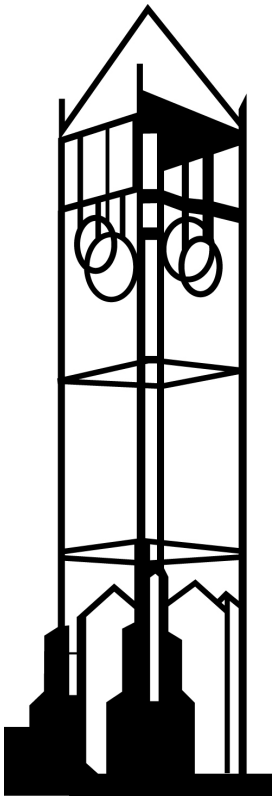
Economics of Biofuels: An Overview of Policies, Impacts and Prospects

GianCarlo Moschini, Jingbo Cui, Harvey Lapan



Working Paper No. 12021
May 2012

IOWA STATE UNIVERSITY
Department of Economics
Ames, Iowa, 50011-1070

Iowa State University does not discriminate on the basis of race, color, age, religion, national origin, sexual orientation, gender identity, genetic information, sex, marital status, disability, or status as a U.S. veteran. Inquiries can be directed to the Director of Equal Opportunity and Compliance, 3280 Beardshear Hall, (515) 294-7612.

Economics of Biofuels:

An Overview of Policies, Impacts and Prospects

GianCarlo Moschini,[1,2] Jingbo Cui[1] and Harvey Lapan[1]

[1] Department of Economics, Iowa State University, Ames, IA 50111, USA
[2] Center for Agricultural and Rural Development, Iowa State University, Ames, IA 50111, USA

Paper prepared for presentation at the 1st AIEAA Conference
'Towards a Sustainable Bio-economy: Economic Issues and Policy Challenges'

4-5 June, 2012
Trento, Italy

Summary

This paper provides an overview of the economics of biofuels. It starts by describing the remarkable growth of the biofuel industry over the last decade, with emphasis on developments in the United States, Brazil and the European Union, and it identifies the driving role played by some critical policies. After a brief discussion of the motivations that are commonly argued in favor of biofuels and biofuel policies, the paper presents an assessment of the impacts of biofuels from the economics perspective. In particular, the paper explains the basic analytics of biofuel mandates, reviews several existing studies that have estimated the economic impacts of biofuels, presents some insights from a specific model, and outlines an appraisal of biofuel policies and the environmental impacts of biofuels. The paper concludes with an examination of several open issues and the future prospects of biofuels.

Keywords: Biodiesel, biofuel policies, ethanol, greenhouse gas emissions, mandates.

JEL Classification codes: Q2, H2, F1.

1. INTRODUCTION

The production and use of biofuels—ethanol and biodiesel—has experienced a remarkable growth over the last decade. According to the US Energy Information Agency (EIA) data, total world biofuel production increased nearly six-fold over the 2000-2010 period, from 315 thousand barrels per day to 1856 thousand barrels per day (Figure 1). Three countries/regions have been leading this development: the United States, Brazil and the European Union (EU). Ethanol has been the leading biofuel in the Unites States (from corn) and in Brazil (from sugarcane), whereas biodiesel is the preferred biofuel in Europe (rapeseed oil is the most important feedstock). Whereas both types of biofuels have experienced a similar upward trend in recent years, ethanol remains the dominant type of biofuel. In 2010 ethanol accounted for three-fourth of world biofuel output (when expressed in energy equivalent units). Ethanol production increases have been particularly impressive in the United States, where the annual rate of growth over the period 2000-2010 was more than double that in Brazil. Indeed, the United States surpassed Brazil as the world's largest ethanol producer in 2006, and by 2010 it produced 57.1% of world's ethanol output.

Whereas the development of this industry draws on roots established long ago, especially in Brazil, its recent boom has been heavily influenced by critical policies that are promoting the production and consumption of biorenewables in general, and biofuels in particular. The rapid developments that have affected biofuel policies and biofuel industries have generated considerable debate, and a number of unresolved issues remain. The purpose of this paper is to provide a brief introduction to economic analyses of biofuels. Needless to say, a comprehensive assessment of models and results in this setting goes beyond the scope of this paper, is probably premature at the current state of knowledge, and will therefore not be attempted. We start with a cursory review of the salient attributes of the biofuel industry growth, with emphasis on the policy drivers. Given the primary importance of ethanol in the current biofuel industry, and the dominant role assumed by the United States in ethanol production, our presentation privileges US issues and policies, although some context is given for the other major players (Brazil and the EU). This is followed by a discussion of the main economic questions that arise in the context of biofuels. Specific attention is given to the basic analytics of biofuel mandates, the review of several existing studies that have estimated the market impacts of biofuels, the insights from a specific model, and an appraisal of biofuel policies and the environmental impacts of biofuels. The paper concludes with an examination of several open issues and the future prospects of biofuels.

2. BOOM OF AN INDUSTRY

In the United States ethanol has been produced from corn for more than three decades. The production trend depicted in figure 2 shows a slow albeit steady growth up to the beginning of the new millennium, and a markedly increased growth rate over the last decade. In 2011 ethanol output reached 13.9 billion gallons, an 80-fold increase relative to the 1980 level. Throughout this period, a few federal policies have played a key role in the development of this industry (Tyner, 2008). An initial stimulus came from the $0.40/gallon subsidy (technically, an excise tax exemption) established by the Energy Tax Act of 1978. In various forms, the federal subsidy was active until it was allowed to expire at the end of 2011. It increased early on to reach $0.60/gallon with the Tax Reform Act of 1984, but has been gradually adjusted downward since 1990. The subsidy (by then a blender tax credit) was last decreased to $0.45/gallon as of January 2009, and it was finally phased out at the end of December 2011. The desire to keep the subsidy for domestic production only motivated the introduction of a $0.54/gallon duty on ethanol imports (to supplement the out-of-quota bound ad valorem import tariff of 2.5%). This specific import duty also expired at the end of 2011. Many other federal (Yacobucci, 2012) and state programs exist that provide biofuel incentives.

Whereas the federal subsidy undoubtedly supported the earlier growth of the US ethanol industry, environmentally-led regulations also played an important role. In particular, the 1990 amendments to the Clean Air Act introduced a 2% oxygen requirement for gasoline (Duffield and Collins, 2006). As concerns eventually arose as to the groundwater contamination potential of methyl tertiary butyl ether (MTBE), an early favorite oxygenate gasoline additive and octane enhancer, and following bans by some states (led by California), the gasoline refining industry began phasing out MTBE in the early 2000s. Ethanol emerged as the most viable oxygenate substitute for MTBE, which fostered a valuable market niche for ethanol as a key gasoline additive.[1]

2.1. The Renewable Fuel Standard

A major change in the policy context for US biofuels in general, and for ethanol in particular, was affected by the Energy Policy Act of 2005 which first introduced a Renewable Fuel Standard (RFS). The law established quantitative mandates for the minimum amount of biofuel to be included in the US transportation fuel. These quantitative mandates were expanded considerably by the Energy

[1] MTBE was completely phased out in 2007, after achieving a maximum use of about 3.3 billion gallons (of gasoline equivalent) per year over the period 1999-2002. Owing to ethanol's lower energy content, to replace that amount of MTBE would require about 4.7 billion gallons of ethanol.

Independence and Security Act (EISA) of 2007 (Schneff and Yacobucci, 2012). The current RFS, after EISA, envisions the total amount of biofuel to increase to 36 billion gallons by 2022. To qualify as "renewable" for the purpose of the RFS, biofuels must achieve at least a 20% reduction in greenhouse gas (GHG) emissions, relative to the conventional fuel it replaces, based on a lifecycle analysis. The US Environmental Protection Agency (EPA) has determined that most biofuels (including corn-based ethanol) meet this carbon reduction requirement. Furthermore, EISA specifies a number of nested requirements as to how the overall biofuel mandate is to be achieved. First, the largest category is that of "advanced biofuels," which are defined as biofuels that achieve at least a 50% GHG emission reduction. This category, from which corn-based ethanol is excluded, encompasses a variety of biofuels, including sugarcane ethanol and biodiesel, and it is supposed to grow to 21 billion gallons by 2012. A portion of the advanced biofuel mandate is reserved for biodiesel, which is to achieve 1 billion gallons from 2012 onward. The largest portion of the advanced biofuel mandate is reserved for cellulosic biofuels, identified as reaching a GHG emission reduction of 60%, which is envisioned to grow to 16 billion gallons by 2022. From all this it follows that corn-based ethanol is implicitly capped to a maximum of 15 billion gallons (from 2015 onward). Also, a portion of the advanced biofuel mandate is unspecified and can be met by a variety of biofuels (including sugarcane ethanol, biodiesel and cellulosic biofuels). This unspecified portion of the advanced biofuel mandate is to grow to 4 billion gallons by 2012.

The EPA is responsible for implementing the RFS. To do so, prior to each year the EPA estimates the total volume of transportation fuel expected to be used. Based on that, it computes the blending percentage obligations (the "standards") that are needed to meet the quantitative requirements of the RFS. For the current 2012 year, these standards require a total blending ratio of 9.23% for total renewable fuel, with corn-based ethanol accounting for as much as 7.104% of the expected consumption of transportation fuel (Schneff and Yacobucci, 2012). This RFS percentage is then used to determine the individual renewable volume obligations (RVOs) that pertain to "obligated parties" (e.g., blenders and fuel refiners). To enforce such quantitative obligations the EPA has developed a Renewable Identification Number (RIN) system.[2]

[2] RINs are identifiers assigned to ethanol batches at production and must follow such ethanol through the marketing chain. RINs are "separated" from ethanol only when the latter is blended with gasoline, and can then be used by obligated parties to show compliance with their volume obligations. Blenders can meet the RIN requirement by buying a sufficient amount of ethanol to satisfy their RVOs or, alternatively, by buying RINs from other obligated parties who are using more ethanol than what they are mandated (McPhail, Westcott and Lutman, 2011).

The EPA has authority to waive specific RFS requirements under certain conditions. It has now used this authority repeatedly for cellulosic biofuel, the mandated quantity of which has been reduced owing to the lack of sufficient commercial capacity for its production. Indeed, the mandate for cellulosic biofuel is emerging as a very controversial feature of the RFS, as many question whether the ambitious cellulosic biofuel mandates are actually feasible. The fact that the EPA has drastically reduced the cellulosic biofuel mandate for the first three years of its implementation is significant. For example, EISA originally envisioned 500 million gallons of cellulosic biofuels for 2012, but the EPA has reduced this year's requirement to 8.65 million gallons.

It is apparent that the current size of the US ethanol industry owes much to the quantitative mandates of the RFS. The change in rate of expansion of the industry in the mid-2000s was concomitant with the expectation of such mandates, formalized in 2005 (figure 1). The RFS provided a floor for the size of the market, and the announced schedule of increases of this mandatory market for ethanol provided a secure environment for the construction of new ethanol plants. As figure 3 shows, the expansion of the industry capacity not only mirrors the schedule of mandated production, but it also shows that the total plant capacity is converging to the maximum of the RFS mandate for corn-based ethanol (to 15 billion gallons by 2015).

An unresolved issue concerning the prospects for the ethanol industry is the so-called "blend wall." This concept refers to the possible limit posed on the use of ethanol in transportation fuel that arises because of regulations and current infrastructure. Ethanol is blended with gasoline to be used as fuel, and most ethanol is used as a 10% component of gasoline, the so-called E10 gasoline blend available at retail refueling stations. The EPA has actually recently approved use of blends up to 15% for vehicles produced in 2001 or later, but the so-called E15 blend is not yet being marketed pending the resolution of a number of practical issues. A higher-ethanol blend that can contain from 51% to 83% ethanol, the so-called E85 fuel, can be used by flexible-fuel vehicles. But the limited size of the flex-fuel vehicle fleet (about 3% of all US vehicles), the comparative scarcity of E85 pumps at refueling stations, and the apparent lack of price competitiveness of E85 fuel,[3] are currently seriously limiting the effectiveness of this avenue for biofuel use expansion (Celebi et al., 2010). Finished motor gasoline consumption in the United States was estimated by the EIA to be 8.736 million barrels per day in 2011 (about 134 billion gallons for the year), down about 6% from the pre-recession consumption level of 2007. Given that the penetration rate of ethanol in gasoline

[3] Because ethanol contains only about 70% of the energy of standard gasoline, E85 should sell at a substantial discount relative to gasoline or E10, which does not appear to be the case (DOE, 2012).

consumption is thus effectively capped at 10%, at current fuel consumption levels the blend wall is therefore at about 13.4 billion gallons of ethanol.

2.2. Biofuels and Biofuel Policies in Brazil and the European Union

Whereas the US ethanol sector stands out for the rate of growth experienced in the last decade, which has made the United States the leading producer of biofuels worldwide, other countries have also experienced rapid increases in both supply and demand of biofuels. Brazil was for the longest time the world's leader in biofuel production. Significant investments in this sector began with the establishment in 1975 of Proalcool, the Brazilian ethanol program to promote domestic energy production as a response to the oil price boom of the 1970s. Public support through various programs, including price controls, subsidized credit and lower taxes for ethanol-powered vehicles, played an important role initially, but price controls were phased out in 1999 (Martines-Filho, Burnquist and Vian, 2006; Miranda, Swinbank and Yano, 2011). Brazilian ethanol is efficiently produced from sugarcane. Most plants produce both sugar and ethanol (with some discretion on the mix of output), and can be energy self-sufficient when bagasse (crushed sugarcane stalks) is used to generate heat and electricity (Valdez, 2011). Two types of ethanol are produced and marketed: hydrous ethanol (a stand-alone fuel for dedicated engines) and anhydrous ethanol (to be blended with gasoline. Brazilian ethanol production has grown steadily, to about 7.4 billion gallons in 2010, although Brazil was overtaken by the United States as the world's largest producer in 2006.

The usefulness of dedicated-engine vehicles was severely tested in the late 1980s when hydrous ethanol suffered widespread shortages (a supply crisis brought about by the competitive pressure of cheap oil). Flexible-fuel vehicles, introduced in 2003 and currently accounting for the vast majority of new vehicles sold in Brazil, marked the beginning of renewed consumer interest in ethanol as transportation fuel. It also allows the government to influence ethanol consumption by means of mandatory blending percentage of anhydrous ethanol with gasoline. The current mandate specifies the range of 18% to 25% (the lower end of this range was revised down from 20% in 2011 to deal with tight ethanol availability). Ethanol continues to benefit from various credit subsidies, and from preferential tax treatment at both federal and state levels. Ethanol also enjoys a 20% import tariff, which was temporarily suspended in 2010 and 2011 (USDA, 2011b). Brazil's support for biodiesel, produced mostly from soybeans, is more recent. There is a biodiesel mandate for blending with diesel fuel, currently set at 5%, and a biodiesel import tariff of 14%.

In the EU the goal of increasing biofuel consumption has been a key ingredient in the pursuit of the Kyoto GHG emission targets. The 5.75% target for the biofuel share of transportation fuel, set in 2003 and to be achieved by 2010, was not mandatory and apparently not very effective. The current overarching ambition, articulated in the 2009 Energy and Climate Change Package, is summarized by the so-called 20/20/20 objective: 20% GHG emission reduction, a 20% increase in energy efficiency, and a 20% share of renewable energy in the EU total energy consumption, all by 2020 (Dixson-Declève, 2012). A part of this EU legislation is the Renewable Energy Directive, which establishes a target of 10% of renewable energy in transportation fuel use (European Union 2009). Whereas the overall aspiration of the 20/20/20 objective is for the EU in the aggregate, the 10% target of renewable fuel for transportation is mandatory for all EU individual countries, although member states are granted flexibility on instruments and modalities to pursue the target. In order to count towards the 10% goal, allowable biofuels have to meet certain sustainability criteria (USDA, 2011a). For example, biofuels must achieve a 35% reduction in carbon emissions relative to fossil fuels, a saving that is to increase to 59% in 2017.

The EU biofuel sector has experienced rapid growth over the last decade. Biodiesel production in the EU relies on a variety of feedstock, the most important of which is rapeseed oil (more than half of the total). Biodiesel production increased steadily from 1,065 MT in 2002 to 9,570 MT in 2010. But, according to the European Biodiesel Board, in 2011 the EU domestic production of biodiesel is expected to decline. Of some note is the fact that the EU biodiesel capacity utilization has been low in recent years (about 44% in 2010 and 2011). Ethanol production has also expanded, from 292 million liters in 2000 to 3,703 million liters in 2009. The favorite feedstock for ethanol production in the EU is sugar beet, but wheat, corn, rye and barley are also being used (USDA, 2011a). As noted, biofuel imports are more important for the EU than for the United States or Brazil. The import tariff for biodiesel is 6.5%, but it is considerably higher for ethanol: euro 102 per thousand liters for denatured ethanol and euro 192 per thousand liters for undenatured ethanol.[4] Apparently, most EU member states permit only use of undenatured ethanol for blending, thereby implicitly enforcing the higher tariff rate (USDA 2011a).

[4] At May 2012 average prices and exchange rates, these tariffs amount to about 22% and 42%, respectively, of the US ethanol price.

3. WHY BIOFUELS AND BIOFUEL POLICIES?

Three reasons are routinely cited to rationalize biofuel production and biofuel support policies: energy security, environmental impacts, and support for agriculture and rural development. Whereas fossil fuels have emerged as the dominant supply of energy since the industrial revolution, efforts to find other sources of energy have a long history. A major motivation is the fact that the stock of fossil fuels is fixed (although its size is uncertain) and we will therefore approach depletion at some point in the future.[5] This consideration implies that fossil fuel prices should be expected to rise over time, on average, as per the insight of Hotelling's (1931) seminal contribution, although the outlook for the intermediate run suggests price levels well below recent record-high spikes (Smith, 2009). Alternative energy sources should, therefore, become competitive as time goes by. The global concern about the scarcity of oil is further heightened at national levels and articulated as an "energy security" issue, a reflection of the anxieties (especially in importing countries) brought about by recurrent shocks, price spikes and the general volatility of the oil market. In the United States, the goal to decrease dependence on foreign energy sources is routinely articulated at the policy level (Council of Economic Advisers, 2008).[6]

What makes biofuels potentially very attractive among alternatives to fossil fuels is the fact that they are renewable, and they are liquid. Similar to other renewable sources (e.g., electricity from hydro or wind), not only do they overcome the exhaustible nature of fossil fuels, but also hold the promise of mitigating GHG emissions. Despite the fact that burning biofuels contributes to carbon emissions, just like burning gasoline, the carbon emitted is (at least partly) simply recycled (having been absorbed from the atmosphere by the feedstock used to produce biofuels). This environmental impact, and its potential benefits in the context of climate change concerns, was much touted earlier on as a justification for bioefuel support policies (Rajagopal and Zilberman, 2007), but, as discussed further below, has emerged as a controversial feature. The intermittent nature of many renewable energy production platforms, and the lack of simple ways to store renewable power, continue to be

[5] When that is likely to happen remains an open question, and indeed non-conventional petroleum sources might turn out to be the most competitive substitutes for conventional oil for many years to come (Aguilera et al., 2009). For example, a major recent development in the United States is the drastic decline in the price of natural gas (at a 10-year low in February 2012, a mere 23.8% of the price level in October 2005), which is attributed to the shale gas boom enabled by the (controversial) use of modern hydraulic fracturing (fracking) technology.

[6] Petroleum accounts for the largest share of US energy sources (37% in 2010 according to the EIA), and only about one third of it is domestically produced.

major drawbacks for renewable energy sources (Heal, 2010). Unlike other renewable energy sources, however, biofuels consist of a liquid fuel that can readily be used for transportation, and this fact is of paramount importance in explaining the enthusiasm for biofuels production.

One of the obvious economic impacts of biofuels is to increase the demand for agricultural output, beyond the traditional uses for food and feed. The resulting price effects positively impact incomes and returns in agriculture, and thus biofuels can play a positive role in the longstanding perceived need (especially in developed economies) to support agriculture. In particular, there is interest in the potential of biofuels to help with rural economic development, by spurring investment and employment in rural areas with sluggish economic activity.

The need for biofuel policies, although commonly taken as implied by the foregoing comments on the potential positive attributes of biofuels, from an economic perspective requires a distinct argument. Ultimately, the case must be made that there exist market failures that impede a desirable allocation of resources, and that the policies under consideration actually improve upon the market outcomes that would otherwise prevail.[7] Externalities that affect the environment, quite clearly, should take center stage in this context. In particular, carbon emissions, which are thought to be a primary cause of global climate change, are presumably not optimally priced (despite a panoply of taxes and regulations that affect them), as evidenced by the stated objective of most countries to reduce their level. The pursuit of energy security can similarly be related to a number of possible market failures. Repeated attempts to exercise market power by OPEC constitute *prima facie* evidence that the competitive conditions that may lead to optimal resource allocation are not met. The unequal distribution of oil wealth around the globe, and the nature of oil extraction and exploitation, make this resource prone to political control (Tsui, 2011), which further weakens the efficiency of the market in this setting. A related issue is the rationalization of a portion of national defense expenditures to protect access to foreign oil, which can be sizeable (Delucchi and Murphy, 2008). Ultimately, from a given country's perspective, the national "energy security" argument ascribes benefits to reducing oil imports, which typically also bring about national welfare gains from terms-of-trade effects (Lapan and Moschini, 2012).

[7] A somewhat higher standard would require these policies to be at least as effective, vis-à-vis the stated goals, as alternative energy policies that could be implemented instead.

4. ASSESSING THE IMPACTS OF BIOFUELS

Considerable work has been done to assess the impacts of biofuels. At its basic level, one of the attributes of the development of biofuels is to affect a fundamental change in the demand for agricultural output. Traditionally, most of the demand for agricultural output has been driven by food demand, either directly or indirectly (e.g., feed used in animal production). At the aggregate (and global) level, the dynamics of agricultural markets has thus been driven by expanding demand stemming from a growing world population and changing diets (towards more animal protein, which require more resources to produce), and by an expanding supply due to productivity increases and some increases in arable land. The recent development of the biofuel industry adds a potentially significant non-food component to total demand.

To illustrate how biofuels might affect agricultural and energy markets, and in view of the fact that mandates are emerging as perhaps the most important policy instrument in this setting, consider the following (extremely stylized) representation of how a biofuel mandate might work. Agricultural output can be used to produce either food or biofuel. Transportation fuel can come from gasoline (obtained from refining oil) and/or biofuel. There is a mandate which specifies that at least a given amount x_b of biofuel must be used. Assume further that biofuel and gasoline are obtained in fixed proportion from the agricultural output and oil, respectively, and that there are no other costs in the production of these two products. If the mandate is binding (i.e., without it the market provision of biofuel would be strictly less than x_b), then the competitive equilibrium in the agricultural and energy markets can be represented as follows:

(1) $S_c(p_c) = D_c(p_c) + x_b/\alpha$ (agricultural market equilibrium)

(2) $\beta S_o(p_o) + x_b = D_f(p_f)$ (fuel market equilibrium)

(3) $\alpha p_b = p_c$ (zero profit condition in biofuel production)

(4) $\beta p_g = p_o$ (zero profit condition in oil refining)

(5) $p_f \cdot D_f(p_f) = p_g\left[D_f(p_f) - x_b\right] + p_b \cdot x_b$ (zero profit condition in fuel blending)

where S denotes (upward-sloping) supply functions, D denotes (downward-sloping) demand functions, p denotes prices, and the subscripts are as follows: c = food, f = fuel, o = oil, g =

gasoline and b = biofuel. Furthermore, the production coefficient α denotes the quantity of biofuel produced by one unit of agricultural output, and the production coefficient β denotes the quantity of gasoline produced by one unit of oil (and units of measurement are presumed adjusted such that gasoline and biofuel have the same energy content and thus are perfect substitutes from the consumers' perspective).

Without biofuel mandates (e.g., $x_b = 0$), under the maintained assumption that no biofuel would be produced in such a case, the price of transportation fuel is simply the price of gasoline, which is in a constant relation with the price of oil and it is determined by the fuel market equilibrium: $D_f(p_g) = \beta S_o(\beta p_g)$. Similarly, the price of food is determined separately in the agricultural market equilibrium: $D_c(p_c) = S_c(p_c)$. With a positive and binding biofuel mandate $x_b > 0$, the price of food is still determined by the equilibrium condition (1), and clearly $dp_c/dx_b > 0$. The price of biofuel is linked to the price of food by (3), and thus $dp_b/dx_b > 0$. Given that the mandate $x_b > 0$ is exogenous and binding, and the price of biofuel is determined in the agricultural market, the conditions in (2), (4) and (5) determine the prices of blended fuel and of gasoline/oil. The implication of the biofuel mandate for the energy market is that of reducing the price of gasoline/oil, $dp_g/dx_b < 0$. Note that a mandate has simultaneously two distinct effects: it is a subsidy to biofuel and a tax on gasoline. The impact of the mandate on the blended fuel price, on the other hand, is indeterminate. One should expect that increasing a binding mandate raises the price of fuel (which, as implied by (5), is a weighted average of the prices of gasoline and biofuel), and thus reduces total consumption. But if the derived supply of ethanol is more elastic than the derived supply of gasoline, then over some domain an increasing ethanol mandate may in fact lower the price of fuel and raise total fuel consumption (de Gorter and Just, 2009b; Lapan and Moschini 2012).

The foregoing makes it clear that, as a consequence of biofuel production expansion, agricultural prices rise and agricultural output expands. The general belief is that the relevant supply function is rather inelastic, and so the price effects could be sizeable and larger than the output effect. In the longer run, a number of market adjustments are set into motion. Supply can expand because of new investments in agriculture, perhaps more land brought into production, and increased productivity by renewed R&D efforts. All of that can neutralize some of the price increase

effects, but the fact that biofuels essentially shift rightward the total demand for agricultural output leaves little doubt as to the nature of the final effects.

This formulation, of course, is too simplistic to provide a sufficient articulation of the important economic impacts of biofuels in real-world settings. The demand and supply in the agricultural and energy markets are affected by many other policies beyond biofuel mandates (e.g., fuel taxes, biofuel subsidies, farm support programs, trade restrictions, environmental regulations), which impact resource allocation at the national level as well as trade flows. Also, the type of feedstock used in biofuel production will matter, as will the geographical distribution of biofuel production. To get a firmer grasp on the estimated economic impacts of biofuels, including environmental and welfare effects, more comprehensive models are desirable. Numerous modeling efforts are now available that study various features of biofuel production, and the key policies believed to be responsible for the expansion of the biofuel sector. Although a simple taxonomy is perhaps reductive, roughly speaking they differ as to whether they adopt a computable general equilibrium (CGE) approach or a partial equilibrium (PE) approach.

Although other CGE models dealing with bioenergy exist (Kretschmer and Peterson, 2010), a modeling framework that has been used extensively in this setting is provided by the Global Trade Analysis Project (GTAP), originally a CGE model of agricultural trade. A series of papers have extended and adapted this model to make it suitable for analyzing biofuels, including the addition of a module that separates global land use in several agro-ecological zones. Some of the most significant published GTAP studies are summarized in the appendix. Not surprisingly, the specific results that one gets depend on the orientation of each modeling endeavor. In general it is found that: rising oil prices were an important element in the "biofuel boom," but the role of various support policies has also been critical; the impact of the biofuel expansion on composition of agricultural production is significant, especially the increase of corn acreage in the United States and the increase of oilseed area in the European Union; the cumulative nature of US and EU policies matters considerably and the analysis of these policies should be done jointly rather than separately; land-use changes are not insignificant with crop cover rising at the expense of pastureland and commercial forests; the policy of biofuel mandates reduces the transmission of price volatility from the energy sector to the agricultural sector, but might exacerbate the impact of agricultural supply shocks; explicitly incorporating by-products in the analysis is important and can considerably change the magnitude of some variables of interest; although the estimated indirect land use change (iLUC)

is lower than that suggested by other studies, the carbon benefits of biofuels relative to gasoline may be negligible.

One of the alternatives to a CGE approach is provided by PE, multi–commodity, multi-country/region models of the agricultural sector. One example is the Food and Agricultural Policy Research Institute (FAPRI) model utilized by some analysts at Iowa State University and the University of Missouri. Some studies that rely on versions of the FAPRI model are summarized in the appendix. One of the results is to emphasize the role of oil prices in determining the development and long-run size of the ethanol industry: at oil prices in the range of 60-75 $/barrel, the corn-based ethanol industry is forecasted to grow to beyond 30 billion gallons/year. A well-known application of this model was the estimation of iLUC effects (Searchinger et al., 2008), which argued that corn-based ethanol actually worsens GHG emissions. But, in another application, Dumortier et al. (2011) make the case for much lower levels of carbon emissions due to iLUC effects. A number of other studies are available, both for CGE and PE; without any claim of an exhaustive coverage, some of these studies are included in the appendix as well.

CGE models are attractive because they can link the agricultural sector to the rest of the economy, and account for feedback effects. GTAP models also link domestic agricultural sectors across countries by trade and in principle can represent bilateral trade flows. GCE models are also attractive for studying iLUC effects because they typically model competition for land across alternative uses in an explicit fashion. Conversely, PE models often rely on reduced-form specifications that sacrifice the structural internal consistency of CGE models in exchange for more disaggregated coverage in the product space, and sometimes a more detailed representation of the policy instruments at work. Evaluating results across models with such structural differences is inherently very difficult. In any event, even a casual comparison of the results summarized in the appendix would suggest that they are hardly definitive. For example, PE extrapolations of the future size of the US corn-based ethanol industry appear suspect. Another issue that has been noted is that CGE models seem to predict much lower agricultural price effects, due to biofuel expansion, than PE models (Kretschmer and Peterson, 2010), and indeed such price effects are often not explicitly discussed in the GTAP models reviewed in the appendix.

4.1. Appraising Biofuel Policies

Assessing the economics of biofuels cannot be divorced from the assessment of the policies that have been critical to support the expansion of this industry. As noted earlier, a myriad of policies

have been implemented at various junctures and/or jurisdictions to support biofuels, and an assessment of biofuel policies *per se* might be desirable. A recent comprehensive review that focuses on policy evaluation is provided by de Gorter and Just (2010). The specific normative evaluation of policy tools, of course, depends critically on the welfare criterion that is used, which in turn depends on the market failures that are presumed. As noted earlier, multiple objectives/market failures are routinely invoked to rationalize biofuel policies, but their explicit characterization is often missing in empirical studies. For example, large partial equilibrium commodity models are notoriously ill suited for welfare evaluation. Some useful conclusions, however, can be gotten from conceptual studies and parameterization of smaller models. One result of some interest is that outright subsidy to biofuel production, such as the blending tax credit implemented in the United States until its expiration at the end of 2011, have questionable impacts. In particular, de Gorter and Just (2009b) show that the introduction of such a subsidy in a setting where the mandate is binding leads to a decrease in the price of fuel (i.e., the blend of gasoline and ethanol) and thus acts as a consumption subsidy. *Ceteris paribus*, this effect increases consumption, which tends to increase (rather than reduce) GHG emissions (one of the stated objectives of biofuel policies).

A particularly interesting result in this setting emerges from the comparison of a subsidy-only policy (a price instrument) and a mandate-only policy (a quantity instrument). Lapan and Moschini (2012) show that, perhaps counter-intuitively, the optimal ethanol mandate yields higher welfare than the optimal ethanol subsidy. Thus, the equivalence between a price instrument and a quantity instrument that one typically expects in competitive models without uncertainty does not apply here. The main reason is that, as shown in Lapan and Moschini (2012), a biofuel mandate, *per se*, is fully equivalent to the combination of an ethanol subsidy and a gasoline tax that are revenue neutral. In the typical setting of interest for biofuel policies, where multiple objectives are relevant, these two effects are both desirable. Thus, in a second-best context where a full set of instruments is not available, biofuel mandates are preferable to biofuel subsidies. A distinct role for production mandates is to stimulate investments in the construction of biofuel production plants by providing assurance as to the size of future demand. The growth of the US corn ethanol capacity depicted in figure 3 certainly lends support to this perspective. To be effective in this role, however, mandates need to be credible, and this credibility might be called into question by the possibility of waivers envisioned by current US policies. A case in point is the RFS mandate for cellulosic ethanol has now been modified and largely waived for three consecutive years. Some implications of a waivable mandate in this setting are explored by Miao, Hennessy and Babcock (2011).

Insofar as a relevant objective of biofuel policies is to support farm incomes, a critical element relates to how they interact with pre-existing agricultural support policies. This is a challenging task because it entails comparing second-best policy instruments, which are typically difficult to rank from a welfare perspective, and because of the many and disparate potentially active farm policies that would need to be explicitly represented in a coherent model. An earlier study by Gardner (2007) concluded that the US ethanol subsidy reduces the deadweight loss of farm programs that are contingent on corn price (e.g., the loan deficiency payment). de Gorter and Just (2009a), by contrast, find that the annual rectangular deadweight costs—which arise because they conclude that ethanol would not be commercially viable without government intervention—dwarf in value the traditional triangular deadweights costs of farm subsidies.

4.2. Some Insights from a Specific Model

The study by Cui, Lapan, Moschini and Cooper (2011), which generalizes in a number of significant ways the framework outlined in equations (1)-(5), can help to provide some insights into the modeling of biofuel policies and the market impacts of biofuels for the case of the United States. The root of this model is provided by the theoretical analysis of Lapan and Moschini (2012) (an earlier version was presented in Lapan and Moschini, 2009), who build a simplified general equilibrium (multimarket) model of the United States that links the agricultural and energy sectors of this country to each other and to the rest of the world. Among other things, the model makes the oil price endogenous (in addition to corn price), thereby relaxing an undesirable feature of many models in this setting that treat the oil price as exogenous. In Cui, Lapan, Moschini and Cooper (2011) this model is extended to account for petroleum by-products and it is parameterized to make it suitable for calibration and simulation. The model's components are: US corn supply equation; US food/feed corn demand equations (exclusive of ethanol use), rest of the world (ROW) demand for corn imports, US oil supply (production) equation, US fuel demand equation, US petroleum by-products demand equation, ROW oil export supply equation. The model treats the ethanol-producing segment as a competitive industry with free entry, with ethanol production represented by a fixed-proportion technology and with explicit recognition of valuable by-products arising from this process (e.g., distillers dried grains with solubles). Refining of oil is also represented as a competitive industry with oil converted (in fixed proportions) into unblended gasoline and other petroleum by-products (e.g., heating oil). Gasoline is blended with ethanol to produce "fuel." Having accounted for the fact that ethanol and gasoline have different energy content per volume unit (one gallon of

ethanol is equivalent to 0.69 gallons of gasoline), ethanol and gasoline are treated as perfect substitutes to satisfy fuel demand.[8] The welfare function includes an accounting of the externality costs of carbon emissions, from the point of view of the United States, and also accounts for how changes in the terms of trade impact US welfare.

Upon calibration of the parameters, to reflect consensus on production coefficients and elasticity estimates, the model is well suited to evaluate the positive and normative impacts of a variety of policy interventions related to biofuels. The policy scenarios considered are: (i) the *status quo* characterized by the (then active) blending subsidy for ethanol and fuel tax (on both ethanol and gasoline); (ii) the *laissez faire* (no taxes nor subsidies); (iii) the no-ethanol policy (tax on fuel but no subsidy for ethanol); (iv) the first-best policy combination, which in this setting consists of oil import and corn export tariffs and a carbon tax; (v) the second-best policy consisting of optimally chosen fuel tax and ethanol subsidy; (vi) a restricted second best in which the only active policy instrument is the ethanol subsidy; and (vii) a restricted second best in which the only active policy instrument is the ethanol mandate.

Among the estimated market impacts, it is found that the status *quo policy* leads to an 11.6% increase in corn production and a 53% increase in the price of corn (relative to the no ethanol policy benchmark). The corn ethanol industry also owes its very existence to *status quo* policies: in the no ethanol policy scenario the industry virtually disappears. But it is important to note that, in the *laissez faire* scenario, the model shows a sizeable ethanol industry, more than half the size of the current industry. This result highlights a critical feature of the institutional setting. That is, the current fuel tax is levied in volume terms (about $0.39/gallon when accounting for both the federal tax and the average of state taxes) and thus, when viewed in energy terms, it is implicitly much higher for ethanol than it is for gasoline (e.g., as modeled, the current fuel tax is effectively a $0.39/gallon tax on gasoline but a $0.57/gallon tax on ethanol). Given such a volume tax on fuel, an ethanol subsidy (or an ethanol mandate) is desirable to level the playing field, even absent any environmental advantage that ethanol might have relative to gasoline.

Two of the reasons invoked to rationalize biofuel policies are to ameliorate the environment (by reducing CO_2 emission) and to lessen US dependence on foreign oil. With respect to the latter, it is found that the first-best solution (relying on an optimal import tariff) would reduce oil imports by about 20% relative to the *laissez-faire* (but the *status quo* policy only reduces oil imports by 4.6%

[8] The model does not consider trade in ethanol on the presumption that the $0.54/gallon ethanol import duty, in place till the end of 2011, effectively acted as a prohibitive tariff.

relative to the no ethanol policy). As for the impact on emissions, first- and second-best policies are essentially equivalent, both reducing carbon emission by 8.5% relative to the *laissez-faire* scenario. But the *status quo* situation actually leads to more emissions than the "no ethanol policy" scenario. As noted by de Gorter and Just (2009b), the ethanol blending subsidy ends up working as a consumption subsidy for final consumers, which, *ceteris paribus*, leads to an expansion of fuel consumption that translates into higher (not lower) carbon emissions levels.

The welfare impacts of the various policy scenarios considered are also illuminating and show that all of the ethanol support policies considered improve US social welfare (relative to both the laissez faire and the no ethanol policy benchmarks). A major reason for this result is due to the favorable terms of trade effects of the various policies; because the United States is a "large country" in the oil and corn markets, policies that reduce oil imports and/or corn exports have price effects that are beneficial to the United States. In addition to this overall welfare impact, the analysis can shed some light on the distributional effects associated with ethanol support policies. To consider this issue in more concrete terms, figure 4 illustrates the components of the welfare effect of the *status quo* as compared with the no ethanol policy scenarios. Not surprisingly, it turns out that there are clear winners and losers from these policies. The biggest beneficiaries of the *status quo* ethanol policies are corn producers and fuel consumers. Corn producers benefit from the increased price of corn (which however penalizes users of corn for food and feed), and fuel consumers benefit from the reduced equilibrium gasoline/fuel price induced by the ethanol subsidy. Users of petroleum by-products experience a welfare loss because the price of petroleum by-products increases with the subsidized increase in ethanol use (this arises because less oil is refined, which, owing to the fixed proportion technology, tightens the supply of these by-products). Figure 4 also illustrates the point mentioned earlier, that the subsidization of ethanol production in the *status quo* scenario actually worsens the externality of carbon emissions. It also shows that the monetary value of the externality amelioration is minor, compared with the other welfare effects.

4.3. Environmental Impacts

A major motivation for biofuels has been the expectation that they might provide a cleaner source of transportation fuel. On an energy equivalent basis, biofuels typically produce lower GHG emissions relative to gasoline, although major differences exist across types of biofuels and processes. For example, the performance of corn-based ethanol is sensitive to the energy used to power ethanol refineries (Wang, Wu and Huo, 2007). A necessary condition for a net positive

environmental impact is that biofuel production, viewed from the perspective of life cycle analysis (LCA), yields more energy than the fossil energy used in its production.[9] Among current (so called "first generation") biofuels, the evidence from a vast literature available suggests that Brazilian ethanol produced from sugarcane leads to the greatest carbon savings.

To evaluate the environmental footprint of biofuels, LCA takes a system-wide approach that is meant also to account for all the energy/carbon associated with the production of inputs used in biofuel production (Miranowski, 2012). But the traditional implementation of LCA essentially assumes that one unit of biofuel (in energy equivalent terms) substitutes for one unit of fossil fuel, which is unrealistic from a number of reasons (Rajagopal, Hochman and Zilberman, 2011). The general concern is that of "carbon leakage," whereby reduced emissions in an activity or country are partly or wholly offset by increased emissions elsewhere. A specific instance in our context relates to "indirect land use" effects that arise because of market adjustments to large-scale biofuel production. For example, diverting corn to ethanol production in the United States might bring new marginal land into production elsewhere because of the increased overall demand for agricultural output. Such indirect land use change (iLUC) effects can dramatically change the assessment of the environmental impacts of biofuels (Searchinger *et al.* 2008, Fargione *et al.* 2008). Whereas there is no doubt that they are plausible, accounting for iLUC effects is a non-trivial matter. Dumortier et al. (2011) show that the results of the model used by Searchinger *et al.* (2008) can be very sensitive to parametric and model assumptions. Several studies in this area have gravitated toward the use of CGE analysis. Using GTAP, Hertel, Tyner and Birur (2010) find that, to jointly meet the biofuel mandate policies of the United States and the EU, coarse grains acreage in the United States rises by 10%, oilseeds acreage in the EU increases dramatically, by 40%, cropland areas in the United States would increase by 0.8%, and about one-third of these changes occur because of the EU mandate policy. The US and EU mandates jointly reduce the forest and pasture land areas of the United States by 3.1% and 4.9%, respectively. Hertel et al. (2010), by a fuller accounting of market-mediated responses and by-product use, find lower estimates of iLUC effects, about one-fourth the value estimated by Searchinger et al. (2008). Still, the estimated iLUC effects are enough to completely eliminate any positive carbon emissions effect from corn-based ethanol.

One consequence of the emerging fuller picture on the environmental effects of biofuel production is the incorporation of iLUC effects into regulatory standards. For example, the EPA

[9] This attribute has actually been disputed by some for the case of corn-based ethanol, but it is now generally accepted as true (Farrell et al., 2008).

accounts for international iLUC in assessing the GHG emissions reduction of various biofuels to meet the RFS requirements (EPA 2010). According to the EPA, corn ethanol still achieves a 21% GHG reduction compared to gasoline and thus meets the minimum requirements established by the RFS; also, sugarcane ethanol qualifies as an advanced biofuel since it achieves an average 61% GHG reduction compared with baseline gasoline. Although the EU has acknowledged the desirability of including iLUC into its biofuel sustainability standards, this has not yet been implemented.

Environmental issues related to iLUC are not limited to the potential for indirect carbon emissions caused by biofuel expansion. More generally, the concern is that a massive expansion of biofuel production is bound to put additional stress on limited global land and water resources. The resulting intensification of production practices, and the stimulus to use marginal land, may lead to increased soil degradation, increased pollution, and may have adverse consequences for wildlife habitat and biodiversity.

5. CONCLUSION AND PROSPECTS FOR THE FUTURE

If the rapid development that biofuels have enjoyed over the last decade is to be sustained, several challenges will have to be overcome. In the United States, expansion of the corn-based ethanol beyond the limit envisioned by the RFS mandate (15 billion gallons by 2015) appears unlikely, and the dynamics of ethanol-plant capacity construction (figure 3) is consistent with this interpretation. A related but distinct issue is represented by the so-called "blend wall," where the current infrastructure might make it difficult to increase the fraction of ethanol in transportation fuel beyond 10% in volume terms. Because this blending ratio is essentially already achieved by current production levels, it is clear that this blend wall is an issue that needs resolution if the contributions of advanced biofuels (including cellulosic ethanol) are to meet the ambitious targets set out by the RFS mandates. And this, it seems, is not the greatest challenge facing so-called "second-generation" biofuels.[10] Commercial production of second generation biofuels is lagging behind the (perhaps overly optimistic) expectations embedded in the RFS mandates. Critical technological feasibility issues are still being sorted out, and the (efficient) solution to the logistical challenges of the feedstock provision, and the scalability of pilot plants into commercially viable entities, remains

[10] Such biofuels include cellulosic ethanol made from lignocellulosic biomass from crop residues (e.g., corn stover) and whole plant biomass from would-be specialized energy crops (e.g., switchgrass, miscanthus, and fast-growing trees such as poplars. Biodiesel from alternative feedstock, such as lipids from microalgae, are also considered promising avenues for second generation biofuels.

fraught with challenges. After a careful review of the state of knowledge on the key production economic issues of second generation biofuels, Carriquiri, Du and Timilsina (2011) conclude that the cost of cellulosic ethanol is two to three times larger than the price of gasoline, and the cost of biodiesel from microalgae many times higher still.

Renewed interest in the next generation of biofuels is also justified by a number of controversies that continue to surround the development of biofuels. Two of the major are: (i) the actual contribution that biofuels can realistically have towards ameliorating GHG emission vis-à-vis climate change concerns; and, (ii) the impact of large-scale biofuel production on food prices, i.e., the "food vs. fuel" debate. As discussed earlier, the contribution of biofuels to reducing carbon emission, while positive, is limited, as is the ability of biofuel to significantly reduce the use of fossil fuels. In particular, some argue that biofuels are inherently ill-suited for that purpose. Jaeger and Egelkraut (2011), for example, conclude that, for the purpose of reducing fossil fuel use and GHG emissions, US biofuels are 14-31 times as costly as other alternatives strategies (such as gas taxes and promotion of energy efficiency.

When considering biofuel policies from the perspective of carbon emissions, the recurring gold standard of an ideal policy response is a "carbon tax." To make such a policy operational, of course, one would need to assign a monetary value to the social cost of carbon pollution.[11] It is useful to note, at this juncture, the considerable uncertainty that surrounds this parameter. Tol (2009) surveys 232 published studies and finds that the mean of these estimates corresponds to a marginal cost of carbon emissions of \$105/tC (metric ton carbon) (this is equivalent to \$28.60/tCO_2). But the standard deviation of these estimates is rather large: \$243/tC (\$66/tCO_2) (all of these figures are expressed in 1995 dollars). The US National Highway Traffic Safety Administration (NHTSA), in calculating their proposed corporate average fuel economy (CAFE) standard, relies on an earlier survey (Tol, 2008) and pegs the global social cost of carbon at \$33/tCO_2 (in 2007 dollars) (NHTSA, 2009). A lower social cost of carbon is presumed by Parry and Small (2005), who use \$25/tC (expressed in year 2000 dollars), which is equivalent to \$6.8/tCO_2 (but they also account for external congestion costs of 3.5¢/mile, and an external accident cost of 3¢/mile). The widely cited "Stern Review" (Stern 2007) provides the much higher estimate of approximately \$80/tCO_2. This is mostly due to the choice of a low discount rate for future economic damage from climate change, an assumption questioned by some. By using a more

[11] The recently proposed new EU Energy Tax Directive (voted down in April 2012), for example, sought to include a common component of euro 20/tCO_2 in the tax rate of all energy products.

conventional discount rate, Hope and Newbery (2008) find that the (global) carbon cost from the Stern report could be reduced to the range of \$20-\$25/tCO_2. Another influential study (Nordhaus, 2008) suggests an estimate of about \$8/tCO_2. Quite clearly, much remains to be understood in this setting. Although this is not a problem unique to biofuel, it is nonetheless central to the design of first- and second-best biofuel policies.

Harnessing the energy of the sun by means of crops, which ultimately is what is attempted by biofuels, has to deal with an overarching constraint: land is scarce, and land used for biofuel production is not available for food production. As discussed earlier, one of the expected impacts is a rise in food prices. Whereas such price increases might be tolerable for developed economies, indeed can be viewed as quite consistent with a long-standing commitment to support the agricultural sector, this pecuniary externality clearly has distributive implications that might be undesirable for less developed countries. In a world where 850 million people are deemed undernourished (FAO, 2011), the price of food is, objectively, a serious obstacle to food security for a significant share of the world's least affluent population. How much responsibility one ought to put on biofuels in this setting depends on their actual impact on food prices, an issue that is somewhat unresolved. Qualitatively, as discussed earlier, it is clear that food prices will increase, and it is believed that biofuel production may impact food prices more than energy prices.[12]

Concerns about the food-price effects of biofuel expansion were heightened by the commodity price hike that culminated in the 2008 food crises. Although no single nor simple explanation for this phenomenon (and similar price booms experienced in the past) appears possible (Carter, Rausser and Smith, 2011; Wright, 2011), it seems clear that a sizeable increase in the diversion of basic staple commodities to biofuel production, that materialized over a short period of time, had the potential to have a very significant effect on commodity prices, especially at a time when the stocks (relative to production and demand) had been running at historically low levels (Wright, 2011). Timilsina and Shresta (2011) review a number of recent studies that have tried to estimate the likely impact of biofuel expansion on commodity and food prices. Although the magnitude of estimated price effects turns out to fall in a fairly wide range and, not surprisingly, to also depend on assumptions and modeling framework (e.g., partial equilibrium models appear to suggest larger price effects that CGE models), there is considerable evidence of a significant impact

[12] For example, in the simulation results presented in Cui, Lapan, Moschini and Cooper (2011), the *status quo* scenario relative to the no ethanol policy scenario shows a 53% increase in the corn price and only a 6% decrease in the gasoline price.

of biofuel production on commodity and food prices. As the full extent of biofuel mandates in the United States, EU and elsewhere materializes over the next few years, and global demand rebounds from the great recession, earlier concerns about the food price effects of biofuel and their implications for food security (Ford Runge and Senauer, 2007) might resurface in a heightened fashion.

The role that international trade can play in the path toward fulfilling biofuel mandates (in the United States, the EU and elsewhere) remains to be clarified. Comparison of production and consumption data of total biofuels from the EIA suggests a fairly sizeable but still somewhat limited extent of international trade in biofuels. For example, for the two most recent years with available data (2009-2010), the EIA shows net exports from Brazil (about 16% of production), net exports from the United States (about 2% of production), and net imports in Europe (about 23% of consumption). For the EU these figures might need to be supplemented by the consideration that a large fraction of feedstock used in biodiesel production (either as vegetable oils or as oilseeds that are crushed in the EU) is imported. A critical consideration in that setting refers to the impact of sustainability standards. For example, the fulfillment of the unspecified portion of advanced biofuels (i.e., apart from cellulosic biofuels and biodiesel) of the RFS mandates in the United States, which is set to reach 4 billion gallons by 2022, may well have to rely on sugarcane ethanol produced in Brazil. Yet the prospect of the United States importing sugarcane ethanol from Brazil to meet low-carbon standards, while exporting corn-based ethanol to Brazil (as observed in 2011), is perplexing. Also, lack of international harmonization of sustainability standards, and lack of uniform guidelines and institution for the certification and enforcement of these standards, holds the potential for such standards to become serious impediments to trade. The plethora of biofuel programs and subsidies can easily create situations ripe for trade conflicts (de Gorter, Drabik and Just, 2011). Still, insofar as reducing carbon emission is a global problem, the contribution of biofuels would be maximized by efficient production and full exploitation of comparative advantages.

Figure 1. World production of biofuels (thousand barrels per day)
Panel A: Ethanol; Panel B: Biodiesel

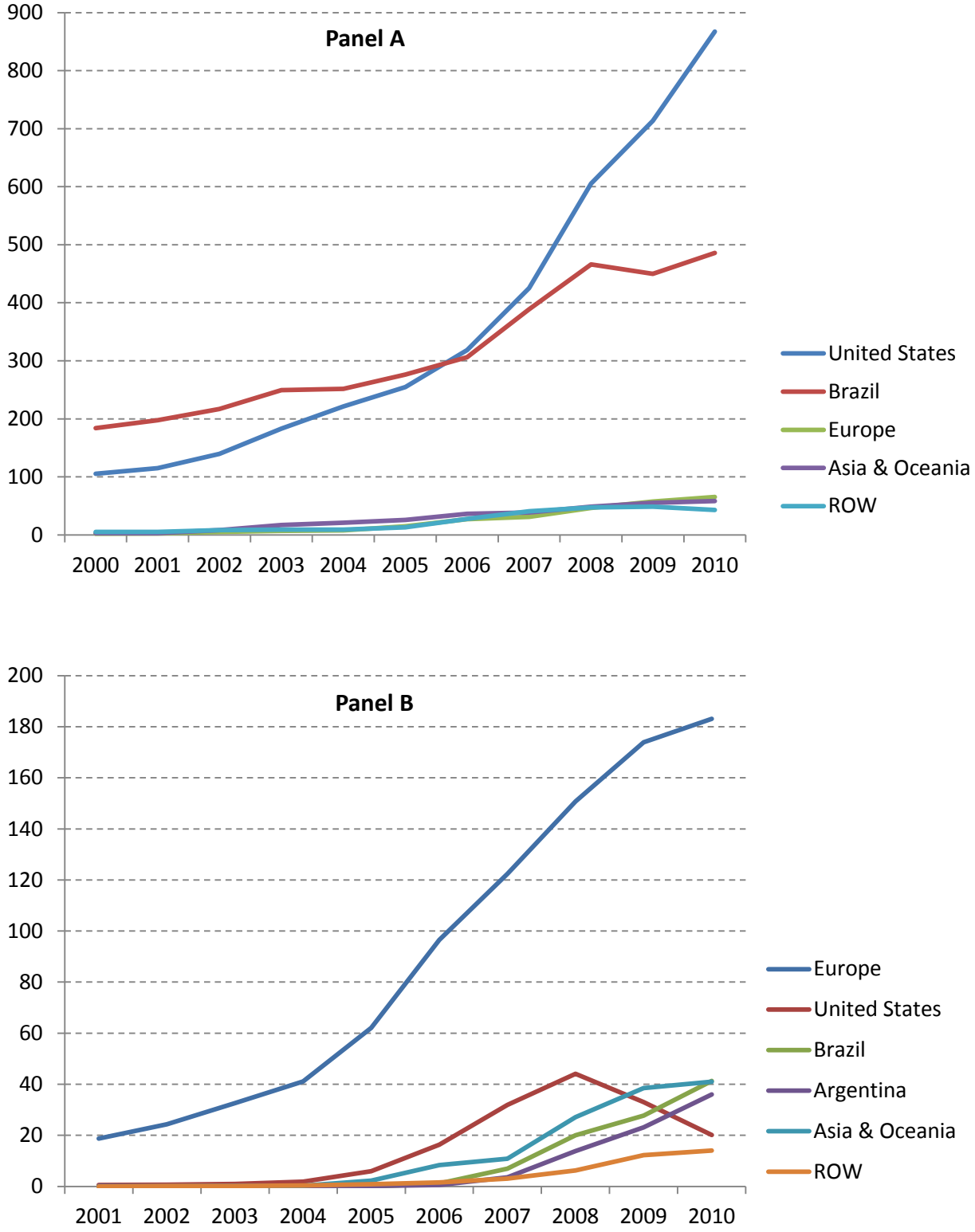
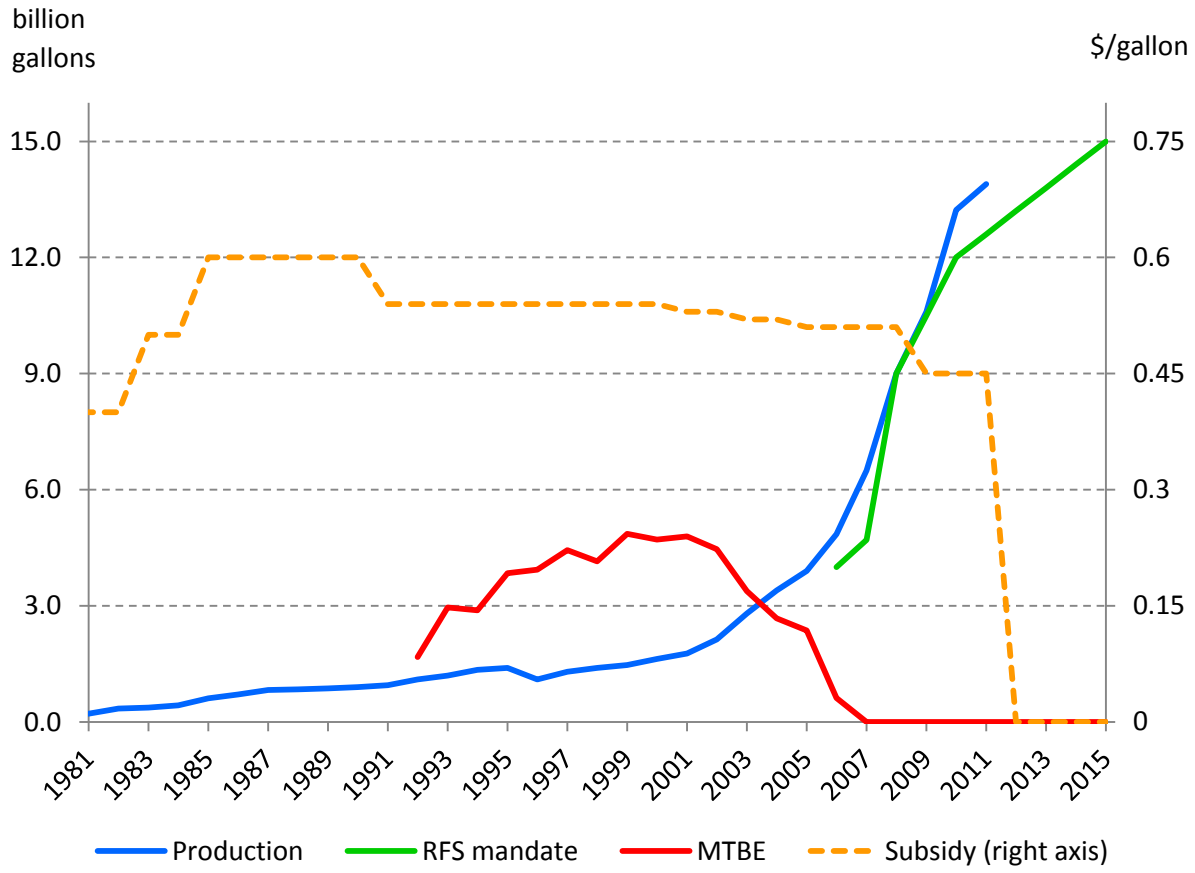


Figure 2. Evolution of the US Ethanol Industry



Note: MTBE quantity expressed in ethanol energy units.

Figure 3. Growth of the US Ethanol Industry: Capacity Expansion

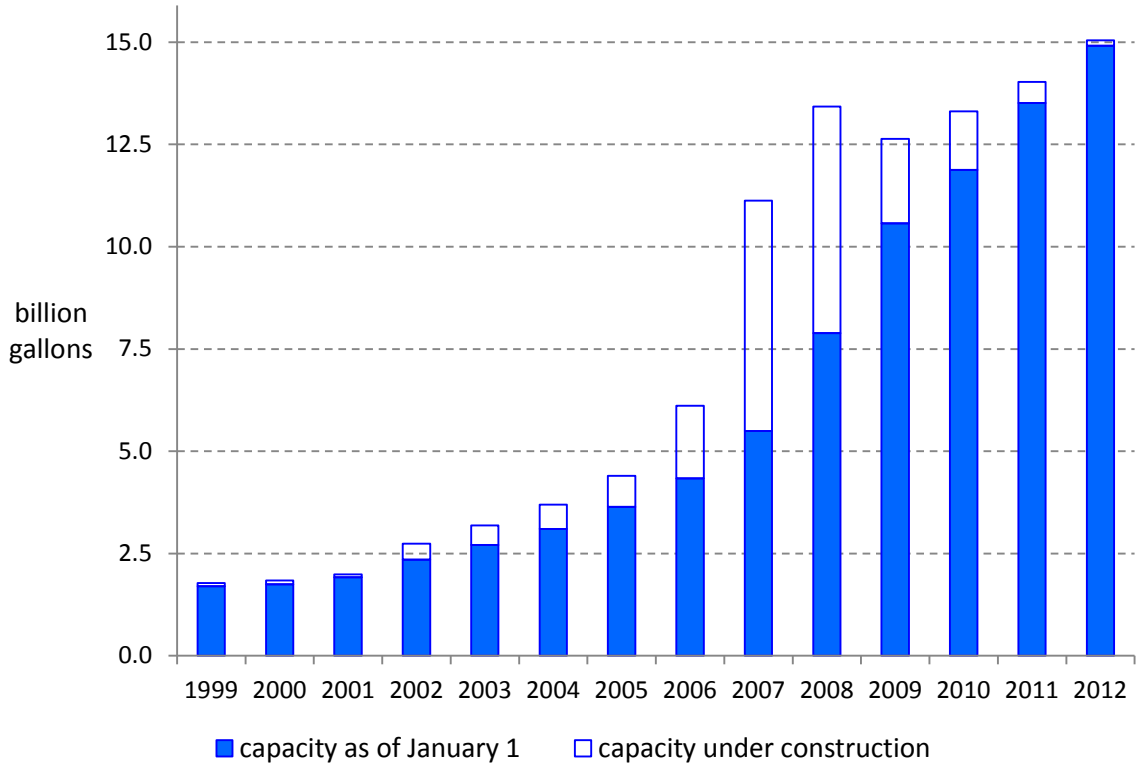
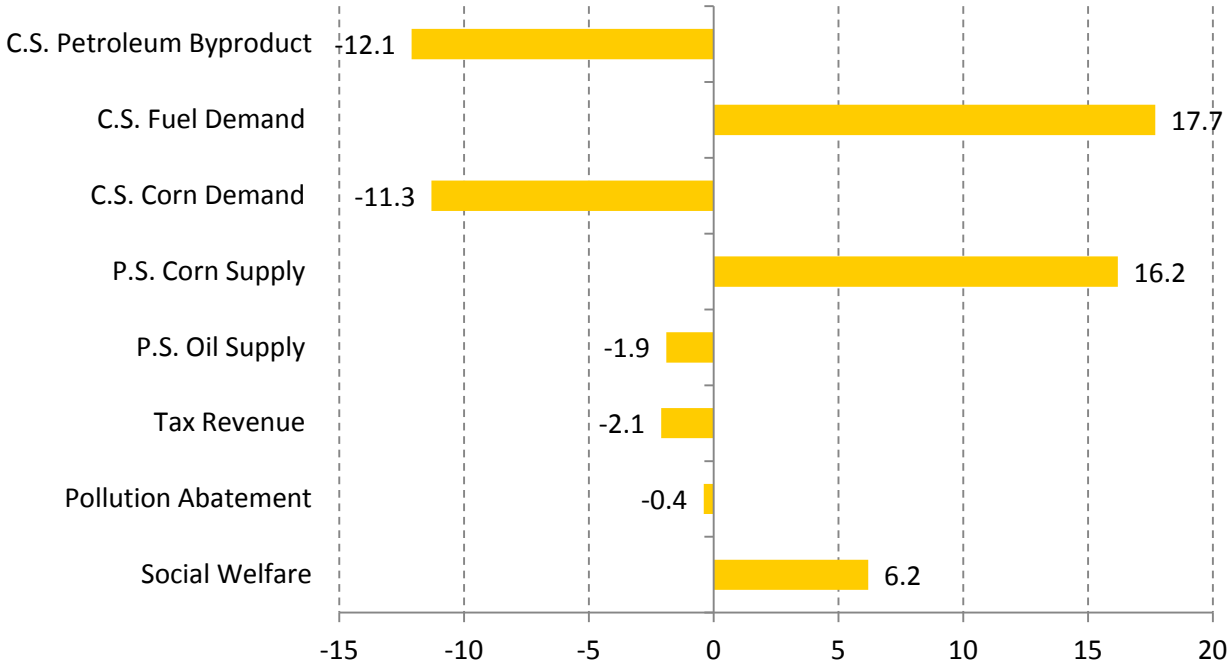


Figure 4. Welfare effects of the *Status Quo* ethanol policy (changes relative to "no ethanol policy"), $ billions (Source: Cui, Lapan, Moschini and Cooper, *AJAE* 2011)



Note: C.S.=Consumer Surplus; P.S.=Producer Surplus.

REFERENCES

Aguilera, R.F., R.G. Eggert, C.C.G. Lagos, and J.E. Tilton (2009). "Depletion and the Future Availability of Petroleum Resources." *Energy Journal*, 30(1): 141–74.

Al-Riffai, P,. B. Dimaranan, and D. Laborde (2010). "European Union and United States Biofuel Mandate: Impacts on World Markets," *Technical Notes* No. IDB-TN-191.

Beckman, J., T. Hertel, F. Taheripour, and W. Tyner (2012). "Structure Change in the Boifuels Era," *European Review of Agricultural Economics*, 39(1): 137-156.

Birur, D., T. Hertel, and W. Tyner (2009). "The Biofuels Boom: Implications for World Food Markets," *The Food Economy Global Issues and Challenges*, edit by Frank Bunte and Hans Dagevos, Wageningen Academic Publishers.

Carter, C.A., G.C. Rausser, and A. Smith (2001). "Commodity booms and busts," *Annual Review of Resource Economics*, 3: 87–118.

Carriquiri, M.A., Du, X. and Timilsina, G.R. (2011). "Second generation biofuels: Economics and policies," *Energy Policy* 39: 4222-4234.

Celebi, M., Cohen, E., Cragg, M., Hutchings, D., and Shankar, M. (2010) "Can the U.S. Congressional Ethanol Mandate be Met?," *Discussion Paper*, The Brattle Group, May.

Chen, X., H. Huang, M. Khanna, and H. Onal (2011). "Meeting the Mandate for Biofuels: Implications for Land Use, Food and Fuel Prices," *NBER Working Paper* 16697.

Council of Economic Advisers (2008). "Searching for Alternative Energy Solutions," Chapter 7 in the *Economic Report of the President*, February.

Cui, J., H. Lapan, G. Moschini and J. Cooper (2011), "Welfare Impacts of Alternative Biofuel and Energy Policies", *American Journal of Agricultural Economics* 93(5): 1235-1256.

DOE (2012). "Clean Cities Alternative Fuel Price Report," U.S. Department of Energy, January.

de Gorter, H., and D.R. Just. (2009a). "The Welfare Economics of a Biofuel Tax Credit and the Interaction Effects with Price Contingent Farm Subsidies," *American Journal of Agricultural Economics* 91(2): 477-488.

de Gorter, H., and D.R. Just. (2009b). "The Economics of a Blend Mandate for Biofuels." *American Journal of Agricultural Economics* 91(3): 738-750.

de Gorter, H., and D.R. Just (2010). "The Social Costs and Benefits of Biofuels: The Intersection of Environmental, Energy and Agricultural Policy," *Applied Economic Perspectives and Policy* 32(1):4-32.

de Gorter, H., D. Drabik and D.R. Just (2011). "The Economics of a Blender's Tax Credit versus a Tax Exemption: The Case of U.S. "Splash and Dash" Biodiesel Exports to the European Union," *Applied Economic Perspectives and Policy* 33(4):510-527.

Delucchi, M. A., & Murphy, J. (2008). "U.S. military expenditures to protect the use of Persian-Gulf oil for motor vehicles." *Energy Policy* 36(6): 2253-2264.

Dixson-Declève, S. (2012). "Fuel Policies in the EU: Lessons Learned from the Past and Outlook for the Future," Chapter 5 in: T.I. Zachariadis (ed.), Cars and Carbon: Automobiles and European Climate Policy in a Global Context, Springer Science Publisher.

Duffield J.A., Collins K. (2006). "Evolution of Renewable Energy Policy," *Choices* 21(1):9-14.

Dumortier, J., D. Hayes, M. Carriquiry, F. Dong, X. Du, A. Elobeid, J. Fabiosa, and S. Tokgoz (2011). "Sensitivity of Carbon Emission Estimates from Indirect Land-Use Change," *Applied Economics Perspective and Policy*, 33(3): 428-448.

Elobeid, A., S. Tokgoz, D. Hayes, B. Babcock, and C. Hart (2007). "The Long-Run Impact of Corn-Based Ethanol on the Grain, Oilseed, and Livestock Sectors with Implications for Biotech Crops," *AgBioForum*, 10(1): 11-18.

EPA (2010). "EPA Finalizes New Regulations for the National Renewable Fuel Standard Program for 2010 and Beyond," U.S. Environmental Protection Agency, EPA-420-F-10-006, February.

European Union (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union L140/16 of 5.6.2009.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne (2008). "Land Clearing and the Biofuel Carbon Debt," *Science* 319(5867): 1235-1237.

Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare, and D.M. Kammen (2006). "Ethanol Can Contribute to Energy and Environmental Goals." *Science* 311(5760): 506–08.

FAO (2011), *The State of Food Insecurity in the World – How does international price volatility affect domestic economies and food security?*, Food and Agriculture Organization, Rome.

Ford Runge, C., and Senauer, B. (2007). "How Biofuels Could Starve the Poor," *Foreign Affairs*, May-June.

Gardner, B. (2007). "Fuel Ethanol Subsidies and Farm Price Support," *Journal of Agricultural & Food Industrial Organization* 5(2), article 4.

Hayes, D., B. Babcock, J. Fabiosa, S. Tokgoz, A. Elobeid, T-H Yu, F. Dong, C. Hart, E. Chavez, S. Pan, M. Carriquiry, J. Dumortier (2009). "Biofuels: Potential Production Capacity, Effects on Grain and Livestock Sectors, and Implications for Food Prices and Consumers," *Journal of Agricultural and Applied Economics,* 41(2): 465-491.

Heal, G. (2010). "Reflections—The Economics of Renewable Energy in the United States," *Review of Environmental Economics and Policy* 4(1):139-154.

Hertel, T., A. Golub, A. Jones, M. O'Hare, R. Plevin, and D. Kammen (2010). "Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-Mediated Responses," *BioSience*, 60(3): 223-231.

Hertel, T., W. Tyner, and D. Birur (2010), "The Global Impacts of Biofuel Mandates," *The Energy Journal*, 31(1): 75-100.

Hope, C., and D. Newbery (2008). "Calculating the Social Cost of Carbon." Chapter in M. Grubb, T. Jamasb and M.G. Pollitt, eds, Delivering a Low Carbon Electricity System: Technologies, Economics and Policy. Cambridge, UK, Cambridge University Press.

Hotelling, H. (1931). "The Economics of Exhaustible Resources," *Journal of Political Economy*, 39: 137-75.

Jaeger, W.K., and T.M. Egelkraut (2011). "Biofuel economics in a setting of multiple objectives and unintended consequences," *Renewable and Sustainable Energy Reviews* 15: 4320-4333.

Keeney, R. and T. Hertel (2009), "The Indirect Land Use Impacts of United States Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses," *American Journal of Agricultural Economics*, 91(4): 895-909.

Khanna, M., A.W. Ando and F. Taheripour (2008). "Welfare Effects and Unintended Consequences of Ethanol Subsidies," *Review of Agricultural Economics* 30(3): 411-421.

Kretschmer, B. and S. Peterson (2010). "Integrating bioenergy into computable general equilibrium models—A survey," *Energy Economics* 32(2010): 673-686.

Lapan, H., and G. Moschini. 2009. "Biofuel Policies and Welfare: Is the Stick of Mandates Better than the Carrot of Subsidies?" Iowa State University Department of Economics *Working Paper* No. 09010.

Lapan, H. and G. Moschini (2012). "Second-best Biofuel Policies and the Welfare Effects of Quantity Mandates and Subsidies," *Journal of Environmental Economics and Management*, 63: 224-241.

Martines-Filho, J., H.L. Burnquist and C.E.F. Vian (2006). "Bioenergy and the rise of sugarcane-based ethanol in Brazil," *Choices* 21(2): 91-96.

McPhail, L., P. Westcott and H. Lutman (2011), The Renewable Identification Number System and U.S. Biofuel Mandates, ERS Report BIO-03, USDA, November.

Miao, R., D. Hennessy, and B. Babcock (2012) "Investment in Cellulosic Biofuel Refineries: Do Waivable Biofuel Mandates Matter?," *American Journal of Agricultural Economics*, 94(3): 750-762.

Miranda, S., Swinbank, A., and Yano, Y., (2011)"Biofuel Policies in the EU, US and Brazil," *EuroChoices*, 10(3): 11–17.

Miranowski, J.A. (2012), Greenhouse Gas Accounting: Life Cycle Analysis of Biofuels and Land Use Changes, OECD report COM/TAD/CA/ENV/EPOC(2010)20/FINAL, April 23.

NHTSA (2009). "Corporate Average Fuel Economy for MY 2011 Passenger Cars and Light Trucks," National Highway Traffic Safety Administration, U.S. Department of Transportation, March.

Nordhaus W. (2008). A Question of Balance: Weighing the Options on Global Warming Policies. New Haven, CT: Yale University Press.

Parry, I. W. H., and K.A. Small (2005). "Does Britain or the United States Have the Right Gasoline Tax?" *American Economic Review*, 95(4): 1276–89.

Rajagopal, D. and D. Zilberman (2007). "Review of environmental, economic and policy aspects of biofuels. Policy Research Working Paper 4341, The World Bank, September.

Rajagopal, D., G. Hochman and D. Zilberman (2011), "Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies," *Energy Policy* 39: 228-233.

Schnepf, R., and B.D.Yacobucci (2012), "Renewable Fuel Standard (RFS): Overview and Issues", CRS Report for Congress 7-5700, Congressional Research Service: Washington, D.C., January 23.

Searchinger, T.D., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T-H. Yu.*et al.* (2008) "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change." *Science* 319 (5867): 1238-1240.

Smith, J.L. (2009). "World Oil: Market or Mayhem?" *Journal of Economic Perspectives,* Volume 23(3): 145–164

Taheripour, F., T. Hertel, W. Tyner, J. Beckman, and D. Birur (2010), "Biofuels and Their By-products: Global Economic and Environmental Implications," *Biomass and Bioenergy*, 34: 278-289.

Timilsina, G.R., and A. Shrestha (2011). "How much hope should we have for biofuels? *Energy* (36): 2055-2069.

Tokgoz, S., A. Elobeid, J. Fabiosa, D. Hayes, B. Babcock, T-H. Yu, F. Dong, and C. Hart (2008). "Bottlenecks, Drought, and Oil Price Spikes: Impact on U.S. Ethanol and Agricultural Sectors," *Review of Agricultural Economics*, 30(4): 16-32.

Tol, R.S.J. (2008). "The Social Cost of Carbon: Trends, Outliers and Catastrophes," *Economics (The Open-Access, Open-Assessment E-Journal)* 2(25):1-24.

Tol, R.S.J. (2009). "The Economic Effects of Climate Change," *Journal of Economic Perspectives* 23(2):29-51.

Tsui, K. K. (2011). "More oil, less democracy: Evidence from worldwide crude oil discoveries." *The Economic Journal*, 121(551):89-115.

Tyner W.E. (2008) The U.S. Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospectus. *BioScience* 58:646–53.

USDA (2011a). "EU-27 Annual Biofuels Report," USDA Foreign Agricultural Service, GAIN Report NL1013, June 24.

USDA (2011b). "Brazil Biofuels Annual 2011," USDA Foreign Agricultural Service, GAIN Report BR110013, July 27.

Valdez, C. (2011). Brazil's Ethanol Industry: Looking Forward, ERS Report BIO-02, USDA, June.

Wang, M., M. Wu and H. Huo (2007). "Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types," *Environmental Research Letters* 2:1-13.

Wright, B.D. (2011). "The Economics of Grain Price variability," *Applied Economic Perspectives and Policy* 33(1):32-58.

Yacobucci, B. (2012). Biofuels Incetives: A Summary of Federal Programs, CRS Report for Congress R40110, Congressional Research Service: Washington, D.C., January 11.

APPENDIX

In this appendix we summarize some contributions that have studied the economics of biofuel with emphasis on their market impacts. The purpose is to allow a quick comparison of the models' methodology, key questions, and conclusions. The studies covered here are not meant to provide an exhaustive list of relevant studies to date: some are omitted for space reasons, others are omitted because they are discussed elsewhere in the text.

A1. Some GTAP studies dealing with biofuels

1. Birur, Hertel, and Tyner (*book chapter*, 2009)
Research questions: Study the impacts of biofuel growth in the EU and US (driven by the oil price shock, replacement of MTBE by ethanol, and ethanol subsidy) on world food markets
Main conclusions: The share of US corn utilized by the biofuel sector more than double from 16% in 2006 to 38% in the projected 2010. Trade balance for petroleum products improves by about $6 billion which is largely offset by deterioration in US agricultural trade balance. The US corn acreage rises by 10%, the EU oilseeds acreage rises by 12%.

2. Keeney and Hertel (*AJAE*, 2009)
Research questions: Study the importance of the acreage response and bilateral trade specification in predicting global land use change.
Main conclusions: Nearly 30% of the five-year output response to a shock of marginal ethanol demand is expected to come from yield gains.

3. Hertel, Tyner, and Birur (*Energy Journal,* 2010)
Research questions: Study the interacted impacts, on global markets, of biofuel mandates in the US and EU (15 billion gallons of ethanol by 2015 in US and 6.25% of total fuel as renewable fuel by 2015 in EU).
Main conclusions: US oilseed output falls by 5.6% in the presence of a US-only mandate, due to the dominance of ethanol in the US biofuel; when the EU policies are added, US oilseed production actually rises. US exports of coarse grains are reduced by nearly $1 billion. EU exports of coarse grains, oilseeds and other food products are sharply reduced. Coarse grain acreage in the US rises by 10%, oilseed acreage in the EU increases dramatically by 40%. Cropland area in the US increases by 0.8%, and about one-third of these changes occur because of the EU mandate. The US and EU mandates jointly reduce the forest and pasture land areas of the United States by 3.1% and 4.9%, respectively. US, EU and world welfare decline.

4. Taheripour et al. (*Biomass and Bioenergy*, 2010)
Research questions: Study the effects of incorporating biofuel byproducts into the GTAP framework by comparing the impacts of the US and EU biofuel mandate policies with and without the byproducts.
Main conclusions: The model with by-products shows smaller changes in the production of cereal grains and larger changes for oilseeds in the US and EU, and the reverse for Brazil. Prices change less in the presence of by-products, e.g., coarse grains in the US increase 13.0% with the presence of by-products instead of 19.8% in the absence of by-products. The model with and without byproducts predicts sharply different changes in trade flows. Incorporating byproducts alters the land use consequences of the joint US and EU mandates, e.g., coarse grain area in the US increases 7.1% when accounting for byproducts instead of 11.3% (without byproducts). With byproducts, less of forest and pasture land are converted to cropland.

5. Beckman et al. (*ERAE,* 2012)
Research questions: Study how energy price volatility transmits to commodity prices, and how energy policy affects the volatility of agricultural commodity prices in the presence of US and EU biofuel mandates.
Main conclusions: The imposition of the US and EU mandates reduces the susceptibility of agricultural markets to energy volatility, but increases the supply-side impacts. US markets are more vulnerable than the EU to supply-side shocks due to their product-specific mandates.

6. Hertel et al. (*BioScience,* 2010)
Research questions: Provide a comprehensive analysis of market-mediated changes in global land use in response to the expansion of US-grown maize for ethanol.
Main conclusions: The associated GHG release due to indirect land use change (iLUC) is 800 grams of CO_2 per megajoule (MJ), which is roughly a quarter of the estimate of emissions reported by Searchinger et al. (2008).

A2. Some CARD/FAPRI studies dealing with biofuels

7. Elobeid et al. (*AgBioForum,* 2007)
Research questions: Study the long-run potential, and impacts on food markets, of corn ethanol.
Main conclusions: Given an exogenous crude oil price of $60 per barrel, the estimated long-run corn price is $4.05 (a 58% increase). The corn-based ethanol production reaches 31.5 billion gallons per year, with corn area and total corn production increasing by about 20%. Soybean price declines.

8. Tokgoz et al. (*Review of Agricultural Economics,* 2008)
Research questions: Study the impact of drought and oil price spikes on ethanol production.
Main conclusions: The projected long-run ethanol production increases by 55% in response to an increase in oil prices of $10 per barrel. The increase of corn acreage is partly offset by a decline in the acreages of soybean and wheat. A US crop shortage similar to the 1988 drought raises the price of corn by 44% (because the RFS mandate prevents ethanol production from dropping substantially).

9. Searchinger et al. (*Science,* 2008)
Research questions: Study the environmental impacts of biofuels through emissions from iLUC.
Main conclusions: Accounting for emissions from iLUC, corn-based ethanol, instead of producing 20% savings, nearly double GHG emissions over 30 years and emits 177 grams CO_2 per MJ. The portion of these emissions due to the iLUC is around 104 grams CO_2 per MJ.

10. Hayes et al. (*Journal of Agricultural and Applied Economics,* 2009)
Research questions: Study the impacts, on agricultural markets, of four different scenarios: high energy price, high energy price without biofuel tax credits, low energy price without biofuel supports, and high energy price with tax credits but without E-85 bottlenecks.
Main conclusions: The baseline scenario with the price of crude oil set exogenously at $75 per barrel projects 32.9 billion gallons of corn-based ethanol production by 2022. The high energy price scenario (price of crude oil set at $105 per barrel) increases ethanol production by 50% relative to the baseline. Removing the biofuel tax credits from the high crude oil price scenario leads to an ethanol production decline of 35%. In the scenario with a low crude oil price ($75) and no biofuel supports, ethanol production drops by 72% relative to the baseline. In the last scenario, corn-based ethanol production reaches 39.8 billion gallons.

11. Fabiosa et al. (*Land Economics,* 2010)
Research questions: Study global land-allocation effects of biofuels by contrasting two exogenous shocks on ethanol demand: i.e., a 10% increase in U.S demand, and a 5% increase in world demand.
Main conclusions: Higher US demand for ethanol only translates into a US ethanol production expansion, with little global ethanol expansion. This US expansion however has strong global effects on land allocation.

In contrast, an expansion in non-US ethanol demand mainly affects the world ethanol market and land used for sugarcane production in Brazil and, to a lesser extent, in other sugar-producing countries. The Brazilian expansion has a small impact on land uses in most other countries.

12. Dumortier et al. (*Applied Economic Perspectives and Policy,* 2011)
Research questions: Provide a sensitivity analysis of GHG emissions from iLUC for the model used in Searchinger et al. (2008)
Main conclusions: Emissions from iLUC are around 63 grams of CO_2 per MJ, which are less than two-thirds of the level calculated by Searchinger et al. (2008).

A3. A few other studies dealing with biofuels

13. Al-Riffai, Dimaranan, and Laborde (*IFPRI Working Paper,* 2010)
Approach: CGE model.
Research questions: Study the impact of the EU and US first-generation biofuel policies with different trade policy scenarios, i.e., mandate policy, and mandates along with trade liberalization.
Main conclusions: The baseline projects that, in 2020, the US produces 1.25 million tons oil equivalent (MTOE) biodiesel and 17.8 MTOE ethanol, while the EU produces 9.10 MTOE biodiesel and 1.87 MTOE ethanol. In the 1st scenario, the EU and US mandates together will lead to a 58.1% increase in US ethanol, and 49.8% increase in EU ethanol. Biodiesel production expands by 115% in the US and by 44.3% in the EU. This leads to a reduction in oil demand and a slight decline in the world oil price (2%). With trade liberalization in place, there is a 18% increase in US ethanol production but a 55% decline in EU ethanol production. The world oil price displays a smaller decline. These two policy scenarios improve US terms of trade (0.36% and 0.21%).

14. Khanna, Ando, and Taheripour (*Review of Agricultural Economics,* 2008)
Approach: Multi-market equilibrium model.
Research questions: Study the welfare impact, for the United States, of a carbon tax ($25 per tC) and ethanol subsidy, assuming pollution externality from fuel consumption and ethanol demand as a gasoline substitute driven by the vehicle miles traveled (VMT) by consumers.
Main conclusions: The fuel tax of $0.387 per gallon and the then-current ethanol subsidy of $0.51 per gallon reduce carbon emissions by 5% relative to the no-tax, *laissez faire* situation. The second best policy of a $0.085 per mile tax with a $1.70 per gallon ethanol subsidy could reduce gasoline consumption by 16.8%, thereby reducing carbon emissions by 16.5% (71.7 million tC).

15. Chen et al. (*NBER Working Paper,* 2011)
Approach: Multi-market equilibrium model with endogenous land allocation.
Research questions: Study the welfare implications of four policy scenarios, for the United States, in the context of both corn-based ethanol and cellulosic ethanol: a carbon tax, RFS mandate alone, RFS mandate with biofuel subsidies, and carbon tax with the RFS and subsidies.
Main conclusions: The business as usual (BAU) scenario projects 50.7 billion liters of corn ethanol production. Compared with the BAU, a carbon tax of $30 per ton of CO_2e raises ethanol consumption by 10.5%, leading to an expansion in corn acreage by 7.5%, an increase in corn price by 7.5%, and a decline in GHG emissions by 0.57 billion metric tons (2%). The RFS alone results in a reduction in GHG emissions by 0.32 billion metric tons. Subsidies in the 3rd scenario make cellulosic ethanol more competitive than corn ethanol, converting cropland (including corn land) to miscanthus acreage. Thus, corn ethanol production falls to 33.4 billion liters while cellulosic production increases to 103.1 billion liters, resulting in a further decline in GHG emissions relative to the BAU scenario. When the carbon tax is applied together with the RFS and subsidies, land uses for miscanthus and for switchgrass (hence the cellulosic ethanol production) further increase, leading to a 5.3% reduction in GHG emissions relative to the BAU.