the producers, the consumer makes his choice between petroleum-energy and ethanol which is composed of CET, MET and SET. The utility tree for the representative consumer is shown in Figure 3.3.

As with the producers, consumer utility is represented by nested Constant Elasticity of Substitution (CES) functions. As an example, the first stage of the nested structure is formulated as:

(3.2)

The utility for the consumer is represented by U. The share parameter for commodity or composite commodity i is α_i, and the substitution parameter for the first stage utility is represented by ρ_U. The consumer's demand for commodity i is represented by Xp_i. The utility level is cardinal and the scale parameter for the utility function is set to one.

The consumer's choice problem is subject to a budget constraint equal to the sum of income from capital, labor and land endowment, and transfers from production taxes and environmental taxes.

3.4 Data Sources

This large-scale model requires many functional parameters. However, relatively few data points on which to base these parameters are available, so econometric methods cannot be used to estimate them. Instead, we use calibration to obtain the required parameters. We first collect data for a benchmark year in which the markets are assumed to have been in equilibrium. Then, we compute model parameters so that the equilibrium solution of the economy satisfies all model equations. With the calculated parameters, new equilibria under different scenarios can then be simulated.

Our benchmark year is 2004. Following customary procedures in CGE modeling, the benchmark equilibrium is summarized in the form of a Social Accounting Matrix (SAM). This is a flow-of-funds matrix for an economy and represents flows of all economic activities/transaction within this economy. The data in the SAM table used in this study are from Global Trade and Analysis Program (GTAP) version 7.0 (Narayanan and Walmsley 2008) with appropriate aggregation and disaggregation. The GTAP 7.0 data are transformed into a SAM at the desired aggregation level following the method of McDonald and Thierfelder (2004).

GTAP 7.0 aggregates fertilizer into the chemical sector. To separate out N fertilizer, we first obtain the N fertilizer usage for different crops from USDA (ERS/USDA: http://www.ers.usda.gov/Data/FertilizerUse/). The market price for N fertilizer was $0.25/lb in 2004 (Schnitkey 2004). We assume the production of fertilizer follows the technology defined by the Bureau of Economic Analysis (BEA) benchmark account 2002 (http://www.bea.gov/industry/io_annual.htm).

Since individual biofuel sectors are not included in GTAP 7.0, one of the major challenges in constructing the SAM used in this study lies in representing the ethanol sector. Taheripour *et al.* (2007) have developed the GTAP_BIO database based on GTAP 6.0 (Dimaranan, 2006) with the introduction of grain-based ethanol, sugarcane ethanol and biodiesel. All ethanol in the benchmark equilibrium is grain-based. It is separated from the processed food sector as in GTAP_BIO. The production technology of CET is assumed to follow the GTAP_BIO database with 2004 production and price data[5]. Since, currently, ethanol is mainly used in a blend with gasoline to serve the transportation market, the consumption of ethanol follows the GTAP_BIO assumption that the consumer is the final buyer of ethanol.

Switchgrass ethanol and *miscanthus* ethanol are not currently in commercial production in the United States. In our model, we treat them as two non-profitable alternative technologies to produce ethanol. With the introduction of different policies, these two bioethanol pathways might become cost-competitive and start to produce. The production technology parameters for

[5] According to EIA (2007), total production of grain-based ethanol in 2004 was 3400 million gallons, and the average price for grain-based ethanol was $1.69/gallon, http://www.neo.ne.gov/statshtml/66.html

both feedstocks and ethanol are based on the optimistic scenario in the study conducted by Khanna *et al.* (2009). Later, sensitivity analysis is conducted to test the effects of different scenarios.

In our model, the ultimate sources of pollution are petroleum energy (FUE), other energy (OEG) and fertilizer (FER). The environmental impacts from all other commodities depend on their use of these inputs. Data for carbon emissions from petroleum energy (FUE) and other energy (OEG) are from GTAP (Lee 2008). We assume carbon emissions are proportional to the domestic usage of petroleum-energy and other energy and the benchmark carbon tax rate is assumed to be zero. Fertilizer contributes not only to GHG emissions as N_2O, but also to nitrate leaching to surface waters. We assume both N_2O releases and nitrogen leaching are proportional to fertilizer application. The total GHG emissions for the system are a weighted potency-sum of CO_2 emissions from FUE and OEG and N_2O emissions from fertilizer.

Besides the construction of the SAM, the elasticities of substitution comprise another important set of parameters in CGE applications. Most of the elasticities used here are from the GTAP database. Following the GTAP setup, the highest level of production processes – the relationship between value-added and intermediate inputs -- follows the Leontief technology. Elasticities of substitution between the factors of production -- land, labor, fertilizer and capital-energy composite -- for different production processes come from GTAP, using the elasticity values between primary factors for similar sectors. The original GTAP model does not include a capital-energy composite. However, the GTAP_E model (Burniaux and Truong 2002) incorporates greenhouse gas effects. We use the elasticity of substitution between capital and energy in the capital-energy composite from GTAP_E.

For the consumption side, the elasticity values are very difficult to define due to sectoral definitions that differ from the literature. For the upper-most level in the utility tree, transportation energy (refined petrofuel and ethanol) and food are two very inelastic sectors. Many studies have estimated the price elasticity of gasoline. Two meta-analysis (Espey 1996; and Goodwin *et al.* 2004) found that the average price-elasticity of demand for gasoline is around -0.25 in the short run. Based on the consumption ratio of energy, the elasticity of substitution between energy and other commodities would be less than 0.2. A more recent study found that the price elasticities of gasoline demand ranged from -0.034 to -0.077 during 2001 to 2006 versus -0.21 to -0.34 for 1975 to 1980 (Hughes *et al.* 2007). This indicates that the demand for gasoline has become less elastic. We use a value of 0.2 for the elasticity of substitution between energy, food and other commodities within the top-most level in the utility tree. Later a sensitivity analysis is conducted to test how this value affects the results. The sub-level in the food sector is assumed to follow the widely used Cobb-Douglas functional form, *i.e.*, the elasticities of substitution among GRN, OCP and OFD are one.

Due to a lack of adequate data, few studies have estimated the elasticities of substitution between petroleum energy and bioethanol. In a modified GTAP_E model application by Birur *et al.* (2008), the elasticity of substitution between petroleum energy and biofuel for the US is defined as 3.95. With this value, they are able to reproduce, with reasonable precision, the biofuel production observed between 2001 and 2006. We use the same value in this model. The different ethanol pathways are represented as a single final product with different technologies.

3.5 Model Scenarios and Results

The model is written in the GAMS-MSPGE environment (Rutherford, 1987). Beginning with the model defined above, one or more of the policy parameters can be changed to obtain a counterfactual equilibrium. By comparing the new equilibrium with the benchmark equilibrium, we can identify the effects of the changed policy parameter(s) for the economy and the environment. We start our analyses by evaluating the effects of current (2009) energy policies.

3.5.1 Effects of Current Policies

Currently in the United States, the major federal policies are designed mainly to stimulate ethanol production. One of the major policies is the ethanol subsidies authorized in the 2008 Farm Bill (P.L. 110-246, Food, Conservation, and Energy Act of 2008). The Farm Bill reduces the previous $0.51/gallon ethanol subsidy for corn ethanol to $0.45/gallon and adds a cellulosic ethanol subsidy of $1.01/gallon.

In the benchmark year for our model, 2004, ethanol producers were subject to the $0.51/gallon subsidy. To evaluate the pure effects of current policies, we replaced the $0.51/gallon ethanol subsidy with the new subsidy. The new subsidy results in corn ethanol production of 3.1 billion gallons and no cellulosic ethanol. This production level is much below the quantity requirement defined by the Renewal Fuel Standard (RFS) program established in the Energy Policy Act of 2005. In 2007, the Energy Independence and Security Act of 2007 (H. R. 6) amended the Renewable Fuels Standard (RFS) and increased the required renewable fuel volume. The expanded RFS is generally refers as RFS2. For example, the volume requirement for 2008 was increased from 5.4 billion gallons to 9 billion gallons, and the final goal of RFS2 is 36 billion gallons of renewable fuels by 2022, including 16 billion gallons from cellulosic feedstocks. Without technology changes or the intervention of other policies, our model suggests that the RFS targets are unlikely to be achieved.

Current energy policies have evolved due to changes of technology and market conditions, and environmental and political pressures. However, data limitation precludes calibration of our model beyond the year 2004. Since we are not able to track current reality with the model, we propose and analyze some hypothetical policies instead. To explore the pure effects of these hypothetical policies, we eliminated the $0.51/gallon ethanol subsidy and recalibrated the model as a policy-free benchmark.

The focus of this study is the environmental impacts of biofuel production and the economic and environmental consequences of public policies intended to mitigate those impacts. Since taxes are an efficient means of deterring environmental externalities, we test three types of externality taxes: CO_2 tax, N fertilizer tax, and GHG tax, and then compare their effects on biofuel production and environmental discharges.

3.5.2 Effects of CO_2 Tax (T_C)

In the benchmark equilibrium, there are no constraints on carbon or nitrogen emissions. However, since increased production of biofuels has been justified, in part, by arguments about their lesser carbon footprints, we introduce a carbon tax as an incentive to control climate change.

To date, no federal restriction has been placed on carbon emissions in the United States. However, several local efforts have introduced regional carbon trading schemes. The Regional Greenhouse Gas Initiative (RGGI) is a non-profit corporation to support the implementation of the CO_2 trading program of the participating states which include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. The trading price for this system is about $3/ton of CO_2 (http://www.rggi.org/co2-auctions/results). Currently, the European Union (EU) has the largest carbon trading market. In the EU market, the price has varied from less than 3¢ to over $40 per ton of CO_2 (http://www.carboncapital.com/kyoto_and_carbon_trading.php#11). The trading price for this fledgling market in a time of economic dislocation and rapid greenhouse policy evolution is not reliable. Instead, the price for the RGGI system ($3/ton) is chosen as the lower bound of T_C tested in this study and the upper bound is chosen to be $40/ton.

As discussed before, we eliminated the $0.51/gallon ethanol subsidy from the benchmark. All of the equilibrium results are documented as percentage changes from the subsidy-free 2004 benchmark. The new equilibrium results are shown in Figures 3.4a to 3.4c, which presents the percentage change of prices, production, and emissions respectively. The full results are documented in Appendix C.

As shown in Figure 3.4a, T_C has the greatest impact on prices of OEG, FUE and ethanol. OEG and FUE are directly affected by T_C. Ethanol is a close substitute for FUE and its energy requirement for production is fairly high, so its price is also affected significantly by T_C. Since FUE and OEG are either a direct or an indirect input for all commodities, the prices of all commodities increase, but at a relatively low rates. Producers adjust output based on the new prices. Correspondingly, production of FUE and OEG decreases. To satisfy the energy demands of consumers and producers, production of CET increases because it is less carbon-intensive than FUE. The impact on overall GHG emissions is surprisingly small. A $40/ton T_C rate would reduce GHG emissions only approximately 1.5%.

Surprisingly, a CO_2 tax also reduces N leaching although by very small amount. Production of fertilizer is highly energy-intensive. Taxes on carbon also affect the fertilizer price. GRN is the most fertilizer-intensive product in the economy. However, GRN is a major input for CET production. The boost in CET production raises the demand for GRN, but the change is very small. The overall percentage change in GRN production is much less than that of CET since only a fraction of GRN is used to produce CET. Although the production of GRN increases, the higher price of fertilizer actually inhibits its use. A \$40/ton T_C would reduce N fertilizer application by 0.4%.

3.5.3 Effects of N Fertilizer Tax (T_N)

Besides GHG emissions, N leaching is also an important issue. Although a CO_2 tax reduces nitrogen leaching, the effect is very small. If we want to control N leaching, a tax on N fertilizer tax seems likely to have more consequences. To test the effects of T_N, this tax alone is introduced into the system. Such a tax has not been used at the federal level. However, although farmers are often exempted from such taxes, most states tax fertilizer. In the states where farmers are not exempted, T_N ranged from \$0.0001 to \$0.00075 per kg in 1996. This compares to a fertilizer price of about \$0.3/kg (Uri 1999). Several studies have simulated the impacts of a higher T_N. Based on Indiana agricultural data, Quiroga *et al*. (1995) concluded that a T_N that is 417% of the fertilizer price would be required to reduce fertilizer use by 30%. Pfeiffer and Whittlesey (1978) used a linear programming model to estimate the required T_N to meet the water quality target (0.30mg/l) in the Yakima Basin of Washington. The tax was determined to be \$1.32/kg, equivalent to 400% of the fertilizer price at that time. Based on a nonlinear mathematical programming model for Iowa field crop production, Huang and Lantin (1993) suggested that a tax rate in excess of 200% would be required to eliminate all nitrate leaching in corn production with rotation. Thus, all of these studies indicate that a relatively large T_N is required to achieve a substantial effect.

In this study, a wide range of T_N values, from \$0.01/kg to \$1.2/kg (1.8% to 218% of the benchmark fertilizer price), are applied to the model to test how such a tax affects GHG emissions and nitrogen leaching. Figures 3.5a to 3.5c show the percentage changes of quantities and prices under new equilibria compared to the benchmark equilibrium. Figure 3.6d illustrates the sources of ethanol in the market. The underlying data are in Appendix D. As shown in Figure

3.6, T_N has noticeable effects only on GRN, OCP and CET. Its effects on the other sectors are negligible.

Just as with T_C, T_N increases prices for all consumption goods, with the price of GRN increasing the most. However, it decreases the price of land slightly. With a positive T_N, due to the intensive nitrogen requirement of GRN, producers of GRN and OCP reduce their production, which drives down the land price. Other things equal, the substitutability of land for fertilizer would increase the price of land as a consequence of more costly fertilizer. However, when other markets are included in the analysis, the substitution of land for fertilizer is not sufficient to overcome the downward pressure on land price due to reductions in GRN and OCP. Food demand is fulfilled by an increase in OFD production. As T_N increases, substitution between fertilizer and land becomes more likely and this pushes the land price upward but not enough to fully offset the reduction in OCP and total GRN outputs with the tax rates tested in this study. After cellulosic ethanol starts to produce, the rate of increase of land price starts to slow down because cellulosic crops are less fertilizer-intensive.

With a positive T_N, production of GRN and OCP declines since fertilizer is an important input. However, their proportionate reductions are much less than the reduction in ethanol because only a small fraction of GRN is used to produce ethanol and the rest is used for food, for which demand is relatively inelastic. With fertilizer-intensive GRN as the most important input, production of ethanol declines as T_N increases. A T_N of approximately $1/kg makes corn ethanol more costly to produce than *miscanthus* ethanol. Producers of ethanol would switch to *miscanthus* as the preferred feedstock, under the assumption that the transition is not costly. The shift from corn ethanol to *miscanthus* ethanol would cause a major reduction in GRN production. As T_N increases further, the reduction of GRN would slow down due to the inelastic demand for food. The rate of reduction in ethanol production would slow down too because *miscanthus* is less N-intensive. As a close substitute for ethanol, production of FUE increases as ethanol decreases. However, since the benchmark volume of FUE is much greater than ethanol, a very small percentage increase in FUE would compensate for the reduction of ethanol.

While T_N reduces nitrogen leaching, it has almost no net effect on GHG emissions. As discussed before, T_N increases the consumption of FUE, which is the most carbon-intensive fuel. Since the percentage change in FUE output is very small, and GHGs decline from less fertilizer usage, the net percentage change of GHG emissions is very small. A T_N increase of 145% reduces nitrogen use by slightly more than 10%.

3.5.4 Effects of GHG Tax (T_G)

N fertilizer not only contributes to N leaching, but also emits N_2O gas which is a potent GHG. The global warming potential of N_2O in a time horizon of 100 years is 298 times of CO_2 (Forster *et al.* 2007). To control climate change, it would be more appropriate to apply a tax not only to CO_2 emissions, but also to N_2O. In this section, GHG taxes are applied to the system to test their effects. The range of the taxes tested is the same as the CO_2 tax we tested in Section 3.5.2, \$3/ton to \$40/ton of CO_2-equivalent. The new equilibrium results are shown in Figures 3.6a to 3.6c, and the full equilibrium results are documented in Appendix E.

As shown in Figure 3.6, the effects of T_G are very similar to the effects of T_C. The major differences lie in the prices and production of GRN and ethanol, since they are affected by fertilizer tax the most. Just as with T_C, a \$40/ton T_G is not enough to induce a switch to cellulosic ethanol and it reduces both GHG emissions (1.7%) and fertilizer application (4%).

3.5.5 Comparison of Policy Instruments

In this section, we apply the three policy instruments to the system to compare their performance. The three instruments levy taxes on different commodities. With T_C, FUE and OEG are directly subject to the tax; with T_N, only fertilizer is subject to the tax; and with T_G, FUE, OEG and fertilizer are all subject to the tax. Assume the tax burden for GHGs is \$20/ton of CO_2-equivalent and the corresponding tax rates are T_C = \$20/ton, T_N = \$0.12/kg, and T_G = \$20/ton. The resulting equilibrium is presented in Figures 3.7a to 3.7c. Complete results are documented in Appendix F.

T_C and T_G have very similar effects on the production of FUE and OEG, on which T_N has almost no effect. In terms of ethanol production, T_C yields the highest increase, while T_N would actually decrease output. It is interesting that T_C and T_G result in similar reduction in GHG emissions.

Even though only T_G applies to fertilizer, the tax burden on fertilizer increases energy consumption as the same time as it reduces N_2O emissions. The two effects on GHG emissions are opposite and the net effect is negligible. Thus the tax burden on energy plays the most important role with T_G. T_G also induces the most fertilizer use reduction. Although T_G induces the highest food price increase, aggregated consumption, although lower than the benchmark level, actually is greater than in the T_C case. Thus T_G performs better than T_C in terms of both consumption and environmental emissions. T_N performs the best in terms of consumption but produces less environmental benefits.

Another way to compare the three policy instruments is to set a policy target and test the tax rates to achieve the target. Since ethanol is produced as a substitute for FUE to reduce GHG emissions and increase energy security, we use an ethanol production level as our policy target and calculate the tax rates needed to achieve this target. As discussed in Section 3.5.3, a fertilizer tax alone would reduce ethanol production. Thus, to achieve the ethanol production increase target, the only options are the CO_2 tax or GHG tax among the three policy instruments. The tax rates to achieve a range of ethanol production increase target, 1% to 50%, are shown in Figure 3.8. The kink points in both curves show the points when ethanol producers shift from CET to MET. The results indicate that to achieve significant increases in ethanol production, very high tax rates are required. Other policy instruments might be more effective to achieve production targets. Between the two taxes, the CO_2 tax is more effective in stimulating total ethanol production. A lesser GHG tax triggers the cellulosic ethanol production because of the tax burden on fertilizer application.

3.6 Sensitivity Analysis

The data used in our model is subject to considerable uncertainty. One of the major sources of uncertainty is the technology data for cellulosic ethanol production. The elasticities of substitution and the emissions rates may also be debated. In this section, different values are tested to see how sensitive the results are to these parameters. In this analysis, the policy instrument is held constant: a $20/ton T_G.

3.6.1 Cellulosic Grass Production Data

In the analyses above, the technology data for cellulosic ethanol production were adapted from the optimistic scenario in Khanna *et al.* (2009), which represents a rather ideal situation for cellulosic grass production: low fertilizer application rate, low replanting probability, high yield, and low harvest loss. However, the cultivation processes in field trials vary widely. In their study, they also presented a “pessimistic” scenario. To test how the technology data affect the results, we examine their pessimistic production data. The responses of the pessimistic system to the policy shocks appear in Tables 3.2a to 3.2c, alongside the optimistic case results.

The policy shock yields exactly the same results. With $20/ton GHG tax, all ethanol is produced from corn. Thus the two scenarios wouldn’t yield any differences. Different production data for cellulosic ethanol would only yield different results if the policy shock is sufficient to induce a switch to cellulosc ethanol. The differences between the two scenarios would depend on the level of impacts of cellulosic ethanol production on the whole economy.

The pessimistic scenario does increase the policy thresholds for cellulosic ethanol production. Under the optimistic case, a $133/ton CO_2 tax, a $84/ton CO_2-equivalent GHG tax, or a $0.95/kg N fertilizer tax (173% of benchmark fertilizer price) would be required for *miscanthus* ethanol to be cost competitive. However, for the pessimistic case, the required tax rates would be T_C=$232/ton, T_G=$174/ton, or T_N=$1.76/kg (320% of benchmark fertilizer price). Thus, the conclusions about tax rates to stimulate the production of cellulosic ethanol are highly sensitive to the technology surrounding cellulosic ethanol production.

3.6.2 Elasticities of Substitution

Several elasticities of substitution play important roles in the analysis. One is the elasticity of substitution at the top utility level, σ_U. In the previous analysis, σ_U is assumed to be 0.2. As discussed before, some recent study suggests that it could be lower. However, technology development (*e.g.*, electric cars) would make substitution easier. If the results are sensitive to σ_U, a more accurate estimate of this parameter would be required to improve the model’s performance. To test its sensitivity, we start from the extreme case where there is no substitution in the upper level of the utility tree and then test several values between 0 and 1. The percentage changes of production levels and emissions are presented in Figure 3.9a and the complete results are documents in Appendix G.

The value of σ_U affects significantly the demand for all types of energy. As σ_U increases, consumers can shift to other goods more easily and this reduces energy demand. The reduction in energy consumption correspondingly reduces GHG emissions. As shown in Figure 3.9a, the curves of energy production and emissions are all downward sloping. Thus overestimation of σ_U (true σ_U is lower than the value used in the model) would yield overestimates of the reductions in FUE and OEG production and GHG emissions.

Another key elasticity concerns the substitution between petro-fuel and ethanol, σ_F. Few studies have estimated this elasticity. The common belief is that they are close but not perfect substitutes. The 3.75 value used in this study is adopted from a GTAP study (Birur *et al.* 2008). The range tested for this parameter is from 1 to 5. The results are shown in Table 3.9b and details can be found in Appendix H. With a GHG tax, σ_F mainly affects the ethanol consumption level and secondarily the consumption of FUE. However, due to the large benchmark value of FUE, its percentage change is small with the \$20/ton GHG tax. As σ_F increases, production of FUE decreases and production of CET increases. When σ_F is low enough, the GHG tax would reduce both gasoline and ethanol production because of the low substitutability between FUE and ethanol. As σ_F increases, the substitution becomes easier. Thus, under the same policy shock, a higher σ_F would result in higher ethanol production and lower FUE production. An overestimated σ_F would overstate the reduction of FUE production and the increase in ethanol production. Regarding environmental issues, σ_F has minimal impact on GHG emissions and nitrogen fertilizer use.

3.6.3 Emission Data

As discussed before, different studies report various emission values. Even when the reported values are consistent, the assumptions behind these studies can be quite different. One such assumption is the conversion factor from N fertilizer to N_2O. The most commonly-used value for the conversion factor is 1% based on IPCC (2006). However, Crutzen *et al.* (2007) believes that the value should be between 3% and 5%. In the analyses above, we used a factor of 1.3% based on GREET 1.8 (Wang *et al.* 2007). In this section, different conversion factors are tested to see how the model responds. The percentage changes of production levels and emissions are presented in Figure 3.9c and the complete results are documents in Appendix I.

As the conversion factor increases, the effect is equivalent to increasing the tax burden on fertilizer since the fertilizer is subject to a higher GHG tax per unit of fertilizer applied. As discussed in Section 3.5.3, a fertilizer tax mainly affects ethanol production and fertilizer application. The conversion factor would also mainly affect these two variables. If the conversion factor is high, a GHG tax would reduce ethanol production because GRN, the main input for ethanol, is highly fertilizer-intensive. Although production of GRN decreases as the conversion factor increases, its change is not very dramatic due to the inelasticity of food demand. If the conversion factor is overestimated, the predicted nitrogen leaching would be notably higher than it actually would be.

3.7 Conclusion

Our closed economy general equilibrium model provides some insights into how biofuel policy options would affect the energy and food sectors, GHG emissions and nitrogen fertilizer use.

A CO_2 tax would reduce FUE and OEG consumption and increase ethanol demand. Net GHG emissions would be reduced, and N fertilizer application would also decline because fertilizer production is fuel-intensive. A $40/ton CO_2 tax would reduce GHG emissions by only 1.5% and fertilizer application by 0.4%. On the other hand, a fertilizer tax would have negative effects on both ethanol production and fertilizer use. Its effects on production of FUE and OEG, and GHG emissions would be fairly small. A GHG tax is practically a combination of a CO_2 tax and a fertilizer tax. A GHG tax, like CO_2 tax, would reduce FUE and OEG consumption and increase ethanol demand. Both GHG emissions and nitrogen leaching would also be reduced with a GHG tax. A $40/ton GHG tax would reduce GHG emissions by only 1.7% and fertilizer application by 4%. Comparison of the three tax instruments reveals that GHG and CO_2 taxes have very similar effects on FUE and OEG consumption, and reduction of GHG emissions. The GHG tax is the most effective policy to reduce nitrogen leaching. In terms of stimulating ethanol production, the CO_2 tax is the most effective. Our results also indicate that very high tax rates are required to stimulate cellulosic ethanol production. When cellulosic ethanol is produced, *miscanthus* ethanol dominates switchgrass due to its lower production cost. With current technology and modest levels of taxation, the ethanol production will still be dominated by corn as the feedstock.

Depending on the focus of the analysis, improvements in some parameter estimates could play an important role in decision making. If the policy maker is primarily focused on stimulating cellulosic ethanol production, accurate cellulosic ethanol production data are most important. If energy security, is the main interest, the elasticity of substitution in consumption, σ_U, is very important. The quantity of ethanol is fairly sensitive to all the parameters we tested, σ_U, σ_F and conversion factors. In terms of environmental emissions, GHG emissions are very sensitive to σ_U and nitrogen leaching is affected substantially by the conversion factor from N fertilizer to N_2O.

This chapter employed a closed economy model to assess the mix of biofuel pathways, and associated economic and environmental considerations, under the influence of public policies. The use of a closed economy model is instructive for studying domestic tradeoffs. However, despite the fact that internal markets dominate the US economy, its trading activities are large and important especially for the agricultural and fossil fuel sectors. Neglecting the trading effects on the domestic market probably exaggerates the competition among sectors for land and other resources. Incorporating the possibility of trading would definitely improve the accuracy of analysis.

Tables

Table 3.1 Definition of Sector Abbreviation

Abbreviation	Sector
GRN	Grain
OCP	Other crops
OFD	Other food, including meat, dairy and all processed food
FUE	Refinery petroleum-energy
OEG	Other energy, including coal, natural gas, and electricity
FER	Nitrogen fertilizer
ROG	Rest of other consumption goods
CET	Corn ethanol
MET	Miscanthus ethanol
SET	Switchgrass ethanol

Table 3.2a % Change in Production with Different Production Data * (Unit: %)

	Optimistic	Pessimistic
GRN	0.03	0.03
OCP	-0.28	-0.28
OFD	0.05	0.05
ROG	-0.01	-0.01
OEG	-0.83	-0.83
FUE	-0.81	-0.81
CET	0.03	0.03

Table 3.2b % Change in Prices with Production Data (Unit: %)

	Optimistic	Pessimistic
GRN	3.40	3.40
OCP	1.59	1.59
OFD	0.83	0.83
ROG	0.81	0.81
OEG	4.33	4.33
FUE	3.72	3.72
FER	6.63	6.63
CET	4.20	4.20
Labor	0.81	0.81
Land	0.41	0.41

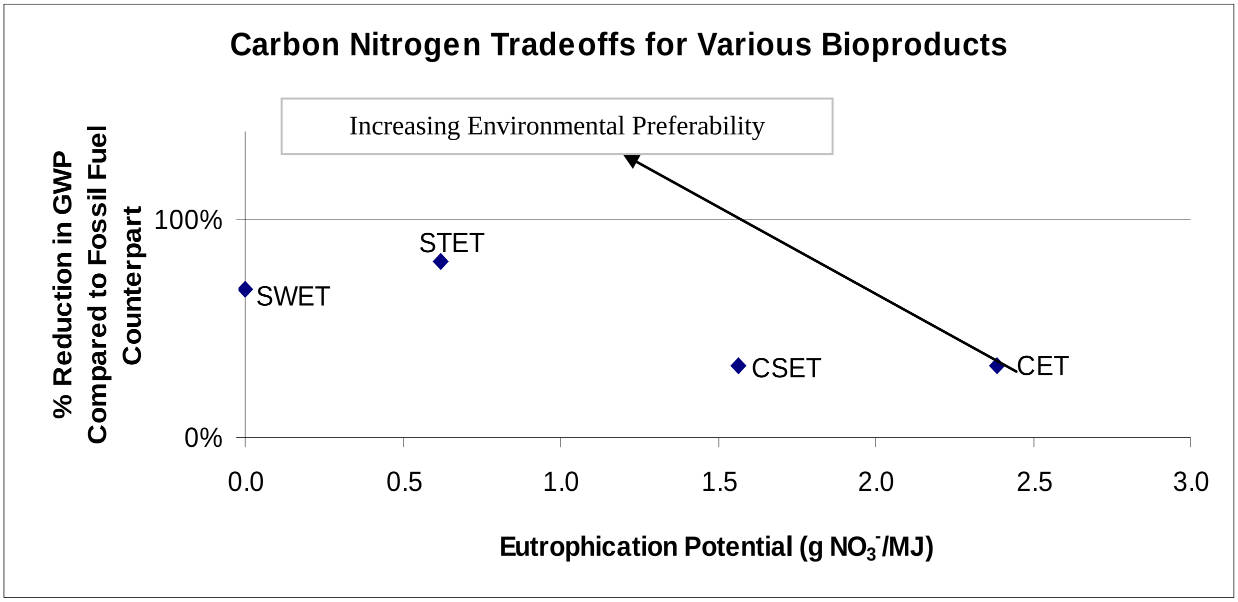
Table 3.2c % Change of Environmental Variables with Production Data (Unit: %)

	Optimistic	Pessimistic
CO2 equivalent GHG	-0.83	-0.83
N Fertilizer Use	-2.03	-2.03

* For details of the ethanol production scenarios, please see Khanna *et al* (2009)

Figures

Figure 3.1 Eutrophication Potential vs. % Reduction in Global Warming Potential for Various Bio-based Products



CET: Corn ethanol **CSET: Corn and stover ethanol**

STET: Stover (corn residue) ethanol **SWET: Switchgrass ethanol**

Source: Miller *et al.* 2007

Figure 3.2 Grain Production Tree

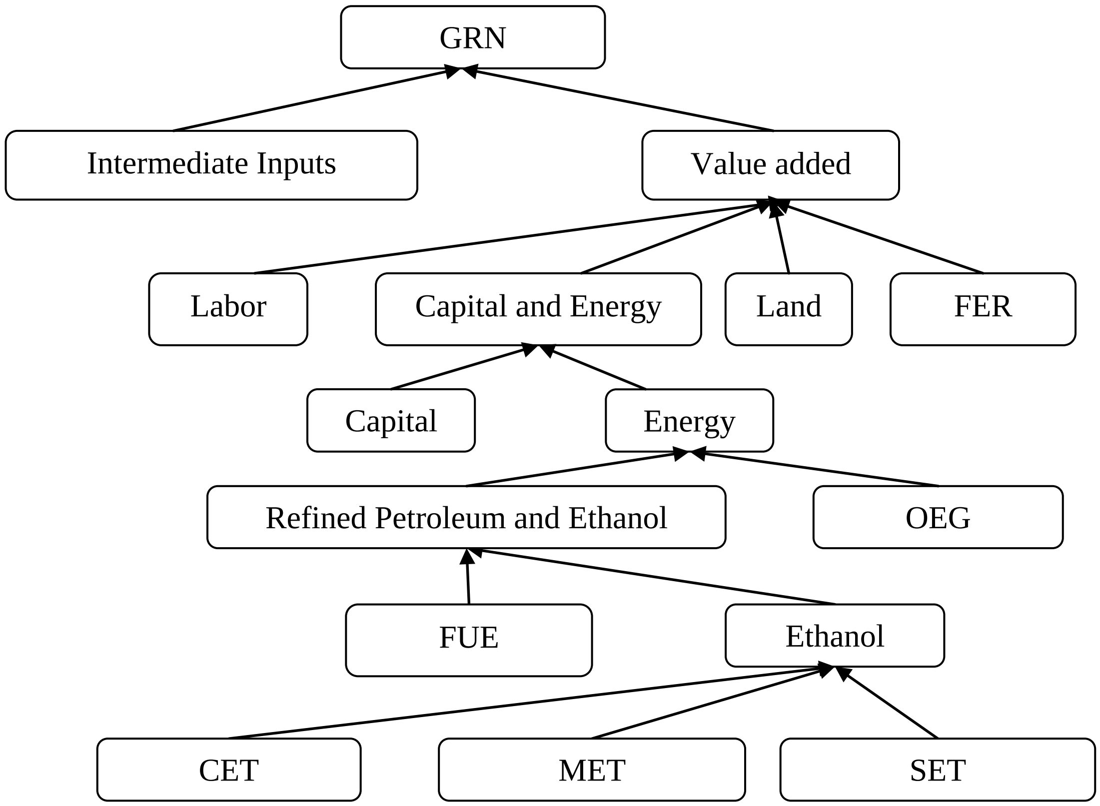


Figure 3.3 Consumer Utility Tree

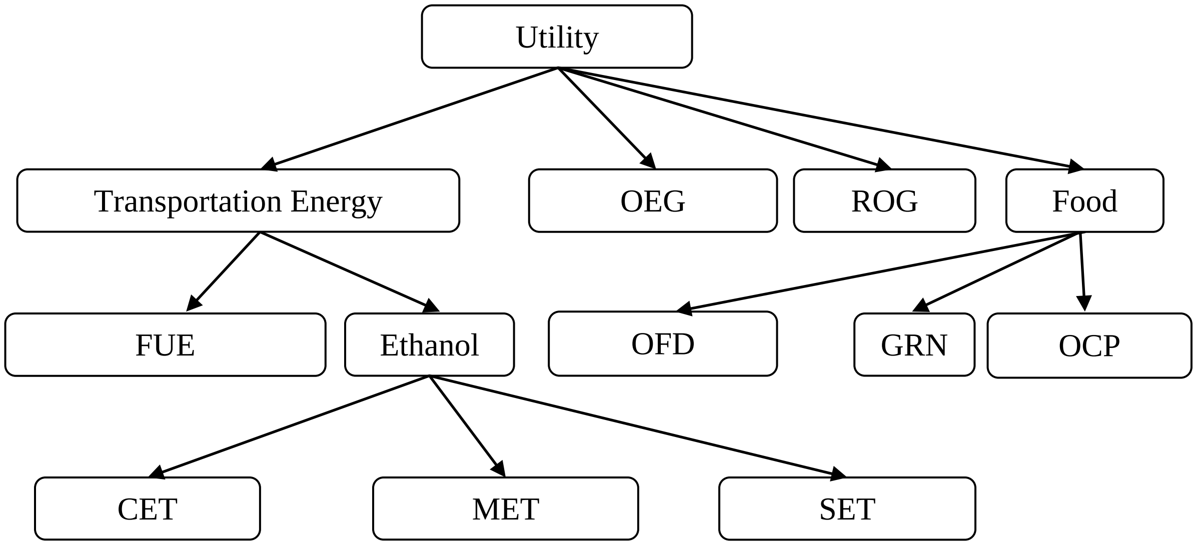


Figure 3.4a % Change of Prices with Different T_C

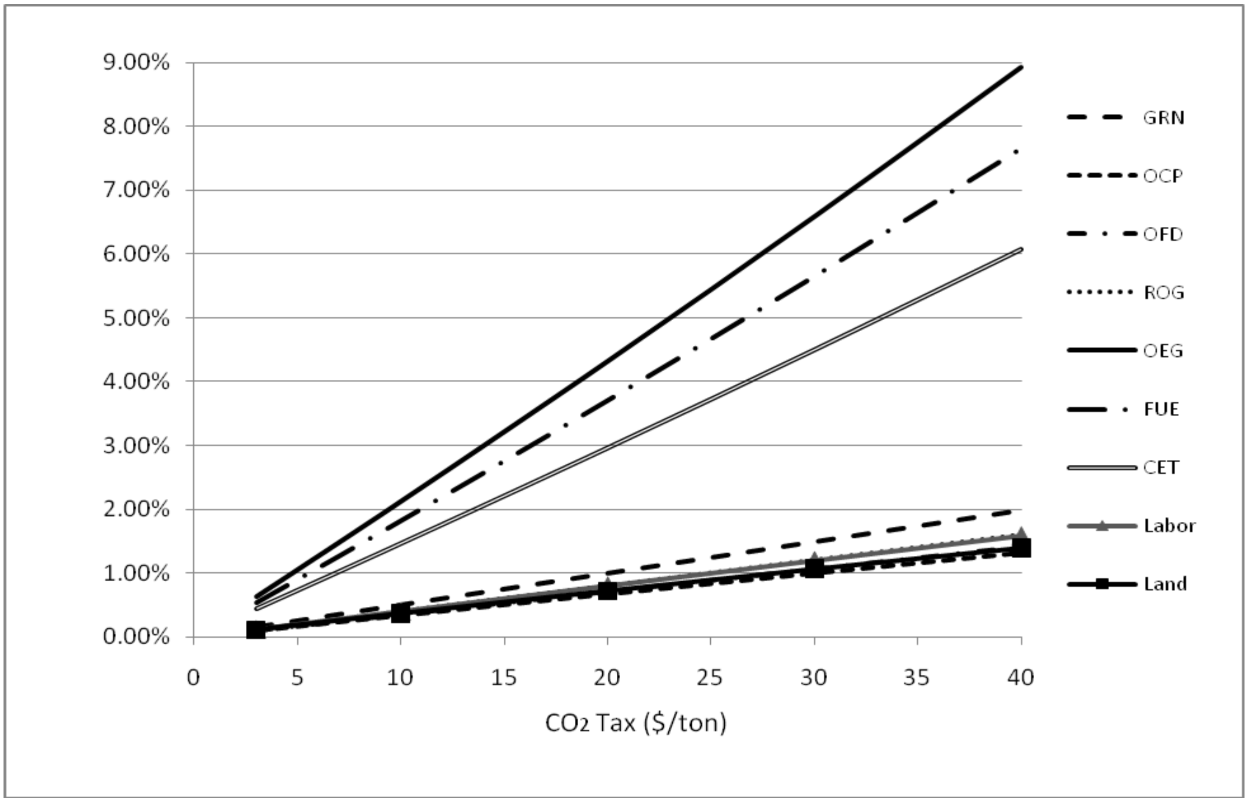


Figure 3.4b % Change of Production with Different T_C

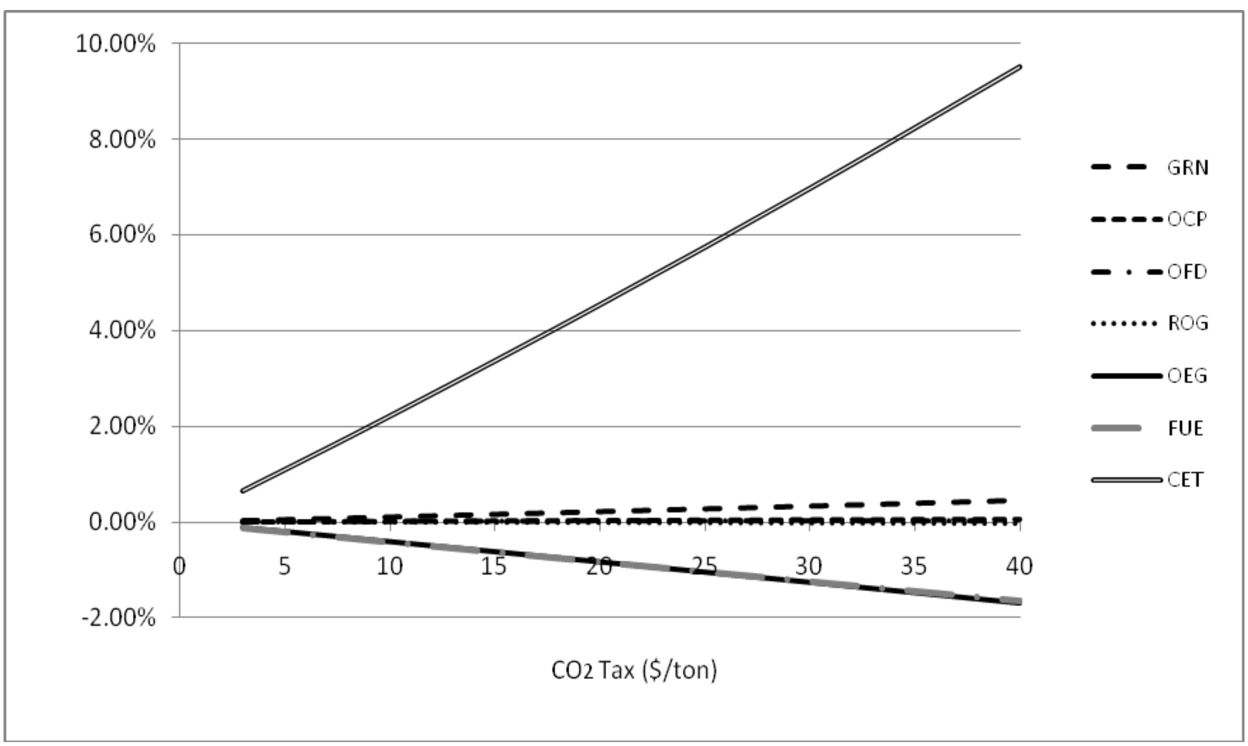


Figure 3.4c % Change in Emissions with Different T_C

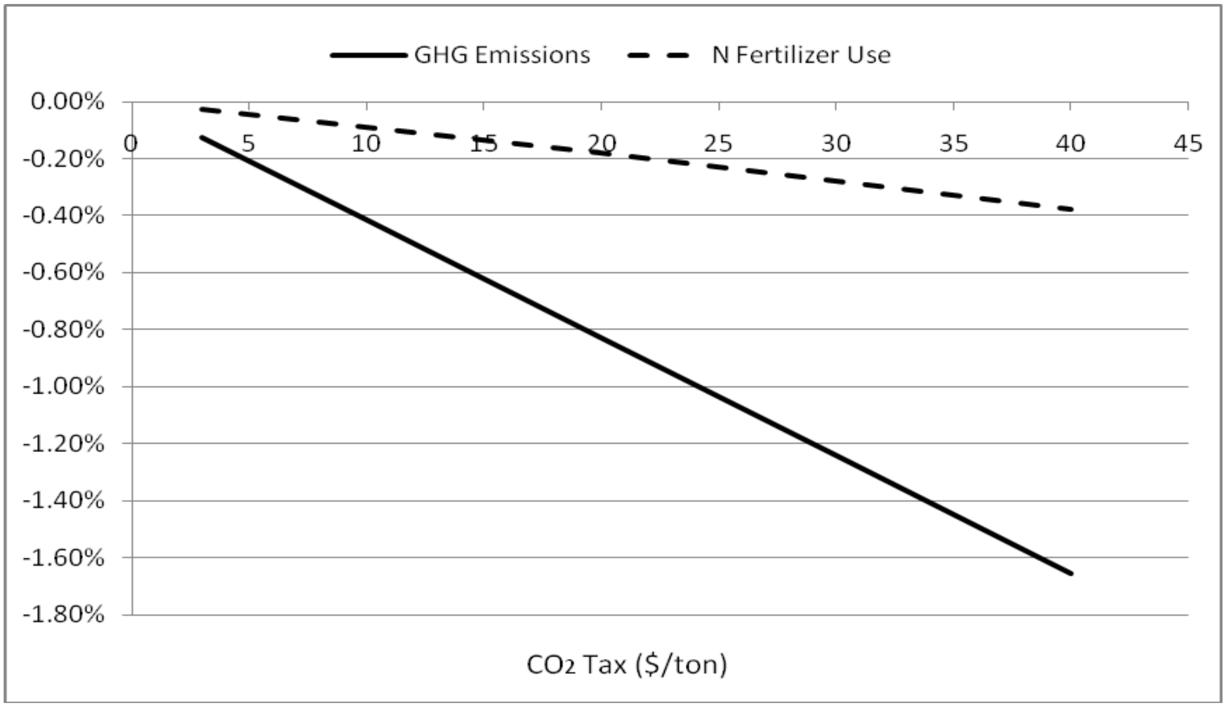


Figure 3.5a % Change of Prices with Different T_N

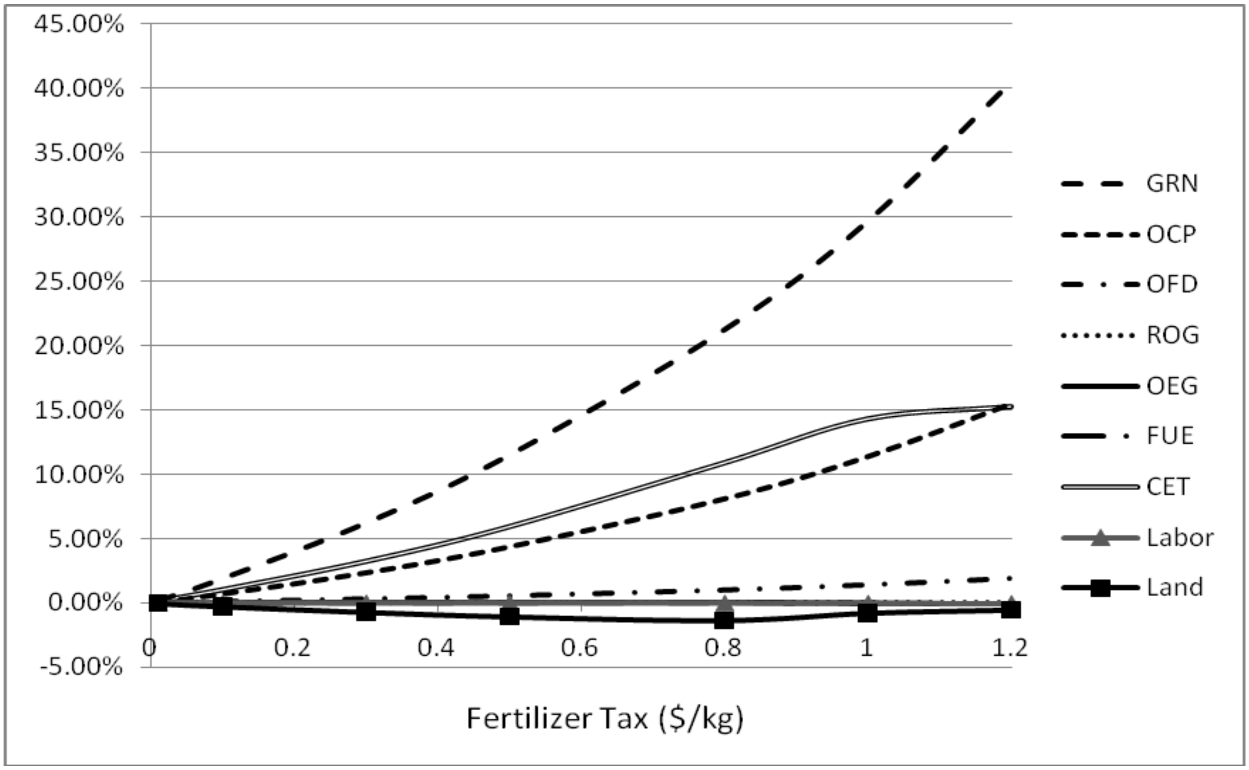


Figure 3.5b % Change of Domestic Production with Different T_N

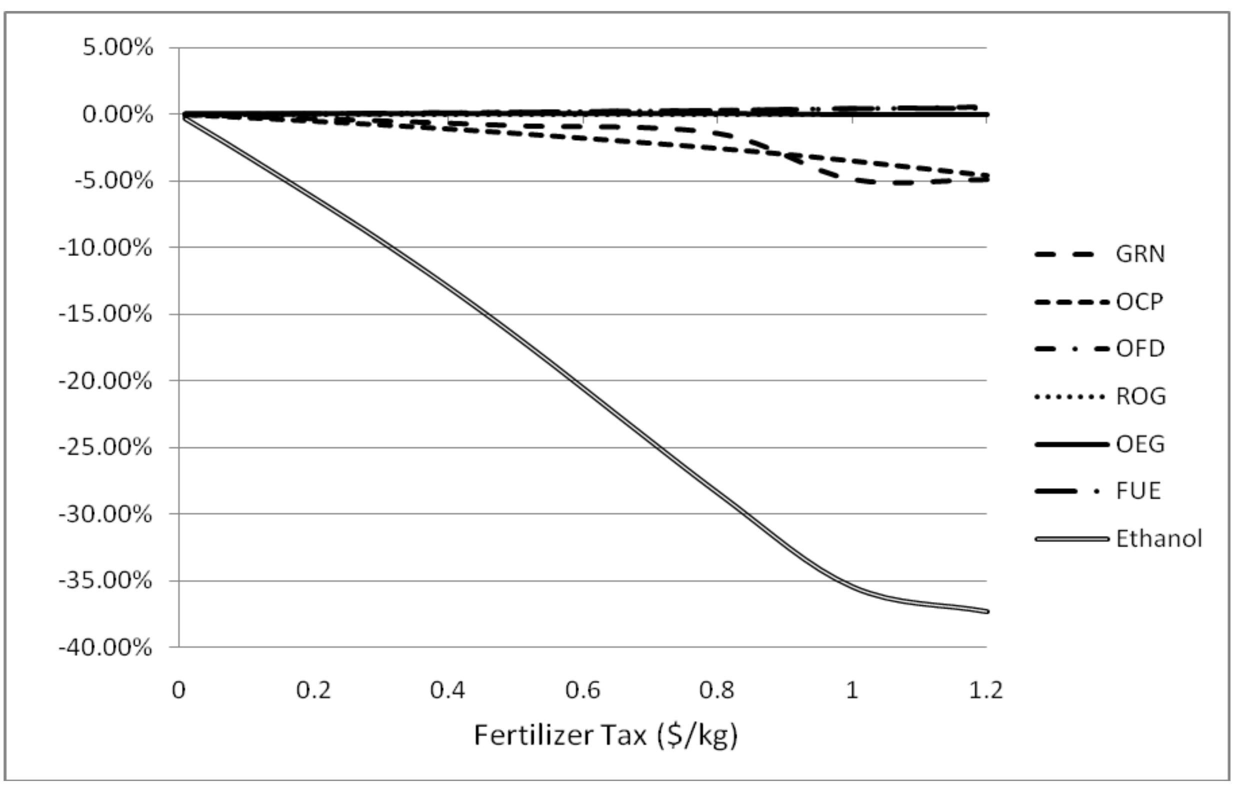


Figure 3.5c % Change of Emissions with Different T_N

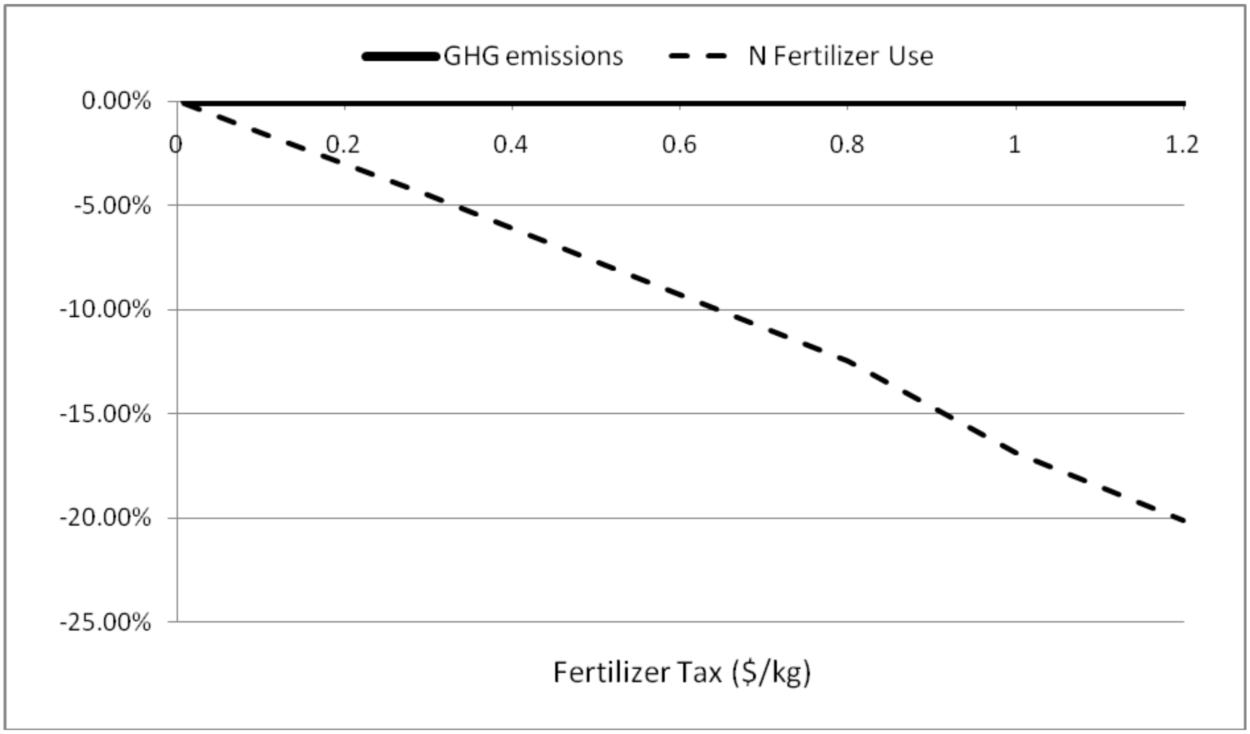


Figure 3.5d Sources of Ethanol in the US Market with Different T_N

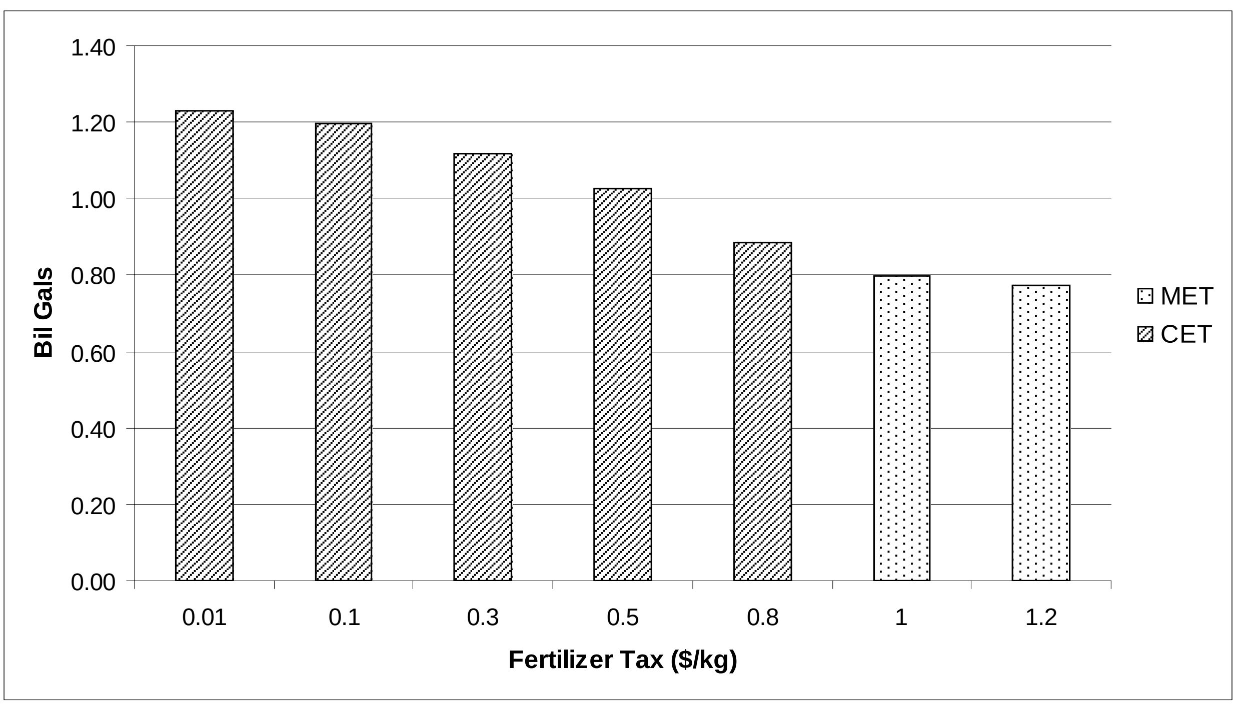


Figure 3.6a % Change of Prices with Different T_G

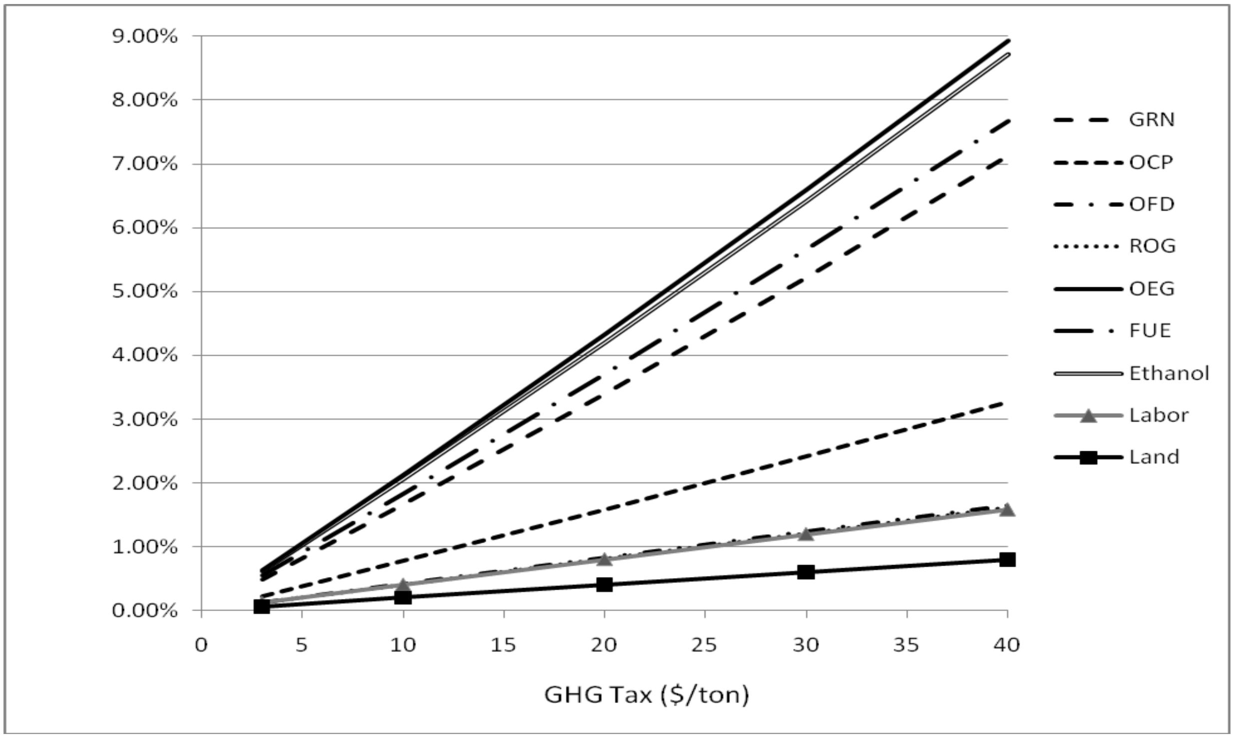


Figure 3.6b % Change of Production with Different T_G

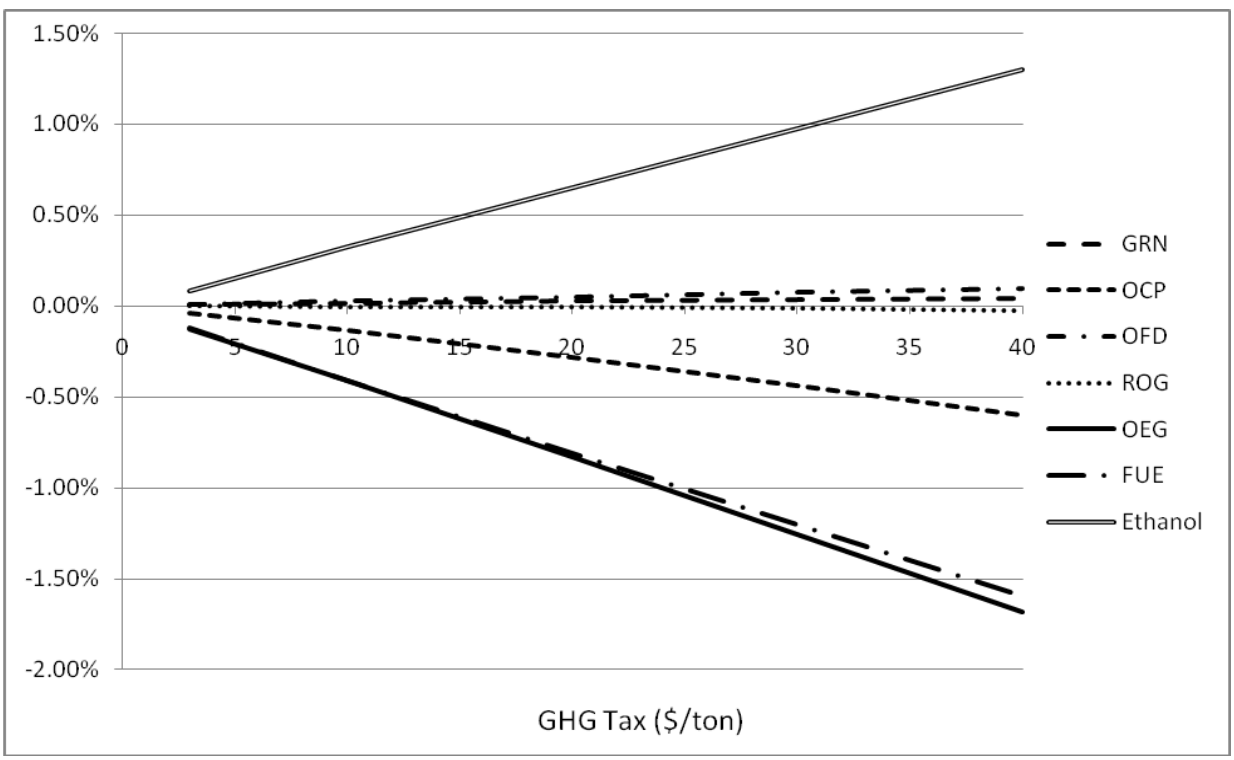


Figure 3.6c % Change in Emissions with Different T_G

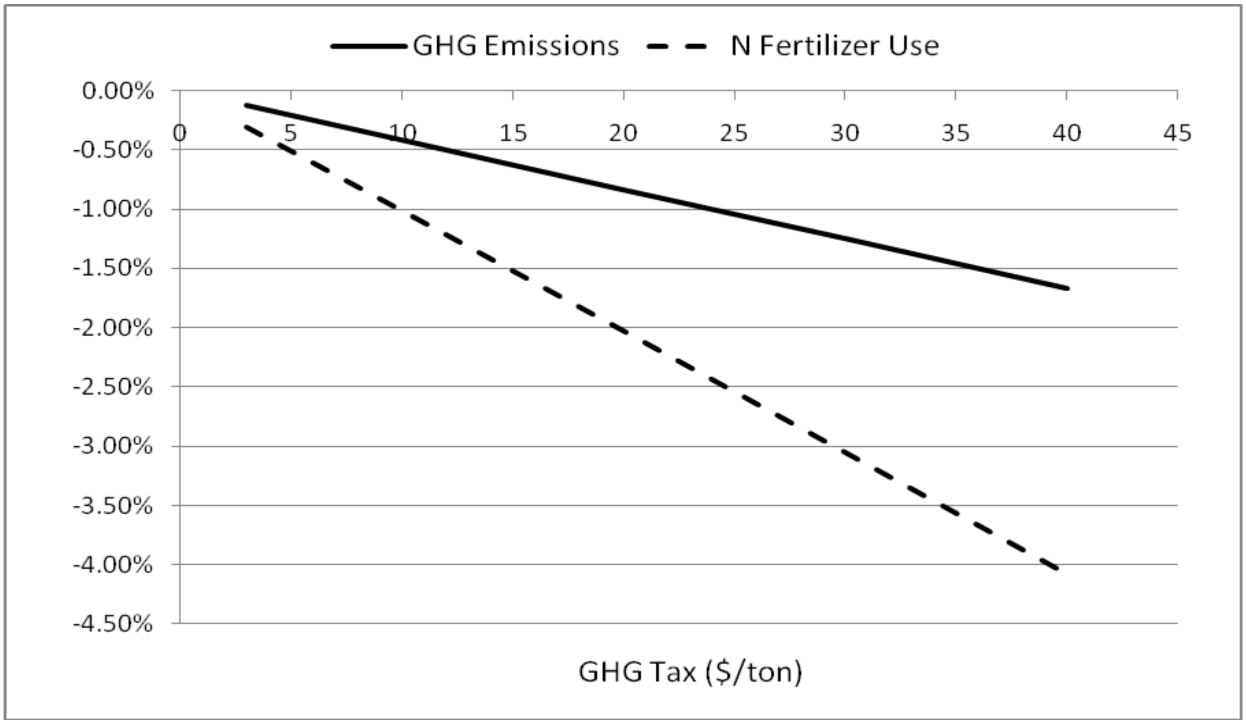


Figure 3.7a % Change of Energy Production with Different Policy Schemes

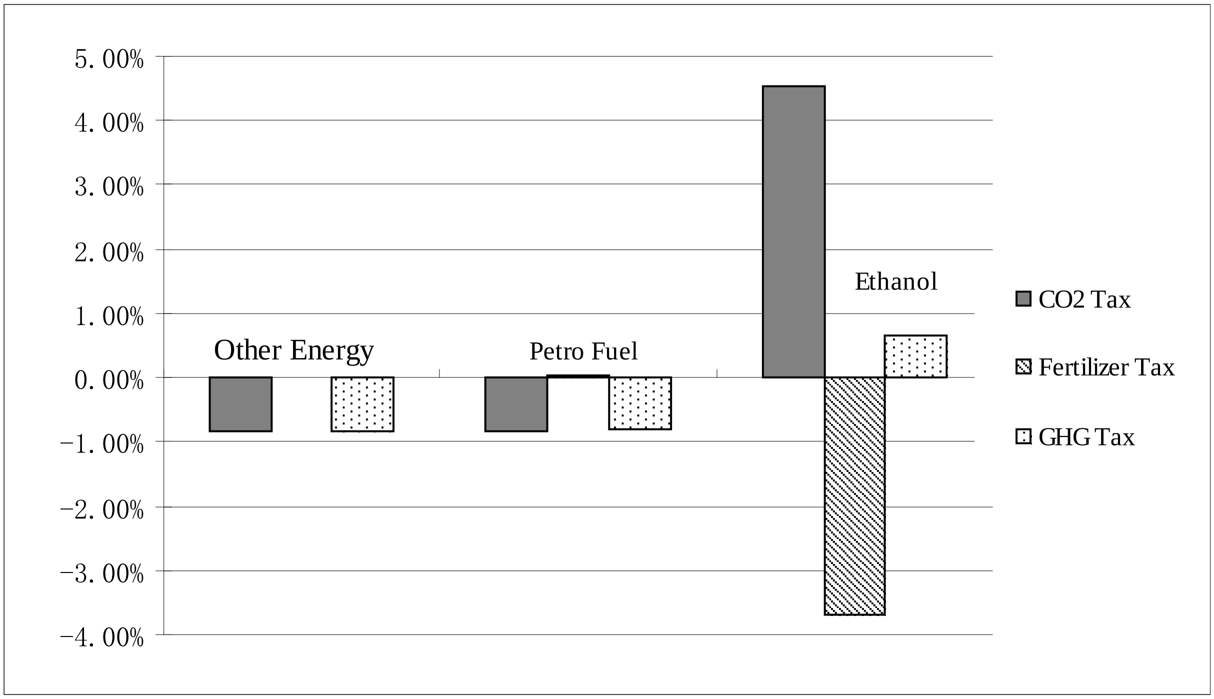


Figure 3.7b % Change of Food Prices with Different Policy Schemes

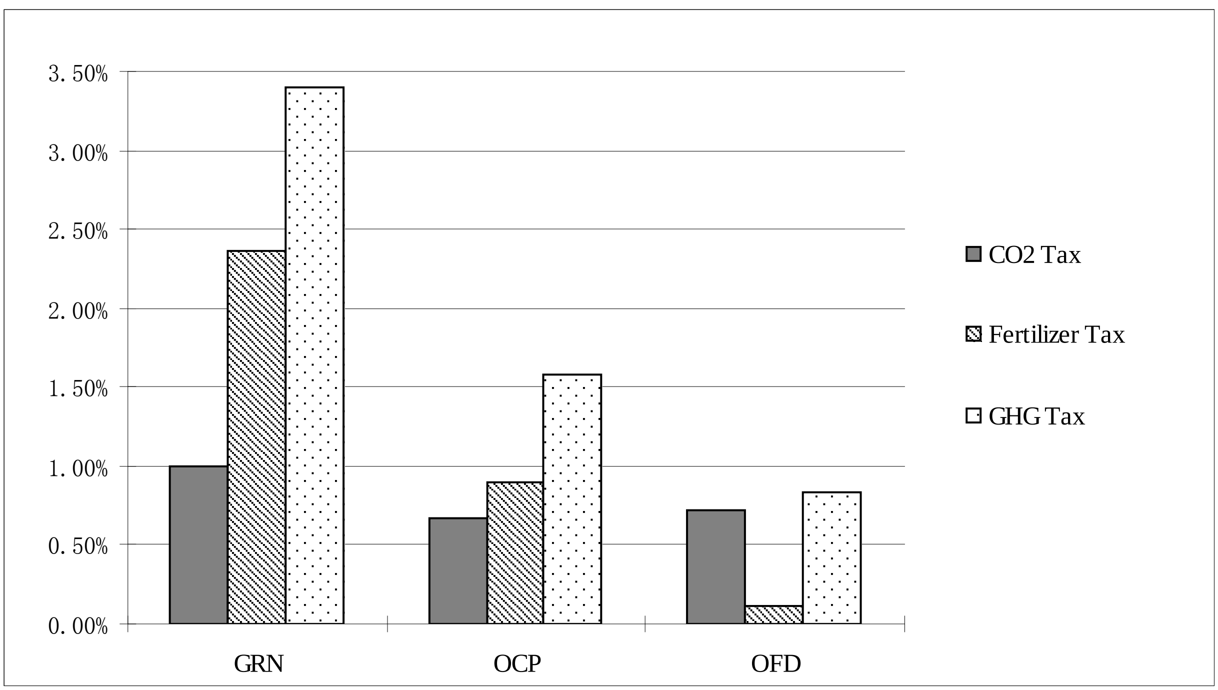


Figure 3.7c % Change of Emissions and Utilities with Different Policy Schemes

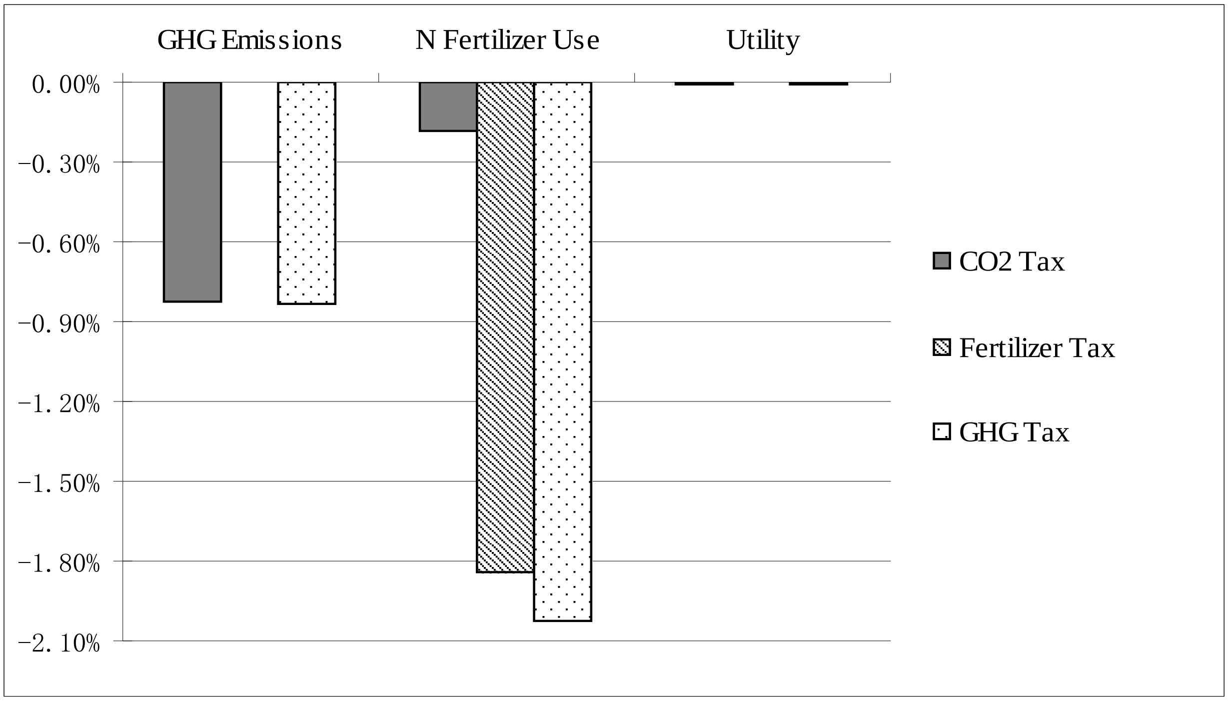


Figure 3.8 Tax Rates Required to Achive Ethanol Production Targets

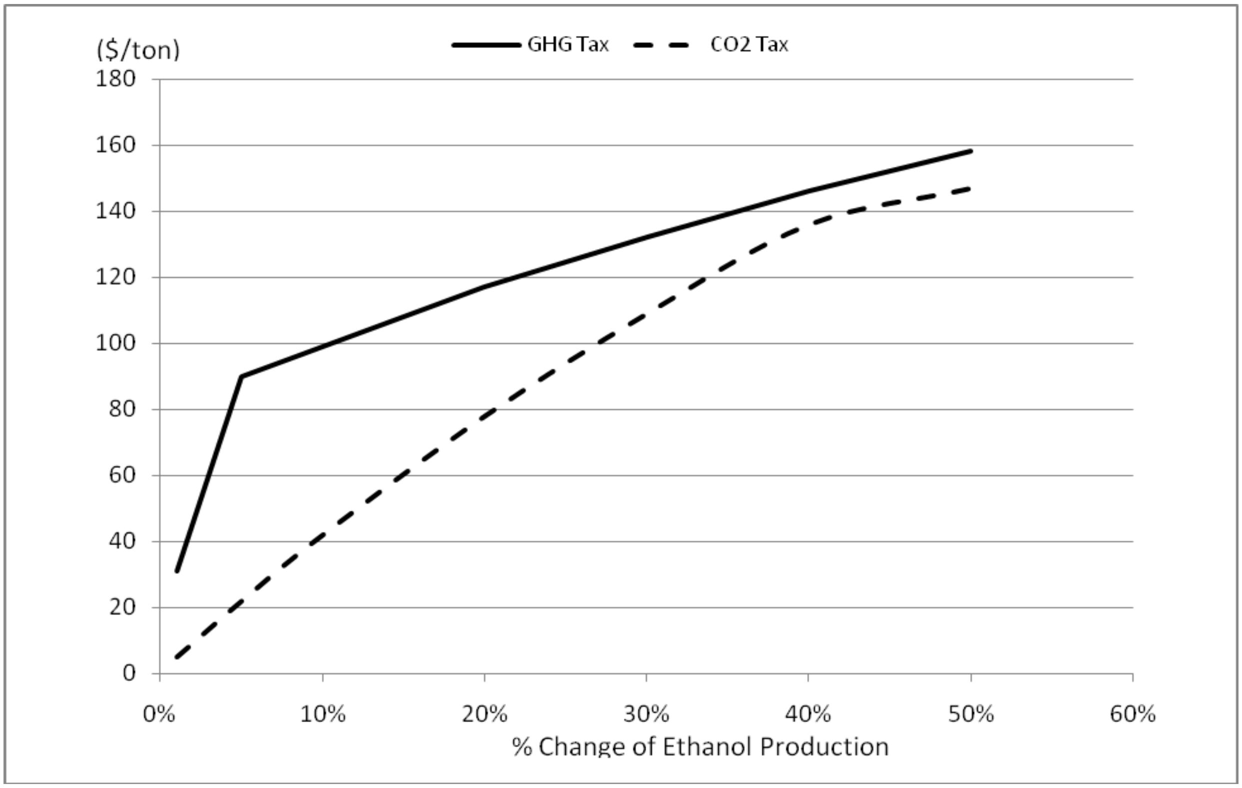


Figure 3.9a Impacts of σ_U on Domestic Production and Environmental Emissions

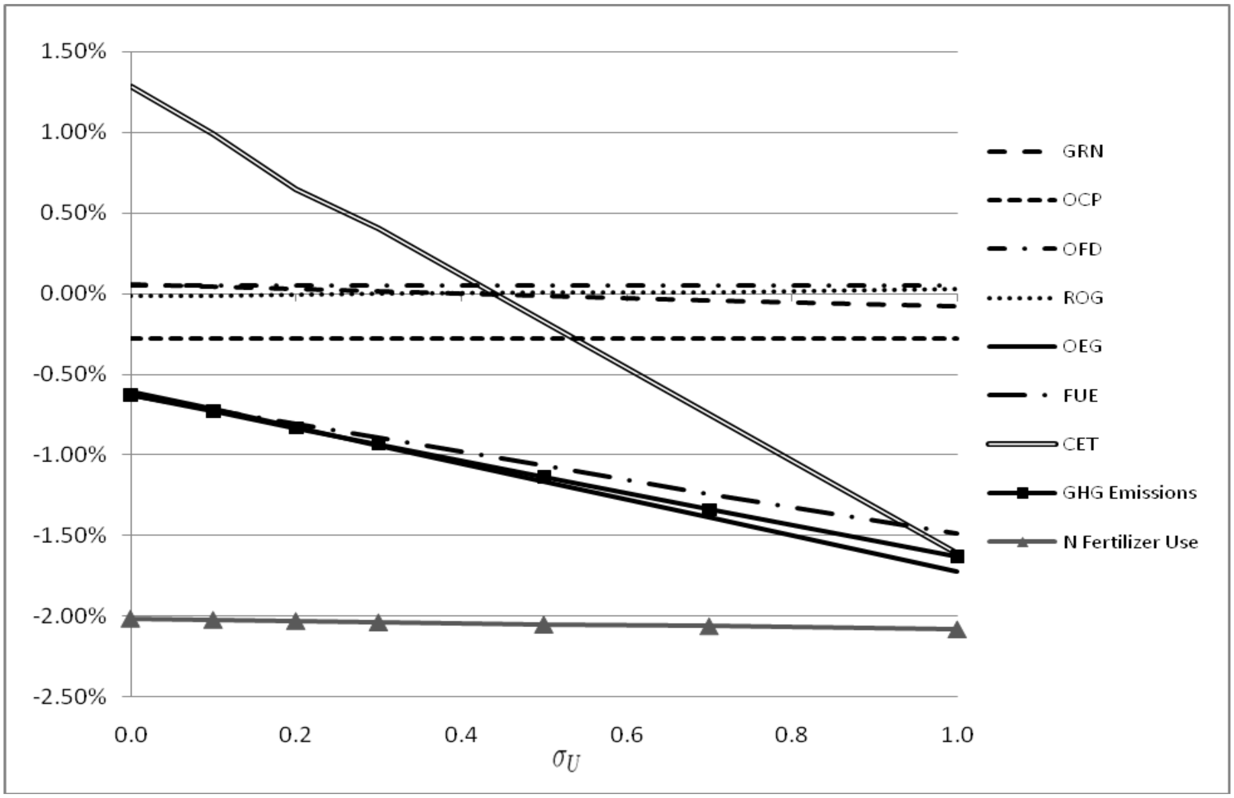


Figure 3.9b Impacts of σ_F on Domestic Production and Environmental Emissions

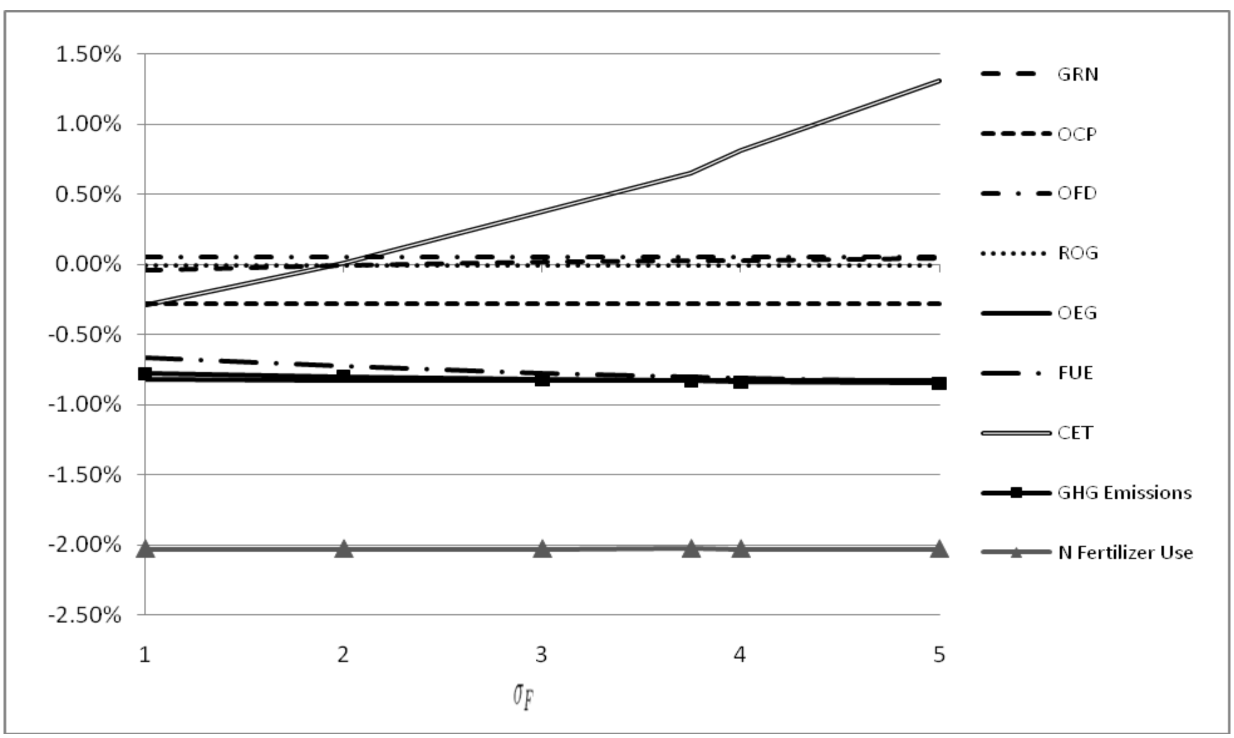
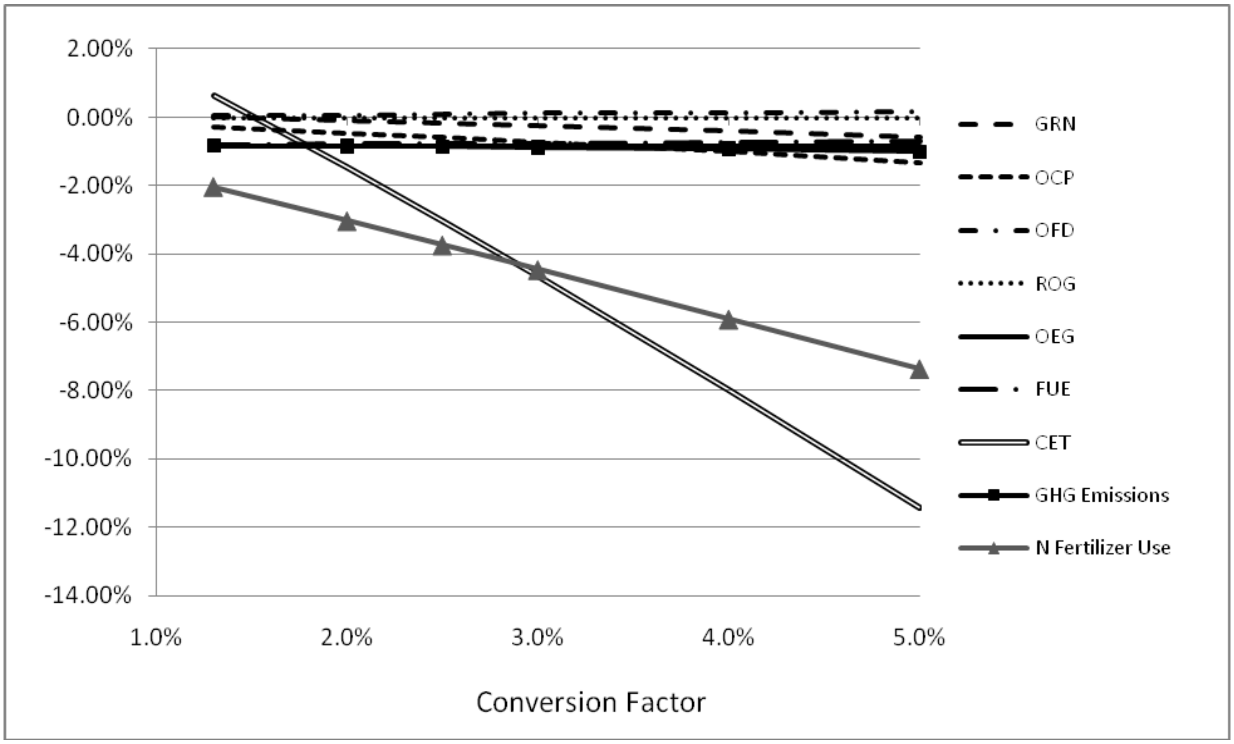


Figure 3.9c Impacts of Conversion Factor on Domestic Production and Environmental Emissions



CHAPTER 4

ENVIRONMENTAL POLICIES AND BIOFUEL PATHWAYS IN THE UNITED STATES: OPEN ECONOMY ANALYSIS

4.1 Introduction

Large scale production of biofuels would have significant effects on global agricultural activities, energy markets, and the environment. Biofuels can be made from a variety of feedstocks using a number of different processes, *i.e.*, different biofuel pathways, and different biofuel pathways may have different effects on both economy and the environment. The common belief is that cellulosic ethanol is better in terms of both greenhouse gas (GHG) emissions and competition with food crops for land (Groode and Heywood 2007; Khanna *et al.* 2009; Schmer *et al.* 2008; Wang *et al.* 1999; and Wang *et al.* 2007). However, current technology for cellulosic ethanol is not cost competitive compared to corn ethanol (Khanna *et al.* 2009; and Perrin *et al.* 2008). With limited resources, especially for land used to grow the feedstocks, promoting an efficient mix of biofuel pathways is an important consideration in improving energy security and fighting climate change.

The previous chapter employed a closed economy CGE model to assess the economic and environmental impacts of the mix of different biofuel pathways under the influence of various public policies. However, despite the fact that internal markets dominate the US economy, its trading activities are large and important. In 2004, the total value of the imports and exports accounted for 15% and 10% of the US total GDP, respectively (http://www.trade.gov/td/industry/otea/usfth/aggregate/H04T05.html). The agricultural and energy sectors are leading areas of US trade. Approximately 20% of US demand for petroleum products and over 90% for crude oil are imported (EIA: http://www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/oil_market_basics/trade_image_us_imports.htm). At the same time, the US exported over $60 billion worth of agricultural commodities, accounting for approximately 8% of total export value (ERS/USDA: Foreign Agricultural Trade of the United States, http://www.ers.usda.gov/Data/Fatus/http://www.trade.gov/td/industry/otea/usfth/aggregate/H04T03.html). With energy and food as our focal sectors, it is important to consider trade effects. In this chapter, we extend the closed economy model developed in the last chapter into an open economy model and re-evaluate the policy effects on the mix of biofuel pathways.

Open economy CGE models have been widely used to evaluate policies. Generally, open CGE models include multiple countries/regions at similar levels of detail (*e.g.*, Narayanan and Walmsley 2008; Pant 2007; and van der Menbrugghe 2005). However, if a single country is of primary interest, or the data for the other countries are not reliable, a single country CGE model enriched with demand and supply functions incorporating international influences may suffice to produce the desired insights (*e.g.*, Fullerton *et al.* 1981; Lofgren *et al.* 2002; and Rausch *et al.* 2009). Many single-country open CGE models are designed for small economies, so world prices are fixed (*e.g.*, Harris 1984; Lofgren *et al.* 2002; and Stifel and Thorbecks 2003). However, as a huge economy entity, changes in the trade patterns of the United States can influence world prices. Thus, it is not appropriate to assume fixed world prices. Thus in this chapter, we develop a large open economy model to re-evaluate the effects of policies on the mix of biofuel pathways and the corresponding environmental impacts.

The chapter is organized as follows. The next section describes the essential elements of the general equilibrium model. The following section discusses the data sources and technology assumptions used in the model. Next, various model scenarios and results are presented, followed by sensitivity analyses.

4.2 Model Structure and Data Sources

Our open economy model specifications and data sources are the same as the closed economy model described in Chapter 3 except that this model allows trade between the US and the rest of the world. The United States has two-way trade, which means that it imports and exports the same commodity in a single period. This can be explained by imperfect substitution between imported, exported and domestically produced goods. If they are perfect substitutes, imports and exports should not happen simultaneously for a single commodity. Following the commonly-used Armington assumption (Armington 1969), the commodities in the market, as intermediate inputs for production or final consumer consumptions, are Armington composite goods from imports and domestic production following a CES functional form, written as

$$A_i = \gamma_i[\alpha_i M_i^{\eta_i} + (1-\alpha_i) D_i^{\eta_i}]^{1/\eta_i} \quad (4.1)$$

where A_i is the output of the ***i***-th Armington composite good, γ_i is the productivity parameter of the ***i***-th composite good production function, M_i is the amount of import of ***i***-th good, D_i is the amount of domestic production of ***i***-th good, α_i is the share parameter of the import of ***i***-th composite good, and $\sigma_i = \frac{1}{1-\eta_i}$ is the Armington elasticity, representing the elasticity of substitution between the domestic production and imports. The Armington elasticity is adapted from GTAP 7.0 for each sector.

Many commodities are exported in a large amount from the United States, so assuming fixed world prices is not appropriate. In our model, a large open economy is assumed and the world prices can change due to the quantities traded. Due to data limitation and to focus on markets in the United States, we represent the rest of the world by trade transformation functions. Here we follow the technique provided by Markusen (2002) to formulate the export functions. Domestic consumption and exports follow a Cobb-Douglas functional form. With different values of the foreign elasticity of export demand obtained from GTAP 7.0, the share parameters in the Cobb-Douglas functions can be calibrated.

4.3 Model Scenarios and Results

4.3.1 Effects of Current Policies

As in Chapter 3, we first analyze the effects of current (2009) energy policies by removing the $0.51/gallon ethanol subsidy in the benchmark and apply the current subsidies ($0.45/gallon subsidy for corn ethanol and $1.01/gallon subsidy for cellulosic ethanol) into the system. With the new subsidy policy, the market supplies 3.25 billion gallons of ethanol, including 0.14 billion gallons of imported ethanol. None of the ethanol is produced from cellulosic feedstocks. Just as with the closed-economy model, this level is much lower than the quantity requirement defined by the Renewal Fuel Standard (RFS) program.

Once again following the pattern established in Chapter 3, in the following sections, we test the effects of three types of hypothetical taxes: CO_2 tax, N fertilizer tax and GHG tax. Following consideration of the individual taxes and their effects on biofuel production and environmental externalities, we compare their effects with each other.

4.3.2 Effects of CO_2 Tax (T_C)

In the benchmark equilibrium, there are no environmental constraints on carbon emissions. However, since increased production of biofuels has been justified, in part, by arguments about their lesser carbon footprints, we introduce a carbon tax as an incentive to control climate change. The tax rates range tested in this chapter is the same as the last chapter: \$3/ton to \$40/ton of CO_2 tax. The benchmark is also the 2004 economy without the \$0.51/gallon of ethanol subsidy. However, the open-economy benchmark differs from the closed-economy counterparts because they are simulated results. The new equilibrium results are shown in Figures 4.1a to 4.1e which present the percentage changes of domestic prices, domestic production, imports, exports and environmental variables, respectively. Figure 4.1f illustrates the sources of ethanol in the market. The full lists of the equilibrium results appear in Appendix J.

As shown in Figure 4.1a, T_C has the greatest impacts on prices of OEG, ethanol and FUE. OEG and FUE are directly affected by T_C. Ethanol is a close substitute for FUE and its energy requirement for production is fairly high, so its price is also affected significantly by T_C. Since FUE and OEG are either a direct or an indirect input for all commodities, the prices of all commodities increase, but at relatively low rates. Producers adjust output based on the new prices. Correspondingly, production of FUE and OEG decrease the most. Even with compensation through increased imports and decreased exports, domestic energy use still declines. To satisfy the energy demands of consumers and producers, production of CET increases because it is less carbon-intensive than FUE. Its import also increases to satisfy the domestic demand. The impact on overall GHG emissions is surprisingly small. A \$40/ton T_C would reduce GHG emissions approximately 2%.

As a close substitute for FUE, production of ethanol increases. As the major input for ethanol production, domestic production of GRN also increases and cause more nitrogen fertilizer use. Although the price of fertilizer increases due to its reliance on energy inputs, its elastic foreign demand and a high elasticity of substitution between its domestic production and imports limit the price increase. Thus, overall, nitrogen use increases with T_C. A \$40/ton T_C would increase N fertilizer application by 0.06%.

4.3.3 Effects of N Fertilizer Tax (T_N)

As we discussed before, nitrogen leaching is also a very important environmental externality. If only CO_2 is taxed, nitrogen leaching would be exacerbated. To control nitrogen leaching, a N fertilizer tax (T_N) is needed. We now test the effects of such a tax.

As with the closed economy model, a wide range of T_N values, from \$0.01/kg to \$1.2/kg (1.8% to 218% of the benchmark fertilizer price), are applied to the model to test how such a tax affects GHG emissions and nitrogen fertilizer use. Figure 4.2a to 4.2e show the percentage changes of quantities and prices under new equilibria compared to the benchmark equilibrium. Figure 4.2f illustrates the sources of ethanol in the market. The underlying data appear in Appendix K. As shown in Figure 4.2, T_N has noticeable effects only on GRN, OCP and CET. Its effects on the other sectors are negligible.

Just as with T_C, T_N increases prices for all commodities. As the most fertilizer-intensive product, the price of GRN increases the most. However, the price of land falls. With a positive T_N, due to their intensive nitrogen requirement, producers of GRN and OCP reduce their production, which drives the land price down. The substitution effect between fertilizer and land, that would increase the price of land, is not sufficient to overcome the land price drop from the reduction in production of GRN and OCP. Food demand is fulfilled by increased imports, decreased exports of GRN and OCP, and an increased supply of OFD.

With fertilizer-intensive GRN as the most important input for corn ethanol, as T_N increases, production of ethanol declines. The proportionate reduction of GRN production is much less than that of ethanol because only a small fraction of GRN is used to produce ethanol and the rest is served as food, for which demand is relatively inelastic.

A T_N greater than \$1/kg makes corn ethanol more costly to produce than *miscanthus* ethanol. Under the assumptions that the cost and time for technology transition are negligible, producers of ethanol would switch to *miscanthus* as a feedstock. The shift from corn ethanol to *miscanthus* ethanol would cause a major reduction in GRN demand and correspondingly, the supply of GRN.

This explains the kink points on the GRN curve in the graphs of domestic production (Figure 4.2b) and imports (Figure 4.2c).

One interesting finding is that T_N reduces not only the domestic production of ethanol, but also its imports. Commonly, we would expect that with reduced domestic production, imports of ethanol would increase to fulfill the domestic demand. With T_N, however, the price of ethanol increases much more than the price of FUE. In the absence of quantity mandates for ethanol, consumers would choose more FUE and less ethanol. Thus domestic consumption of FUE would increase and domestic demand for ethanol would decline. The reduction in demand would affect not only domestic production but also imports, although the reduction of imports is at a lower rate than the decline in domestic production.

T_N reduces nitrogen leaching but has very little effect on GHG emissions. Although T_N increases the consumption of FUE, the most carbon-intensive fuel, since the percentage change in the output level of FUE is very small, and N_2O declines from less fertilizer usage, the net percentage change of GHG emissions is very small. A 145% T_N reduces nitrogen leaching by slightly more than 10%.

4.3.4 Effects of GHG Tax (T_G)

N fertilizer not only contributes to N leaching, but also emits N_2O gas which is an important GHG. The global warming potential of N_2O in a time horizon of 100 years is 298 times of CO_2 (Forster *et al.* 2007). To control the climate change, it would be more appropriate to apply a tax not only to CO_2 emissions, but also to N_2O. In this section, GHG taxes are applied to the system to test their effects. The range of the taxes tested is the same as the CO_2 tax we tested in Section 4.3.2, \$3/ton to \$40/ton of CO_2-equivalent. The new equilibrium results are shown in Figures 4.3a to 4.3f. and the full equilibrium results are documented in Appendix L

As shown in Figure 4.3, the effects of T_G are very similar to the effects of T_C. The major differences lie in the prices and production of GRN and ethanol, since they are affected by a fertilizer tax the most. As a source of N_2O emissions, fertilizer is also subject to T_G. OCP production decreases because fertilizer is an important input. GRN is the most fertilizer-intensive product in the economy. Thus, its domestic production falls more than OCP. However, GRN is a major input for CET production. The increased demand of GRN from the boost in CET production increases the imports of GRN and reduces its exports. Unlike the scenario with T_C, with T_G, fertilizer application is reduced due to the domestic reductions of GRN and OCP. A \$40/ton T_G would reduce GHG emissions approximately 2% and fertilizer use by approximately 3.5%. As with T_C, a \$40/ton T_G is not enough to induce a switch to cellulosic ethanol.

4.3.5 Comparison of Policy Instruments

In this section, we apply the three policy instruments to the system to compare their performance. The three instruments levy taxes on different commodities. With T_C, FUE and OEG are directly subject to the tax; with T_N, only fertilizer is subject to the tax; and with T_G, FUE, OEG and fertilizer are all subject to the tax. Assume the tax burden for GHGs is \$20/ton of CO_2-equivalent and the corresponding tax rates are T_C = \$20/ton, T_N = \$0.12/kg, and T_G = \$20/ton. The resulting equilibrium is presented in Figures 4.4a to 4.4d. Complete results are documented in Appendix M.

CO_2 tax and GHG tax have very similar effects on the production of FUE and OEG, on which the fertilizer tax has almost no effect. As indicated by Figure 4.4a and 4.4d, the CO_2 tax yields the highest increase in ethanol production and imports, while the fertilizer tax would actually decrease ethanol production. One interesting finding is that T_C and T_G result in similar reduction in GHG emissions. The reason is that the GHG tax burden on fertilizer increases energy consumption as the same time as it reduces N_2O emissions. The two effects on GHG emissions are opposite and the net effect is negligible. Thus the tax burden on energy plays the most important role to reduce GHG emissions with a GHG tax. The fertilizer tax induces the most fertilizer use reduction, although the difference compared to the reduction with GHG tax is insignificant. The GHG tax induces the highest food price increase and the greatest reduction in aggregate consumptions. Thus, the GHG tax performs the best in terms of GHG emissions but the worst in terms of aggregate consumption. The fertilizer tax is the most effective in reducing nitrogen fertilizer application and yields the highest aggregation consumption, but the climate change benefit is minimal.

Another way to compare the three policy instruments is to set a policy target and test the tax rates required to achieve the target. As in Chapter 3, ethanol use is assumed as our policy target and the tax rates (CO_2 tax or GHG tax) needed to achieve this target are calculated. The policy targets range from a 1% to a 50% increase in ethanol use. The results are shown in Figure 4.5. The kink points in both curves show the points when the ethanol producer shifts from CET to MET. The results indicate that, to achieve a significant increase in ethanol production, very high tax rates are required. Other policy instruments might be more effective to achieve quantity targets. Between the two taxes, the CO_2 tax achieves the ethanol production targets at lower rates. However, at high tax levels, more specifically, after the switch to cellulosic ethanol, the GHG tax is more effective although the differences are small. A much lower GHG tax is required to trigger the cellulosic ethanol production because of the tax burden on fertilizer application.

4.4 Sensitivity Analysis

The data used in our model is subject to considerable uncertainty. One of the major sources of uncertainty is the technology data for cellulosic ethanol production. Other key parameters include the elasticity of substitution and emission values. In this section, different values are tested to see how sensitive the results are to these parameters. In this analysis, the policy instrument applied is held constant: T_G=\$20/ton.

4.4.1 Cellulosic Grass Production Data

In the analyses above, the technology data for cellulosic ethanol production were adapted from the "optimistic" scenario in Khanna *et al.* (2009). That scenario represents a rather ideal situation for cellulosic grass production: low fertilizer application rate, low replanting probability, high yield, and low harvest loss. However, the results of field trials vary widely. In their study, they also presented a "pessimistic" scenario. To test how the technology data affect the model results, we adopt the data for their "pessimistic" production scenario. The responses of the system to the policy shocks are replicated in Tables 4.1a to 4.1f, juxtaposed to the results of the "optimistic" case for comparison.

With the two scenarios, the policy shock yields exactly the same results. With a $20/ton GHG tax, all the ethanol in the market is produced from corn and no cellulosic ethanol is produced.

Thus the two different scenarios wouldn't yield any differences. Different production data of cellulosic ethanol would only yield different results when cellulosc ethanol is produced with the same policy shock, and the differences between the two scenarios would depend on the level of impacts of cellulosic ethanol production on the whole economy.

However, the pessimistic scenario does increase the policy thresholds for cellulosic ethanol production. Under the optimistic case, a \$142/ton CO_2 tax, a \$90/ton CO_2-equivalent GHG tax, or a \$1.18/kg of N fertilizer tax (215% of benchmark fertilizer price) would be required for *miscanthus* ethanol to be cost competitive. However, for the pessimistic case, the required tax rates would be T_C=\$260/ton, T_G=\$194/ton, or T_N=\$3.25/kg N fertilizer (589% of the benchmark fertilizer price). Thus, the conclusions about tax rates to stimulate the production of cellulosic ethanol are highly sensitive to the technology surrounding cellulosic ethanol production.

4.4.2 Elasticities of Substitution

Several elasticities of substitution play important roles. One is the elasticity of substitution at the top utility level, σ_U. In the previous analysis, σ_U is assumed to be 0.2. Some recent studies suggest that it could be lower as discussed in the Data section. However, technology development (*e.g.*, electric cars) could make substitution easier. If the results are sensitive to σ_U, a more accurate estimate of this parameter would be required to improve the model's performance. To test its sensitivity, we start from the extreme case where there is no substitution in the upper level of the utility tree and then test several values between 0 and 1. The percentage changes of production levels and emissions are presented in Figure 4.6a and the complete results are documents in Appendix N.

The value of σ_U affects the demand of all types of energy the most. With a low value of σ_U, the substitutability of energy with other commodities is low. As σ_U increases, consumers can shift to other goods more easily and this reduces energy demand. The reduction in energy consumption correspondingly reduces GHG emissions. As shown in Figure4.6a, the curves of energy production and emissions are all downward sloping. Thus overestimation of σ_U (true σ_U is lower than the value used in the model) would yield overestimates of the reductions in FUE and OEG production and GHG emissions.

Another key elasticity concerns the substitution between petro-fuel and ethanol, σ_F. Few studies have estimated this elasticity. The common belief is that they are close but not perfect substitutes. The 3.75 value used in this study is adopted from a GTAP study (Birur *et al.* 2008). The range tested for this parameter is from 1 to 5. The results are shown in Table 4.6b and details can be found in Appendix O. With a GHG tax, σ_F mainly affects ethanol use. The level of FUE also is affected. However, due to its large benchmark value, the percentage change in FUE is fairly small with the $20/ton GHG tax. As σ_F increases, production of FUE decreases and production of CET increases. When σ_F is low enough, a GHG tax would also reduce ethanol production because of the low substitutability between FUE and ethanol. As σ_F increases, the substitution becomes easier. Thus, under the same policy shock, a higher σ_F would result in higher ethanol production and lower FUE production. An overestimated σ_F would overstate the reduction of FUE production and increase in ethanol production. Regarding environmental issues, σ_F has minimal impact on GHG emissions and nitrogen leaching.

4.4.3 Emission Data

As discussed before, there is variation in emission estimates. Even when the reported values are consistent, the assumptions behind these studies can be quite different. One such assumption is the conversion factor from N fertilizer to N_2O. The most commonly-used value for the conversion factor is 1% based on the IPCC study (2006). However, Crutzen *et al.* (2007) believe that the value should be between 3% and 5%. In the analyses above, we used a factor of 1.3% based on GREET 1.8 (Wang *et al.*, 2007). In this section, we test different conversion factors to see how the model responds. The percentage changes of production levels and emissions are presented in Figure 4.6c and the complete results are documents in Appendix P.

As the conversion factor increases, the effect is equivalent to increasing the tax burden on fertilizer since the fertilizer is subject to a higher GHG tax per unit of fertilizer applied. As discussed in Section 4.3.3, a fertilizer tax mainly affects the production of GRN, OCP and ethanol, and the level of nitrogen leaching. The conversion factor would also mainly affect these variables. If the conversion factor is high, a GHG tax would reduce ethanol production because

GRN, the main input for ethanol, is highly fertilizer-intensive. If the conversion factor is overestimated, the predicted nitrogen leaching would be notably higher than it actually would be.

4.5 Conclusion

We developed an open economy CGE model to quantify the effects of biofuel policies on the energy and food sectors, GHG emissions, and nitrogen fertilizer use.

A CO_2 tax applied would reduce FUE and OEG consumption and increase ethanol demand. Total GHG emissions are reduced as expected. Nitrogen leaching is increased because production of GRN, the most fertilizer-intensive product, rises with a CO_2 tax. A $40/ton CO_2 tax would reduce GHG emissions by 2% and increase nitrogen leaching by 0.06%. On the other hand, a fertilizer tax would have negative effects on ethanol production and decrease N leaching. Its effects on production of FUE and OEG, and GHG emissions are fairly small. A GHG tax is practically a combination of CO_2 tax and fertilizer tax. Similar to a CO_2 tax, a GHG tax would, reduce FUE and OEG consumption and increase ethanol demand. Both GHG emissions and nitrogen leaching would also be reduced with a GHG tax. A $40/ton GHG tax would reduce GHG emissions by 2% and nitrogen fertilizer use by 4%. Comparison of the three tax instruments reveals that GHG tax and CO_2 tax have very similar effects on FUE and OEG consumption, and reduction of GHG emissions. A fertilizer tax is the most effective policy to reduce nitrogen leaching. In terms of stimulating ethanol production, a CO_2 tax is the most effective. Our results also indicate that very high tax rates are required to stimulate cellulosic ethanol production. When cellulosic ethanol is produced, *miscanthus* ethanol dominates switchgrass due to the lower production cost of *miscanthus* ethanol. With current technology and modest levels of taxation, the ethanol production will still be dominated by corn ethanol.

Depending on the focus of the analysis, improvements in some parameter estimates could play an important role in decision making. If the policy maker is primarily focused on stimulating cellulosic ethanol production, accurate cellulosic ethanol production data are most important. If energy security, *i.e.*, production and consumption of energy, is the main interest, the elasticity of substitution in consumption, σ_U, is very important. The quantity of ethanol is fairly sensitive to all the parameters we tested, σ_U, σ_F and conversion factors. In terms of environmental emissions, GHG emissions are very sensitive to σ_U and nitrogen fertilizer use is affected substantially by the conversion factor from N fertilizer to N_2O.

Table

Table 4.1a % Change in Domestic Production with Different Production Data *(Unit: %)

	Optimistic	Pessimistic
GRN	-0.95	-0.95
OCP	-0.76	-0.76
OFD	0.09	0.09
ROG	0.02	0.02
OEG	-2.34	-2.34
FUE	-2.32	-2.32

Table 4.1b % Change in Domestic Price with Production Data (Unit: %)

	Optimistic	Pessimistic
GRN	5.22	5.22
OCP	3.45	3.45
OFD	2.99	2.99
ROG	3.02	3.02
OEG	6.43	6.43
FUE	6.05	6.05
FER	6.81	6.81
CET	6.62	6.62
Labor	3.02	3.02
Land	1.43	1.43

Table 4.1c % Change in Imports with Production Data (Unit: %)

	Optimistic	Pessimistic
GRN	2.88	2.88
OCP	0.82	0.82
OFD	-0.13	-0.13
ROG	-0.12	-0.12
OEG	13.88	13.88
FUE	5.14	5.14
FER	9.12	9.12

Table 4.1d % Change in Exports with Production Data (Unit: %)

	Optimistic	Pessimistic
GRN	2.88	2.88
OCP	0.82	0.82
OFD	-0.13	-0.13
ROG	-0.12	-0.12
OEG	13.88	13.88
FUE	5.14	5.14
FER	9.12	9.12

Table 4.1e % Change of Environmental Variables with Production Data (Unit: %)

	Optimistic	Pessimistic
CO2 equivalent GHG	-1.06	-1.06
N Fertilizer Use	-1.81	-1.81

Table 4.1f Ethanol Sources with Different Production Data (Unit: Billion Gallons)

	Optimistic	Pessimistic
Domestic CET	1.37	1.37
Domestic MET	0.00	0.00
Imported Ethanol	0.11	0.11

* For details of the ethanol production scenarios, please see Khanna *et al* (2009).

Figures

Figure 4.1a % Change of Domestic Price with Different T_C

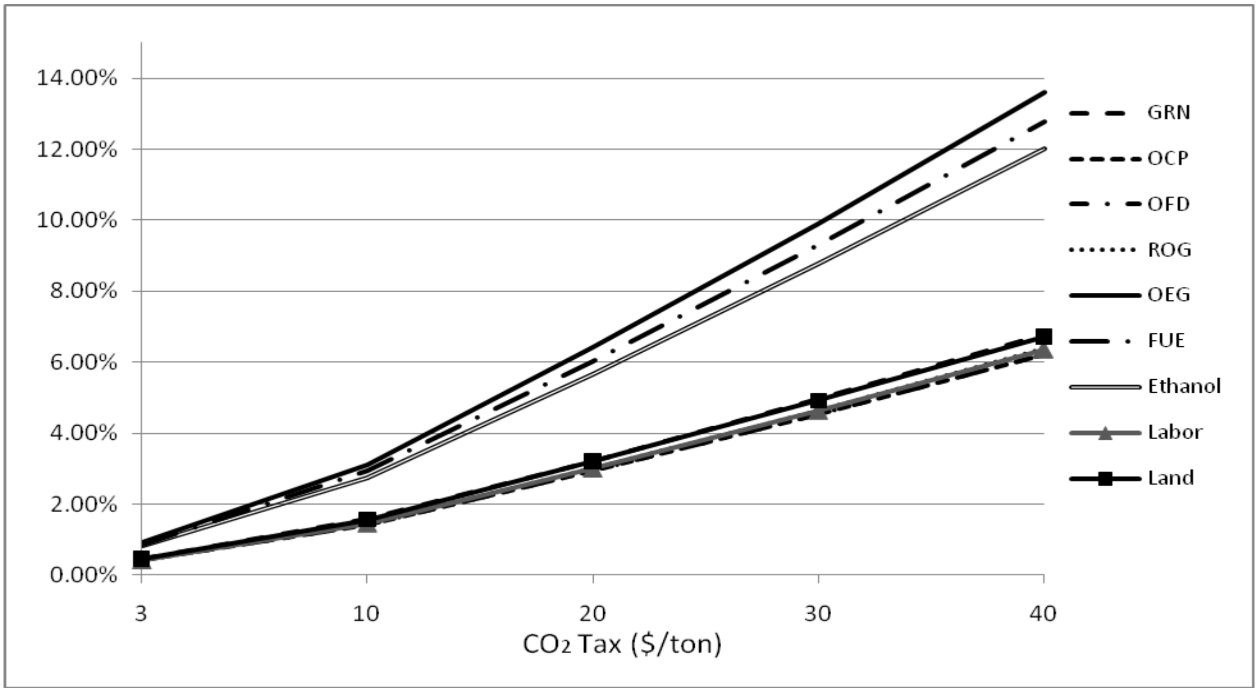


Figure 4.1b % Change of Domestic Production with Different T_C

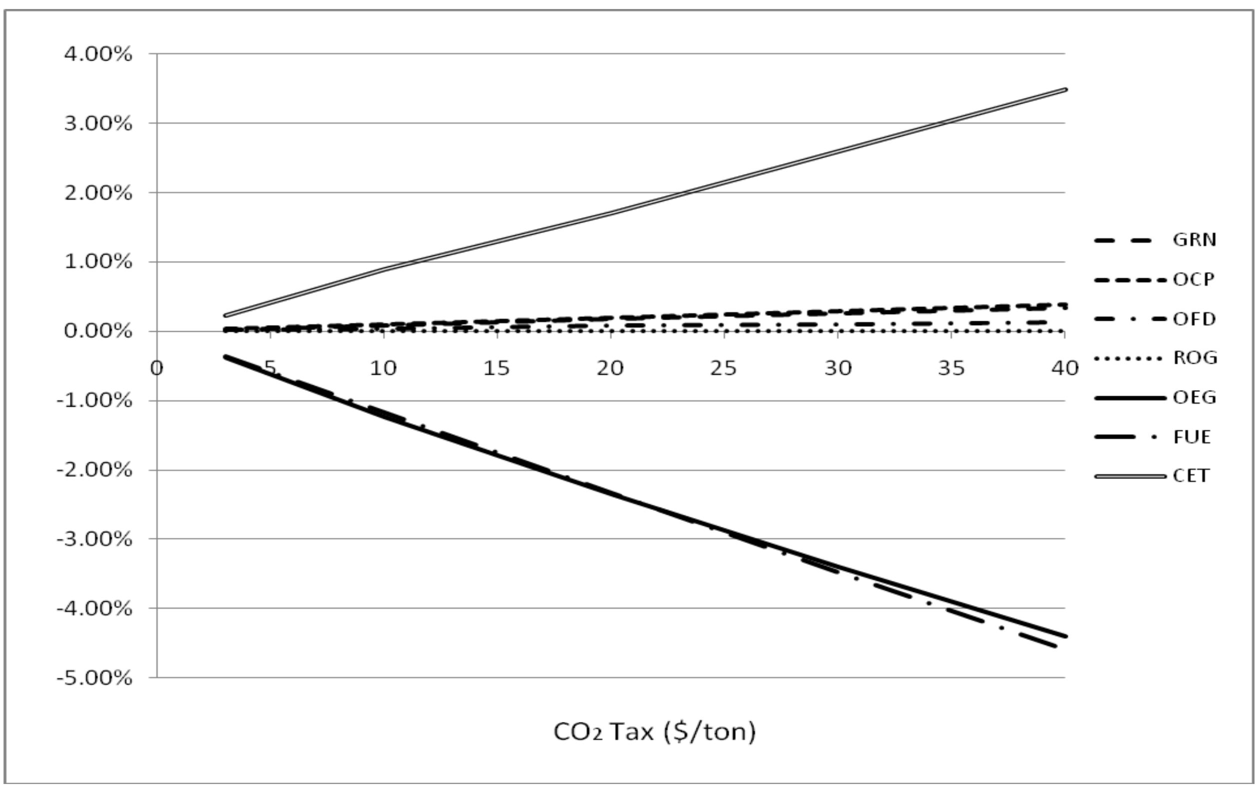


Figure 4.1c % Change of Imports with Different T_C

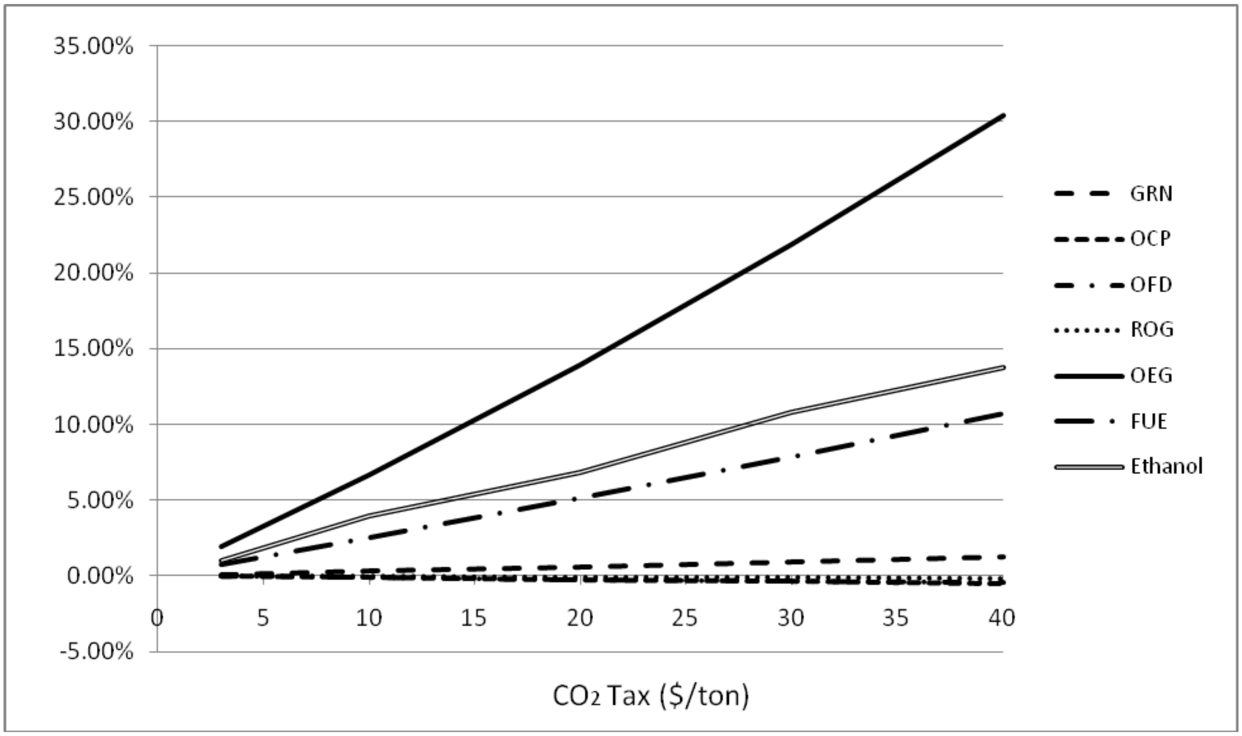


Figure 4.1d % Change of Exports with Different T_C

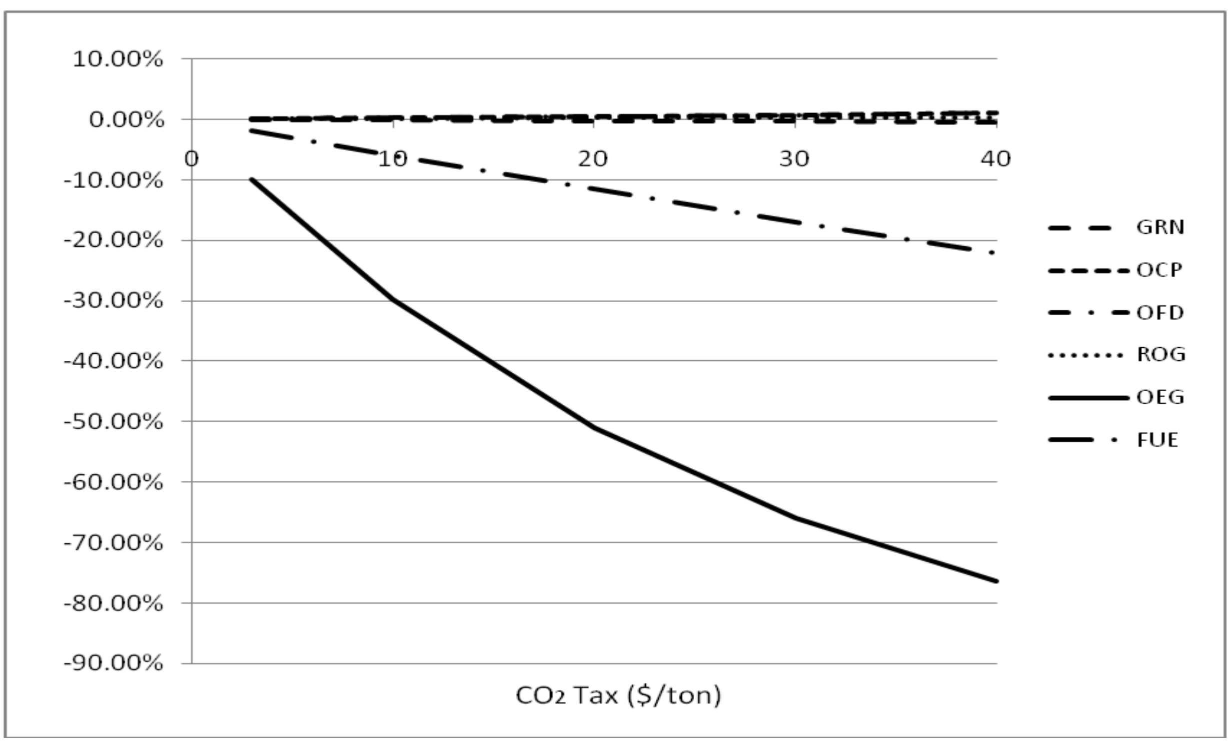


Figure 4.1e % Change in Environmental Variables with Different T_C

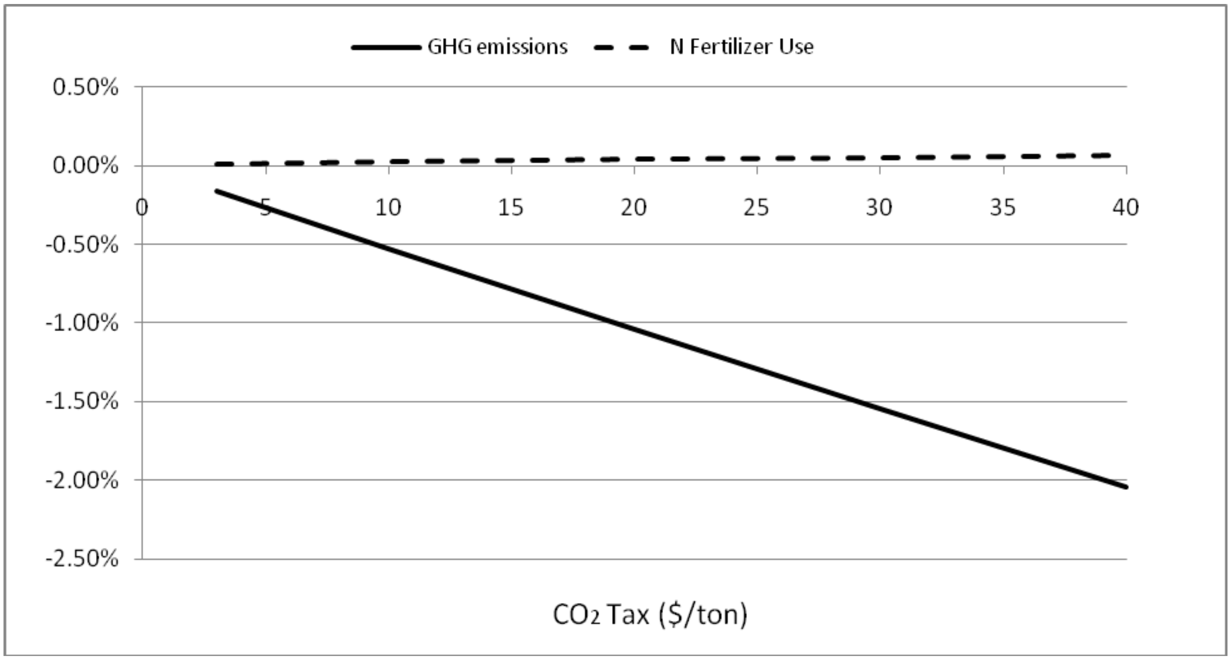


Figure 4.1f Sources of Ethanol in the US Market with Different T_C

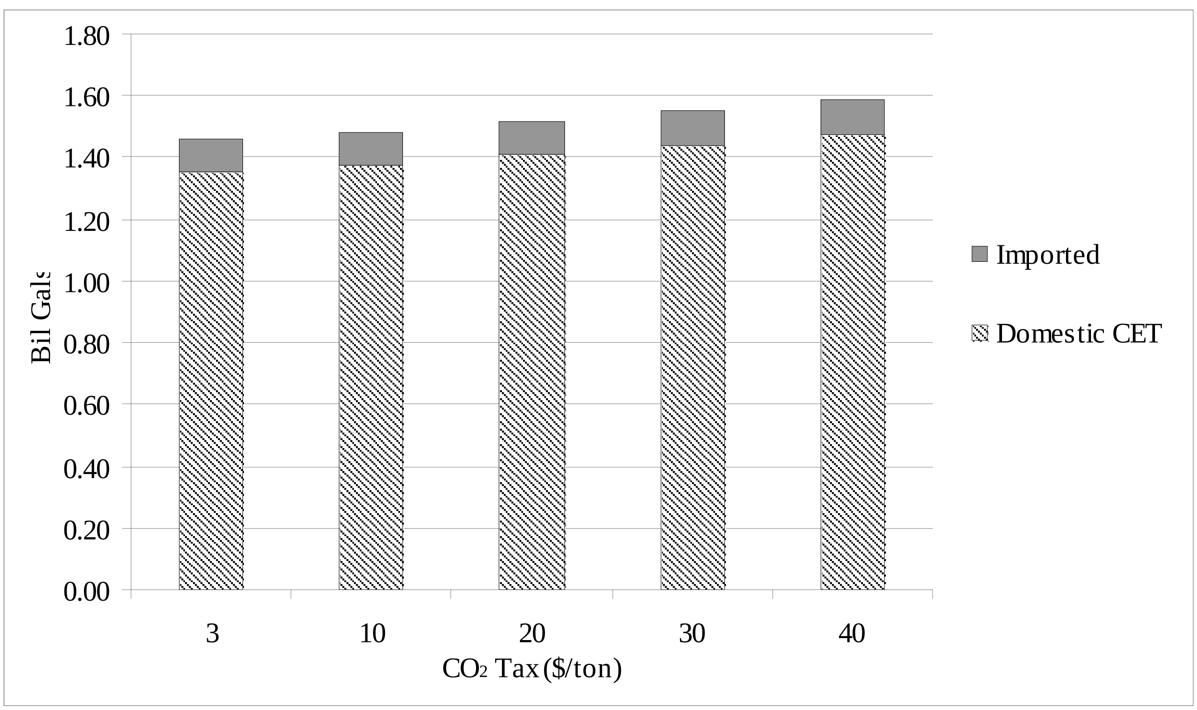


Figure 4.2a % Change of Domestic Price with Different T_N

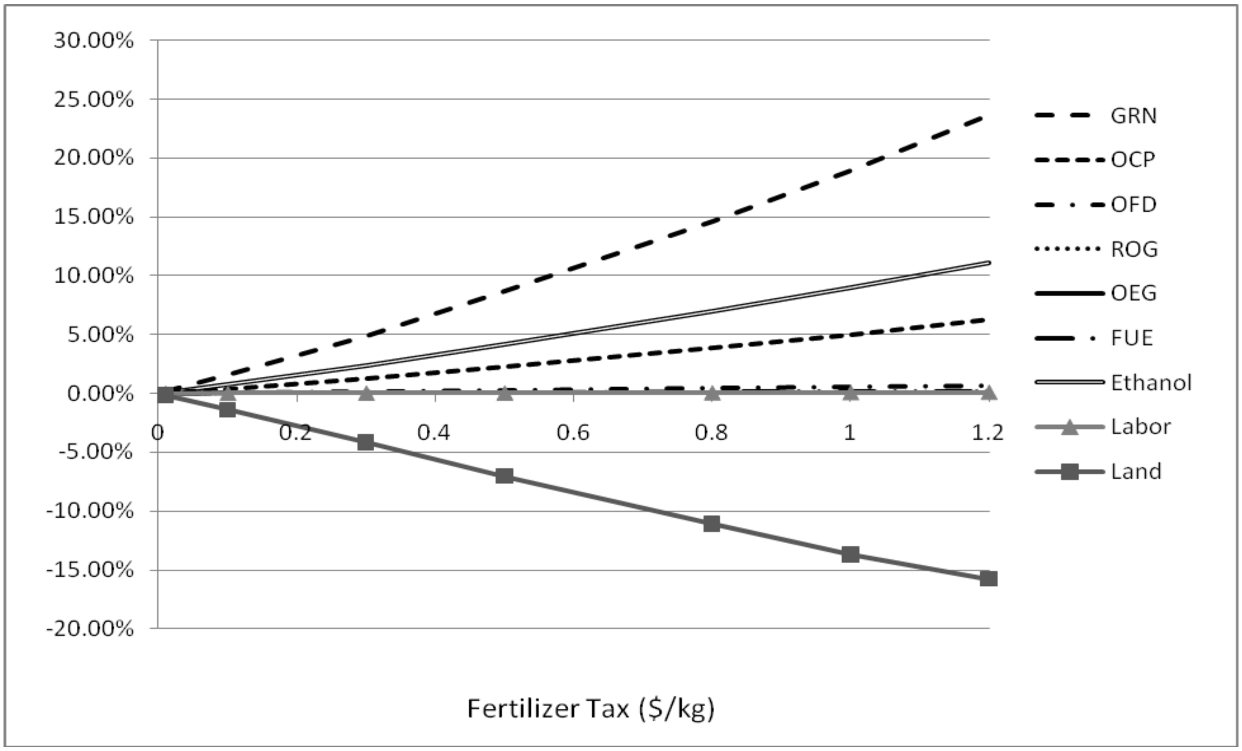


Figure 4.2b % Change of Domestic Production with Different T_N

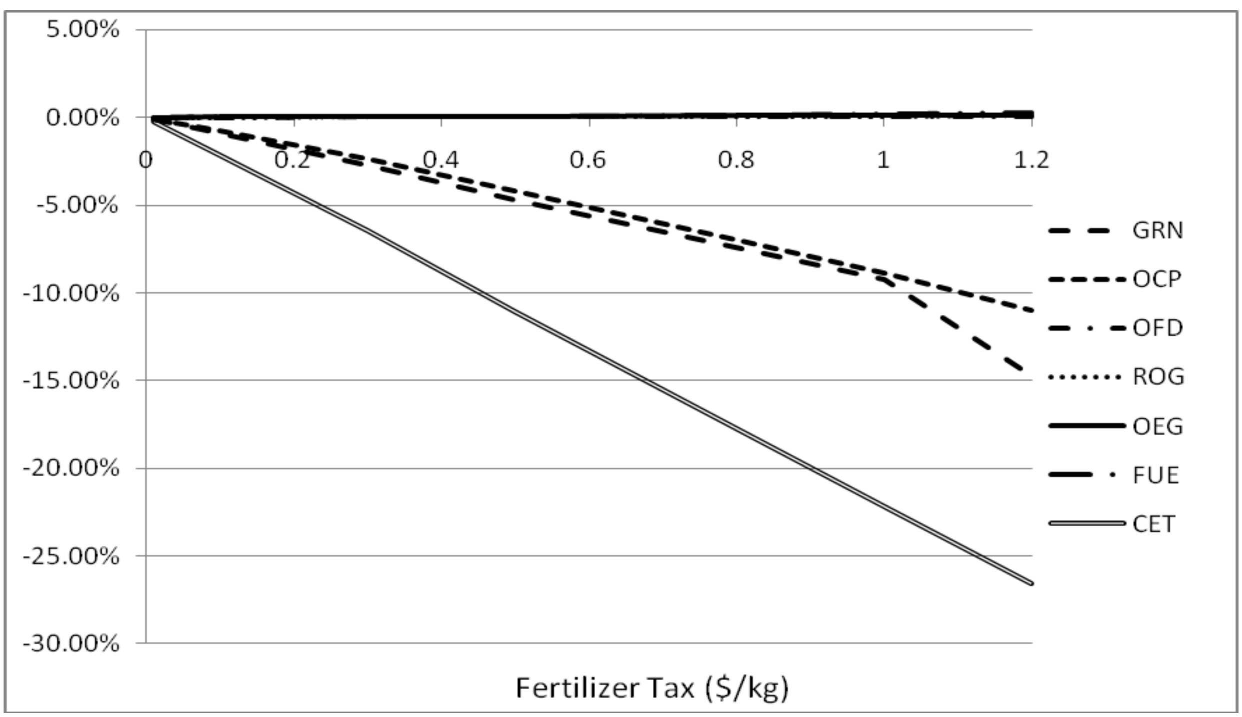


Figure 4.2c % Change of Imports with Different T_N

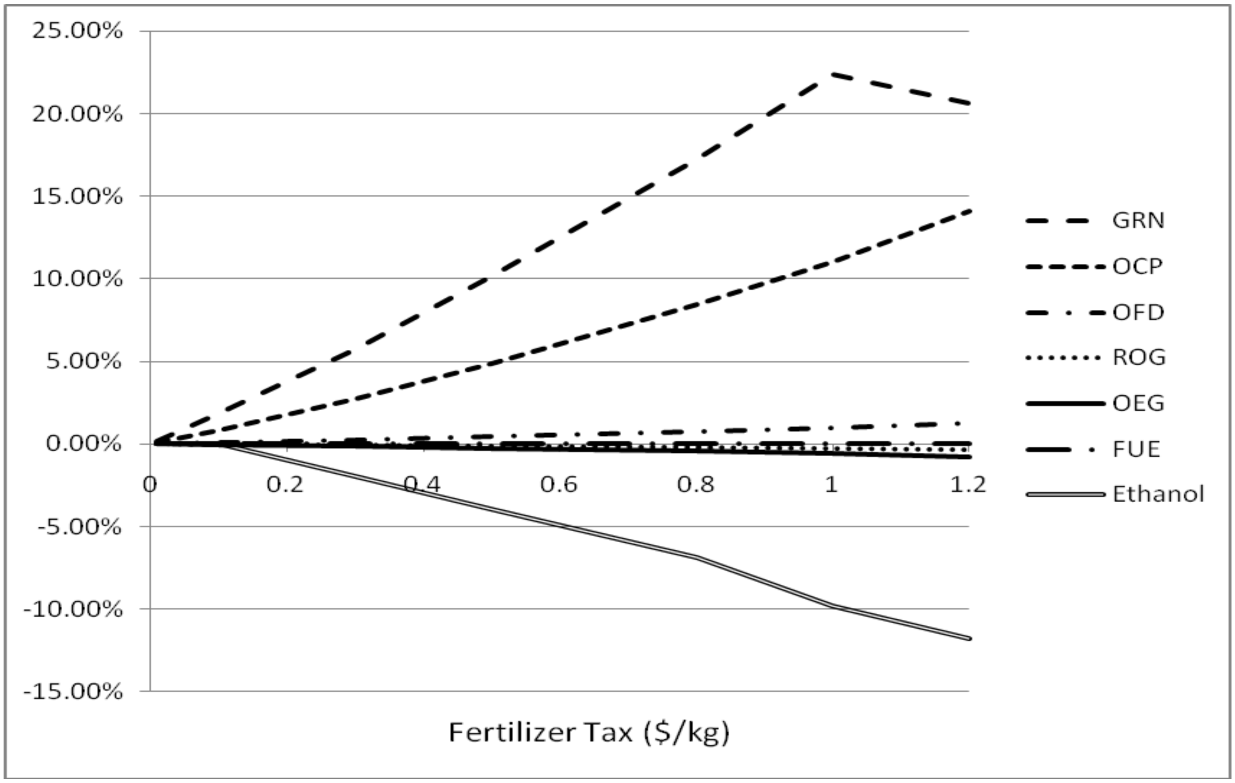


Figure 4.2d % Change of Exports with Different T_N

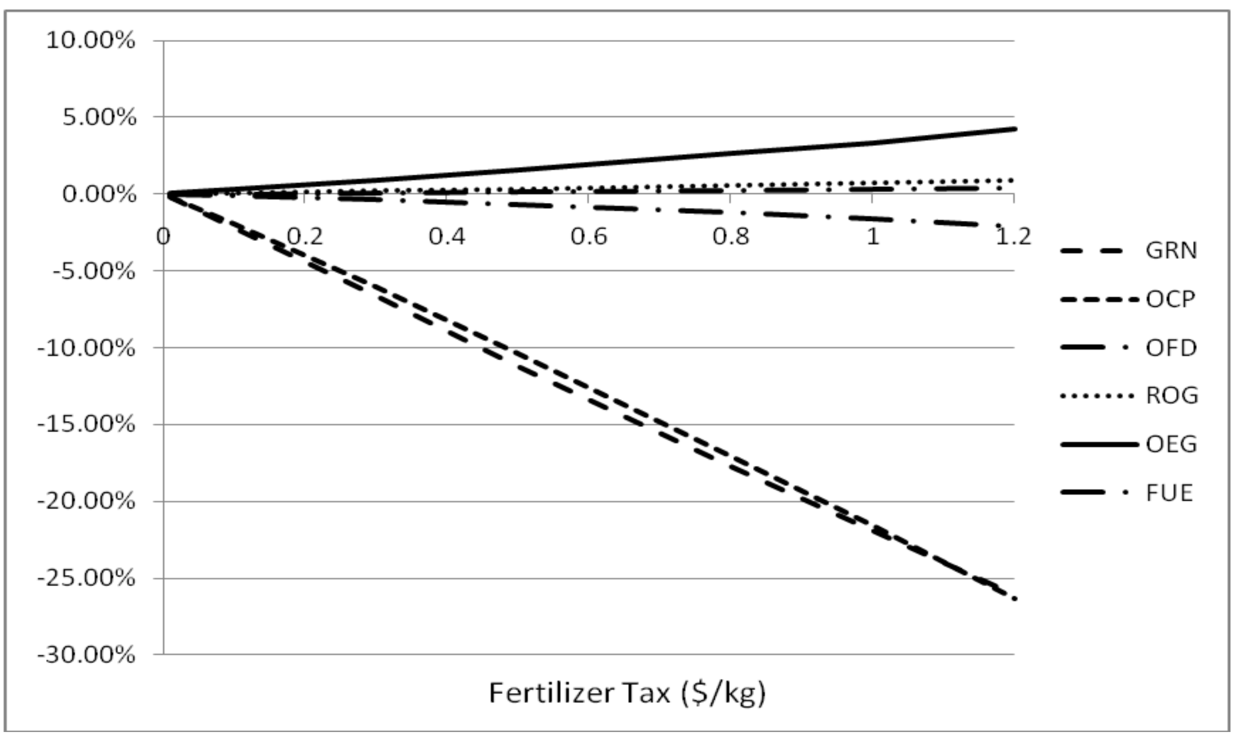


Figure 4.2e % Change of Environmental Variables with Different T_N

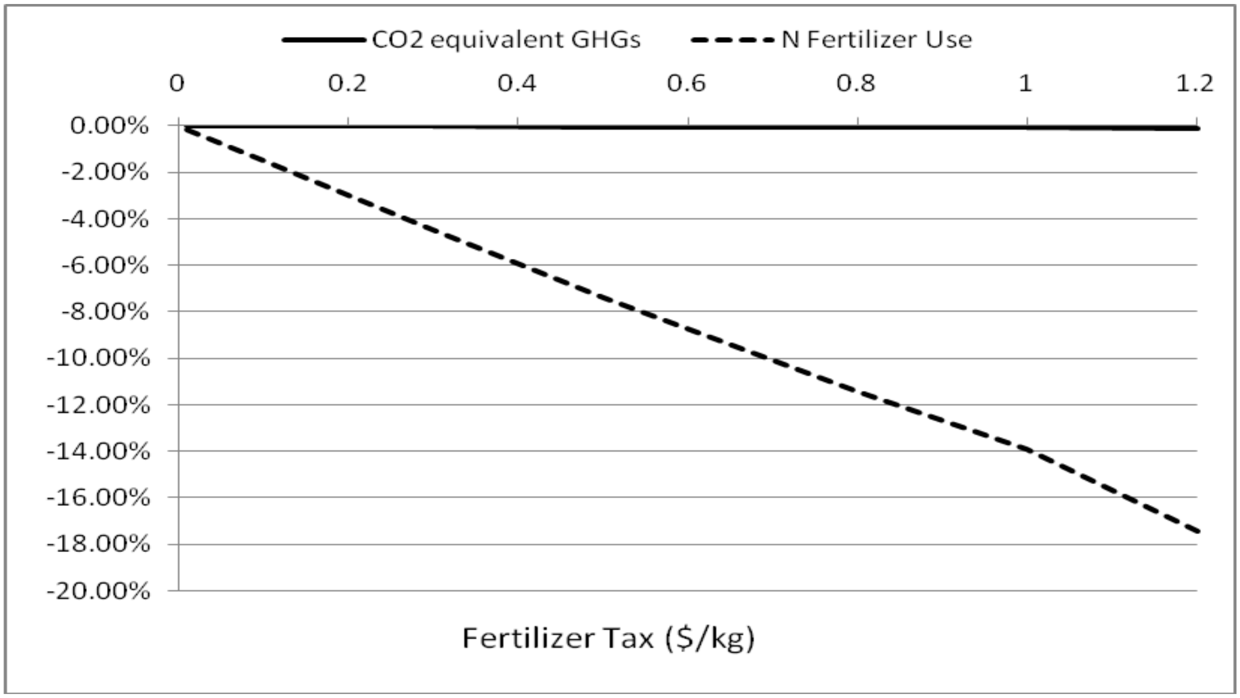


Figure 4.2f Sources of Ethanol in the US Market with Different T_N

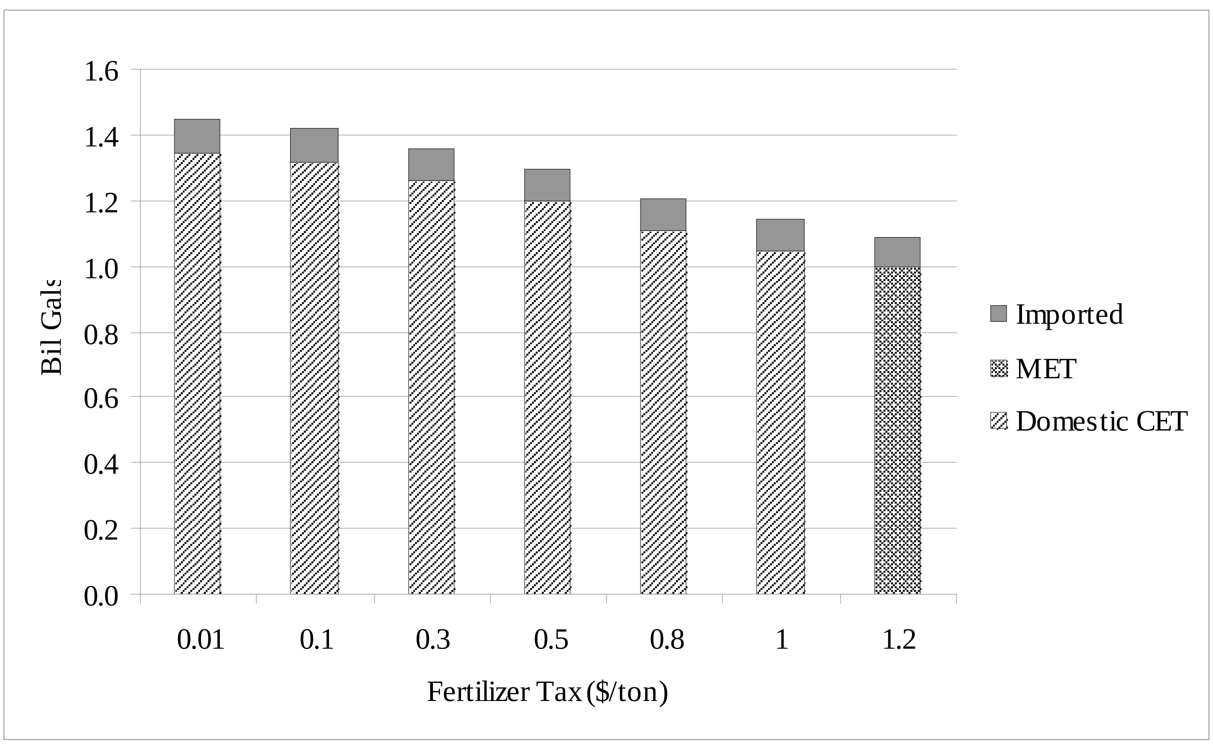


Figure 4.3a % Change of Domestic Price with Different T_G

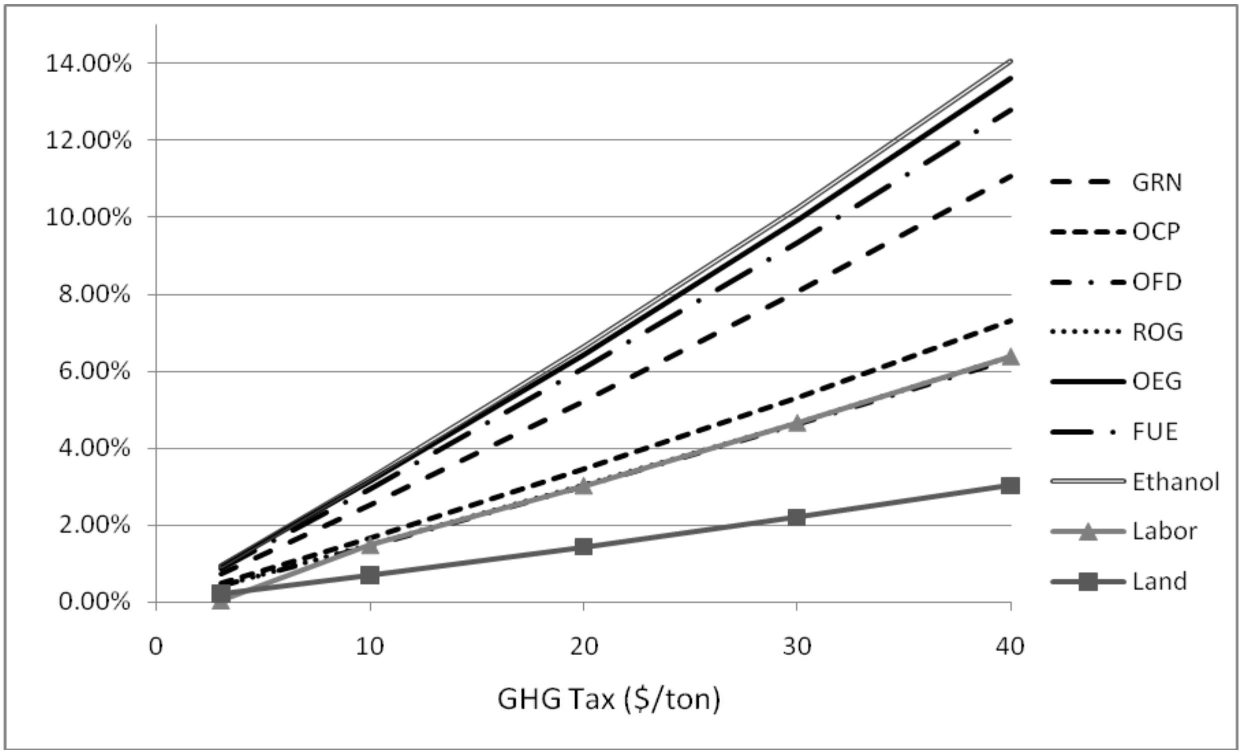
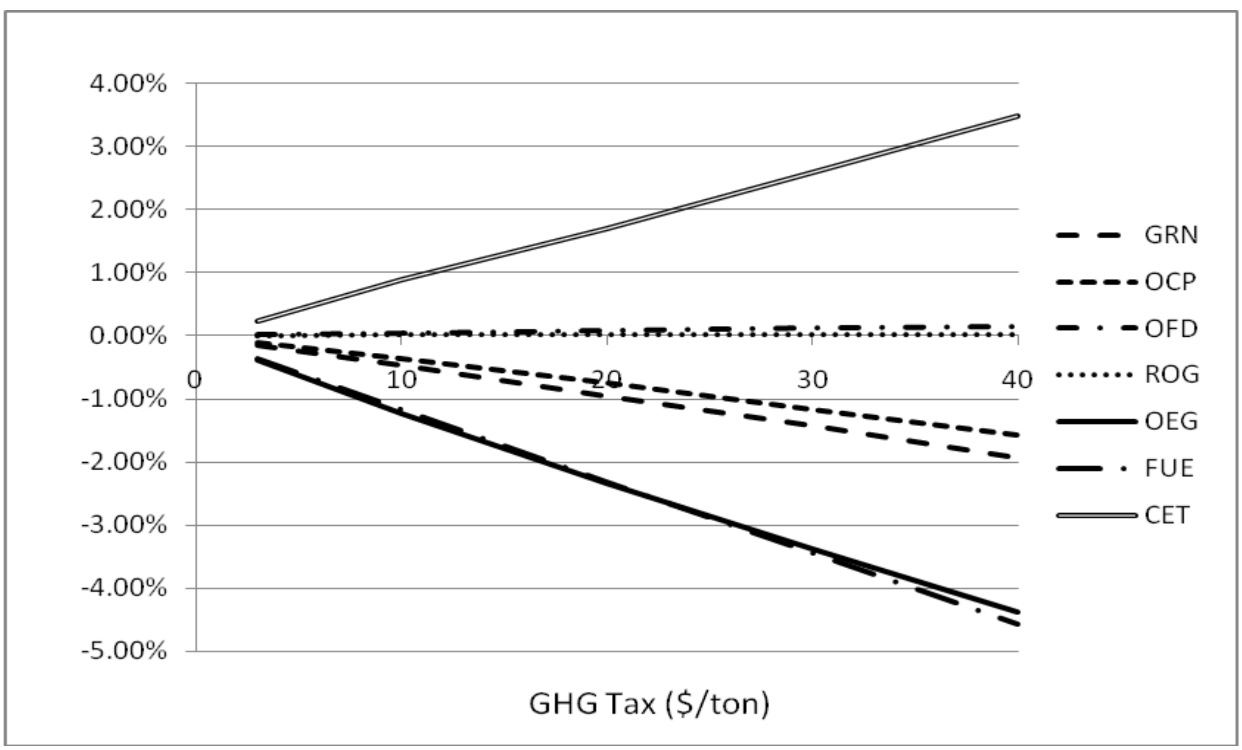


Figure 4.3b % Change of Domestic Production with Different T_G



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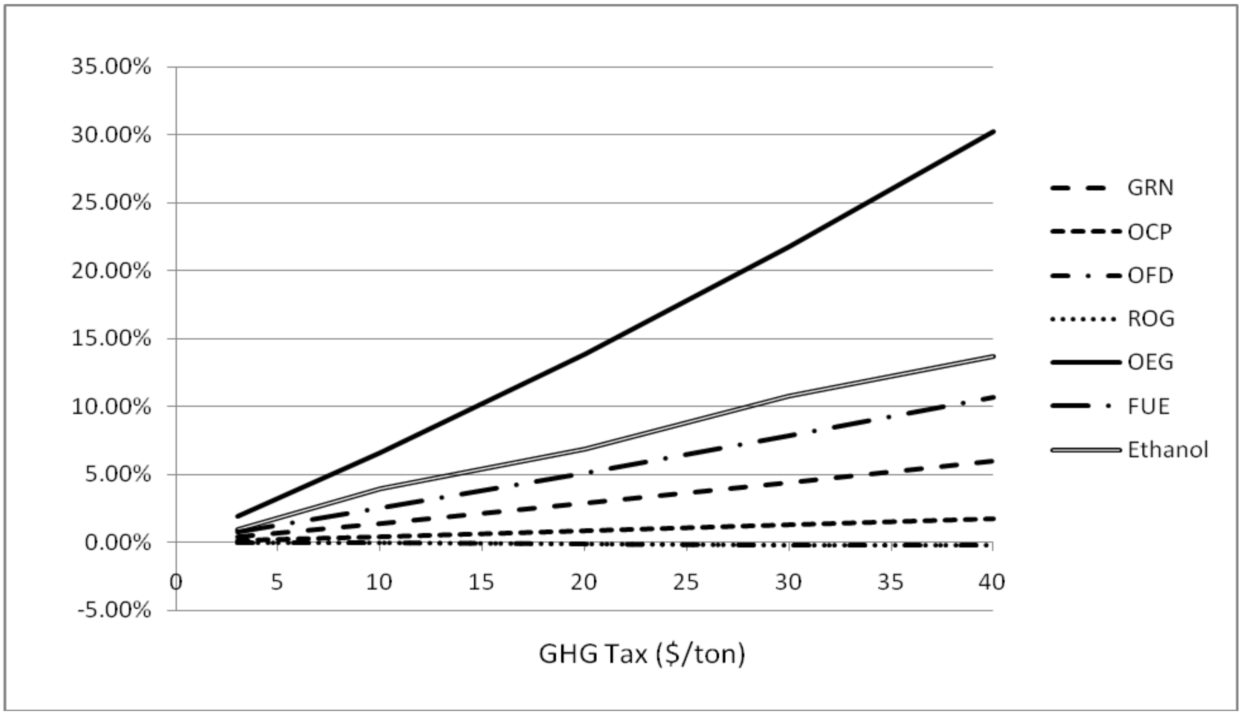


Figure 4.3d % Change of Exports with Different T_G

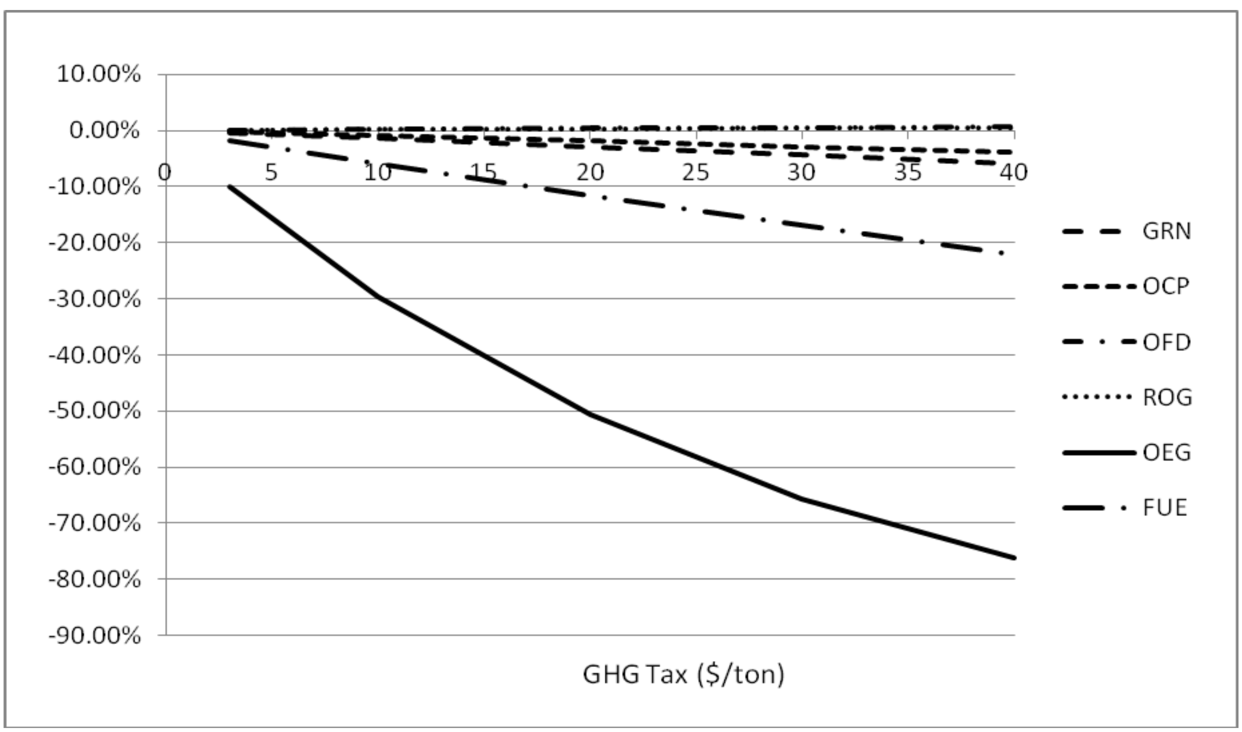


Figure 4.3e % Change in Environmental Variables with Different T_G

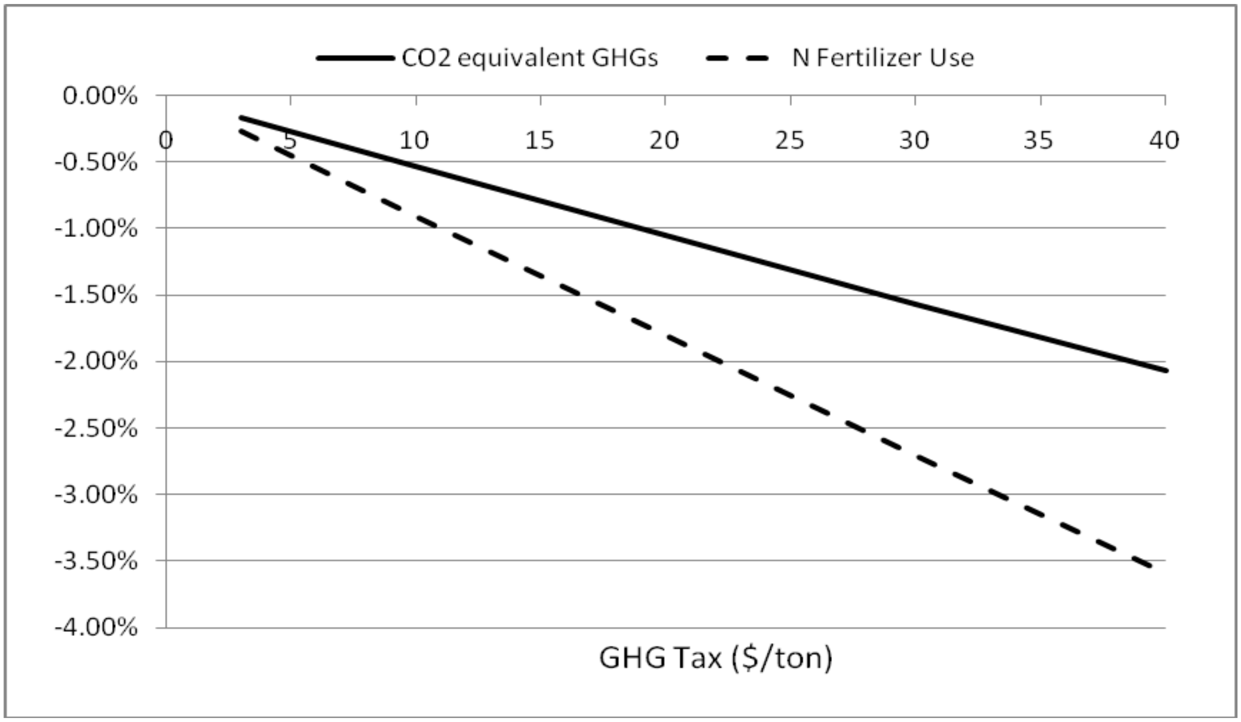


Figure 4.3f Sources of Ethanol in the US Market with Different T_G

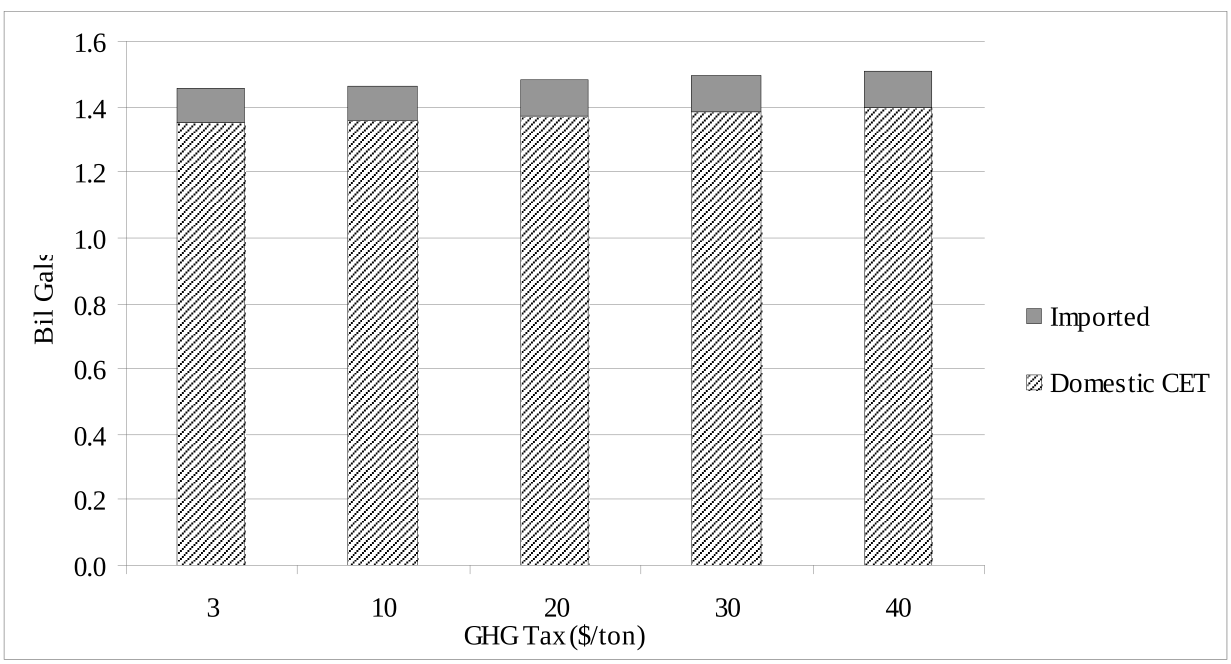


Figure 4.4a % Change of Energy Production with Different Policy Schemes

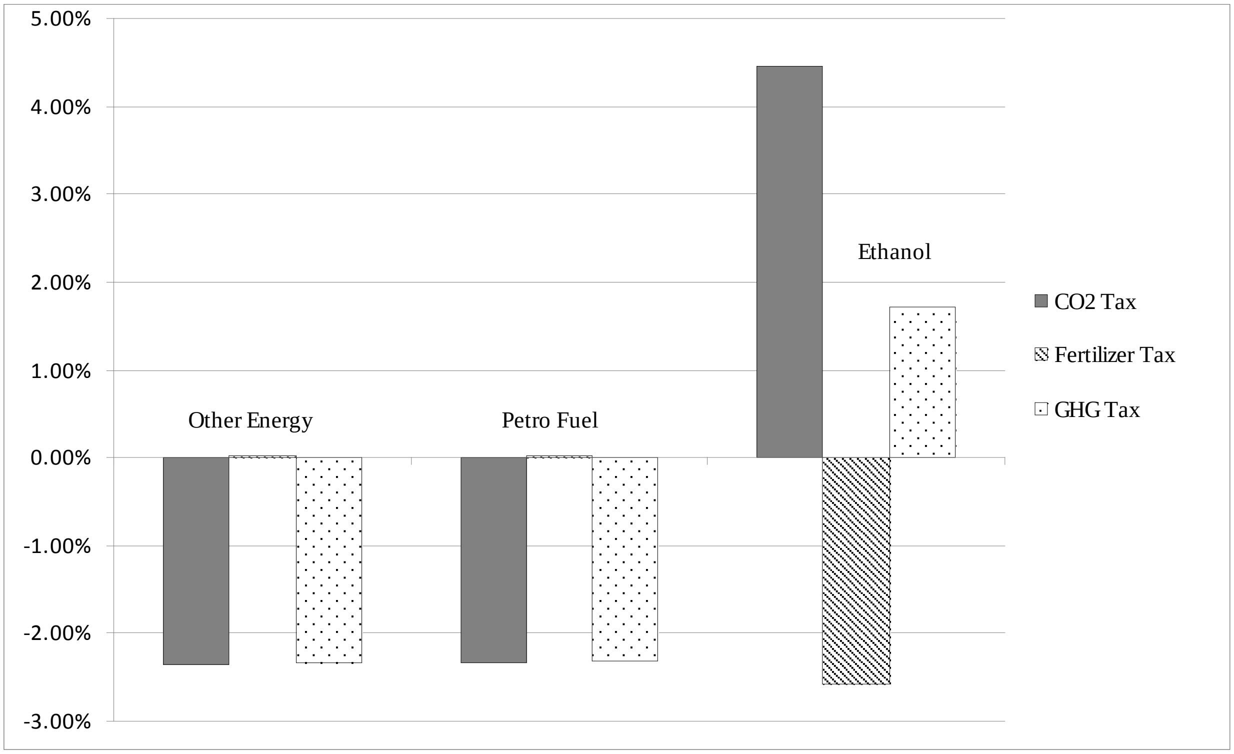


Figure 4.4b % Change of Food Prices with Different Policy Schemes

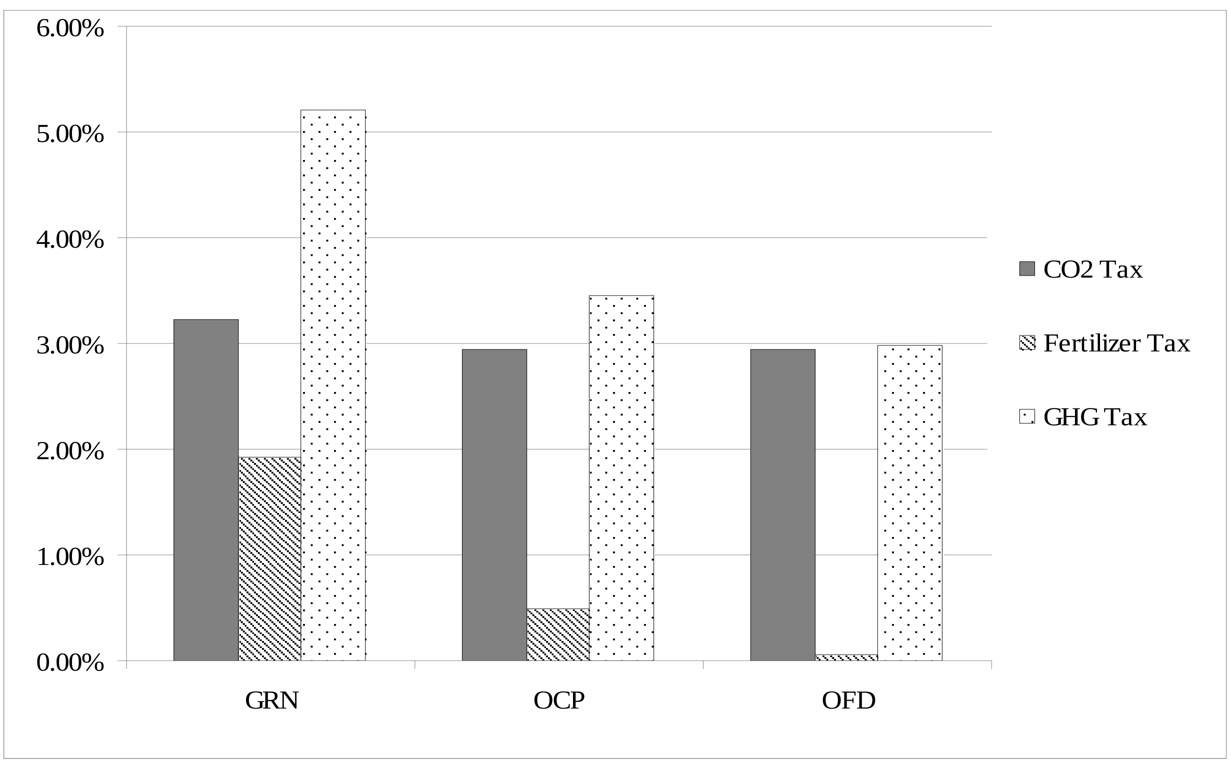


Figure 4.4c % Change of Environmental Variables and Utilities with Different Policy Schemes

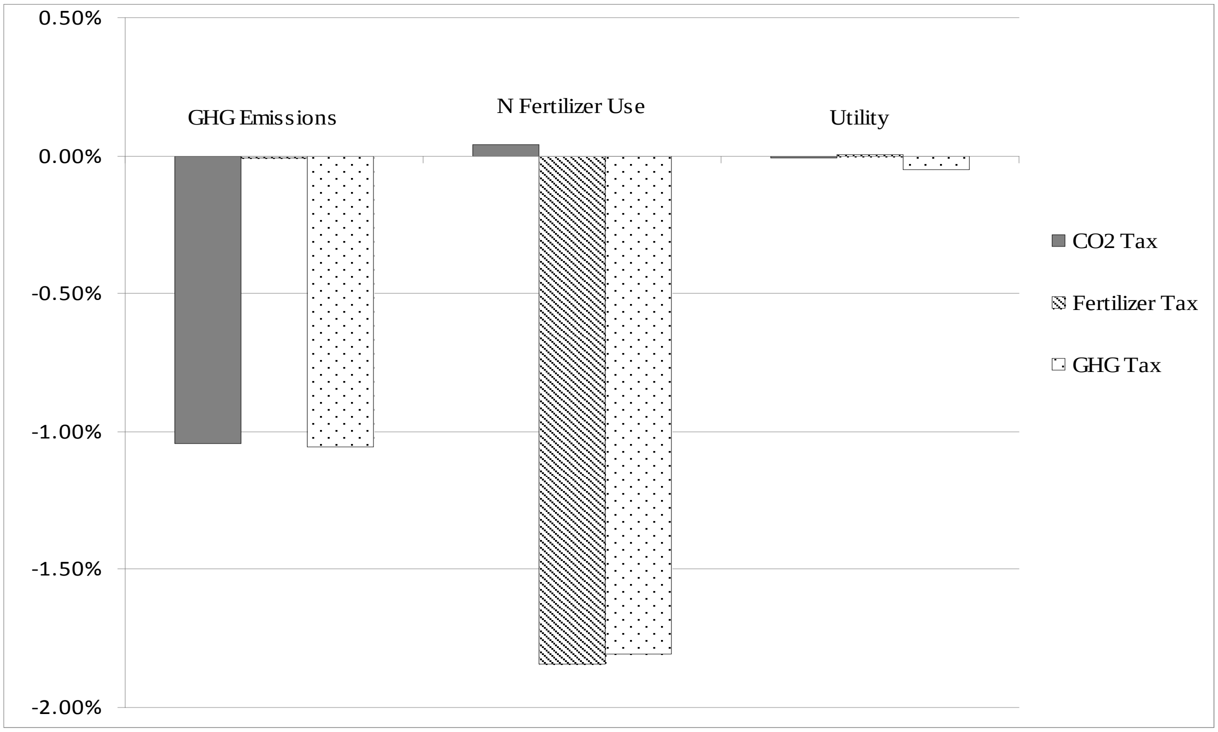


Figure 4.4d Sources of Ethanol in the US Market with Different Policy Schemes

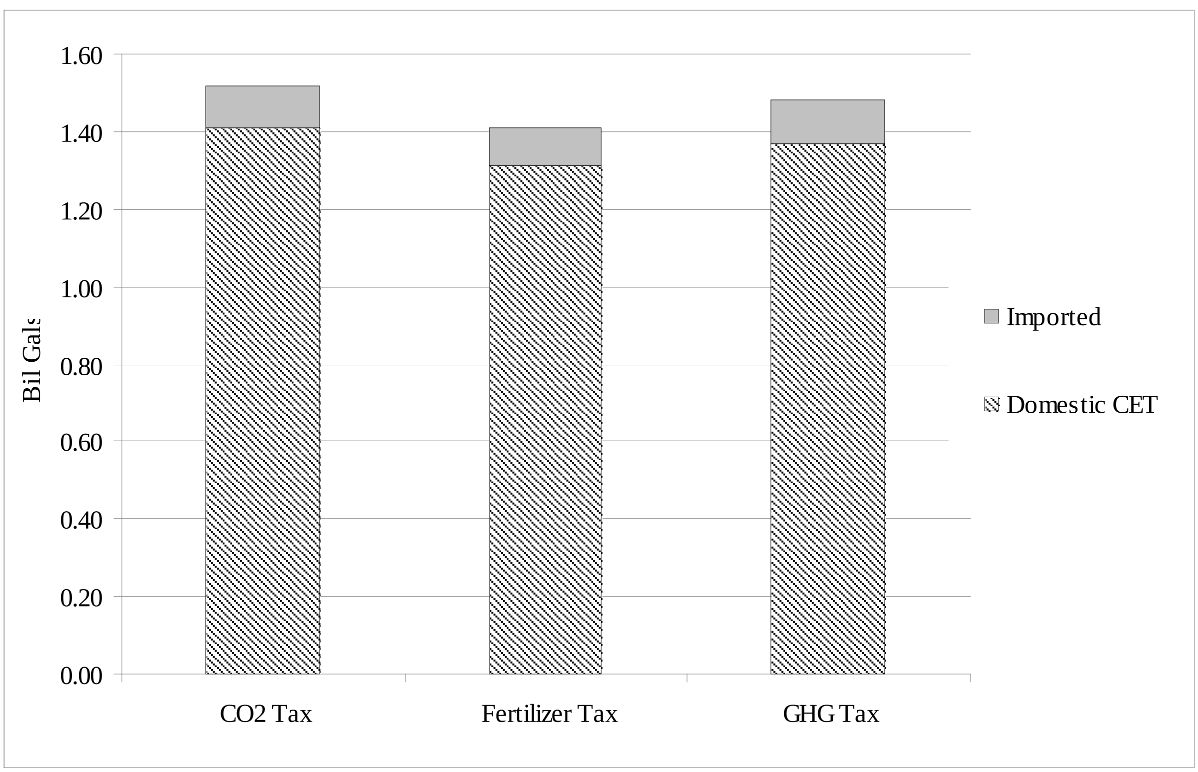


Figure 4.5 Tax Rates Required to Achive Ethanol Production Targets

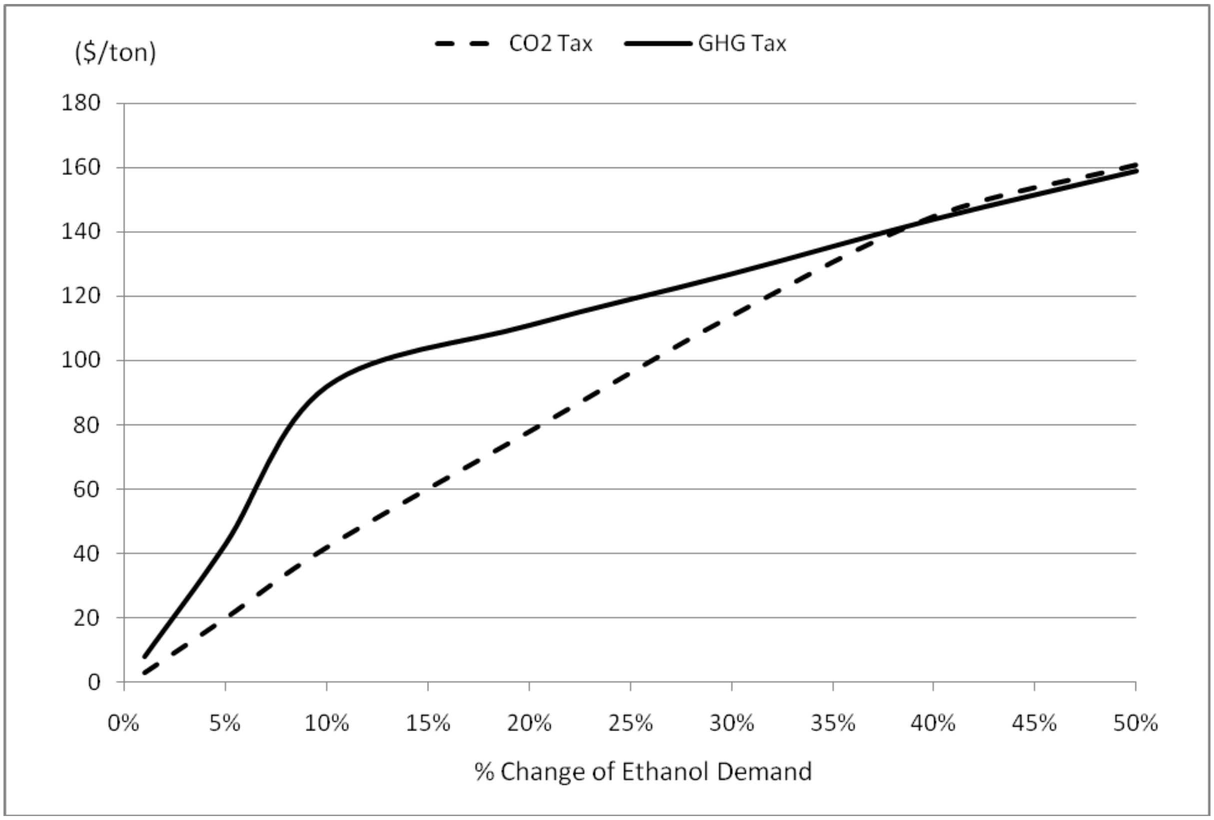


Figure 4.6a Impacts of σ_U on Domestic Production and Environmental Variables

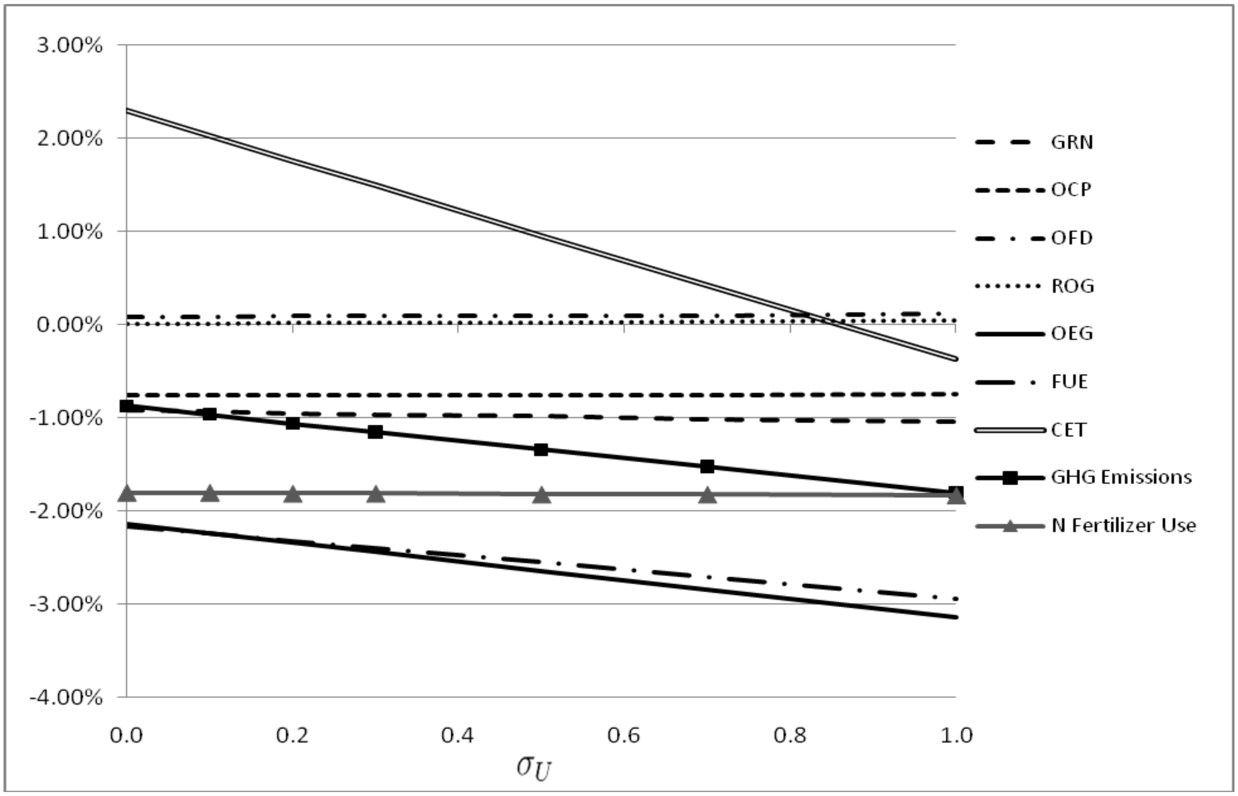


Figure 4.6b Impacts of σ_F on Domestic Production and Environmental Variables

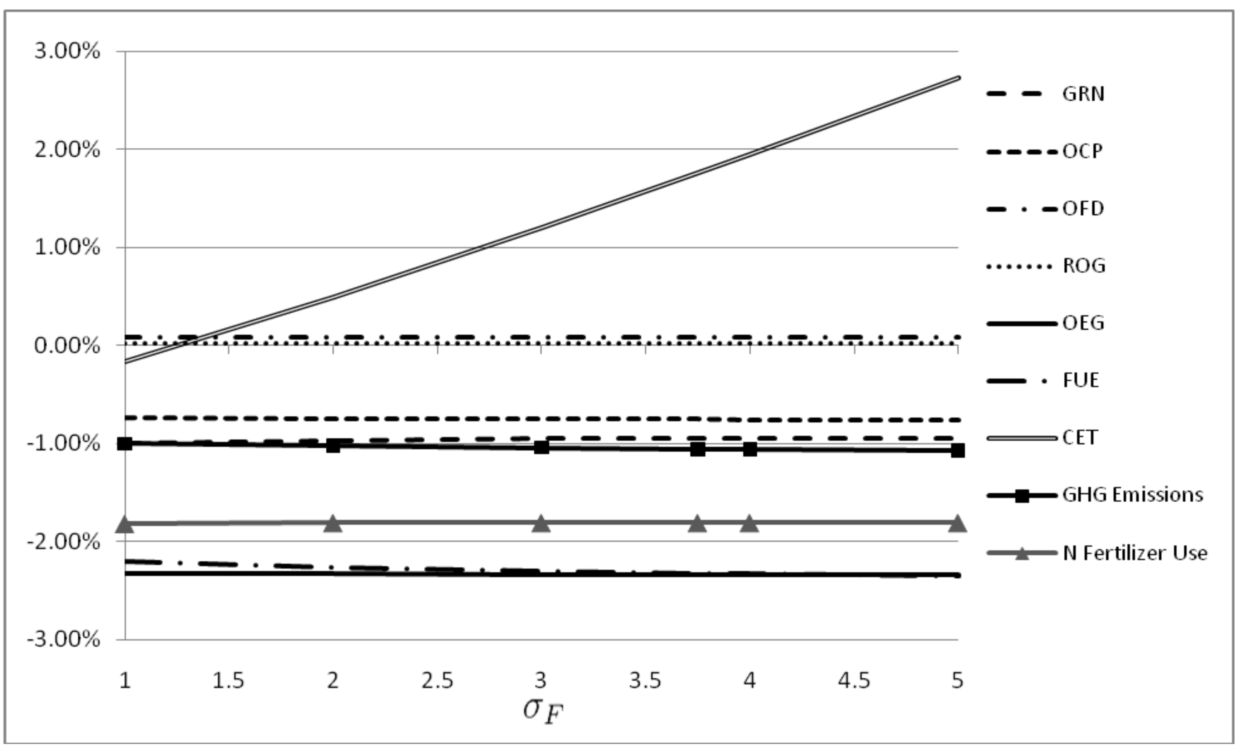
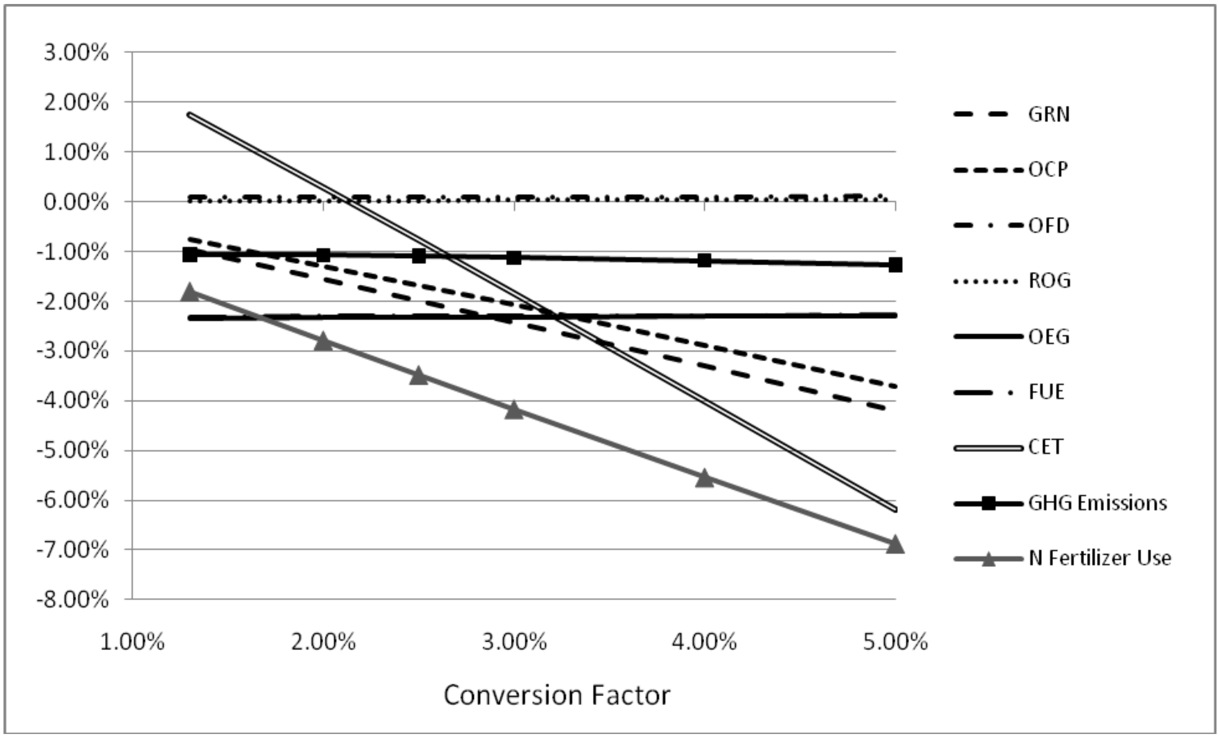


Figure 4.6c Impacts of Conversion Factor on Domestic Production and Environmental Variables



CHAPTER 5

CONCLUSIONS AND EXTENSIONS

5.1 Summary

Reductions in greenhouse gas emissions (GHG) are at the forefront of environmental policies worldwide. Promoting bio-based products is one oft-proposed solution to reduce carbon emissions because the feedstocks capture carbon, offsetting at least partially the carbon discharges resulting from use of the products. However, several life cycle analyses point out that, while biofuels may emit less life cycle net carbon emissions than fossil fuels, they may exacerbate other parts of biogeochemical cycles, notably nutrient loads in the aquatic environment. The elevated nutrient loads cause hypoxia in several watershed in the United States. Added production of nutrient-intensive feedstocks to support increasing use of biofuel would be adding to the hypoxia problem.

Biofuels can be made from a variety of feedstocks using a number of different processes, *i.e.*, different biofuel pathways, and different biofuel pathways will have different effects on global agricultural activities, energy markets, and the environment. With limited resources, promoting the most efficient mix of biofuel pathways would be essential. If considered solely as sources of energy, biofuels are not economically competitive compared to their petroleum-based counterparts. However, when environmental considerations are introduced, biofuels may play a role in the market in reducing carbon emissions although this may come at a cost in water quality. In the absence of market correction for the environmental externalities, policies are required to promote the production of biofuels. Policies that promote biofuel feedstocks that efficiently balance both economic and environmental impacts will be important in improving energy security and fighting climate change without exacerbating the problem of hypoxia.

This dissertation first uses a theoretical general equilibrium model to evaluate interactions between policies for externality-generating products that are also close substitutes, using the biofuel-fossil fuel case as an example. It goes on to develop computable general equilibrium models to evaluate how different policies affect the efficient mix of biofuel pathway production and the corresponding economic and environmental impacts with a focus on the tradeoff between the GHG emissions and nitrogen leaching.

Chapter 2 developed a three-sector theoretical general equilibrium model to evaluate the interaction effects of multiple policies. The analysis contributes new insights into the theory of second-best policies. Motivated by the case of bio-based ethanol as a substitute for petroleum-based fuel, our model incorporates two environmental externalities generated by different processes that also produce substitute goods. Multiple environmental externalities have been rarely considered in the literature. The few studies that incorporate the interactions of multiple environmental externalities assume that the externalities are generated from a single activity (*e.g.*, Caplan and Silva 2005; and Peterson 1999). In contrast, our scenario generalizes the case of biofuel and fossil fuel production and the associated environmental externalities of greenhouse gases (GHG) and nitrogen runoff to surface waters. The two environmental externalities are associated with two different production processes that yield goods that are substitutes. The interaction between the two pollutants acts through the relative demands for the two products. Two taxes are available to control the two externalities. Because the two externalites are connected through their sources, emissions of both externalities are jointly determined by the two taxes and the direction of the effects of one tax on the emissions of the other externality is analytically ambiguous. The first-best policy scheme sets each tax equal to its marginal environmental damage. However, the first-best policy scheme is not already feasible. Then the second-best tax could be lower or higher than the first-best tax, depending on the nature of the distortion in the other externality and their interactions between the final goods. In certain unlikely cases, the second-best tax could equal the first-best policy. The analytical ambiguity is mitigated through the use of a numerical example, where petroleum fuel is chiefly responsible for one externality and biofuel is responsible for the other. Biofuels come in several varieties with varying effects on the two externalities. The results of the numerical exercise indicate that a tax on the first externality will increase demand for the substitute and production of the associated externality. If the benchmark tax on externality 2 is lower than the marginal environmental damage and other parameters are set at plausible levels, then the optimal tax on externality 1 is less, and could be much less, than the marginal damages associated with externality 1. The sensitivity analysis allows us to determine the most important parameters in defining the optimal taxes. The second best tax rate for externality 1 is most sensitive to the technical parameter in the production process associated with externality 1, and the parameter that determines the substitution levels between the two final goods.

Chapter 3 developed a closed-economy computable general equilibrium (CGE) model of the United States to analyze the economic and environmental consequences of alternative biofuel feedstocks under existing and potential policies. Closed-economy models are fairly common in evaluating bioenergy impacts (*e.g.*, Johansson and Azar 2007; and McDonald and Thierfelder 2005). Currently, the major issue motivating bioenergy analyses is the competition between food products and bioenergy feedstocks due to constraints on the availability of land. Since land is not internationally tradable, a closed-economy model can provide insights into the issues that are of most concern, especially for countries where internal markets dominate the economy, such as the US. Three tax instruments are tested with this model. A CO_2 tax applied alone would reduce FUE and OEG consumption and increase ethanol demand. Total GHG emissions are reduced as expected. However, nitrogen fertilizer use is also reduced a little with this closed-economy model because fertilizer is a high fuel-intensive production. On the other hand, a fertilizer tax would have negative effects on ethanol production and decrease fertilizer use. Its effects on production of FUE and OEG, and GHG emissions are fairly small. A GHG tax is practically a combination of CO_2 tax and fertilizer tax. A GHG tax would, similar to CO_2 tax, reduce FUE and OEG consumption and increase ethanol demand. Both GHG emissions and fertilizer use would also be reduced with a GHG tax. Among the three tax instruments, GHG tax is the most effective policy to reduce nitrogen use, and CO_2 tax is the most effective to stimulate ethanol production. Our results also indicate that very high tax rates are required to stimulate cellulosic ethanol production. And when cellulosic ethanol is produced, *miscanthus* ethanol dominates switchgrass due to the lower production cost of *miscanthus* ethanol. With current technology and modest levels of taxation, the ethanol production will still be dominated by corn ethanol. The sensitivity analyses reveal that different objectives are sensitive to different parameters. The tax rates that are able to stimulate cellulosic ethanol production are most sensitive to cellulosic production costs. Production levels of energy are most sensitive to the elasticity of substitution of the consumer's consumption. The quantity of ethanol is fairly sensitive to all the parameters we tested, σ_U, σ_F and conversion factors. In terms of environmental emissions, GHG emissions are very sensitive to σ_U and nitrogen fertilizer use is affected substantially by the conversion factor from N fertilizer to N_2O.

Chapter 4 extends the second essay to achieve greater realism by introducing trade between the US and other countries in a large open-economy model. Although the use of a closed-economy model is instructive for studying domestic tradeoffs, neglecting the trading effects on the domestic market probably exaggerates the competition among sectors for land and other resources since the trading activities of the US are large and important especially for the agricultural and fossil fuel sectors. The same policy shocks examined in Chapter 3 are applied to the system and the qualitative results are similar to those of the closed economy model. Due to the possibility of trading, supply and demand of feedstocks and fuels are more elastic. The results of the closed- and open-economy models shown in Chapter 3 and Chapter 4 are not directly comparable because their benchmarks are different. To show the pure effects of the policies we proposed, we obtain our benchmarks by shocking the system by eliminating the actual $0.51/gallon ethanol subsidy from the 2004 baseline. Since the two models are different, the resulting simulated equilibria, which constitute our benchmarks for the two models, are different. However, by representing the model results as percentage changes from the real 2004 US economy, we can compare the closed economy results to the open economy outcomes. The domestic production for each commodity in 2004 is the same in both cases. Since net trades are treated as positive or negative endowments for the US market in the closed economy model, the domestic demand for each commodity is also the same in 2004 for the two models. Thus, if the results are presented as the percentage change from the 2004 US economy, the domestic supplies and demands are directly comparable between the two models. To confirm our hypothesis, Figure 5.1a to 5.1c show the supply and demand of other energy (OEG), petro-fuel (FUE), and corn ethanol (CET) with respect to a GHG tax shocks, with the benchmark as real 2004 economy. For the closed-economy model, the domestic supply equals domestic demand. Thus the curve for the closed-economy model represents the equilibrium quantities for both domestic supply and domestic demand. Clearly, given the same policy shock, the open economy model yields higher percentage changes for domestic supply and demand. The different slopes for the curves indicate that the domestic supply and demand prediction in the open economy model are more elastic with respect to policy shocks than those from the closed model

5.2 Caveats and Future Research

This dissertation employs CGE models to answer policy and environmental questions, surrounding the biofuel markets. Due to data credibility and availability, one major issue not fully addressed in this dissertation concerns direct and indirect land use change. In this dissertation, we assume that the total land endowment is fixed and the land not under production in the benchmark equilibrium is not available for production. Ruling out the possibility of increased acres of land is likely to overstate the competition between food and fuel crop production. As reliable data on productivity levels of marginal land for biofuels become available, incorporating marginal land into the analysis would yield more accurate results, especially on the impacts of energy policies on food markets.

Another issue around land use change concerns soil organic carbon (SOC) sequestration, especially that associated with cellulosic feedstock production. Gebhart *et al.* (1994) suggest that the SOC sequestration by perennial grasses is considerable. The contribution of SOC sequestration is ignored in this dissertation due to the lack of scientific data. This might lead to an underestimate of the GHG reduction potential for cellulosic ethanol and reduce their apparent competitiveness in the market.

The environmental issues associated with biofuel production are one of the foci of this dissertation. We consider two major GHGs, CO_2 emissions from the combustion of fossil fuel and N_2O emissions from nitrogen fertilizer application. Methane is another important GHG that we neglect in our analysis. The primary source of methane is livestock. In this dissertation, livestock is aggregated into the OFD sector. Separating out the livestock sector and including the emissions of methane would enhance the GHG analysis.

Because this dissertation focuses on activities in the United States, the rest of the world is lumped together in the open economy model. It would be useful and interesting to disaggregate the rest of the world so that regional differences, and policy interactions between countries, could be understood. This extension remains for future research.

Figures

Figure 5.1a % Changes of Domestic Supply and Demand of OEG with Respect to GHG Taxes

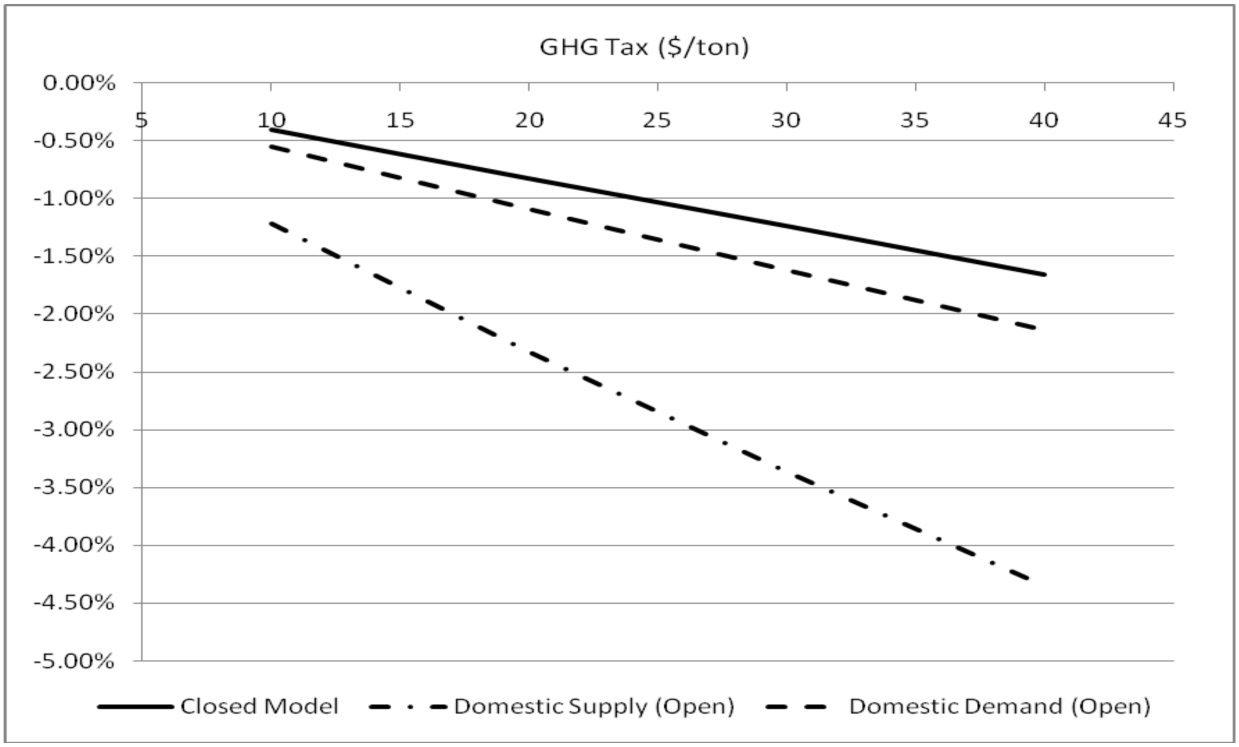


Figure 5.1b % Changes of Domestic Supply and Demand of FUE with Respect to GHG Taxes

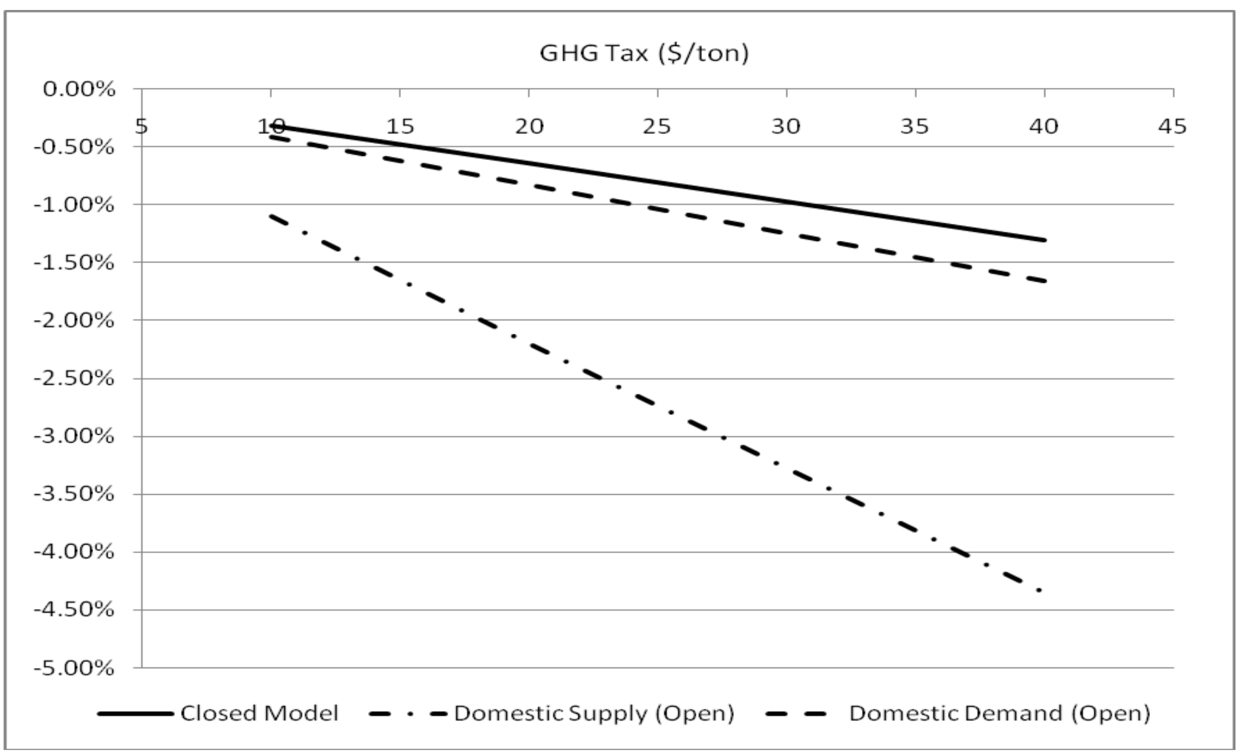
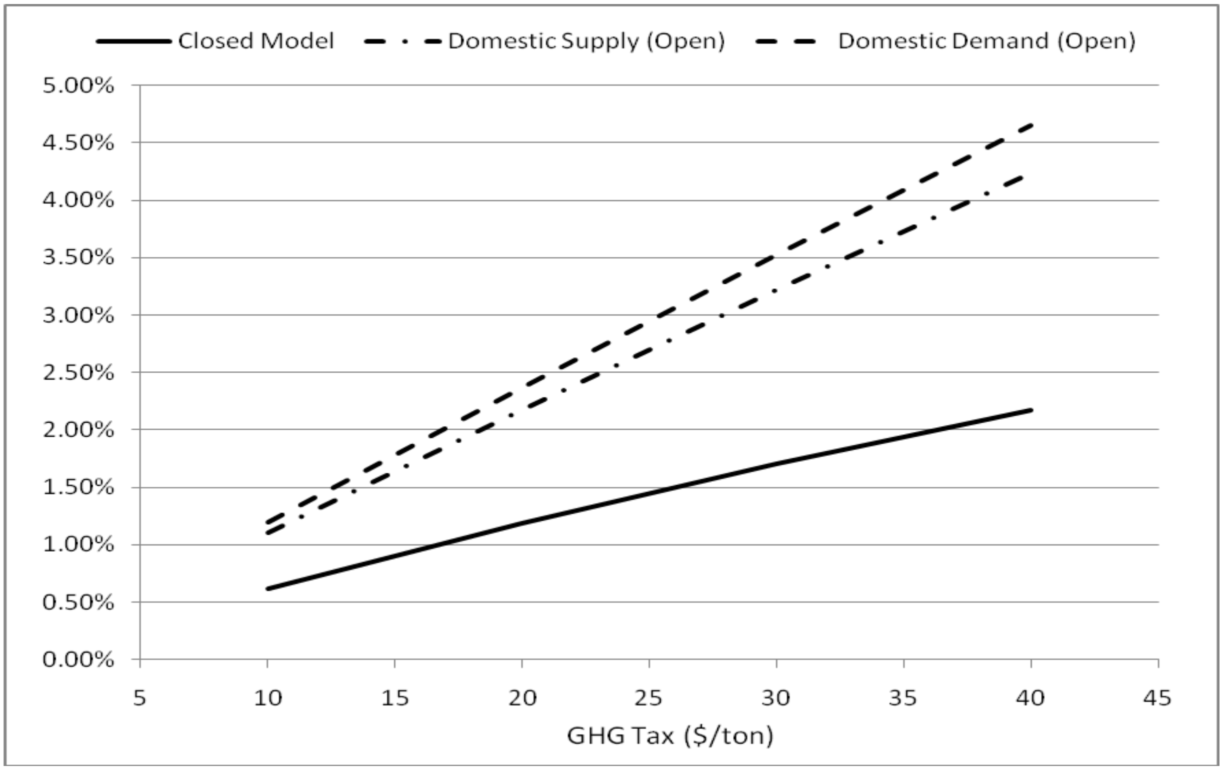


Figure 5.1c % Changes of Domestic Supply and Demand of CET with Respect to GHG Taxes



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APPENDIX A

SOLUTIONS WITH NITROGEN TAX CHANGE

$$\hat{P_F} = 0$$

$$\hat{P_B} = \frac{\theta_{XL}\theta_{BN}}{D_1}\hat{\tau_N}$$

$$\hat{P_E} = \frac{\theta_{XL}\theta_{BN}\theta_{EB}}{D_1}\hat{\tau_N}$$

$$\hat{P_L} = -\frac{\theta_{XE}\theta_{BN}\theta_{EB}}{D_1}\hat{\tau_N}$$

$$\hat{F} = [-\frac{\theta_{BN}\theta_{EB}A_4}{\theta_{EF}\theta_{FC}D_1D_2}\sigma_X - \frac{\theta_{BN}\theta_{EB}A_5}{D_1D_2}\sigma_U + \frac{\theta_{XL}\theta_{BN}(D_2 - A_2)}{D_1D_2}\sigma_E - \frac{A_1A_7}{D_1D_2}\sigma_B]\hat{\tau_N}$$

$$\hat{C} = [-\frac{\theta_{BN}\theta_{EB}A_4}{\theta_{EF}\theta_{FC}D_1D_2}\sigma_X - \frac{\theta_{BN}\theta_{EB}A_5}{D_1D_2}\sigma_U + \frac{\theta_{XL}\theta_{BN}(D_2 - A_2)}{D_1D_2}\sigma_E - \frac{A_1A_7}{D_1D_2}\sigma_B]\hat{\tau_N}$$

$$\hat{B} = [-\frac{\theta_{BN}\theta_{EB}A_4}{\theta_{EF}\theta_{FC}D_1D_2}\sigma_X - \frac{\theta_{BN}\theta_{EB}A_5}{D_1D_2}\sigma_U - \frac{\theta_{XL}\theta_{BN}A_2}{D_1D_2}\sigma_E - \frac{A_1A_7}{D_1D_2}\sigma_B]\hat{\tau_N}$$

$$\hat{N} = [-\frac{\theta_{BN}\theta_{EB}A_4}{\theta_{EF}\theta_{FC}D_1D_2}\sigma_X - \frac{\theta_{BN}\theta_{EB}A_5}{D_1D_2}\sigma_U - \frac{\theta_{XL}\theta_{BN}A_2}{D_1D_2}\sigma_E - \frac{(A_1 + \theta_{BL}D_2)A_7}{D_1D_2}\sigma_B]\hat{\tau_N}$$

$$\hat{E} = [-\frac{\theta_{BN}\theta_{EB}A_4}{\theta_{EF}\theta_{FC}D_1D_2}\sigma_X - \frac{\theta_{BN}\theta_{EB}A_5}{D_1D_2}\sigma_U - \frac{\theta_{XL}\theta_{BN}(A_2 - \theta_{EF}D_2)}{D_1D_2}\sigma_E - \frac{A_1A_7}{D_1D_2}\sigma_B]\hat{\tau_N}$$

where $A_7 = 1 - \theta_{XE}\theta_{EF}$. The definitions of A_1 to A_5, D_1 and *D2* are the same as in the paper.

APPENDIX B

DETERMINING THE SIGNS FOR PARAMETERS

1): A_1

$$\begin{aligned} A_1 &= \beta_{LB}\theta_{BN} - \gamma_{XU}\beta_{LX}\theta_{BL}\theta_{IN} \\ &= \frac{L_B}{\bar{L}}\frac{\tau_N N}{P_B B} - \frac{X_U}{X}\frac{L_X}{\bar{L}}\frac{P_L L_B}{P_B B}\frac{\tau_N N}{I} = \frac{L_B \tau_N N}{\bar{L} P_B B}(1 - \frac{X_U L_X P_L}{XI}) > 0 \end{aligned}$$

Since $X_U < X$, $P_L L_X < P_L \bar{L} < I$, then $\frac{X_U L_X P_L}{XI} < 1$. Thus $A_1 > 0$

2): A_3

$$\begin{aligned} A_3 &= \theta_{FC}\gamma_{XT} - \theta_{FX}\theta_{IC}\gamma_{XU} \\ &= \frac{\tau_C C}{P_F F}\frac{X_T}{X} - \frac{P_X X_F}{P_F F}\frac{\tau_C C}{I}\frac{X_U}{X} = \frac{\tau_C C X_T}{P_F F X}(1 - \frac{X_U}{I}) > 0 \end{aligned}$$

Since $X_U = P_X X_U < I$, then $A_3 > 0$

3): $D_2 - A_2$

$$\begin{aligned} D_2 - A_2 &= 1 - \gamma_{XU}\beta_{LX}\theta_{IL} - \gamma_{XF}\beta_{LX} - \gamma_{XU}\beta_{LX}\theta_{IC} \\ &= 1 - \gamma_{XF}\beta_{LX} - \gamma_{XU}\beta_{LX} + \gamma_{XU}\beta_{LX} - \gamma_{XU}\beta_{LX}\theta_{IL} - \gamma_{XU}\beta_{LX}\theta_{IC} \\ &= 1 - \beta_{LX} + \gamma_{XU}\beta_{LX}\theta_{IN} \\ &= \beta_{LB} + \gamma_{XU}\beta_{LX}\theta_{IN} > 0 \end{aligned}$$

APPENDIX C

RESULTS WITH T_C WITH CLOSED-ECONOMY MODEL

Table C1 % Change in Production with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
GRN	0.03	0.11	0.22	0.34	0.46
OCP	0.01	0.02	0.03	0.04	0.05
OFD	0.00	0.01	0.01	0.02	0.01
ROG	0.00	0.00	-0.01	-0.02	-0.03
OEG	-0.12	-0.42	-0.83	-1.26	-1.68
FUE	-0.13	-0.42	-0.84	-1.24	-1.65
CET	0.65	2.21	4.54	6.97	9.50

Table C2 % Change in Prices with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
GRN	0.15	0.50	0.99	1.49	1.98
OCP	0.10	0.34	0.68	1.00	1.32
OFD	0.11	0.36	0.72	1.06	1.41
ROG	0.12	0.41	0.81	1.20	1.60
OEG	0.63	2.13	4.33	6.59	8.93
FUE	0.54	1.83	3.71	5.66	7.66
FER	0.24	0.82	1.64	2.47	3.31
CET	0.44	1.46	2.96	4.50	6.08
Labor	0.12	0.40	0.80	1.19	1.58
Land	0.11	0.37	0.72	1.07	1.40

Table C3 % Change of Environmental Variables with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
CO_2 equivalent GHG	-0.13	-0.42	-0.83	-1.24	-1.66
Nitrogen Use	-0.03	-0.09	-0.18	-0.28	-0.38

Table C4 Ethanol Sources with Different T_C (Unit: Billion Gallons)

CO_2 Tax ($/ton)	3	10	20	30	40
CET	1.24	1.26	1.29	1.32	1.35
MET	0.00	0.00	0.00	0.00	0.00

APPENDIX D

RESULTS WITH T_N WITH CLOSED-ECONOMY MODEL

Table D1 % Change in Production with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
GRN	-0.02	-0.15	-0.48	-0.84	-1.43	-4.90	-4.91
OCP	-0.02	-0.25	-0.79	-1.45	-2.59	-3.54	-4.65
OFD	0.00	0.03	0.10	0.17	0.31	0.42	0.54
ROG	0.00	0.00	0.00	0.00	0.00	0.00	-0.01
OEG	0.00	0.00	0.00	0.01	0.01	-0.05	-0.05
FUE	0.00	0.03	0.09	0.16	0.27	0.39	0.41

Table D2 % Change in Prices with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
GRN	0.19	1.92	6.23	11.51	21.23	29.66	40.46
OCP	0.07	0.73	2.37	4.38	8.11	11.39	15.48
OFD	0.01	0.09	0.30	0.55	1.01	1.42	1.93
ROG	0.00	0.01	0.02	0.02	0.03	0.03	0.03
OEG	0.00	0.00	0.01	0.01	0.01	0.00	-0.02
FUE	0.00	0.00	0.01	0.01	0.01	0.00	-0.02
FER	0.38	3.98	12.86	23.70	43.68	60.83	83.11
Ethanol	0.10	0.99	3.19	5.88	10.85	14.26	15.21
Labor	0.00	0.00	0.01	0.01	0.00	-0.01	-0.04
Land	-0.03	-0.26	-0.71	-1.06	-1.35	-0.77	-0.52

Table D3 % Change of Environmental Variables with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
CO_2 equivalent GHG	0.00	0.00	-0.01	-0.01	0.00	-0.03	-0.05
Nitrogen Use	-0.15	-1.51	-4.54	-7.71	-12.46	-16.84	-20.14

Table D4 Ethanol Sources with Different T_N (Unit: Billion Gallons)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
CET	1.23	1.20	1.12	1.03	0.88	0.00	0.00
MET	0.00	0.00	0.00	0.00	0.00	0.80	0.77

APPENDIX E

RESULTS WITH T_G WITH CLOSED-ECONOMY MODEL

Table E1 % Change in Production with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
GRN	0.01	0.02	0.03	0.04	0.04
OCP	-0.04	-0.14	-0.28	-0.44	-0.60
OFD	0.01	0.03	0.05	0.07	0.09
ROG	0.00	0.00	-0.01	-0.02	-0.03
OEG	-0.12	-0.41	-0.83	-1.25	-1.68
FUE	-0.12	-0.41	-0.81	-1.20	-1.59
CET	0.01	0.02	0.03	0.04	0.04

Table E2 % Change in Prices with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
GRN	0.49	1.66	3.40	5.22	7.13
OCP	0.23	0.78	1.59	2.42	3.27
OFD	0.13	0.42	0.83	1.24	1.65
ROG	0.12	0.41	0.81	1.21	1.61
OEG	0.63	2.13	4.33	6.60	8.94
FUE	0.54	1.83	3.72	5.66	7.67
FER	0.95	3.23	6.63	10.20	13.96
CET	0.61	2.06	4.20	6.41	8.71
Labor	0.12	0.41	0.81	1.20	1.58
Land	0.06	0.20	0.41	0.60	0.80

Table E3 % Change of Environmental Variables with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
CO_2 equivalent GHG	-0.13	-0.42	-0.83	-1.25	-1.67
Nitrogen Use	-0.30	-1.01	-2.03	-3.05	-4.08

Table E4 Ethanol Sources with Different T_G (Unit: Billion Gallons)

GHG Tax ($/ton)	3	10	20	30	40
CET	1.23	1.24	1.24	1.25	1.25
MET	0.00	0.00	0.00	0.00	0.00

APPENDIX F

POLICY COMPARISON WITH CLOSED-ECONOMY MODEL

Table F1 % Change in Production with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GRN	0.22	-0.19	0.03
OCP	0.03	-0.30	-0.28
OFD	0.01	0.04	0.05
ROG	-0.01	0.00	-0.01
OEG	-0.83	0.00	-0.83
FUE	-0.84	0.03	-0.81
CET	4.54	-3.69	0.65

Table F2 % Change in Price with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GRN	0.99	2.36	3.40
OCP	0.68	0.89	1.59
OFD	0.72	0.11	0.83
ROG	0.81	0.01	0.81
OEG	4.33	0.00	4.33
FUE	3.71	0.00	3.72
FER	1.64	4.88	6.63
CET	2.96	1.21	4.20
Labor	0.80	0.00	0.81
Land	0.72	-0.31	0.41

Table F3 % Change of Environmental Variables and Utilities with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GHG Emissions	-0.83	0.00	-0.83
Nitrogen Use	-0.18	-1.84	-2.03
Utility	-0.01	0.00	-0.01

APPENDIX G

SENSITIVITY ANALYSIS OF σ_U FOR CLOSED-ECONOMY MODEL

Table G1 % Change in Production with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
GRN	0.06	0.04	0.03	0.01	-0.01	-0.04	-0.08
OCP	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28
OFD	0.05	0.05	0.05	0.05	0.05	0.05	0.05
ROG	-0.02	-0.01	-0.01	0.00	0.01	0.01	0.03
OEG	-0.60	-0.72	-0.83	-0.94	-1.17	-1.39	-1.72
FUE	-0.63	-0.72	-0.81	-0.89	-1.07	-1.24	-1.49
CET	1.28	0.99	0.65	0.41	-0.18	-0.75	-1.61

Table G2 % Change in Prices with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
GRN	3.40	3.40	3.40	3.40	3.40	3.40	3.40
OCP	1.59	1.59	1.59	1.59	1.58	1.58	1.58
OFD	0.83	0.83	0.83	0.83	0.83	0.83	0.83
ROG	0.81	0.81	0.81	0.81	0.82	0.82	0.82
OEG	4.33	4.33	4.33	4.33	4.33	4.32	4.32
FUE	3.72	3.72	3.72	3.72	3.71	3.71	3.71
FER	6.62	6.62	6.63	6.63	6.63	6.63	6.64
CET	4.20	4.20	4.20	4.19	4.19	4.19	4.18
Labor	0.80	0.80	0.81	0.81	0.82	0.82	0.83
Land	0.41	0.41	0.41	0.40	0.39	0.38	0.37

Table G3 % Change of Environmental Variables with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
CO_2 equivalent GHGs	-0.63	-0.73	-0.83	-0.93	-1.14	-1.34	-1.63
Nitrogen Use	-2.01	-2.02	-2.03	-2.04	-2.05	-2.06	-2.08

APPENDIX H

SENSITIVITY ANALYSIS OF σ_F FOR CLOSED-ECONOMY MODEL

Table H1 % Change in Production with Different σ_F

σ_F	1	2	3	3.75	4	5
GRN	-0.04	-0.01	0.02	0.03	0.03	0.04
OCP	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28
OFD	0.05	0.05	0.05	0.05	0.05	0.05
ROG	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
OEG	-0.82	-0.83	-0.83	-0.83	-0.83	-0.83
FUE	-0.67	-0.73	-0.78	-0.81	-0.81	-0.84
CET	-0.29	0.01	0.38	0.65	0.81	1.31

Table H2 % Change in Prices with Different σ_F

σ_F	1	2	3	3.75	4	5
GRN	3.40	3.40	3.40	3.40	3.40	3.40
OCP	1.58	1.58	1.59	1.59	1.59	1.59
OFD	0.83	0.83	0.83	0.83	0.83	0.83
ROG	0.81	0.81	0.81	0.81	0.81	0.81
OEG	4.33	4.33	4.33	4.33	4.33	4.33
FUE	3.72	3.72	3.72	3.72	3.72	3.72
FER	6.63	6.63	6.63	6.63	6.62	6.62
CET	4.20	4.20	4.20	4.20	4.20	4.20
Labor	0.80	0.80	0.80	0.81	0.80	0.81
Land	0.39	0.40	0.40	0.41	0.41	0.41

Table H3 % Change of Environmental Variables with Different σ_F

σ_F	1	2	3	3.75	4	5
CO_2 equivalent GHGs	-0.78	-0.80	-0.82	-0.83	-0.84	-0.85
Nitrogen Use	-2.03	-2.03	-2.03	-2.03	-2.03	-2.03

APPENDIX I

SENSITIVITY ANALYSIS OF CONVERSION FACTOR FOR CLOSED-ECONOMY MODEL

Table I1 % Change in Production with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
GRN	0.03	-0.08	-0.16	-0.24	-0.41	-0.59
OCP	-0.28	-0.46	-0.59	-0.72	-1.01	-1.32
OFD	0.05	0.07	0.09	0.11	0.14	0.18
ROG	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
OEG	-0.83	-0.83	-0.83	-0.83	-0.83	-0.83
FUE	-0.81	-0.79	-0.78	-0.76	-0.74	-0.71

Table I2 % Change in Prices with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
GRN	3.40	4.80	5.85	6.93	9.24	11.75
OCP	1.59	2.12	2.51	2.93	3.81	4.77
OFD	0.83	0.89	0.94	0.99	1.10	1.22
ROG	0.81	0.82	0.82	0.82	0.82	0.83
OEG	4.33	4.33	4.33	4.33	4.33	4.34
FUE	3.72	3.72	3.72	3.72	3.72	3.72
FER	6.63	9.51	11.67	13.91	18.67	23.82
CET	4.20	4.91	5.45	6.00	7.18	8.46
Labor	0.81	0.81	0.81	0.81	0.81	0.81
Land	0.41	0.25	0.14	0.05	-0.13	-0.29

Table I3 % Change of Environmental Variables with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
CO_2 equivalent GHGs	-0.83	-0.85	-0.86	-0.88	-0.93	-1.01
Nitrogen Use	-2.03	-3.03	-3.74	-4.46	-5.91	-7.36

APPENDIX J

RESULTS WITH T_C WITH OPEN-ECONOMY MODEL

Table J1 % Change in Domestic Production with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
GRN	0.03	0.09	0.17	0.26	0.34
OCP	0.03	0.10	0.20	0.29	0.38
OFD	0.01	0.04	0.08	0.10	0.13
ROG	0.00	0.01	0.01	0.00	0.00
OEG	-0.39	-1.23	-2.35	-3.40	-4.40
FUE	-0.36	-1.18	-2.33	-3.47	-4.59

Table J2 % Change in Domestic Price with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
GRN	0.46	1.57	3.22	4.96	6.80
OCP	0.42	1.43	2.94	4.53	6.21
OFD	0.42	1.43	2.94	4.53	6.21
ROG	0.43	1.47	3.02	4.65	6.38
OEG	0.92	3.12	6.42	9.91	13.62
FUE	0.87	2.94	6.04	9.31	12.77
FER	0.52	1.75	3.59	5.53	7.58
CET	0.81	2.76	5.67	8.76	12.03
Labor	0.43	1.47	3.01	4.64	6.36
Land	0.46	1.57	3.20	4.92	6.72

Table J3 % Change in Imports with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
GRN	0.09	0.31	0.62	0.94	1.27
OCP	-0.03	-0.12	-0.23	-0.35	-0.48
OFD	-0.03	-0.11	-0.22	-0.33	-0.45
ROG	-0.02	-0.05	-0.09	-0.13	-0.16
OEG	1.95	6.68	13.95	21.84	30.39
FUE	0.74	2.52	5.15	7.88	10.74
FER	0.25	0.83	1.68	2.54	3.42

Table J4 % Change in Exports with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
GRN	-0.04	-0.12	-0.25	-0.38	-0.51
OCP	0.08	0.26	0.51	0.77	1.03
OFD	0.08	0.27	0.52	0.76	1.00
ROG	0.04	0.11	0.20	0.27	0.33
OEG	-9.98	-29.72	-50.91	-65.91	-76.46
FUE	-1.81	-5.94	-11.60	-16.98	-22.10
FER	-0.63	-2.09	-4.18	-6.26	-8.34

Table J5 % Change of Environmental Variables with Different T_C (Unit: %)

CO_2 Tax ($/ton)	3	10	20	30	40
CO_2 equivalent GHG	-0.16	-0.53	-1.04	-1.55	-2.05
Nitrogen Use	0.01	0.02	0.04	0.05	0.06

Table J6 Ethanol Sources with Different T_C (Unit: Billion Gallons)

CO_2 Tax ($/ton)	3	10	20	30	40
Domestic CET	1.36	1.38	1.41	1.44	1.47
Domestic MET	0.00	0.00	0.00	0.00	0.00
Imported Ethanol	0.10	0.11	0.11	0.11	0.12

APPENDIX K

RESULTS WITH T_N WITH OPEN-ECONOMY MODEL

Table K1 % Change in Domestic Production with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
GRN	-0.09	-0.91	-2.76	-4.67	-7.43	-9.21	-14.71
OCP	-0.08	-0.77	-2.40	-4.19	-6.97	-8.88	-10.99
OFD	0.00	0.01	0.02	0.04	0.05	0.05	0.05
ROG	0.00	0.01	0.02	0.04	0.06	0.07	0.09
OEG	0.00	0.01	0.04	0.07	0.11	0.14	0.11
FUE	0.00	0.01	0.04	0.08	0.13	0.16	0.25

Table K2 % Change in Domestic Price with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
GRN	0.15	1.57	4.92	8.67	14.64	18.91	23.59
OCP	0.04	0.40	1.26	2.24	3.83	4.98	6.31
OFD	0.00	0.04	0.13	0.23	0.41	0.53	0.70
ROG	0.00	0.01	0.02	0.04	0.06	0.08	0.11
OEG	0.00	0.00	0.01	0.02	0.04	0.05	0.07
FUE	0.00	0.01	0.04	0.06	0.10	0.13	0.17
FER	0.26	2.56	7.69	12.93	20.32	24.94	29.38
Ethanol	0.07	0.75	2.35	4.14	6.98	9.00	11.06
Labor	0.00	0.01	0.02	0.03	0.04	0.05	0.09
Land	-0.14	-1.40	-4.18	-7.03	-11.09	-13.70	-15.76

Table K3 % Change in Imports with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
GRN	0.18	1.83	5.75	10.17	17.28	22.42	20.63
OCP	0.08	0.85	2.72	4.87	8.43	11.05	14.10
OFD	0.01	0.07	0.24	0.43	0.75	1.00	1.29
ROG	0.00	-0.03	-0.08	-0.14	-0.22	-0.28	-0.34
OEG	-0.01	-0.05	-0.16	-0.28	-0.46	-0.58	-0.80
FUE	0.00	0.00	0.00	-0.01	-0.01	0.00	0.04
FER	0.59	6.03	18.72	32.49	52.97	66.27	76.81

Table K4 % Change in Exports with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
GRN	-0.22	-2.20	-6.61	-11.17	-17.70	-21.88	-26.05
OCP	-0.19	-1.94	-6.00	-10.40	-17.07	-21.55	-26.37
OFD	-0.01	-0.11	-0.36	-0.67	-1.20	-1.60	-2.10
ROG	0.01	0.07	0.21	0.36	0.59	0.75	0.92
OEG	0.03	0.30	0.92	1.59	2.62	3.33	4.24
FUE	0.00	0.03	0.08	0.14	0.23	0.29	0.36
FER	-2.03	-18.58	-46.05	-64.75	-80.94	-87.22	-91.42

Table K5 % Change of Environmental Variables with Different T_N (Unit: %)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
CO_2 equivalent GHG	0.00	-0.01	-0.02	-0.04	-0.05	-0.06	-0.10
Nitrogen Use	-0.15	-1.52	-4.46	-7.39	-11.42	-13.92	-17.44

Table K6 Ethanol Sources with Different T_N (Unit: Billion Gallons)

Fertilizer Tax ($/kg) (% of base price)	0.01 (1.81%)	0.1 (18%)	0.3 (54%)	0.5 (91%)	0.8 (145%)	1 (181%)	1.2 (218%)
Domestic CET	1.35	1.32	1.26	1.20	1.11	1.05	0.00
Domestic MET	0.00	0.00	0.00	0.00	0.00	0.00	0.99
Imported Ethanol	0.10	0.10	0.10	0.10	0.10	0.09	0.09

APPENDIX L

RESULTS WITH T_G WITH OPEN-ECONOMY MODEL

Table L1 % Change in Domestic Production with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
GRN	-0.14	-0.47	-0.95	-1.43	-1.92
OCP	-0.11	-0.37	-0.76	-1.16	-1.58
OFD	0.01	0.05	0.09	0.12	0.15
ROG	0.00	0.01	0.02	0.02	0.01
OEG	-0.38	-1.23	-2.34	-3.38	-4.37
FUE	-0.35	-1.17	-2.32	-3.45	-4.57

Table L2 % Change in Domestic Price with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
GRN	0.75	2.54	5.22	8.05	11.06
OCP	0.49	1.68	3.45	5.32	7.29
OFD	0.43	1.46	2.99	4.61	6.33
ROG	0.43	1.47	3.02	4.66	6.40
OEG	0.92	3.13	6.43	9.92	13.63
FUE	0.87	2.95	6.05	9.33	12.80
FER	0.99	3.34	6.81	10.44	14.23
CET	0.95	3.22	6.62	10.23	14.06
Labor	0.03	1.47	3.02	4.65	6.37
Land	0.21	0.70	1.43	2.20	3.03

Table L3 % Change in Imports with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
GRN	0.42	1.42	2.88	4.39	5.95
OCP	0.12	0.40	0.82	1.26	1.72
OFD	-0.02	-0.07	-0.13	-0.19	-0.25
ROG	-0.02	-0.06	-0.12	-0.17	-0.23
OEG	1.94	6.65	13.88	21.72	30.22
FUE	0.74	2.52	5.14	7.87	10.72
FER	1.33	4.49	9.12	13.88	18.76

Table L4 % Change in Exports with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
GRN	-0.44	-1.46	-2.93	-4.41	-5.90
OCP	-0.27	-0.92	-1.89	-2.89	-3.92
OFD	0.06	0.20	0.38	0.55	0.71
ROG	0.05	0.16	0.29	0.40	0.50
OEG	-9.93	-29.60	-50.73	-65.72	-76.28
FUE	-1.81	-5.92	-11.57	-16.94	-22.05
FER	-4.28	-13.60	-25.40	-35.63	-44.47

Table L5 % Change of Environmental Variables with Different T_G (Unit: %)

GHG Tax ($/ton)	3	10	20	30	40
CO_2 equivalent GHG	-0.16	-0.54	-1.06	-1.57	-2.07
Nitrogen Use	-0.27	-0.91	-1.81	-2.70	-3.59

Table L6 Ethanol Sources with Different T_G (Unit: Billion Gallons)

GHG Tax ($/ton)	3	10	20	30	40
Domestic CET	1.35	1.36	1.37	1.38	1.40
Domestic MET	0.00	0.00	0.00	0.00	0.00
Imported Ethanol	0.10	0.11	0.11	0.11	0.12

APPENDIX M

POLICY COMPARISON WITH OPEN-ECONOMY MODEL

Table M1 % Change in Domestic Production with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GRN	0.17	-1.11	-0.95
OCP	0.20	-0.94	-0.76
OFD	0.08	0.01	0.08
ROG	0.01	0.01	0.02
OEG	-2.35	0.02	-2.34
FUE	-2.33	0.02	-2.32
CET	4.45	-2.58	1.71

Table M2 % Change in Domestic Price with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GRN	3.22	1.92	5.22
OCP	2.94	0.49	3.45
OFD	2.94	0.05	2.99
ROG	3.02	0.01	3.02
OEG	6.42	0.01	6.43
FUE	6.04	0.01	6.05
FER	3.59	3.12	6.81
CET	5.67	0.92	6.62
Labor	3.01	0.01	3.02
Land	3.20	-1.70	1.43

Table M3 % Change in Imports with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GRN	0.62	2.24	2.88
OCP	-0.23	1.05	0.82
OFD	-0.22	0.09	-0.13
ROG	-0.09	-0.03	-0.12
OEG	13.95	-0.06	13.88
FUE	5.15	0.00	5.14
FER	1.68	7.37	9.12
CET	7.55	-1.08	6.86

Table M4 % Change in Exports with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GRN	-0.25	-2.68	-2.93
OCP	0.51	-2.37	-1.89
OFD	0.52	-0.14	0.38
ROG	0.20	0.08	0.29
OEG	-50.91	0.36	-50.73
FUE	-11.60	0.03	-11.57
FER	-4.18	-22.12	-25.40

Table M5 % Change of Environmental Variables and Utilities with Potential Policies (Unit: %)

	CO_2 Tax ($20/ton)	Fertilizer Tax ($0.12/kg)	GHG tax ($20/ton)
GHG Emissions	-1.04	-0.01	-1.06
Nitrogen Use	0.04	-1.84	-1.81
Utility	-0.01	0.00	-0.05

APPENDIX N

SENSITIVITY ANALYSIS OF σ_U FOR OPEN-ECONOMY MODEL

Table N1 % Change in Domestic Production with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
GRN	-0.92	-0.93	-0.95	-0.96	-0.98	-1.01	-1.04
OCP	-0.76	-0.76	-0.75	-0.75	-0.75	-0.75	-0.74
OFD	0.08	0.08	0.09	0.09	0.10	0.10	0.12
ROG	0.01	0.01	0.02	0.02	0.02	0.03	0.04
OEG	-2.14	-2.24	-2.34	-2.44	-2.64	-2.84	-3.14
FUE	-2.16	-2.24	-2.32	-2.40	-2.55	-2.71	-2.94
CET	2.30	2.03	1.76	1.49	0.95	0.42	-0.37

Table N2 % Change in Domestic Price with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
GRN	5.21	5.21	5.22	5.22	5.23	5.23	5.24
OCP	3.44	3.44	3.45	3.45	3.46	3.46	3.47
OFD	2.98	2.99	2.99	2.99	3.00	3.01	3.02
ROG	3.02	3.02	3.02	3.03	3.03	3.04	3.05
OEG	6.42	6.43	6.43	6.43	6.44	6.44	6.45
FUE	6.05	6.05	6.05	6.06	6.06	6.07	6.07
CET	6.62	6.62	6.62	6.63	6.63	6.64	6.65
Labor	3.01	3.01	3.02	3.02	3.03	3.05	3.06
Land	1.42	1.42	1.43	1.43	1.44	1.45	1.47

Table N3 % Change in Imports with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
GRN	2.92	2.90	2.88	2.87	2.83	2.80	2.75
OCP	0.81	0.82	0.82	0.83	0.84	0.85	0.87
OFD	-0.15	-0.14	-0.13	-0.13	-0.11	-0.10	-0.08
ROG	-0.13	-0.13	-0.12	-0.11	-0.10	-0.09	-0.07
OEG	14.12	14.00	13.88	13.76	13.52	13.28	12.93
FUE	5.32	5.23	5.14	5.05	4.87	4.70	4.44
CET	6.96	6.68	6.39	6.11	5.55	4.99	4.17

Table N4 % Change in Exports with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
GRN	-2.93	-2.93	-2.93	-2.93	-2.94	-2.94	-2.94
OCP	-1.88	-1.88	-1.89	-1.89	-1.90	-1.91	-1.92
OFD	0.39	0.39	0.38	0.38	0.37	0.36	0.35
ROG	0.30	0.29	0.29	0.28	0.26	0.25	0.23
OEG	-50.74	-50.73	-50.73	-50.73	-50.73	-50.73	-50.72
FUE	-11.57	-11.57	-11.57	-11.57	-11.57	-11.56	-11.56

Table N5 % Change of Environmental Variables with Different σ_U

σ_U	0	0.1	0.2	0.3	0.5	0.7	1
CO_2 equivalent GHGs	-0.87	-0.96	-1.06	-1.15	-1.34	-1.52	-1.80
Nitrogen Use	-1.80	-1.80	-1.81	-1.81	-1.82	-1.82	-1.83

APPENDIX O

SENSITIVITY ANALYSIS OF σ_F FOR OPEN-ECONOMY MODEL

Table O1 % Change in Domestic Production with Different σ_F

σ_F	1	2	3	3.75	4	5
GRN	-1.00	-0.97	-0.95	-0.95	-0.95	-0.95
OCP	-0.74	-0.75	-0.75	-0.75	-0.76	-0.76
OFD	0.08	0.08	0.08	0.09	0.09	0.09
ROG	0.02	0.02	0.02	0.02	0.02	0.02
OEG	-2.33	-2.33	-2.34	-2.34	-2.34	-2.34
FUE	-2.20	-2.26	-2.30	-2.32	-2.33	-2.35
CET	-0.17	0.49	1.20	1.76	1.95	2.73

Table O2 % Change in Domestic Price with Different σ_F

σ_F	1	2	3	3.75	4	5
GRN	5.21	5.21	5.22	5.22	5.22	5.22
OCP	3.44	3.45	3.45	3.45	3.45	3.45
OFD	2.99	2.99	2.99	2.99	2.99	2.99
ROG	3.02	3.02	3.02	3.02	3.02	3.02
OEG	6.43	6.43	6.43	6.43	6.43	6.43
FUE	6.05	6.05	6.05	6.05	6.05	6.05
CET	6.62	6.62	6.62	6.62	6.62	6.62
Labor	3.02	3.02	3.02	3.02	3.02	3.02
Land	1.43	1.43	1.43	1.43	1.43	1.43

Table O3 % Change in Imports with Different σ_F

σ_F	1	2	3	3.75	4	5
GRN	2.71	2.79	2.85	2.88	2.89	2.91
OCP	0.80	0.81	0.82	0.82	0.82	0.83
OFD	-0.14	-0.14	-0.13	-0.13	-0.13	-0.13
ROG	-0.13	-0.12	-0.12	-0.12	-0.12	-0.12
OEG	13.87	13.87	13.88	13.88	13.88	13.88
FUE	5.28	5.21	5.17	5.14	5.13	5.11
CET	4.37	5.06	5.81	6.39	6.59	7.42

Table O4 % Change in Exports with Different σ_F

σ_F	1	2	3	3.75	4	5
GRN	-2.92	-2.93	-2.93	-2.93	-2.93	-2.93
OCP	-1.86	-1.87	-1.88	-1.89	-1.89	-1.89
OFD	0.39	0.39	0.38	0.38	0.38	0.38
ROG	0.30	0.29	0.29	0.29	0.29	0.28
OEG	-50.71	-50.72	-50.73	-50.73	-50.73	-50.74
FUE	-11.56	-11.57	-11.57	-11.57	-11.57	-11.57
FER	-2.92	-2.93	-2.93	-2.93	-2.93	-2.93

Table O5 % Change of Environmental Variables with Different σ_F

σ_F	1	2	3	3.75	4	5
CO_2 equivalent GHGs	-1.00	-1.02	-1.04	-1.06	-1.06	-1.07
Nitrogen Leaching	-1.82	-1.81	-1.81	-1.81	-1.81	-1.81

APPENDIX P

SENSITIVITY ANALYSIS OF CONVERSION FACTOR FOR OPEN-ECONOMY MODEL

Table P1 % Change in Domestic Production with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
GRN	-0.95	-1.56	-1.99	-2.43	-3.31	-4.20
OCP	-0.75	-1.29	-1.68	-2.07	-2.88	-3.72
OFD	0.09	0.09	0.09	0.10	0.10	0.11
ROG	0.02	0.02	0.02	0.03	0.03	0.04
OEG	-2.34	-2.33	-2.33	-2.32	-2.31	-2.30
FUE	-2.32	-2.31	-2.31	-2.30	-2.29	-2.28
CET	1.76	0.28	-0.78	-1.85	-4.01	-6.19

Table P2 % Change in Domestic Prices with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
GRN	5.22	6.34	7.16	8.00	9.73	11.52
OCP	3.45	3.73	3.94	4.16	4.61	5.08
OFD	2.99	3.02	3.04	3.06	3.11	3.16
ROG	3.02	3.03	3.03	3.04	3.04	3.05
OEG	6.43	6.43	6.43	6.44	6.44	6.45
FUE	6.05	6.06	6.07	6.08	6.09	6.10
CET	6.62	7.16	7.55	7.95	8.78	9.63
Labor	3.02	3.02	3.03	3.03	3.03	3.04
Land	1.43	0.47	-0.21	-0.89	-2.25	-3.61

Table P3 % Change in Imports with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
GRN	2.88	4.16	5.09	6.05	8.03	10.08
OCP	0.82	1.42	1.87	2.33	3.28	4.28
OFD	-0.13	-0.08	-0.04	0.00	0.08	0.17
ROG	-0.12	-0.14	-0.15	-0.16	-0.19	-0.21
OEG	13.88	13.84	13.81	13.78	13.72	13.65
FUE	5.14	5.14	5.13	5.13	5.13	5.13
CET	6.39	5.75	5.28	4.81	3.84	2.86

Table P4 % Change in Exports with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
GRN	-2.93	-4.39	-5.43	-6.48	-8.57	-10.66
OCP	-1.89	-3.22	-4.19	-5.18	-7.18	-9.23
OFD	0.38	0.30	0.24	0.18	0.04	-0.10
ROG	0.29	0.33	0.37	0.40	0.47	0.54
OEG	-50.73	-50.63	-50.56	-50.49	-50.34	-50.19
FUE	-11.57	-11.55	-11.54	-11.53	-11.50	-11.48

Table P5 % Change of Environmental Variables with Different N Conversion Factors

CF	1.3%	2%	2.5%	3%	4%	5%
CO_2 equivalent GHGs	-1.06	-1.07	-1.09	-1.12	-1.18	-1.27
Nitrogen Leaching	-1.81	-2.79	-3.48	-4.17	-5.54	-6.87

APPENDIX Q

CGE MODEL CODE

```
*CGE OPEN ECONOMY
$TITLE: AN OPEN CONOMY GENERAL EQUILIBRIUM MODEL FOR BIOFUEL
SETS
    U          SAM TABLE INPUT              /GRN, OCP, OFD, ROG, OIL, OEG, FUE, FER, STH, MET, SWI,
MIS, CET,  CAP, LAB, LAD, TAX, TM, HOH, INV, SAV, IM, EXT, PR/
    ALTF(U)  FEEDSTOCK FOR NEW TECHNOLOGY    /SWI, MIS/
    ALT(U)    NEW TECHNOLOGY               /STH, MET/
    I(U)       COMMODITY                    /GRN, OCP, OFD, ROG, OIL, OEG, FUE, FER, CET/
    HH(U)     FINAL DEMAND ENTITY          /HOH, INV/
    FO(I)      FOOD                         /GRN, OCP, OFD/
    H(U)       FACTORS                      /CAP, LAB, LAD/
    HE(H)      FACTORS EXCEPT CAPITAL       /LAB, LAD/
    CE(I)      ENERGY INPUT                 /FUE, OIL,OEG/
    IN(I)      OTHER INTERMEDIATE INPUTS      /GRN, OCP, OFD, ROG/;

ALIAS (U,V), (I,J), (IN1,IN), (ALTF, ALTF1);

TABLE SAM(U,V)  SAM
```

	GRN	OCP	OFD	ROG	OIL	OEG	FUE	FER	CET
GRN	155	0	12143	1418	0	2	0	0	2934
OCP	192	3334	33712	19350	38	37	4	0	4
OFD	34	104	214840	151476	12	36	72	15	6
ROG	11025	43943	243012	7515916	15599	122309	20651	3841	790
OIL	0	0	0	0	4	23	204517	8	0
OEG	2	62	8903	220183	2641	85041	26074	0	923
FUE	909	2936	2472	176180	0	14073	27668	251	0
FER	2396	4153	0	0	0	0	0	1066	0
CET	0	0	0	0	0	0	0	0	0
LAD	4002	21104	8575	0	0	0	0	0	0
LAB	4698	25092	123349	6629062	8018	49866	2511	749	219
CAP	4685	25524	90670	2601646	39548	152109	3911	180	2608
TAX	-3988	-8538	19510	1590027	5798	32212	8289	42	-1735
HOH	0	0	0	0	0	0	0	0	0
SAV	0	0	0	0	0	0	0	0	0
IMP	459	17140	54289	1395705	132749	17907	36132	2243	252
TM	0	550	2630	20732	295	0	489	0	0

	LAD	LAB	CAP	TAX	HOH	INV	EXT	TM	PR
GRN	0	0	0	0	308	1	7608	0	19020
OCP	0	0	0	0	49427	5	29303	0	8880
OFD	0	0	0	0	412568	64	34878	0	9965
ROG	0	0	0	0	9168182	2183093	993334	0	211348
OIL	0	0	0	0	0	0	150	0	16
OEG	0	0	0	0	123737	0	6046	0	299
FUE	0	0	0	0	89004	0	16825	0	6009
FER	0	0	0	0	0	0	780	0	166
CET	0	0	0	0	6002	0	0	0	0
LAD	0	0	0	0	0	0	0	0	0
LAB	0	0	0	0	0	0	0	0	0
CAP	0	0	0	0	0	0	0	0	0
TAX	0	0	0	0	193654	15290	0	0	0
HOH	33682	6843563	1875360	1850561	0	0	0	24695	0
SAV	0	0	1045522	0	584979	0	567952	0	0
IMP	0	0	0	0	0	0	0	0	0
TM	0	0	0	0	0	0	0	0	0

TABLE NEWF(U,ALTF) THE INPUT REQUIRED TO PRODUCE ALTERNATIVE FEEDSTOCK

	SWI	MIS
ROG	963.95435	541.66697
FUE	493.39952	314.36686
FER	495.65605	104.55192
SWI	179.51878	0.00000
MIS	0.00000	629.41698
LAD	2092.79717	1000.06087
LAB	880.66805	690.74648
CAP	421.81247	330.84597;

TABLE NEW(U,ALT) THE INPUT REQUIRED TO PRODUCE THE SAME QUANTITY OF BASELINE ETHANOL (CET)

	STH	MET
ROG	2480.66185	2523.70672
FUE	263.89437	263.89437
OEG	-156.45239	-156.45239
SWI	5527.80639	0.00000
MIS	0.00000	3611.65605
LAB	1434.82907	1391.78420
CAP	1332.34128	1292.37105

;

```
PARAMETER C(J) CO2 EMISSIONS IN 2004 (UNIT: TONNES)
/FUE        2452204300
 OEG        3616927100
 OIL            411500
/;

PARAMETER     Y0(J)    COMPOSITE FACTOR OR  VALUE ADDED
        F0(H,J)        THE H-TH FACTOR INPUT BY THE J-TH FIRM
        X0(I,J)        INTERMEDIATE INPUT (I-TH INPUT IN J-TH FIRM)
        Z0(J)          OUTPUT OF THE J-TH GOOD
        XP0(I)         HOUSEHOLD CONSUMPTION OF THE I-TH GOOD
        IM0(J)         IMPORT
        E0(J)          EXPORT
        YB0(J)         DOMESTIC SUPPLY OF THE J-TH GOOD
        INC0           INITAL INCOME
        COMP0          TOTAL CONSUMPTION
        N0(J)          NITROGEN RUNOFF VALUE
        D0(I)          DOMESTIC DEMAND
        CEP0(J)        CAPITAL-ENERGY INPUT
        FUEU0          TOTAL FUEL DEMAND
        FOOD           FOOD DEMAND
        SAV0           CONSUMER SAVINGS
        INV0(I)        INVESTMENT DEMAND
        FS0            FOREIGN SAVINGS
        FF(H)          FACTOR ENDOWMENT
        DEP0(H)        DEPRECIATION
        RP(I)          RENT FOR THE EXPORT DEMAND FUNCTION

        XALT0(U,ALT)    INTERMEDIATE INPUT FOR ALTERNATIVE NEW PRODUCTION
        YALT0(ALT)      COMPOSITE FACTOR OR  VALUE ADDED
        FALT0(H,ALT)    THE H-TH FACTOR INPUT BY THE J-TH FIRM
        ZALT0(ALT)      OUTPUT OF THE J-TH GOOD
        XALTF0(U,ALTF)       INTERMEDIATE    INPUT    FOR    ALTERNATIVE    NEW    PRODUCTION
FEEDSTOCK
        YALTF0(ALTF)    COMPOSITE FACTOR OR  VALUE ADDED FOR NEW FEEDSTOCK
        FALTF0(H,ALTF)  THE H-TH FACTOR INPUT BY THE J-TH FIRM  FOR NEW FEEDSTOCK
        ZALTF0(ALTF)    OUTPUT OF THE J-TH GOOD  FOR NEW FEEDSTOCK
```

```
          CEPALT0(ALT)    CAPITAL-ENERGY INPUT
          CEPALTF0(ALTF)  CAPITAL-ENERGY INPUT

          TAX0(J)         INDIRECT TAX
          TAXH0(HH)       TAX FOR FINAL DEMAND
          TR0(J)          INDIRECT TAX RATE
          TM0(J)          IMPORT TAX
          TMR(J)          IMPORT TAX RATE
          TRH0(HH)        TAX RATE FOR FINAL DEMAND

          DCK(J)          MARKET CLEARING CHECK
          BUDCK           BUDGET CHECK
          FACK(H)         FACTOR CLEARING CHECK
          INVCK           INVESTMENT CHECK
;

*SUPPLY SIDE
*INTERMEDIATE INPUT I IN INDUSTRY J  (FUEL IS IN THE VALUE-ADDED PART, BUT FOR MODELING PURPOSE, THE INPUT DEMAND IS REPRESENTED AS X0)
X0(I,J) =SAM(I,J);
*FACTOR INPUTS
F0(H,J) =SAM(H,J);
*CAPITAL AND ENERGY INPUT
CEP0(J)= F0('CAP',J)+X0('FUE',J)+X0('OEG',J)+X0('CET',J);

*INTERMEDIATE INPUT I IN ALTERNATIVE INDUSTRY  (FUEL IS IN THE VALUE-ADDED PART, BUT FOR MODELING PURPOSE, THE INPUT DEMAND IS REPRESENTED AS X0)
XALT0(U,ALT) =NEW(U,ALT);
*FACTOR INPUTS
FALT0(H,ALT) =NEW(H,ALT);
*CAPITAL AND ENERGY INPUT
CEPALT0(ALT)= FALT0('CAP',ALT)+XALT0('FUE',ALT)+XALT0('OEG',ALT)+XALT0('CET',ALT);
*TOTAL VALUE
ZALT0(ALT)=SUM(U,NEW(U,ALT));

*INTERMEDIATE INPUT I IN ALTERNATIVE FEEDSTOCK  (FUEL IS IN THE VALUE-ADDED PART, BUT FOR MODELING PURPOSE, THE INPUT DEMAND IS REPRESENTED AS X0)
```

```
XALTF0(U,ALTF) =NEWF(U,ALTF);
*FACTOR INPUTS
FALTF0(H,ALTF) =NEWF(H,ALTF);
*CAPITAL AND ENERGY INPUT
CEPALTF0(ALTF)=
FALTF0('CAP',ALTF)+XALTF0('FUE',ALTF)+XALTF0('OEG',ALTF)+XALTF0('CET',ALTF);
*TOTAL VALUE
ZALTF0(ALTF)=SUM(U,NEWF(U,ALTF));

*DEMAND SIDE
*HOUSEHOLD CONSUMPTION
XP0(I)  =SAM(I,"HOH");
*FUEL DEMAND
FUEU0=XP0('CET')+XP0('FUE');
*FOOD DEMAND
FOOD=SUM(FO,XP0(FO))+XP0("GRN");

*FINAL DEMAND TAX
TAXH0(HH) = SAM('TAX',HH);

*HOUSEHOLD TOTAL CONSUMPTION COST
COMP0=SUM(I,XP0(I))+TAXH0('HOH');

*HOUSEHOLD INCOME
INC0 = SUM(U, SAM('HOH',U));
*INVESTMENT DEMAND
INV0(I)=SAM(I,'INV');
*HOUSEHOLD FACTOR ENDOWMENT
FF(H)=SAM('HOH',H);

*DEPRECIATION
DEP0(H)=SAM('SAV',H);

*SAVING
SAV0=SAM('SAV','HOH');
*FOREIGN SAVINGS
FS0=SAM('SAV','EXT');
```

```
*TRADE
E0(J) = SAM(J,"EXT");
IM0(J)=SAM("IM",J);

*INDIRECT TAX FOR PRODUCTION
TAX0(J) = SAM('TAX',J);

*IMPORT TAX
TM0(J)=SAM("TM",J);

*TOTAL PRODUCTION QUANTITY
Z0(J)= SUM(U, SAM(U,J));

*DOMESTIC SUPPLY
YB0(J)=Z0(J)-IM0(J)-TM0(J)-E0(J);

*INDIRECT TAX RATE
TR0(J) = TAX0(J)/(Z0(J)-IM0(J)-TM0(J));

*IMPORT TAX RATE
TMR(J)$IM0(J)=TM0(J)/IM0(J);

*FINAL DEMAND TAX RATE
TRH0('HOH')=TAXH0('HOH')/COMP0;
TRH0('INV')=TAXH0('INV')/(SUM(J,INV0(J))+TAXH0('INV'));

*RENT GENERATES FOR EXPORT DEMAND FUNCTION
RP(I) = SAM(I, 'PR');

*DOMESTIC DEMAND
D0(J)=SUM(I,X0(J,I))+XP0(J);

*BALANCE CHECK
DCK(J)=Z0(J)-E0(J)-D0(J)-INV0(J);
BUDCK=INC0-SUM(I,XP0(I))-SAV0-TAXH0('HOH');
FACK(H)=SUM(J,F0(H,J))-FF(H)-DEP0(H);
```

```
DISPLAY DCK,BUDCK,FACK;

PARAMETER CCOEF(J) CARBON COEFFICIENT  (TONS OF C PER DOLLAR OR UNIT OF OUTPUT)
        NCOEF N2O CONVERSION FACTOR (TONS OF CO2 EQUIVALENT PER DOLLAR OF FERTILIZER)
        PF   FERTILIZER INITIAL PRICE (DOLLAR PER KG)
;
PF = 0.25/0.45359237;
CCOEF(J)= 1E-6*C(J)/D0(J);
NCOEF= 1.3/100 * 44/28 * 298/1000/PF;

PARAMETER  TF          FERTILIZER ENVIRONMENTAL EXTERNALITY TAX
        TALT(ALT)      CELLULOSIC ETHANOL TAX
;
TF = 0;
TALT(ALT)=0;

PARAMETER  TC BENCHMARK CARBON TAX ($ PER TON) /0.0/;

PARAMETER          EIM(J)       ELASTICITY OF SUBSTITUTION BETWEEN IMPORTS AND DOMESTIC
PRODUCTION
/GRN      1.3
OCP       2.7
OFD       2.4
ROG       2.4
OIL       5.2
OEG       4.4
FUE       2.1
FER       3.3
CET       2.1
/;

PARAMETER       EFE       ELASTICITY OF SUBSTITUTION BETWEEN PETRO FUEL AND ETHANOL
             EF       ELASTICITY OF SUBSTITUTION AMONG ALL FOOD FOR CONSUMERS
             ECU       ELASTICITY OF SUBSTITUTION AMONG RIVAL GOODS ON THE UPPER LEVEL OF
UTILITY ;
EFE = 3.75;
```

EF=1;
ECU=0.2;

PARAMETER EE(I) ELASTICITY OF SUBSTITUTION BETWEEN FUEL AND OTHER ENERGY
/GRN 0.2
OCP 0.2
OFD 0.2
ROG 0.2
OIL 0.2
OEG 0.2
FUE 0.2
FER 0.2
CET 0.2
/;

PARAMETER EEALT(ALT) ELASTICITY OF SUBSTITUTION BETWEEN FUEL AND OTHER ENERGY FOR ALTERNATIVE TECHNOLOGY
/STH 0.1
MET 0.1
/;

PARAMETER EEALTF(ALTF) ELASTICITY OF SUBSTITUTION BETWEEN FUEL AND OTHER ENERGY FOR ALTERNATIVE FEEDSTOCK
/SWI 0.1
MIS 0.1
/;

PARAMETER ECE(I) ELASTICITY OF SUBSTITUTION BETWEEN CAPITAL AND ENERGY IN PRODUCTION OF J
/GRN 0.1
OCP 0.1
OFD 0.1
ROG 0.1
OIL 0.1
OEG 0.1
FUE 0.1
FER 0.1

CET 0.1
/;

PARAMETER ECEALT(ALT) ELASTICITY OF SUBSTITUTION BETWEEN CAPITAL AND ENERGY IN PRODUCTION OF ALT
/STH 0.1
MET 0.1
/;

PARAMETER ECEALTF(ALTF) ELASTICITY OF SUBSTITUTION BETWEEN CAPITAL AND ENERGY IN PRODUCTION OF ALTF
/SWI 0.1
MIS 0.1
/;

PARAMETER EFA(I) ELASTICITY OF SUBSTITUTION AMONG FACTORS IN PRODUCTION OF J INCLUDING FERTILIZER
/GRN 0.2
OCP 0.3
OFD 0.9
ROG 1.3
OIL 0.2
OEG 0.3
FUE 0.3
FER 0.3
CET 1.1
/;

PARAMETER EFAALT(ALT) ELASTICITY OF SUBSTITUTION AMONG FACTORS IN PRODUCTION OF ALT INCLUDING FERTILIZER
/STH 1.3
MET 1.3
/;

PARAMETER EFAALTF(ALTF) ELASTICITY OF SUBSTITUTION AMONG FACTORS IN PRODUCTION OF ALTF INCLUDING FERTILIZER
/SWI 0.3

```
MIS      0.3
/;

PARAMETER EY(I)      ELASTICITY OF SUBSTITUTION AMONG UPPER LEVEL OF PRODUCITON PROCESS OF J: INTERMEDIATE AND VALUE ADDED
/GRN      0
OCP      0
OFD      0
ROG      0
OIL      0
OEG      0
FUE      0
FER      0
CET      0
/;

PARAMETER EYALT(ALT)      ELASTICITY OF SUBSTITUTION AMONG UPPER LEVEL OF PRODUCITON PROCESS OF ALT: INTERMEDIATE AND VALUE ADDED
/STH      0
MET      0
/;

PARAMETER EYALTF(ALTF)      ELASTICITY OF SUBSTITUTION AMONG UPPER LEVEL OF PRODUCITON PROCESS OF ALTF: INTERMEDIATE AND VALUE ADDED
/SWI      0
 MIS      0
/;

$ONTEXT

$MODEL:USA_CN

$COMMODITIES:
        P(I)        !    PRICE INDEX OF COMMODITIES
        PA(I)       !    PRICE INDEX OF ARMINGTON AGGREGATION
        PFX         !    PRICE INDEX OF FOREIGN EXCHANGE
        W(HE)       !    PRICE INDEX OF FACOTRS
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        PK               !      PRICE INDEX OF CAPITAL
        PCEP(J)          !      CAPITAL-ENERGY PRICE INDEX
        PC               !      CONSUMPTION PRICE INDEX
        PSAV             !      INVESTMENT
        PR(I)$E0(I)      !      RENT THAT GENERATES THE EXPORT DEMAND FUNCTION
        PALTF(ALTF)      !      PRICE OF FEEDSTOCK
        PCEPALT(ALT)     !      CAPITAL-ENERGY PRICE INDEX OF ALTERNATIVE ENERGY
        PCEPALTF(ALTF)   !      CAPITAL-ENERGY PRICE INDEX OF FEEDSTOCK

$SECTORS:
        A(J)             !      ARMINGTON AGGREGATION
        Z(I)             !      TOTAL PRODUCTION INDEX
        ZALT(ALT)        !      ALTERNATIVE PRODUCTION OF ETHANOL
        ZALTF(ALTF)      !      PRODUCTION INDEX FOR ALTERNATIVE FEEDSTOCK
        CEP(J)           !      CAPITAL-ENERGY DEMAND IN PRODUCTION J
        CEPALT(ALT)      !      CAPITAL-ENERGY DEMAND IN PRODUCTION ALT
        CEPALTF(ALTF)    !      CAPITAL-ENERGY DEMAND IN PRODUCTION ALTF
        CW               !      CONSUMPTION
        INVEST           !      AGGREGATE INVESTMENT
        EXPORT(I)$E0(I)  !      EXPORT

$CONSUMERS:
       RA                !      HOUSEHOLD INCOME (TOTAL)
       FA                !      FOREIGN AGENT INCOME LEVEL


$REPORT:
       V:QA(I) O:PA(I)         PROD:A(I)
       V:Q(I)  O:P(I)          PROD:Z(I)
       V:QW(HE,I)  I:W(HE)     PROD:Z(I)
       V:QK(I)  I:PK           PROD:CEP(I)
       V:QFE(I) I:PA("FER")    PROD:Z(I)
       V:QOIL(I)     I:PA("OIL")   PROD:Z(I)
       V:QF(I)  I:PA("FUE")        PROD:CEP(I)
       V:QOEG(I)   I:PA("OEG")     PROD:CEP(I)
       V:QFALT  I:PA("FUE")        PROD:CEPALT
       V:QOEGALT   I:PA("OEG")     PROD:CEPALT
```

```
        V:QFEALTF I:PA("FER")      PROD:ZALTF
        V:QWALTF(HE,ALTF)  I:W(HE)         PROD:ZALTF(ALTF)

        V:DNF      I:PA("ROG") PROD:CW
        V:DOGU   I:PA("OEG")      PROD:CW
        V:DFO(FO)        I:PA(FO) PROD:CW
        V:DFUE    I:PA("FUE")   PROD:CW
        V:DCET    I:PA("CET")   PROD:CW
        V:DCOM        O:PC         PROD:CW
        V:EXPO(I)           I:P(I)           PROD:EXPORT(I)
        V:IMPO(I)             I:PFX           PROD:A(I)
        V:QALT(ALT)     O:P("CET")    PROD:ZALT(ALT)


$PROD:A(I)       S:EIM(I)
        O:PA(I)         Q:(Z0(I)-E0(I))
        I:PFX           Q:IM0(I)        P:(1+TMR(I))     A:RA    T:TMR(I)
        I:P(I)          Q:YB0(I)

$PROD:Z(I) S:EY(I)   A:EFA(I)
        O:P(I)  Q:(YB0(I)+E0(I))       P:(1-TR0(I))         A:RA    T:TR0(I)
        I:PA(IN) Q:X0(IN,I)
        I:PA("OIL")   Q:X0("OIL",I)   P:((1+CCOEF("OIL")*TC))    A:RA  T:(CCOEF("OIL")*TC)
        I:W(HE) Q:F0(HE,I)  A:
        I:PA("FER")    Q:X0("FER",I)  P:(1+TF)         A:RA    T:TF  A:
        I:PCEP(I)       Q:CEP0(I)       A:

$PROD:CEP(I)  S:ECE(I)  A: EE(I)
        O:PCEP(I)       Q:CEP0(I)
        I:PK   Q:F0("CAP",I)
        I:PA("OEG")   Q:X0("OEG",I)  P:(1+CCOEF("OEG")*TC)    A:RA  T:(CCOEF("OEG")*TC)    A:
        I:PA("FUE")$X0("FUE",I)     Q:X0("FUE",I)    P:(1+CCOEF("FUE")*TC)     A:RA   T:(CCOEF("FUE")*TC)
A:

$PROD:ZALT(ALT) S:EYALT(ALT)   A:EFAALT(ALT)
        O:P("CET")  Q:(YB0("CET")+E0("CET"))         P:(1-TALT(ALT))         A:RA    T:TALT(ALT)
        I:PA(IN) Q:XALT0(IN,ALT)
```

```
        I:PALTF(ALTF)   Q:XALT0(ALTF,ALT)
        I:W(HE) Q:FALT0(HE,ALT)  A:
        I:PA("FER")    Q:XALT0("FER",ALT)   P:(1+TF)        A:RA    T:TF   A:
        I:PCEPALT(ALT)      Q:CEPALT0(ALT)      A:

$PROD:CEPALT(ALT)  S:ECEALT(ALT)     A: EEALT(ALT)
        O:PCEPALT(ALT)      Q:CEPALT0(ALT)
        I:PK   Q:FALT0("CAP",ALT)
        I:PA("OEG")    Q:XALT0("OEG",ALT)        P:(1+CCOEF("OEG")*TC)     A:RA   T:(CCOEF("OEG")*TC)
A:
        I:PA("FUE")$XALT0("FUE",ALT)      Q:XALT0("FUE",ALT)           P:(1+CCOEF("FUE")*TC)      A:RA
T:(CCOEF("FUE")*TC)   A:

$PROD:ZALTF(ALTF) S:EYALTF(ALTF)   A:EFAALTF(ALTF)
        O:PALTF(ALTF)  Q:ZALTF0(ALTF)
        I:PA(IN) Q:XALTF0(IN,ALTF)
        I:PALTF(ALTF1)   Q:XALTF0(ALTF1,ALTF)
        I:W(HE) Q:FALTF0(HE,ALTF)  A:
        I:PA("FER")    Q:XALTF0("FER",ALTF)   P:(1+TF)        A:RA    T:TF   A:
        I:PCEPALTF(ALTF)      Q:CEPALTF0(ALTF)      A:

$PROD:CEPALTF(ALTF)  S:ECEALTF(ALTF)        A: EEALTF(ALTF)
        O:PCEPALTF(ALTF)      Q:CEPALTF0(ALTF)
        I:PK   Q:FALTF0("CAP",ALTF)
        I:PA("OEG")        Q:XALTF0("OEG",ALTF)                          P:(1+CCOEF("OEG")*TC)           A:RA
T:(CCOEF("OEG")*TC)      A:
        I:PA("FUE")$XALTF0("FUE",ALTF)     Q:XALTF0("FUE",ALTF)       P:(1+CCOEF("FUE")*TC)     A:RA
T:(CCOEF("FUE")*TC)    A:

$PROD:EXPORT(I)$E0(I)  S:1
        O:PFX$E0(I)   Q:(E0(I)+RP(I))
        I:P(I)$E0(I)  Q:E0(I)
        I:PR(I)$E0(I) Q:RP(I)

$PROD:CW S:ECU     A: EF        B:EFE
        O:PC    Q:COMP0         A:RA    T:TRH0("HOH")
        I:PA("ROG") Q:XP0("ROG")
```

```
        I:PA("OEG")$XP0("OEG") Q:XP0("OEG")      P:(1+CCOEF("OEG")*TC)    A:RA  T:(CCOEF("OEG")*TC)
        I:PA("OIL")$XP0("OIL") Q:XP0("OIL")      P:((1+CCOEF("OIL")*TC))    A:RA  T:(CCOEF("OIL")*TC)
        I:PA("FER")$XP0("FER") Q:XP0("FER")     P:(1+TF)        A:RA    T:TF
        I:PA(FO) Q:XP0(FO)       A:
        I:PA("FUE")   Q:XP0("FUE")   P:(1+CCOEF("FUE")*TC)    A:RA  T:(CCOEF("FUE")*TC)    B:
        I:PA("CET")      Q:XP0("CET")   B:

$PROD:INVEST
        O:PSAV          Q:(SUM(I,INV0(I))+TAXH0('INV'))      A:RA    T:TRH0("INV")
        I:PA(I)$INV0(I)        Q: INV0(I)



$DEMAND:RA
        D:PC
*FACTOR ENDOWMENT
        E:W(HE)         Q:(FF(HE)+DEP0(HE))
        E:PK            Q:(FF("CAP")+DEP0("CAP"))

*EMISSION TAX INCOME
*         E:PCARB$CARBLIM         Q:CARBLIM R:CTAX$TC

*FOREIGN SAVING
        E:PFX          Q: FS0
*INVESTMENT
        E:PSAV          Q:(-SAV0-FS0-SUM(H,DEP0(H)))

$DEMAND: FA
        D:PFX   Q:(SUM(I,RP(I)))
        E:PR(I)$E0(I) Q:RP(I)

$OFFTEXT
$SYSINCLUDE MPSGESET USA_CN
OPTION MCP = PATH;

PK.FX = 1;
* FREE SOLVE
USA_CN.ITERLIM = 80000;
```

```
$INCLUDE USA_CN.GEN
SOLVE USA_CN USING MCP;
DISPLAY Z.L, P.L;
```