CHAPTER 6

Modeling Biofuels Policies in General Equilibrium: Insights, Pitfalls, and Opportunities

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Abstract
Over the past decade, biofuels production in the European Union and the United States has boomed – much of this due to government mandates and subsidies. The United States has now surpassed Brazil as the world's leading producer of ethanol. The economic and environmental impact of these biofuel programs has become an important question of public policy. Due to the complex intersectoral linkages between biofuels and crops, livestock as well as energy activities, CGE modeling has become an important tool for their analysis. This chapter reviews recent developments in this area of economic analysis and suggests directions for future research.

Keywords: Biofuels, economic analysis, general equilibrium, renewable fuel standard, land use

1. Motivation

1.1. Why is it important to provide quantitative analyses of biofuels?

Ethanol has been produced for fuel in the United States for over 30 years. The industry launch was initiated by a subsidy of 40 cents/gallon provided in the Energy Policy Act of 1978. Between 1978 and today, the ethanol subsidy has ranged between 40 and 60 cents/gallon. The federal subsidy in 2010 for corn ethanol is 45 cents/gallon. The subsidy has always been a fixed amount that is invariant with oil or corn prices (Tyner and Quear, 2006).

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In addition to the federal blending credit subsidy, there are also some other federal and state subsidies. Many states have complicated combinations of state subsidies, renewable fuel standards, producer incentives, etc. For example, the current Minnesota producer tax credit is 20 cents/gallon. (Schumacher, 2006). In fact, Koplow (2006) calculates the total ethanol subsidy in 2006 to range between $1.05 and $1.38 per gallon or between $1.42 and $1.87 of gasoline equivalent. Many would regard these figures as being high, but they do demonstrate that the ethanol industry has been one with substantial subsidies.

In addition to these state and federal subsidies, there is also a tariff on imported ethanol of 54 cents/gallon plus 2.5% of the import value (Tyner, 2008b). This tariff was originally designed to offset the ethanol subsidy that applies to both domestic and imported ethanol. Congress wanted to subsidize domestic ethanol and not imported ethanol, so the import barrier was created. No doubt, this import protection has prevented lower-cost foreign ethanol from entering in the volumes that might be possible without the tariff.

In 1990, the Clean Air Act was passed, which required vendors of gasoline to have a minimum oxygen percentage in their product. Adding oxygen enables the fuel to burn cleaner, so a cleaner environment became another important justification for ethanol subsidies. By requiring the oil industry to meet an oxygen percentage standard instead of a direct clean air standard, the policy favored additives like ethanol that contain a high percentage of oxygen by weight. However, methyl tertiary butyl ether (MTBE), a competitor for oxygenation, was generally cheaper than ethanol and was produced by the oil industry, so it continued to be the favored way of meeting the oxygen requirements.

Crude oil price as measured by composite U.S. refinery acquisition cost (IEA, 2009) in nominal terms has ranged between $10 and $30 per barrel between 1983 and 2003, except for a couple of short-term spikes. Thus, for most of the period we have had a fixed ethanol subsidy, while the crude oil price has been around $20 per barrel. That subsidy together with oil in the $10 to $30 range was sufficient to permit growth in ethanol production from about 430 million gallons in 1984 to about 3.4 billion gallons in 2004 (Tyner, 2007). In other words, production grew 149 million gallons/year. In 2004, the crude oil price began its steep climb to around $70 per barrel, and in 2008 topped $140 per barrel. This rapid increase in the crude price while the ethanol subsidy remained fixed led to a tremendous boom in construction of ethanol plants. In addition, MTBE was found in many local water sources, and it is highly toxic. In the 1990s, states began to ban MTBE, and the ban was complete in May of 2006. Thus, ethanol became the primary oxygenate and octane enhancer for gasoline (Tyner, 2008a; Hertel *et al*., 2010b).

In 2007, Congress passed the Energy Independence and Security Act (U.S. Congress, 2007). That legislation substantially increased the

Renewable Fuel Standard (RFS) from 7.5 billion gallons to 36 billion gallons total, which must be achieved by 2022. Of the 36 billion gallons total, 15 billion can be corn-based ethanol, which must be attained by 2015. On an energy equivalent basis, the 36 billion gallons amounts to about 15% of projected U.S. liquid fuel consumption in 2022.

By 2009 U.S. corn ethanol production had increased to about 10.5 billion gallons. But capacity had grown to about 12.4 billion gallons. During 2008–2009, there was at times over 2 billion gallons of capacity shut down because of adverse economic conditions (high corn price and low ethanol and gasoline prices).

Perhaps the biggest barrier facing the biofuels industry in the United States today is the blend wall (Taheripour and Tyner, 2008). In the United States, ethanol blends at present are limited to 10% for standard vehicles. There is a second blend called E85, which is up to 85% ethanol, but can only be used in flexible-fuel vehicles (FFVs) designed to accommodate the higher ethanol blends. The E85 market in the United States is miniscule, so most ethanol is marketed through the E10 channel. The U.S. total gasoline-type fuel consumption is about 140 billion gallons/year. If every drop of gasoline could be blended with ethanol, the maximum ethanol consumption at the 10% blend limit would be 14 billion gallons. However, for infrastructure and environmental reasons, ethanol cannot be blended at the maximum level in every region and throughout the year. Our estimate is that the effective maximum blending level is about 9% or about 12.5 billion gallons. The United States already has this level of ethanol production capacity, so the industry has hit the blend wall. EPA has indicated it will rule on the request to increase the blending limit in the summer of 2010. If the limit is not increased, the ethanol industry cannot grow at all, and the 15-billion gallon RFS will not be attained. If it is increased to 15%, then the effective blend wall becomes about 19 billion gallons. In that case corn ethanol can meet its RFS level, but there will be little room under the blend wall for cellulose-based biofuels.

The European Union also has ambitious biofuel mandates and significant production levels at present. The EU target is 10% of liquid fuels on an energy basis from renewable resources by 2020. This target is part of a broader goal of 20% of total energy consumption from renewable sources by 2020. The EU is producing and consuming both ethanol from sugar and wheat and biodiesel from oilseeds, primarily rapeseed. Biodiesel is by far the largest share of renewable liquid fuels in the EU as the automobile fleet utilizes a much higher fraction diesel than in the United States. The EU target has detailed sustainability criteria including greenhouse gas (GHG) emissions reductions targets. Indirect land use change (iLUC) must be considered in measuring GHG impacts as in the United States.

The other leading biofuel producer is Brazil. Over the past three decades Brazil has been the leading global producer of sugarcane, the primary input for ethanol in the country (Zuurbier and van de Vooren, 2008).

Ethanol production took off in the 1970s when oil prices skyrocketed and sugar prices had experienced a sharp decline and the Brazilian government created a program in order to promote growth within the ethanol industry. In the 1980s, oil prices began to decline following the second oil crisis, and Latin America began experiencing financial difficulties and hyperinflation (Martines-Filho *et al.*, 2006). In the mid-1990s ethanol prices were deregulated and the industry began to flourish once again. In 2002, the first FFVs were introduced by Ford (Sandlow, 2006). In early 2008, ethanol consumption exceeded gasoline consumption for the first time. Also, in that year, the United States surpassed Brazil to become the leading ethanol producer in the world.

Many other nations are also experimenting with biofuels and have biofuels targets in place, including Argentina, Canada, China, Colombia, India, Indonesia, Peru, the Philippines, and Thailand. All in all, the biofuel industry has developed a very significant global presence, with subsidies, tariffs, quantitative restrictions all in operation. What is the welfare cost of these policies? What is the distribution of costs and benefits from the policies across sectors and across countries? What are the environmental impacts of these policies? How much do they affect the global demand for petroleum, and hence oil prices? Are they likely to lead to increased or decreased commodity market price volatility? All of these are important questions that need to be addressed. The next section of this chapter explains why applied general equilibrium analysis is the preferred vehicle for such analysis.

1.2. Why CGE analysis?

In principle, if the biofuels sector is a small portion of the total economy, it would seem that partial equilibrium analysis of the sector should be sufficient. These policies are unlikely to significantly affect economy-wide wages and national spending. However, as one looks more closely at the issue it becomes difficult to ascertain where to draw the line between the modeled sectors and the rest of the economy. Take for example the feedstock used to produce ethanol. Since corn comprises such an important share of total ethanol costs, their production must be explicitly modeled. As the ethanol industry expands, a key issue is how fast corn prices will rise. Ultimately, these rising feedstock costs are what choke off ethanol expansion.

Of course how much corn prices rise depends on the availability of land. In the United States, the first impact of increased corn production has been to divert acreage from competing crops – shifting, for example, from corn–soybean rotations to continuous corn production. Modeling these other crops is important since reductions in U.S. soybean production translate into increases in soybean production overseas. And this increased production has been the subject of considerable policy debate (Searchinger *et al.*, 2008a, 2008b). Does it lead to increased deforestation and hence GHG emissions? Part of the problem in the early days of U.S. biofuel policy formation was that more comprehensive models were not used in the environmental assessment of the U.S. ethanol program. Initial estimates of the GHG emissions impacts of ethanol were based solely on commodity-specific, partial equilibrium analysis. These studies (e.g., Farrell *et al.*, 2006) highlighted the GHG emissions reductions likely to ensue if ethanol produced from corn were used to replace petroleum in the liquid fuel economy. It was on this basis that the U.S. renewable fuel mandate for corn ethanol was proposed, assuming that it would benefit the environment, while reducing dependence on imported oil and boosting farm incomes. Only when more comprehensive economic modeling was undertaken did the phenomenon of indirect land use (to be further discussed in the following text) enter the debate. This turned out to reverse the conclusions. Therefore, it is clearly important to include the competing land-using activities in any biofuels policy model – specifically livestock pasture and forestry. At this point we have argued in favor of expanding the partial equilibrium model beyond the ethanol sector to include agricultural cropping, livestock production, and forestry (Figure 1).

But there are further important linkages that must also be taken into account in order to obtain an accurate assessment of biofuels policies. Turning to the demand side, we note that the demand for ethanol in the United States depends critically on the overall demand for liquid fuels in transportation. As noted previously, once ethanol use reaches 10% of fuel demand, the blend wall becomes binding. So it is important to model aggregate liquid fuel demand explicitly, as biofuels policy affects fuel prices

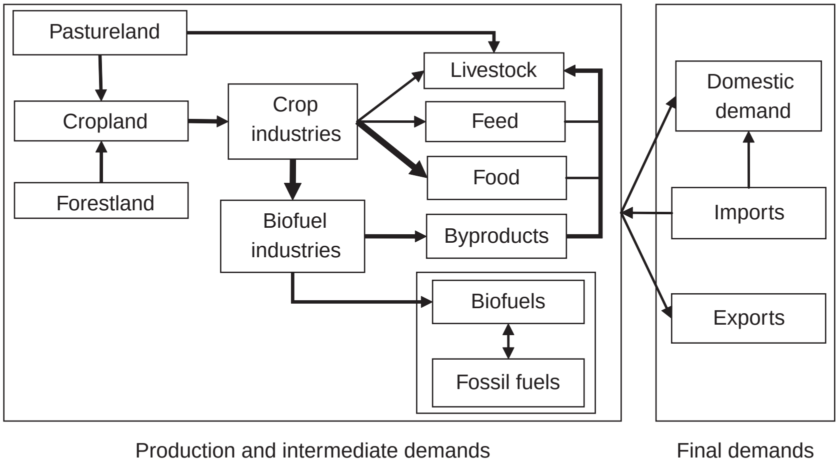

Fig. 1. Key economic linkages between biofuels and other sectors of the economy.

and fuel prices affect aggregate demand. This involves following what happens to petroleum prices, which are expected to fall under significant biofuel developments, as petroleum is displaced in the fuel mix. Adding energy markets significantly expands the scope of the model.

However, this is not the end of the story when it comes to expanding the model. In the case of ethanol, about 16.5% of industry revenue comes from by-products (dried distillers' grains with solubles, or DDGS) Taheripour *et al*. (2010). This figure is even larger in the case of biodiesel processing. DDGS substitutes for corn in livestock feeding (Figure 1). In effect, the process of ethanol production does not fully exhaust the feed value of the corn. So if one wants an accurate picture of the impact of ethanol production on global land use, for example, it is critical to take into account the role of by-products in filling part of the niche vacated by the corn being diverted from the livestock sector to energy production. This entails developing a proper model of the livestock feeding decision. In short, if one were to take a partial equilibrium approach to the problem, it would be hard to know where to draw the line on which components of the economy to model and which to ignore. In the end, it is easier to take a general equilibrium approach in order to ensure that nothing important has been missed.

An additional dimension of this strategic modeling decision has to do with the trade-off between econometric and CGE/simulation modeling of biofuels. With recent advances in structural econometric modeling and statistical estimation of CGE models, the line between these two methodologies has blurred somewhat. However, the fact remains that in order to undertake effective econometric estimation of key economic parameters, it is necessary to have a reasonably long time series of data for estimation of the biofuel supply and demand relationships. However, in most parts of the world, the biofuel boom is a relatively recent phenomenon and estimation of the key parameters is simply not a realistic option. This is another factor favoring the use of CGE analysis for biofuels.

2. *Modeling framework*

2.1. Key elements of the GTAP model for biofuel analysis

The Global Trade Analysis Project (GTAP) (Hertel, 1997) model is widely used for global economy wide analysis of trade, energy, and environmental issues. The great strength of the standard GTAP model is the fact that it is well documented, publicly available, and readily modified. In this chapter we focus on a variant of the standard GTAP model nick-named GTAP-BIO (Birur *et al*., 2008). GTAP-BIO is modification of the GTAP-E model (Burniaux and Truong, 2002; McDougall and Golub, 2007) designed for the energy–economy–environment–trade linkages analysis. With respect to biofuels, the most important feature of GTAP-E is energy substitution – a key factor for environmental policy analysis, which is absent from the standard GTAP model.

Birur *et al.* (2008) modify the GTAP-E model to incorporate both the Leontief demand for ethanol as a fuel oxygenator as well as the potential for ethanol and other biofuels to substitute for petroleum products as an energy source. We adopt this specification. Furthermore, we draw on the revised set of parameters proposed by Beckman *et al.* (2010), who undertake a historical validation exercise and find that the energy demand elasticities in the standard GTAP-E model were far too elastic. Here, we focus on several key elements of the GTAP-BIO model that are important for the subsequent applications considered. These model features include the specification of bilateral trade, the determination of land cover changes in response to increased biofuel feedstock production, and the response of crop yields – both at the intensive and extensive margins – to higher prices induced by biofuel policies.

2.1.1. Bilateral trade specification

Increasing production of biofuels from crops results in price increases for feedstocks and related crops, sending the signal to producers to expand the area under cultivation. While most of this increased area will likely come from other crops, eventually some is expected to come from the conversion of pastureland and forests, which in turn results in increased GHG emissions. The extent of such land cover conversion and the carbon intensity of the land cover that is converted to crops depend critically on the country/agro-ecological zone (AEZ) where this conversion occurs. Accordingly, the specification of international trade in the economic model is critical. There are two different views on how patterns of trade in commodity markets affect the crop replacement: "Armington" and integrated world market (IWM) for agricultural commodities. And these two approaches give rise to quite different predictions about the location of land cover change.

Under the Armington approach to import demand, utilized in the GTAP model, products are differentiated by national origin. This introduces a strong element of economic geography into the analysis. In the GTAP trade specification, agents first decide on the sourcing of their imports, and then, on the basis of the resulting composite import price, they determine the optimal mix of imported and domestic goods. In the case of increased production of biodiesel in the EU, the Armington model tends to predict that a majority of the cropland conversion will arise domestically, within the EU, followed by its dominant export competitors and import suppliers. This makes intuitive sense. However, the downside of this modeling approach is that price differences are allowed to persist over time for products that many would consider to be relatively homogeneous.

The main alternative to the Armington view is that of IWMs, which postulates a single global market for agricultural commodities and a single market clearing price. This is the modeling approach utilized in the study by Searchinger *et al*. (2008a). Under this view of the world, land cover change in response to an EU or U.S. biofuels program is equally likely to take place anywhere in the world where the product is currently produced, *ceteris paribus*. As a result, that study predicted significant land cover change in India – a country that trades relatively little in agricultural commodities. (Of course, other considerations enter into the determination of land cover change in both modeling frameworks, including the supply responsiveness of crops in each region.)

The trade specification not only determines what regions and ecosystem types the additional cropland comes from, but also affects the size of the net global cropland requirement, depending on relative yields in the different regions. Consider the case of U.S. corn production for ethanol. U.S. yields are among the highest in the world. When one hectare of corn grown for food is displaced by one hectare of corn for fuel in the United States, more than one hectare in the rest of the world will be needed to cover the shortage of corn for food. As we move from the Armington to the integrated world market assumption, the shock originated in the United States is more easily transmitted through the global economy and the production change in the rest of the world is greater. Because U.S. corn yields are higher than corn yields in other regions of the world, the net global land requirement under integrated world market will be higher than under Armington assumption. In summary, the trade specification selected for biofuels analysis will have an important impact in determining how "green" the biofuel is determined to be.

Ultimately, it is an empirical question as to which trade specification is more appropriate for a particular biofuels scenario. Villoria and Hertel (2009) formulate an econometric model that permits them to test these competing hypotheses. Their model seeks to predict the pattern of global cover change, as reported by the FAO, in response to U.S. coarse grains prices, among other things. In the IWM formulation of the model, U.S. export prices are a significant explanatory variable in this land cover change equation. However, when geographic variables (e.g., measures of export competition in third markets) are permitted to enter the model, the world price effect is no longer significant. Thus, they reject the IWM hypothesis in favor of the Armington model.

However, this finding is not definitive, and it does not apply to all markets. Since the analysis is done at the level of coarse grains, it could be argued that the Armington effect is being picked up due to differences in product composition. It would be good to test this hypothesis at the level of a more narrowly defined commodity (e.g., corn). Even if the IWM hypothesis is rejected for corn, it may still be valid for other feedstocks (e.g., sugar or oilseeds). This is fundamentally an empirical question that should ideally be tested in the case of each biofuel feedstock.

Finally, there is the question of length of run. While these geography effects surface in annual time series data, do they persist over a period of 10 years? Some evidence on this matter may be gleaned from a cross-sectional approach to the estimation of trade share equations, as in Hertel *et al.* (2007). Those authors estimate the responsiveness of import trade shares to bilateral variations in international trade and transport costs. They obtain highly significant estimates of the associated Armington parameters, ranging from 30 for natural gas (essentially confirming the IWM hypothesis) to 2.6 for the heterogeneous category of "other crops." In the work discussed below, on the basis of the GTAP model, we utilize Hertel *et al.* (2007) econometric estimates of the Armington parameters.

2.1.2. Land use component

When modeling competition for land, it is important to recognize that land is a heterogeneous endowment. Following the pioneering work of Darwin *et al.* (1995), this heterogeneity can be reflected in a CGE model via the introduction of AEZs (Lee *et al.*, 2005). In each region of GTAP-BIO, there may be as many as 18 AEZs that differ along two dimensions: growing period (six categories of 60-day growing period intervals) and climatic zones (three categories: tropical, temperate, and boreal). Building on the work of the FAO and IIASA (2000), the length of growing period depends on temperature, precipitation, soil characteristics, and topography. The suitability of each AEZ for production of alternative crops and livestock is based on currently observed practices, so that the competition for land within a given AEZ across uses is constrained to include activities that have been observed to take place in that AEZ. The different AEZs then enter as inputs into a national production function for each land-using sector (e.g., wheat). With a sufficiently high elasticity of substitution in use, the returns to land across AEZs, but within a given use, will move closely together as would be expected in the case of a homogeneous product produced in 18 different regions of the country (Hertel *et al.*, 2009).

However, even after introducing AEZs, further adjustments are required to reflect observed behavior in land use. Empirical evidence on land rental differentials suggests that land does not move freely between alternative uses. There are many other factors, beyond agronomic factors, that limit land mobility within an AEZ. These include costs of conversion, managerial inertia, unmeasured benefits from crop rotation, among others. Therefore, in the model, such movement is constrained by a constant elasticity of transformation (CET) frontier. Thus, within an AEZ/region in the model, the returns to land in different uses are allowed to differ. A nested CET structure of land supply is implemented

(Ahammad and Mi, 2005) whereby the rent-maximizing land owner first decides on the allocation of land among three economic uses/broad land cover types, that is, forest, cropland, and grazing land, based on relative returns to land. The land owner then decides on the allocation of land between various crops, again based on relative returns in crop sectors.

A CET parameter governs the ease of land mobility across uses within each AEZ. The parameter in the cropland, grazing, and forestland nest determines the ease with which land is transformed across the three economic uses (e.g., from pastureland to cropland). Similarly, the CET parameter in the crop nest determines the ease to transformation of land from one cropping activity to another (e.g., oilseeds to corn). The absolute value of the CET parameter represents the *upper bound* (the case of an infinitesimal share for that use) on the elasticity of supply to a given use of land in response to a change in its rental rate. The more dominant a given use in total land revenue, the smaller is its own-price elasticity of acreage supply. The lower bound on this supply elasticity is zero (if all land in an AEZ is devoted to crops, then there is no scope for cropland to expand within the AEZ). Therefore, the actual supply elasticity is dependent on the relative importance (measured by land rents share) of a given land use in the overall market for land and is therefore endogenous. The CET parameters among the three land cover types and among crops are set according to the recommendations in Ahmed *et al*. (2008), based on earlier econometric investigations by Lubowski (2002).

While the CET function is a popular device in CGE models and permits these models to be calibrated to estimated land supply elasticities, it has some significant drawbacks. As with the constant elasticity of substitution (CES)/Armington specification, it allows significant differences in returns to land in the same AEZ to persist over time. One might expect that such differences might result in more conversion over time, and indeed Ahmed *et al*. (2008) suggest raising the absolute value of this parameter as the time frame for analysis lengthens.

Another important limitation of the CET function is that the fundamental constraint in the CET production possibility frontier for land in a given AEZ is *not* expressed in terms of physical hectares, but rather in terms of *effective* hectares – that is productivity-weighted hectares. "… this creates a rift between the physical world and the economic model which can pose problems when attempting to relate model results back to the physical environment" (Golub *et al*., 2009). To estimate LUCs measured in physical hectares, GTAP-BIO incorporates a new structure that translates changes in effective hectares to physical hectares. This is done by incorporating an additional constraint into the model that requires physical hectares employed in cropping (all crops together), grazing, and forestry to add up (i.e., remain unchanging). Satisfaction of this additional equation is permitted via introduction of an endogenous variable that adjusts AEZ-wide economic productivity to reflect the changing mix of cropping, grazing, and forestry activities. Thus, if relatively low productivity pastureland (productivity is inferred from the observed level of land rents per hectare) is converted to cropping, the average productivity of cropland is expected to fall, as the new land is less productive than the existing cropland. In addition, we expect the average productivity of the pastureland to fall, as the best pastureland is converted to crops. Overall, in this case, the productivity of the AEZ would need to fall in order to continue to satisfy the adding up constraint for physical hectares.

Such productivity adjustments can have a significant impact on the results, and since they are largely driven by differences in per hectare land rents, there is some concern that these may not be accurate in some cases. This is particularly true in the case of the lower-level CET nest where land cover is determined. The GTAP-AEZ database shows very large differences in per hectare land rents; yet we believe that, with some investments, the converted pastureland or forestland might be nearly as productive as current cropland. For this reason, we have modified this lower-level land productivity story by specifying a model parameter, the value of which can be set exogenously, and which determines how many additional hectares of marginal lands are required to make up for one hectare of average cropland. In the specification used below, we will assume that it takes three additional hectares of pastureland and forestland to produce the same amount as two hectares of displaced current croplands. This assumption determines the extensive margin of cropland expansion under biofuels, as will be discussed in the next section.

2.1.3. Changes in yield

Yield changes in the wake of a biofuels program are central in the analysis with GTAP-BIO. Here, there is both an intensive (higher yields on existing lands in response to higher prices) and an extensive margin (lower yields on new lands in response to cropland expansion). They work in opposite directions, but which one dominates in which AEZs, and then on a global basis, is an empirical question.

Yield intensification: As feedstock prices rise, with land in relatively inelastic supply, producers have an incentive to increase use of nonland inputs to boost production per unit of land. This change in yield, which is endogenous to the increases in demand for biofuels, must be modeled as such in order to properly estimate the change in land area due to biofuels production. The strength of this response is governed by the potential for substitution among inputs in the CES production function. In contrast to standard GTAP model (Hertel, 1997), where value added and intermediate inputs are used in fixed proportion, crop production functions of GTAP-BIO are not Leontief in intermediate inputs, since increased application of fertilizer, pesticides, and other purchased inputs can be an important avenue for boosting yields in response to higher commodity prices.

Keeney and Hertel (2009) review the literature on yield response to corn prices and find evidence that this price response has been diminishing in recent years. They focus on the more recent studies and take a simple average of these estimates in order to obtain an elasticity of yield to corn price of 0.25. This suggests that a permanent increase of 10% in crop price, *relative to variable input prices*, would result in roughly a 2.5% rise in yields. If the long-run price of the crop were to double, from $2 per bushel to $4 per bushel, and the price of land substituting inputs increased by 50%, then the output–input price ratio would rise by 33.33% and the expected yield increase would be $0.25 \times 33.33\% = 8.33\%$. In current applications of GTAP-BIO, the same long-run elasticity is adopted for all crops and all regions. In the future, as more data from different countries and for different crops become available, crop- and region-specific estimates will be incorporated and this is likely to be important for the results on global LUC.[1]

Yield extensification: As identified by Searchinger *et al.* (2008a), we expect there to be an offsetting effect on yields, as cropland cover is extended beyond current levels. We define the extensive margin as the change in crop yields when land employed in other uses (other crops, pasture, or forest) is converted to grow crops in question. There are two important contributors to yield extensification in the model. Taking corn as an example – first, there is the change in corn yields as corn replaces other crops on existing cropland (e.g., shifting from a corn–soybean rotation to continuous corn). This effect is estimated by referring to the differential in net returns to land in existing uses. If U.S. corn production expands onto lower productivity land, then average corn yields will fall. If EU oilseeds production expands into higher productivity lands, then average oilseeds yield will increase. (Recall the discussion of the CET land supply functions above.) The second extensive margin measures the change in average crop yields as cropland area is expanded into pastureland, and possibly forestland. In the absence of strong empirical evidence, we simply assumed a value of 0.66 in our earlier work, as per the discussion above. This suggests that it takes three additional hectares of marginal cropland to offset the impact of diverting two hectares of current (average) cropland to biofuels production. In a recent work Tyner *et al.* (2010) have estimated regional land conversion factors at the AEZ level using a terrestrial ecosystem model (TEM). These land conversion factors measure productivity of existing cropland versus new cropland. Future econometric work aimed at estimating this parameter more precisely is a high priority, and we discuss below the impact of systematic sensitivity analysis on this parameter.

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[1] Keeney and Hertel (AAEA presentation in 2009) explore the implications of systematic differences between developing and developed country yield response for indirect land use change from biofuel production in the United States.

2.2. Extensions to the GTAP model for biofuel analysis

Thus far, we have discussed features of the model and parameter settings that, while important for biofuel analysis, are not specific to biofuels. We now turn to those features of GTAP-BIO that are specific to biofuels. We begin with those designed to appropriately characterize the demand for biofuel, and then turn to the supply side.

2.2.1. Modeling demand for biofuels

Ethanol plays two roles in fuel use. As noted in the introduction to this chapter, until recently in the United States, the main role of ethanol was as a fuel additive – aimed at allowing the fuel to burn cleaner, thereby meeting air quality standards. This type of demand is best treated as a Leontief-derived demand by the petroleum refining sector. As the aggregate demand for liquid fuels expands, so too does the additive demand for ethanol. There is no price responsiveness to this demand. Indeed, until 2006 when this demand was satiated, ethanol was priced at a premium over petroleum, despite its inferior energy content.

The second type of ethanol demand is based on its energy content. Once the additive demand is satiated, further ethanol expansion lowers, the price of ethanol as it must now compete with petroleum, at the margin, on an energy basis. This derived demand is very sensitive to price. At high oil prices, there is great potential for ethanol use – provided the blend wall is not binding. Once the blend wall is reached, this derived demand becomes wholly inelastic. As noted in the introduction, U.S. ethanol consumption is virtually "at the blend wall" at present, sharply altering the demand for ethanol until such time as the blend wall is adjusted (e.g., to 12% or 15% – this is a regulatory decision) or until such time as the fleet of FFVs and E-85 service stations expands markedly.

The situation is clearly different with biodiesel, which is not subject to these constraints and which can be blended freely with diesel fuel. In this case, it is just the energy substitution margin that matters. The structure of household demand for private goods including biofuels is shown in Figure 2.

2.2.2. Modeling the supply of biofuels

Three new sectors have been introduced into GTAP-BIO in order to properly handle the supply side of the biofuel markets. The first sector represents grain-based ethanol (mainly corn ethanol for the United States and wheat ethanol for EU region). The second sector represents sugarcane-based ethanol (mainly produced in Brazil) and finally the third sector produces biodiesel from vegetable oil. Taheripour *et al*. (2007) have introduced these sectors in the standard GTAP database to support this modeling framework. A key feature of these biofuel sectors is that they typically produce by-products. In some cases, sale of these by-products

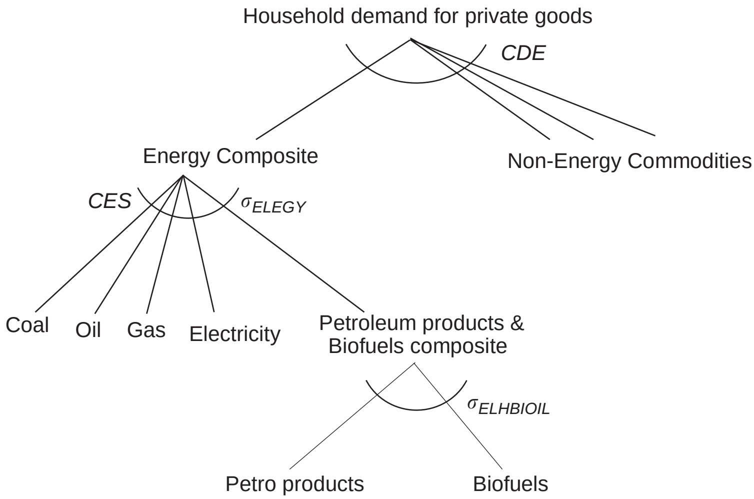

Fig. 2. Structure of consumption side of the GTAP-BIO model (Birur et al., 2008).

represents a very important revenue source for the industry, so explicit modeling of the by-product market and price determination is necessary in order to provide an appropriate estimate of revenue for the industry.

In the case of grain-based ethanol, it is produced in conjunction with various distillers' grains products, mainly DDGS. Producing biodiesel from vegetable oil also increases the supplies of oilseed meals (Vegetable Oils By-Products (VOBP)) that are joint products obtained from production of vegetable oils from oilseeds. In general, DDGS and oilseed meals are valuable inputs for the livestock industry.

An important outcome of this joint production process in the biofuel industry is that when biofuel production is encouraged, for example, due to government subsidies or positive oil price shocks, the production of these by-products also increases and as a result their prices fall relative to other animal feed ingredients. This encourages livestock producers to use more biofuel by-products in their production processes and avoid high-cost crops. Another important aspect of biofuel by-products is that they help mitigate the environmental consequences of expansion by the biofuel industry. For example, DDGS substitutes for both corn and soybean meal in livestock rations but mainly for corn. This ultimately reduces the land use consequences of biofuel production and eases the demand for chemical inputs, such as fertilizers and pesticides, in crop production. Hence, it is crucial for biofuel analyses to introduce production and consumption of DDGS and oilseed by-products into the modeling framework.

The standard GTAP framework does not permit multiproduct sectors. Therefore, Taheripour *et al.* (2010) have modified the model to handle joint production. Three new equations are required. The first refers to the percentage change in the index of activity level in the industries with joint products (grain-based ethanol and crude vegetable oil industries), qz_j. The second determines the percentage change in unit return to activity in each industry, pz_j. The model endogenously determines the activity level variables according to the following zero-profit condition:

$$pz_j = \sum_i \theta_{ij} pf_{ij} \quad \text{for } j = \text{EthanolC, Cveg\_Oil} \tag{1}$$

In this equation θ_{ij} and pf_{ij} represent, respectively, the share of input i in total costs of producing commodity j and the percentage change in price of input i paid by sector j, respectively. The change in return to activities in the two industries is simply a composite price index, comprising prices of the main and by-products according to the following equations:

$$pz_j = \sum \Omega_{kj}.ps_{kj} \quad \begin{array}{l} \text{for } j = \text{EthanolC and } k = \text{ethanol 1, DDGS,} \\ \text{for } j = \text{Cveg\_oil and } k = \text{Cveg\_Oil 1, VOBP.} \end{array} \tag{2}$$

Here, Ω_{kj} is the revenue share of the kth product in total revenues of sector j.

Output levels for the industry are a function of activity level and relative prices, where $\sigma_j^T \leq 0$ represents the CET parameter between the main and by-products in industry j:

$$qo_{kj} = qz_j + \sigma_j^T (pz_j - ps_{kj}) \quad \begin{array}{l} \text{for } j = \text{EthanolC and } k = \text{ethanol 1, DDGS,} \\ \text{for } j = \text{Cveg\_Oil and } k = \text{Cveg\_Oil 1, VOBP.} \end{array} \tag{3}$$

Finally, we modify the derived demand functions for inputs into the grain-based ethanol and crude vegetable oil industries by replacing the indices of outputs with the indices of sector activity levels:

$$qf_{ij} = qz_j + \sigma_j (pz_j - pf_{ij}).$$

This completes the supply side modifications in the model to handle by-products.

2.2.3. Modeling the demand for biofuel by-products

Several successive efforts to introduce consumption of DDGS and oilseed meals into the GTAP modeling framework have been undertaken. Taheripour *et al.* (2009) represent the latest modifications in this area. This chapter uses a three-level nesting structure for the demand for animal feedstuffs in the livestock industry. Figure 3 depicts this nesting structure composite. At the lowest level, DDGS and coarse grains are combined to create a feedstuff energy composite. At this level oilseeds and oilseed meals

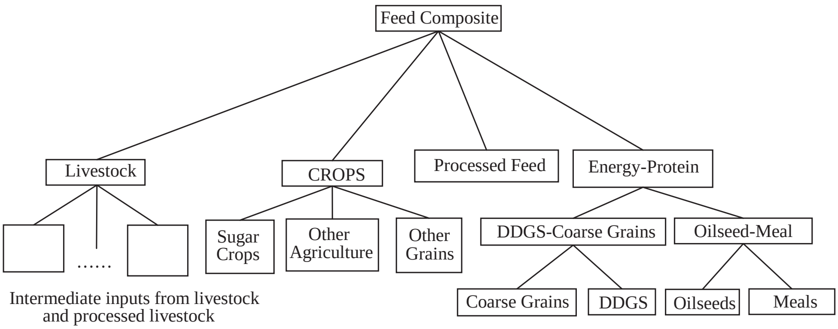

Fig. 3. Structure of nested demand for feed in livestock industry.

are combined to create a protein feedstuff as well. At a higher level the protein and energy feed ingredients are combined. At this level other crop-based feedstuffs are also introduced. The livestock industry receives some feedstuff inputs from processing sectors as well, and these materials are bundled together at the second level too. Finally, all feed ingredients are combined to create a feed composite. Taheripour *et al.* (2009) assigned elasticities of substitution to the different components of the demand for feed in order to permit replication of changes in the prices of DDGS and meals in the United States and EU during the time period of 2001–2006. In addition, those authors did several experimental simulations and sensitivity tests to reach the desired displacement ratios between DDGS, grains, oilseeds, and oilseed meals according to the literature in this area.

3. Selected applications

3.1. Historical analysis of the biofuels boom

One of the first applications undertaken with the biofuels model was a historical validation exercise. Since this is a global general equilibrium model, there are many different variables upon which we could focus our attention. However, we believe the most important of these is the *share of total liquid fuels provided by biofuels*. Indeed many of the biofuel mandates are expressed in terms of such a share, so being able to track this over the 2001–2006 period is quite important. Hertel *et al.* (2010b) note that the U.S. share tripled from 2001 to 2006, rising from less than 0.6% to more than 1.8%. Most of this increase came in the form of domestically produced, corn-based ethanol, but a seventh of the total came in the form of imports of sugarcane-based ethanol; finally, a very small amount came from biodiesel. In the EU, the share of biofuels in total liquid fuel consumption rose more than sixfold over this period, from 0.2% to 1.23%, with the majority being delivered as biodiesel.

According to Hertel *et al.* (2010b), the major drivers of this growth in biofuels have been petroleum prices, biofuel subsidies, and the ban on competing fuel additives in the United States. They illustrate the roles of these different forces using the following partial equilibrium expression for the change in ethanol output, qo^*:

$$qo^* = \frac{\varepsilon_S[(1-\alpha)ai - \varepsilon_D(p+s)]}{\varepsilon_S - \varepsilon_D} \tag{4}$$

Here the key drivers of ethanol output change are as follows: ai is the percentage change in the input–output ratio prescribing additive use in gasoline (this rises under the MTBE oxygenator ban discussed in the introduction); p, the percentage change in the price of composite liquid fuels; and s, the percentage change in the power of the *ad valorem*-equivalent subsidy on ethanol production (i.e., s is one plus the subsidy rate). The parameters in this equation are as follows: $\varepsilon_D = -\alpha\sigma$ is the composite price elasticity of demand for ethanol (the product of the share of ethanol going to the price-sensitive (energy-substitution) side of the market, α, and the elasticity of substitution in use between ethanol, biodiesel, and petroleum, σ); $\varepsilon_S = v_c\theta_c^{-1}$ is the price elasticity of supply for ethanol, which is determined by the product of the own-price elasticity of supply of corn, v_c, and the inverse of the share of costs of corn in ethanol production, θ_c^{-1}.

From Equation (4), the authors obtain some useful insights into the impact of these drivers on the growth in biofuels output. First of all, the contribution of changes in the additive requirements of gasoline to total ethanol output depends on the change in the input–output ratio, ai, as well as the initial share of total sales going to this market segment. The price-sensitive portion of the market depends on what happens to the price of energy in general, p, and the power of the subsidy, s. When the change in the latter is expressed as the change in the power of the *ad valorem* subsidy equivalent (as is the case here), these two effects are additive. Their combined significance depends on the share of the total market for ethanol that is price sensitive (α) and the ease of substitution between ethanol and other fuels (σ). Furthermore, we see from Equation (4) that feedstock supply response is also important. If the total availability of feedstock (corn) is fixed ($v_c = 0$), then $qo^* = 0$. Furthermore, as v_c rises and the share of corn in overall ethanol costs falls ($\theta_c \to 0$), $v_c\theta_c^{-1} = \varepsilon_S$ rises, thereby boosting supply.

Given estimates of the other parameters and shocks in Equation (4), the authors choose σ to replicate the historically observed value of qo. The main drivers of the biofuel boom during 2001–2006 as offered by Birur *et al.* (2008) are the increase in crude oil price, which rises by 136% (from \$25 per barrel to \$60), the increase in additive demand for ethanol in the United States which rises by 49%, a subsidy of \$0.51 per gallon of ethanol and $1 per gallon of biodiesel in the United States, and tax credit of $1 per gallon of ethanol and $1.9 per gallon of biodiesel in the EU.

The estimated elasticities of substitution between biofuels and petroleum products (σ) are as follows: Brazil = 1.35, EU = 1.65, and USA = 3.95. The authors note that the relatively low elasticity in Brazil reflects the fact that ethanol already commands a large share of that market, and large percentage changes become more difficult as ethanol becomes more dominant. The estimated elasticity of substitution in the United States is high, relative to Europe, particularly in light of the fact that the EU renewable fuel share grew by a much larger percentage over this period. However, the latter growth is well explained by the significant subsidies implicit in the fuel tax exemptions in France and Germany. In addition, in the base period (2001), the share of U.S. ethanol going to the price inelastic additive market was quite high (about 75%). This requires the elasticity of substitution in the price-sensitive part of the market to be higher. Finally, the economic "power" of the U.S. ethanol subsidy has been diminishing as the prices of gasoline and ethanol rise. For all these reasons, a large elasticity of substitution is required to explain the growth in the renewable fuel share in the United States.

Given these estimates of the elasticity of substitution between biofuels and other energy products, the authors are able to decompose the impact of the main drivers of renewable fuel output growth in the EU and U.S. markets over the 2001–2006 period. Of the total change in ethanol growth in the United States (133.5%), 64% of the total figure is attributed to the MTBE ban, 93% is attributed to the rise in petroleum prices, −23% is due to the diminishing relative importance of the $.51 per gallon blenders' subsidy. In the case of EU biodiesel growth over this period (341%), the most important driver is the fuel tax exemptions (202%) since the *ad valorem* equivalent of the power of the EU subsidy on biodiesel rose by 81.2% over this period. This is followed by the contribution of higher oil prices (140%).

3.2. Global GHG emissions from land use change

Probably the most controversial feature of biofuels in the past decade has been the impacts on global land use and associated "indirect" GHG emissions. This has been the subject of legislation in the EU (EC Directive 2009/29/EC), the United States (the National Renewable Fuel Standard program as mandated in the Energy Independence and Security Act of 2007: EISA), and California (California Air Resource Board Low Carbon Fuel Standard: CARB-LCFS adopted in April 2009). In all of these regulations, biofuels' environmental impact measures include estimates of emissions due to (i) feedstock production, (ii) fuel production (e.g., corn to ethanol), and (iii) global iLUCs triggered by expanded biofuels production. The first two components, emissions from feedstock and fuel production, are usually calculated using a life cycle model (e.g., GREET (Wang, 2005)). The third, iLUC component requires estimation with a global economic model that links global production, consumption and trade, and energy, biofuel, and agricultural markets within and across regions. The total emissions are then compared to a life cycle emission for gasoline to evaluate whether biofuels contribute to GHG reductions in transportation.

In this section we focus on two GTAP-BIO applications, Hertel *et al.* (2010a) and Tyner *et al.* (2009), investigating environmental impacts of U.S. corn ethanol. Both analyses combine economic modeling results with assumptions about the carbon fluxes (emission factors) from land cover changes. While the CGE models used in the two studies are very similar[2] (both based on the GTAP-BIO model of Birur *et al.*, 2008), the experimental design and assumptions behind calculation of emission factors are different, resulting in different GHG emissions per unit of ethanol produced.

Hertel *et al.* (2010a) focus on the so-called market-mediated changes in global land use in response to the expansion of U.S.-grown corn for ethanol. They model expansion of U.S. maize ethanol use from 2001 levels to the 2015 mandated level of 15 billion gallons/year by forcing 13.75 billion gallons of additional ethanol production with the increased costs passed forward to consumers in the form of higher fuel prices. It is important to emphasize that the task in Hertel *et al.* (2010a) is to estimate the independent effect of the increase in corn ethanol production, and not to predict total land use change (or its GHG discharge) caused by the many other factors that affect land use. It may be, for example, that technological change will increase maize yields so much that, even as biofuel production expands over some future period, total maize acreage actually falls over the same period of time. But that is not the point of this study, which seeks instead to assess by how much more land use would have fallen without the biofuel increase. This comparative static analysis has the great advantage of simplicity and transparency. It also facilitates relatively detailed analysis of the impacts of biofuels on global markets. An alternative approach, used, for example, by the EPA in its analysis for the renewable fuel standard (USEPA, 2009), involves projecting changes over time with and without a given quantity of biofuels production. This has the great advantage of being more appealing to decision makers who are not accustomed to thinking in terms of comparative statics. The drawback is that often much more effort is devoted to construction of the

[2] Regional and sectoral aggregations of the version 6 of GTAP database are different in two studies. While both use 18 regions, there are differences in how African and Asian countries are aggregated.

baseline, thereby shortchanging the time and resources available for analysis of the actual biofuels impacts.

On the basis of the estimates of Hertel *et al.* (2010a), the naïve estimate of the global land requirements needed to achieve the 15 billion gallon mandated level of corn ethanol production in the United States is about 15 million ha.[3] This gross land requirement is reduced to 4.2 million ha due to number of market-mediated effects that include availability of coproducts, the reduction in food consumption due to higher prices, and increased yields due to higher prices. This figure is further reduced to 3.8 million ha once the growth in baseline yields is taken into account.[4]

The first panel of Figure 4 summarizes the continental pattern of land conversion induced by increased ethanol production. In the majority of AEZs, cropland increases at the expense of both pasture and forestry. However, some of this decrease in forestry is compensated for elsewhere in AEZs where both forestry and cropland increase at the expense of pasture. Most cropland conversion arises within the United States, followed by its dominant export competitors and trading partners. This geographic approach to trade is supported by the recent econometric work of Villoria and Hertel (2009). Compared to study by Searchinger *et al.* (2008a) where IWM hypothesis is employed, this study finds far less conversion in some of the large, but relatively closed, agricultural economies such as India.

To examine the global warming implications of these land conversions, Hertel *et al.* (2010a) developed an emission factor for each type of transition predicted, in each region: forest-to-crop, pasture-to-crop, and pasture-to-forest. The emissions factors are based on the model developed by Searchinger *et al.* (2008a), which in turn relies on data compiled by the Woods Hole Research Institute (see Searchinger *et al.*, 2008b, for the model details). The emission factors account for changes in above- and below-ground carbon stocks, as well as changes in 30-year carbon sequestration by ecosystems actively gaining carbon. Hertel *et al.* (2010a) modified the calculation of emission factors to include small replacement cropping system carbon storage, assumption of 10% of forest biomass sequestered in timber products or charcoal in soil upon forest clearance, and exclusion of non-CO_2 emissions in the calculation. These assumptions

[3] If corn ethanol yield is 2.6 gallons/bushels, baseline coarse grains yield is 335 bushels/ha and additional ethanol volume is 13.75 billion gallons, then gross area required is about 15 million ha.

[4] With time and improved technologies, we expect the efficiency of ethanol conversion as well as corn yields to increase, both of which will reduce the land requirements for ethanol. While ethanol conversion efficiency has not changed significantly since the base period (2001) for the Hertel *et al.* (2010a) analysis, USDA reports that corn yields had risen by 9.3% by 2007. This has a direct impact on the amount of land required to fulfill a given level of ethanol mandate – reducing the land use requirement by a factor of 8.5% in the United States and globally.

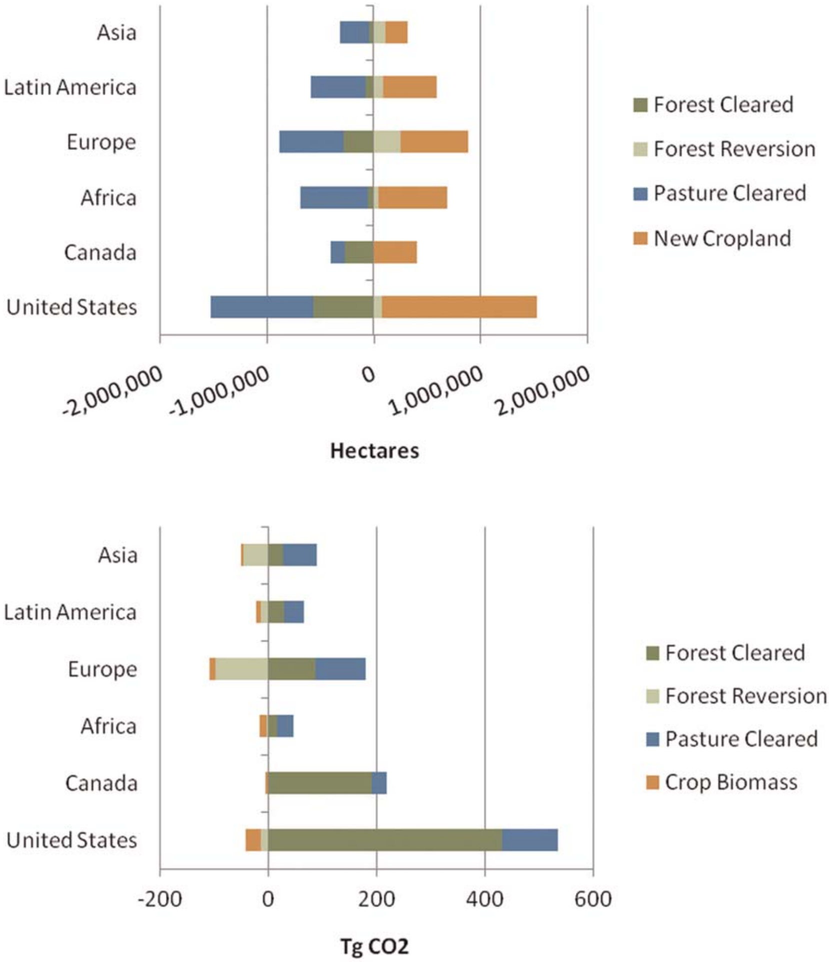

Fig. 4. Global land conversion and associated GHG emissions due to increased maize ethanol production of 50.15 Gl/year at 2007 yields in the United States, by region. Source: Hertel et al. (2010a).

result in slightly lower emission factors than shown in Searchinger *et al.* (2008a).[5]

Applying the emission factors to land conversions predicted by GTAP, Hertel *et al.* (2010a) found 870 Tg of CO_2 emissions, or 800 g/MJ of increased annual ethanol production. The second panel of Figure 4 shows emissions by region and conversion type. The largest shares of emissions

[5] For more information on emission factors used in the study, see Hertel *et al.* (2010a) and the supplementary online material at https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3160.

occur in the United States and Canada, where a greater proportion of the forest is expected to be cleared for crops.

To calculate iLUC emissions per mega joule (MJ), it is necessary to make an assumption about length of biofuel production period. If production continues for 30 years, then using straight-line amortization results in iLUC emissions of 27 g CO_2 per MJ, roughly one-fourth the value estimated by Searchinger *et al.* (2008a). It is important to note that assumptions about timing and the length of biofuel production period are very important in this analysis (see O'Hare *et al.*, 2009). Assuming 20 years instead of 30 years of production increases emissions per mega joule value implied by 800 g initial discharge by 50%, from 27 to 40 g CO_2/MJ.

Adding 27 g CO_2 per MJ iLUC emissions to 65 g CO_2 per MJ direct emissions from typical U.S. corn ethanol production (emissions during cultivation and industrial processing of ethanol) "... would nearly eliminate carbon benefit of this biofuel relative to typical gasoline (94 to 96 g/MJ; Farrell *et al.*, 2006; Wang *et al.*, 2007)" (Hertel *et al.*, 2010a).

Tyner *et al.* (2009) evaluate carbon emissions due to the global land use changes induced by US. corn ethanol production. Their analysis of land use changes is also based on GTAP-BIO model, but employs different experimental design and assumptions about carbon fluxes. Those authors start from version 6 of the GTAP database representing global economy in 2001 and update the data to 2006. It is important to understand how the database is updated and what exogenous variables are shocked. To update the database, Tyner *et al.* (2009) follow the approach outlined in Hertel *et al.* (2010b). Instead of shocking all the exogenous variables in the economy, only those variables are shocked that are important in determining *structure* of biofuel economy. Under this approach, the information requirements for historical 2001–2006 simulation are greatly reduced. In the historical simulation, the focus is only on those elements of the history that are critical in shaping structure of biofuel economy as it changed from 2001 to 2006: rise in petroleum prices, the replacement of MTBE by ethanol as gasoline additive, and the subsidies to the ethanol and biodiesel industries in the United States and the European Union. Because changes in other exogenous variables are not targeted (e.g., population, labor, trade policies, technological change, and/or income growth), the update from 2001 to 2006 is in terms of *shares* of renewable fuels in total liquid fuel consumption. Thus, this historical simulation replicates historical changes in shares, but not in quantities of biofuels in 2006, and the resulting quantity of biofuels produced are smaller than actually observed in 2006 (3 billion gallons vs. 7 billion gallons).

Starting from the updated database, several simulations are conducted: from 3 to 7 billion gallons, and then from 7 to 15 billion gallons by increment of 2 billion gallons. Cumulative simulation result indicates that an increase in U.S. corn ethanol production from 2001 to mandated 15 billion gallons requires additional 3.55 Mha of cropland globally at 2001 yields. This requirement is smaller than 4.2 Mha (at 2001 yield) reported in Hertel *et al.* (2010a), which is due to the different simulation design. Tyner *et al.* (2009) find that net land required for production of extra 1000 gallons of ethanol rises (and hence carbon emissions) as we move to higher levels of ethanol production. For example, moving from 3 to 7 billion gallons requires 0.25 ha per 1000 gallons. While obtaining 2 billion gallons of corn ethanol after 13 billion gallons already produced requires 0.31 billion gallons per 1000 gallons, similar to per 1000 gallons land requirement reported in Hertel *et al.* (2010a) when large increment is modeled in one step from 2001 to 2015 mandated level.

Tyner *et al.* (2009) utilize two different sets of emission factors. The first set of emission factors is calculated on the basis of the model developed by Searchinger *et al.* (2008a), similar to Hertel *et al.* (2010a), but with different assumptions. For example, Tyner *et al.* (2009) do not take into account carbon storage in replacement cropping systems and assume that 75% of the carbon stored in the forest type vegetation will be released into the atmosphere at the time of land conversion and that 25% are stored in buildings, furniture, etc., while Hertel *et al.* assume a 90%/10% analogous split. As a result, emission factors used in the two studies differ. Because of the differences in emission factors and simulation design, in Tyner *et al.* (2009) the one time discharge from land use change due to increase in corn ethanol production to 15 billion gallons is 766 Tg vs. 870 Tg of CO_2, below 870 Tg of CO_2 reported in Hertel *et al.* (2010a).

The second set of emissions factors reported in Tyner *et al.* (2009) is calculated on the basis of the IPCC land and land cover carbon profiles. The IPCC data set provides data at a global scale with no geographic distribution. IPCC factors are much larger than the corresponding regional factors derived from the Woods Hole data set, and result in 2489 Tg of CO_2 emissions.

Finally, Tyner *et al.* (2009) sum emissions due to production and consumption of ethanol with obtained emissions from land use changes to compare life cycle GHG discharges from ethanol (pure ethanol fuel, or E100) with conventional gasoline using emissions per mile metric. With Woods Hole emission factors, average total GHGs emissions due to production and consumption of E100 (including land use emissions) are about 96% of those for gasoline. With the IPCC carbon profile, emissions released due to production and consumption of E100 per mile are 66.2% more than the conventional gasoline emissions per mile. The overall conclusion from Tyner *et al.* (2009) does not depart from Hertel *et al.* (2010a); unless corn is grown for fuel for 100 years; there is no environmental benefit in producing U.S. corn ethanol to displace gasoline.

3.3. Interplay between biofuels and the livestock sectors

A very important, yet under-researched aspect of the biofuel impacts is the interplay between the livestock and biofuels industries. Taheripour *et al.* (2009) analyze these linkages in considerable detail for the case of biofuel mandates in the United States and the EU. The most obvious consequence of large-scale biofuel production for the livestock industry is higher crop prices, which increase input costs. Biofuel production also raises returns to cropland, which, in turn, encourages conversion of some pastureland to crops, thereby further increasing production costs for ruminant livestock. On the other hand, biofuels are produced in conjunction with valuable by-products that can be used in the livestock industry as animal feeds and can substitute for the higher priced crops in animal rations. This serves to dampen the cost increases confronting livestock producers.

However, not all livestock industries are well placed to capitalize on the increased availability of biofuel by-products. Ruminants (dairy and beef) are better able to make use of DDGS in their feed rations and are therefore better positioned to gain from increased DDGS availability – particularly when compared to other livestock sectors that may not be able to adjust their feed rations as readily to take advantage of the increased supply of DDGS. As noted previously, biofuel by-products represent an important component of biofuel industry revenues. If the livestock industry could not absorb these by-products, their prices would fall sharply, thereby limiting expansion of the biofuel industry. In addition, both industries compete for crop feedstocks. The interactions between these industries become even more complicated when we take into account other economy-wide linkages with energy and agricultural markets.

Taheripour *et al.* (2009) find that, due to the U.S. and EU biofuel mandates, the overall global volume of livestock and processing livestock industries is expected to fall by about \$3.7 billion (Figure 5). About 61.7% of this reduction is estimated to take place within non–biofuel-producing regions. The United States show only a minor reduction (\$0.9 billion) in its livestock and processed livestock products, while the EU also experiences a slight increase. In general, the livestock industries of the United States and EU do not suffer significantly from biofuel mandates, which is rather surprising. However, closer investigation by those authors reveals that this muted impact is due to their ability to make use of biofuel by-products to ameliorate the cost consequences of higher crop prices. This stands in sharp contrast to the livestock industries of other regions (including Brazil) that do not have the same access to biofuel by-products. Here production falls by much more than in the EU and the United States (Figure 5). This is due to a combination of factors. In Brazil, the other major biofuel-producing region, the sugarcane by-product is not a feedstuff, rather it is used to power the sugarcane processing facilities. One might expect that international trade would distribute the by-products to the global livestock

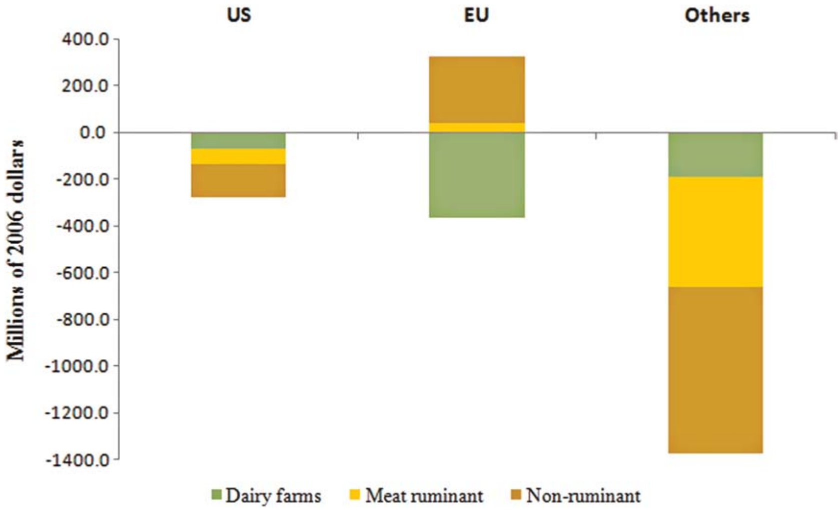

Fig. 5. Changes in global livestock outputs due to the EU and U.S. 2015 biofuel mandates. Source: Taheripour et al. (2009).

industry. However, the geography of global trade is such that the greatest benefits from the increased by-product availability remain in the producing region.

Figure 5 shows the impacts of biofuel mandates on the outputs (in $US millions at constant prices) of dairy farms, meat ruminant, and nonruminant activities by region. As shown in this figure the outputs of these industries fall in all regions except for the EU. The outputs of the meat ruminant and nonruminant activities of the EU slightly grow due to biofuel mandates. At the global level the nonruminant sector will experience the greatest output volume reduction among all livestock sectors.

Taheripour *et al.* (2009) also find that the impact mandate varies significantly across livestock subsectors due to differential potentials for absorbing the by-products. Their results show that the mandates will significantly reduce the cost share of coarse grains in feed rations in the United States and EU and will raise shares of DDGS and oilseed meals across all livestock industries (see panels A, B, and C of Figure 6). The ruminant meat industry benefits more from the expansion of DDGS than other livestock activities as shown in Figure 6. One can see a similar pattern of by-product use in the EU.

Several papers indicate that dairy and ruminant industries are in better positions to use more DDGS in their feed rations compared to nonruminant industry (e.g., Arora *et al.*, 2008). This suggests that they could take advantage of these by-products and move away from using expensive corn in their feed rations in the presence of corn ethanol production. A large expansion in corn ethanol production in the United

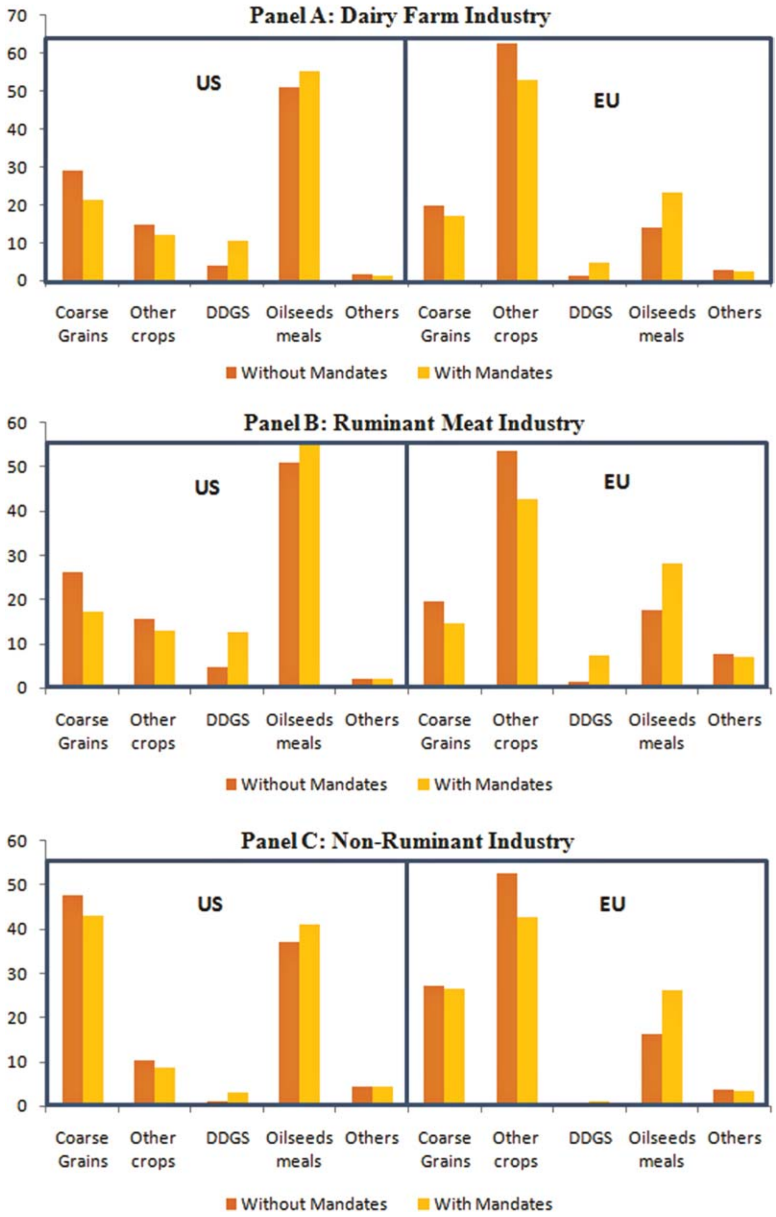

Fig. 6.* *Shares of coarse grains, DDGS, and oilseeds meals in total costs of animal feed rations without and with the EU and U.S. 2015 biofuel mandates (figures represent cost shares calculated at constant 2006 prices). Source: Taheripour et al. (2009).

States increases significantly the supply of DDGS (6.5 lb DDGS are produced per gallon of ethanol). Other factors being equal, this reduces the price of DDGS versus corn. Since ruminants species (say dairy and cattle beef in the United States) can digest DDGS better than nonruminants, dairy and meat ruminant producers will add more DDGS in their animal rations. This increases share of DDGS and decreases share of corn in feed costs of these industries, as shown in Figure 6. This helps dairy and beef cattle producers to partially offset adverse cost impacts of higher corn prices. However, nonruminant producers are more limited in their substitution possibilities; hence, they suffer more than other livestock producers and therefore curb their production more, as shown in Figure 5.

3.4. How robust are these findings? Sensitivity analysis of biofuel impacts

With the increased use of CGE models for policy analysis, decision makers have begun to insist more on formal sensitivity analysis of results with respect to parametric uncertainty. In their analysis of the global land use impacts of biofuels, Keeney and Hertel undertake a comprehensive sensitivity analysis. Hertel *et al.* (2010a) also provide a complete sensitivity analysis with respect to the GHG emissions impacts of the U.S. corn ethanol program. We draw on both of these studies here.

Keeney and Hertel (2009) specify uncertainty in key model parameters as follows. The CET transformation parameters describing land supply are drawn from Lubowski *et al.* (2006) and Ahmed *et al.* (2008) and these are judged to range over the interval [−0.03, −0.19] with mean −0.11. Keeney and Hertel (2009) use this same range (±80% of the point estimate) to define the distribution for acreage response across crops, implying an interval of [−0.10, −0.90] about the −0.5 point estimate. For nonland factor supplies, the authors maintain the ratio of labor and capital supply elasticities in their base model and consider a distribution symmetric about the base assumption of a common multiplicative factor, λ, which equals 1.0 in the base case. A reasonable lower bound for this value is assumed to be zero, indicative of the short run when factors are immobile between agriculture and nonagriculture sectors. With this lower bound assumption, a symmetric treatment for the upper bound implies an interval for λ of [0.00, 2.00] and hence a labor and capital supply elasticity range of [0.00, 1.40] and [0.00, 2.00], respectively. As previously discussed, the substitution component of the yield elasticity is derived from the literature estimates for corn with a range of [0.00, 0.50] surrounding the 0.25 point estimate for the long-run yield response to price. The trade elasticities are drawn from Hertel *et al.* (2007), each of which is estimated with a standard error. The authors only conduct sensitivity on the trade elasticities for crop sectors and draw directly from the point estimates and standard errors provided by those authors.

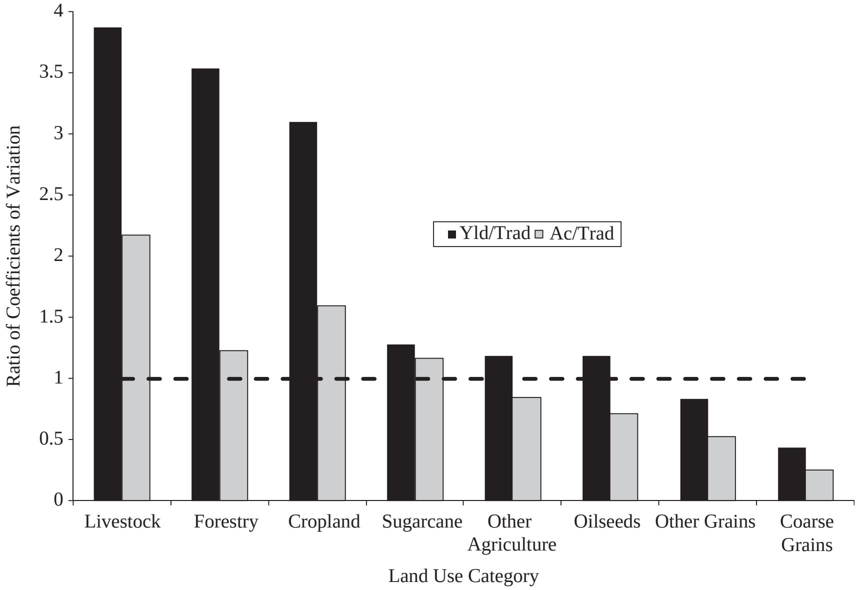

***Fig. 7.** The relative importance of supply response versus bilateral trade response assumptions in uncertainty about land use changes. Source: Keeney and Hertel (2009). Notes: Systematic sensitivity analysis for yield response includes factor supply and substitution parameters. Acreage response includes both levels of land allocation). Bilateral trade response includes all trade elasticities for commodities featured in this figure using the confidence intervals from Hertel et al. (2007).*

We focus here on Keeney and Hertel's analysis of the sensitivity of land cover change results with respect to variation in one set of parameters at a time. Their key findings are summarized in Figure 7 by focusing on the relative coefficients of variation (CVs) for land use change associated with the three major sources of model uncertainty. Since the CV reports the ratio of the standard deviation to the mean of the variable, a high CV reflects a large degree of uncertainty in the land use change results. By reporting the CVs in Figure 7 in ratios, we can readily see which sources of parameter uncertainty are most influential in driving the land cover change results.

Turning to the details of Figure 7, we have two sets of bars. Each measures the CV of one source of uncertainty, relative to the base uncertainty that is driven by uncertainty in the trade elasticities. Specifically, the darker columns in this figure show the ratio of CVs deriving from yield uncertainty versus uncertainty in trade elasticities, while the lighter columns report the ratio of CVs stemming from acreage response versus trade elasticities. Upon studying this figure, we see that for broad categories of forestry, livestock, and crops it is the case that the yield response determinants dominate the uncertainty in predicted changes in land use, with CVs much larger than those from the acreage and trade elasticity assumptions. For land use changes within the agricultural sector, we find that in general the trade elasticities, yield, and acreage assumptions all make comparable contributions to uncertainty in model predictions, with the exception of the other grains and coarse grains sectors where uncertainty in trade elasticities dominate (i.e., the height of the vertical bars is considerably below the dashed line at a value of one). The assumed ease with which adjustment of export and import levels of these crop commodities occurs, in particular in the case of coarse grains (where the U.S. demand shock initially acts), represents a critically important assumption when predicting the global land use change following the mandated increase in biofuel production.

Naturally in policy analyses where a particular estimate, say the grams of CO_2 equivalent GHG emissions per mega joule of biofuel produced, is of critical importance, one wants to establish a comprehensive confidence interval on the findings. This was the task of Hertel *et al.* (2010a) who sought to estimate the GHG emissions from indirect land use change associated with corn ethanol for purposes of establishing the California LCFS. As with Keeney and Hertel, those authors specified distributions on their parameters. However, in addition to uncertainty in the economic behavioral parameters, those authors included uncertainty in the physical GHG emissions factors associated with land use change as well. The authors then sampled from these distributions following the Gaussian quadrature (GQ) approach to estimate means and standard deviations of model results (DeVuyst and Preckel, 1997; Pearson and Arndt, 2000). For large models, the GQ method is more tractable than a full Monte Carlo analysis.[6] Hertel *et al.* (2010a) found the CV with global iLUC (global additional cropland) to be 0.37. The CV associated with global emissions from land use change is 0.46, with a mean value of 27 g/MJ of corn ethanol produced annually. The associated 95% confidence interval, which ranges from 2 to 52 g/MJ suggests considerable uncertainty in this key value. It also suggests that zero emissions from land use change are also a very unlikely outcome.

4. Conclusions and future challenges

The application of CGE analysis to biofuels has been a boom industry in the past few years – fueled by the need to provide solid quantitative analysis of a rapidly growing industry that has been the recipient of numerous government subsidies, mandates, and regulations. The use of

[6] This model solves in approximately 12 min. A Monte Carlo analysis using just 1000 simulations would take more than 8 days.

one of the variants of the GTAP model described in this chapter in the formulation of California's LCFS raised this type of CGE analysis to a new level of scrutiny and criticism. As a result, the use of CGE models in this area has become rather sophisticated, with numerous special features aimed at addressing previous limitations. This chapter has reviewed the motivation for the use of CGE models for biofuel analysis, as well as the key conceptual issues that have arisen in the course of this work.

As with much of such policy modeling, this work has highlighted the need for improved parameter estimates. The very wide, 95% confidence interval on the CARB-LCFS emission estimates reported in this study shows the need for additional econometric work to narrow the underlying parameter distributions – both for the economic parameters and for the physical GHG emissions parameters. Areas of particular concern include the land supply functions and the feedstuff demand elasticities – both of which have spotty econometric underpinnings, but have proven crucial to our findings. Also, the yield response to price – both the intensive and extensive margins – needs more work. The latter, in particular, has received almost no attention in the literature.

Additional econometric work aimed at discriminating between competing models of key components of the analytical framework is also important. We find that the international trade specification makes a big difference in the global location of additional production in the wake of a national biofuels program. Depending on the location of production, the total amount of area converted as well as the GHG emissions per hectare converted can vary greatly. And this global distribution of production depends on the assumptions made about the role of geography in international trade.

One of the most pervasive challenges over the course of the research experience documented here involves bridging the economic and physical worlds, which come together in the context of biofuel analysis. Since the ultimate objective of much of this work has been to produce an estimate of physical emissions per unit of physical energy, the base economic data and parameters need to bear a close relationship to the underlying physical data. This is rather different from the usual requirements of CGE analysis, where the focal point is economic welfare or aggregate output and employment changes, measured in dollars terms or as price or quantity index changes. In order to meet this objective in future work, several key links between the economic and physical data should be improved. First, there is the matter of the matching quantities with values of crops produced as reported from international statistical resources (e.g., FAO and IEA). It is also important to match quantities of oilseeds produced, traded, and crushed along with produced and traded vegetable oil and oilseed meals all across the world with their corresponding values in GTAP. An important and crucial key link in analyzing land use impacts of biofuel production is the link between value added of land in livestock and forest industries with contribution of physical land to the physical outputs of these industries.

As one looks ahead, one of the most significant challenges facing those seeking to undertake CGE analysis of biofuels relates to the modeling of the so-called second-generation biofuels. These include ethanol or hydrocarbons produced from agricultural residues, municipal wastes, or dedicated energy crops such as miscanthus, switchgrass, and poplar.

In the United States, the part of the biofuels mandate that can be filled with corn is essentially complete, so the future growth will be mainly from these cellulosic materials. The U.S. mandate is for 20 billion gallons ethanol equivalent (roughly 13.6 billion gallons gasoline equivalent) of advanced biofuels by 2022. The mandate for advance biofuels began in 2010 at a level of 100 million gallons, but EPA was forced to waive all but 6.5 million gallons of that mandate because the plants to produce cellulosic biofuels have not been developed.

There are three main sources of uncertainty that inhibit private sector investment in cellulosic biofuels: market, technology, and government policy. Most technology developers believe their technology could be viable without government subsidies if crude oil were $120 per barrel. However, crude oil is far from $120, and investors are not willing to invest in a technology that requires $120 crude oil to be viable. Even though technology developers may believe they can be competitive with $120 oil, no commercial plants have been built, so there still remains huge technology uncertainty. In addition to market and technology uncertainty, we also have government policy uncertainty. For example, the U.S. subsidy on corn ethanol is set to expire in 2010, and the cellulose biofuel subsidy in 2012. Even if the subsidies are renewed this year, they will likely be renewed for five years – not long enough to pay off a $400 million cellulosic biofuel plant. The RFS is also uncertain. Right now, it is the only assurance of a market for second-generation biofuels, but as we have seen from the U.S. experience in 2010, the RFS can be waived. There is similar government policy uncertainty in the EU. While the EU mandates technically are just that, in reality, they are more like targets that can be relaxed or even ignored.

Given these huge uncertainties, it is not surprising that the needed investments in second-generation biofuels have not yet materialized. However, the slowdown gives us the needed time to prepare economic, environmental, and policy analyses for these second-generation biofuels. That is the future direction for research in this arena. In addition to the food/fuel, GHG, and other environmental issues, we will face in this new analysis the question of water constraints. To what extent will production of these feedstocks face binding water constraints?

In summary, while CGE analyses of the impacts of biofuels on the economy and the environment have made great strides over the past few years, there is much yet to be done if economic analysis is to meet the needs of policy makers interested in designing policies related to renewable energy, climate change mitigation, and energy security.

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