Long-run effects of falling cellulosic ethanol production costs on the US agricultural economy

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Abstract
Renewable energy production has been expanding at a rapid pace. New advances in cellulosic ethanol technologies have the potential to displace the use of petroleum as a transportation fuel, and could have significant effects on both the agricultural economy and the environment. In this letter, the effects of falling cellulosic ethanol production costs on the mix of ethanol feedstocks employed and on the US agricultural economy are examined. Results indicate that, as expected, cellulosic ethanol production increases by a substantial amount as conversion technology improves. Corn production increases initially following the introduction of cellulosic technology, because producers enjoy new revenue from sales of corn stover. After cellulosic ethanol production becomes substantially cheaper, however, acres are shifted from corn production to all other agricultural commodities. Essentially, this new technology could facilitate the exploitation of a previously under-employed resource (corn stover), resulting in an improvement in overall welfare. In the most optimistic scenario considered, 68% of US ethanol is derived from cellulosic sources, coarse grain production is reduced by about 2%, and the prices of all food commodities are reduced modestly.

Keywords: biofuels, grain ethanol, cellulosic ethanol, corn stover, switchgrass, food prices, land-use change, greenhouse gas emissions

1. Introduction

The production of biofuels has increased dramatically in recent years. In the United States, ethanol production has increased from 1.6 billion gal in 2000 to 9 billion gal in 2008 (Renewable Fuels Association 2009). The quantity of US ethanol demanded has increased from 2 billion gal in 2002 to 9.6 billion gal in 2008 (Renewable Fuels Association 2009). Various factors, such as rising oil prices, fossil fuel depletion, renewable energy policy, and reduced MTBE use, have contributed to the surge in ethanol demand.

As their production has increased, the effects of biofuels on agricultural markets and the environment have become increasingly important topics, yet much uncertainty still remains. Biofuels have the potential to displace the use of petroleum as a transportation fuel and lower toxic emissions. However, the majority of US ethanol is currently produced from corn grain, and much controversy exists regarding the net energy content of grain ethanol and the use of food crops for fuel. Most studies agree that biofuels have contributed to recent increases in food prices; however, there are conflicting views on how much of the increases can actually be attributed to biofuels. Both Mitchell (2008) and Trostle (2008) found increased biofuel production was but one among many factors contributing to higher food prices. Mitchell (2008), however, concluded that increased biofuel production in the US and the EU was the primary cause of food price increases from 2002 to 2008. In contrast, the CBO estimated that only 10–15% of the increase in food prices between April 2007 and April 2008 could be attributed to increased ethanol production (US Congress 2009).
The evolution of new biofuel production technologies could help alleviate some of the concerns regarding the use of food for fuel by facilitating the use of non-food feedstocks, and could alleviate some of the environmental concerns associated with grain ethanol production. In particular, cellulosic ethanol production is believed to hold great promise in this regard, even though there are currently no commercial-scale plants in the United States.

In an effort to realize these potential benefits, US biofuel policy encourages the development of cellulosic ethanol and other second generation biofuels. The Energy Independence and Security Act of 2007 established ambitious standards for the production of ‘advanced biofuels’. The renewable fuel standard (RFS) requires the annual use of 36 billion gal of renewable fuels by 2022, including 21 billion gal from advanced biofuels and up to 15 billion gal from corn-based ethanol. Advanced biofuels, as defined in the Act and subsequent rulemaking, include any renewable fuels other than ethanol produced from corn starch that have lifecycle greenhouse gas emissions (GHG) at least 50% less than baseline GHG emissions for gasoline or diesel. Lifecycle greenhouse gas emissions include all phases of fuel and feedstock production and distribution. Accounting for indirect land use changes in the lifecycle GHG calculations has become a particularly contentious issue—an issue intimately related to agricultural market responses to increasing demand for particular feedstocks.

The use of different types of biomass for increasing production of advanced biofuels will have different implications for agricultural markets and the environment. Of particular interest is the use of crop or forest residues to produce biofuels, since this could be more economical in the initial stages than producing a dedicated biomass crop for biofuel production. There is still a high level of uncertainty regarding the probability of economic success of particular biofuel technologies and associated biomass sources, however. Alternative trajectories for biofuels industries will have varying implications for agricultural market responses to increasing demand for particular feedstocks.

Different approaches to increasing biofuels production will have varying effects on food insecurity as well. Increasing use of some feedstocks could increase the price of food either because food crops are used for fuel production or energy crops compete with food crops for agricultural lands. Many are concerned that commodities are being diverted away from food and feed uses to drive current biofuel production, which has led to increased concerns about the food insecurity of the world’s poor. Food security in developing countries could be threatened because cereal grains make up 80% of the world’s food supply (Pimentel and Pimentel 1996). According to Regmi et al (2001), a 1% increase in food prices causes an average 0.75% decline in food consumption in developing countries. In addition to reducing caloric intake as food prices increase, low-income people also switch to less nutritious food (von Braun 2007).

Identifying all of the potential benefits and costs of conventional and cellulosic ethanol production for both the US agricultural economy and the environment is essential for effective policy making. In this letter, we have examined the effects of falling cellulosic ethanol production costs on the US agricultural economy and the mix of ethanol feedstocks employed among grain, switchgrass and corn stover.

2. Background

Of the various possible feedstocks for production of cellulosic ethanol, corn stover and switchgrass have significant potential. In recent studies by USDA (2007) and Milbrandt (2005), corn stover was found to be one of the most likely biomass sources during the initial stages of cellulosic ethanol production. Gallagher et al (2003) also found that crop residues are likely the lowest cost biomass source. According to Atchison and Hettenhaus (2003), over 240 million dry tons of corn stover is produced each year in the United States. In the ‘billion-ton study’ conducted by Perllack et al (2005), the quantities of corn stover that can be sustainably harvested were determined to be the single largest unused biomass resource available for advanced biofuel production.

Although corn stover may have tremendous potential as a feedstock, there is currently little or no collection of corn stover. A very significant but under-researched aspect of corn stover collection is the damage to the soil resulting from stover removal. A portion of the corn stover can be collected and used as a biomass source for cellulosic ethanol production, but a certain percentage must be left on the ground to prevent soil erosion. The amount that can be removed varies by region, soil conditions, and harvest activities. As a higher percentage of corn stover is removed, the risk of soil loss from wind erosion and runoff from water erosion increases (Brechbill and Tyner 2008). Corn stover is also very important in preserving the organic matter and nutrients in the soil following corn grain harvesting (Brechbill and Tyner 2008). In many areas, nutrients, such as nitrogen, phosphorus, and potassium, must be added back to the soil, which could lead to additional environmental concerns.

Perennial crops, cultivated specifically for use in bioenergy production, were determined by Perllack et al (2005) to potentially be available at quantities similar to corn stover. However, an increase in the production of such crops would require a decrease in the acres of other agricultural crops or pastureland—a major concern that must be addressed. Changes in land use could result in higher food prices (as less food crops are grown or less pasture is available for grazing) and increased feedstock production costs, which could lead to reduced market outcomes given only this subset of possibilities. We do not assert that other biofuels, feedstocks, and production technologies are unlikely to enjoy widespread adoption. In a December 2009 survey of 26 known US advanced biofuels projects under active development, cellulosic ethanol constituted 40% of expected 2012 production capacity (590 million gal yr−1), diesel from algae constituted 29%, and other biofuels accounted for the remainder (Biofuels Digest 2009). Among the large (>10 million gal yr−1) cellulosic ethanol projects, agricultural waste was the planned feedstock for 78% of planned 2012 capacity, with municipal waste, forest residues and wood waste dividing the remainder. The results presented here therefore reflect only some plausible scenarios among many possibilities.

3 We have necessarily considered only a subset of the numerous possible combinations of advanced biofuel production technologies and feedstocks that might be employed in the future, and the results presented here reflect market outcomes given only this subset of possibilities. We do not assert that other biofuels, feedstocks, and production technologies are unlikely to enjoy widespread adoption. In a December 2009 survey of 26 known US advanced biofuels projects under active development, cellulosic ethanol constituted 40% of expected 2012 production capacity (590 million gal yr−1), diesel from algae constituted 29%, and other biofuels accounted for the remainder (Biofuels Digest 2009). Among the large (>10 million gal yr−1) cellulosic ethanol projects, agricultural waste was the planned feedstock for 78% of planned 2012 capacity, with municipal waste, forest residues and wood waste dividing the remainder. The results presented here therefore reflect only some plausible scenarios among many possibilities.
grazing) and will figure into lifecycle greenhouse gas emission calculations. The state of California recently adopted a new low-carbon fuel standard (LCFS) that considers these indirect land use changes (ILUC) from biofuel production. While there is still much debate about how to accurately measure emissions from ILUC, this may become an increasingly important issue if more jurisdictions adopt a similar standard. Searchinger et al (2008) note that most studies estimating carbon credits from biofuels exclude emissions from land use changes. Basically, only the carbon benefits (from using the land to grow biofuels), not the carbon costs (loss in carbon sequestration resulting from indirect land use changes), are generally counted (Searchinger et al 2008). Results of their study indicated that using waste products as an ethanol feedstock may be a more desirable option, since the production of both additional corn grain and switchgrass for ethanol production increases GHG emissions by a substantial amount. Among the potential dedicated energy crops, switchgrass has received much attention (Duffy 2007, Duffy and Nanhou 2001, McDonald et al 2006, Perrin et al 2004, 2008, Raneses et al 1998, Searchinger et al 2008, Vogel 2007, Walsh et al 2003).

There are many potential cellulosic ethanol feedstocks beyond corn stover and switchgrass, however. Perlack et al (2005) note that a substantial amount of forest residue is produced each year, although a considerable amount is already used in the forest products, residential construction, and other commercial industries. Other dedicated energy crops include miscanthus and prairie grass. In the analysis that follows, we consider only corn stover and switchgrass as potential cellulosic ethanol feedstocks given their noteworthy potential. It is, however, possible that other feedstocks could be substantially employed, and the model we have used here admits only a subset of all possible future scenarios.

Significant improvements to two broad technologies for converting biomass into biofuels are being pursued under US national research and development priorities (DOE 2009). A biochemical approach employs biocatalysts, such as enzymes and microorganisms, in converting cellulose and hemicelluloses into fermentable sugars. Thermochemical approaches such as pyrolysis and gasification employ heat and chemicals to convert biomass into intermediate fluid and solid products, which can be further processed into liquid fuels. In this study we have chosen to model the biochemical conversion approach, and have reviewed detailed cost information regarding enzymatic hydrolysis of biomass as described in the following section4.

3. Methodology

A comparative static computable general equilibrium (CGE) model of the world economy was used for this study. The CGE approach allowed for analysis of the broad effects of US conventional and cellulosic ethanol production on the entire economy, including fossil energy markets. CGE models are very useful for analyzing economy-wide effects of a particular shock or policy change, as they allow for much greater detail than analytic general equilibrium models. In recent years, several studies have analyzed new biofuel technologies in a CGE framework (Dixon et al 2007, Gurgel et al 2007, McDonald et al 2006, Gan and Smith 2002, Kancs and Kremers 2002, Raneses et al 1998). However, most of these studies do not include both an explicit sector for production of dedicated biomass feedstocks and allow for joint production of agricultural waste streams.

The benchmark data used for this analysis include a Social Accounting Matrix (SAM) representation of version 6 of the GTAP database (Hertel 1997, McDonald and Thierfelder 2004). The GTAP database contains data on the circular flow of funds in the year 2001 among 57 production sectors in each of 87 regions, as well as trade between regions, taxes and tariffs. The GTAP data were aggregated down to nine world regions, and to 32 production sectors, including seven agricultural sectors and four biofuel sectors. The model assumes full mobility of the primary factors of production (land, labor, capital, and natural resources) across production sectors (but not regions). The calculated counterfactual equilibria are therefore considered long-run, and would be expected to emerge following a potentially lengthy adjustment process.

The model used for this study incorporated ethanol production from corn grain, corn stover, and switchgrass. Miscanthus has been discussed as another possible perennial grass feedstock. However, since switchgrass is native to the US and has been researched for a longer period of time in the US than miscanthus, we chose to incorporate switchgrass into the model. The model includes an explicit sector for switchgrass production in the US, and allows for joint products from corn production (i.e. corn stover). Cellulosic ethanol is not yet produced on a commercial scale in the United States, but switchgrass and corn stover have been identified as possible feedstocks. While this model allows for cellulosic ethanol production from only switchgrass and corn stover, we do not assert that these two feedstocks will be used exclusively or exclusively in cellulosic ethanol production. Other feedstocks could be used for cellulosic ethanol production, and this analysis reflects only a subset of possible future scenarios for cellulosic ethanol production.

Based on a review of the literature, a one-to-one ratio of corn stover to corn grain production was assumed (i.e. one ton of corn grain produces one dry ton of corn stover). Many studies have estimated possible corn stover removal rates ranging from 25% to 80% (Graham et al 2007, Petrolia 2006, Wallace et al 2005, Sheehan et al 2004, Gallagher et al 2003, Montross et al 2003, Perlack and Turhollow 2003, Shinners et al 2003, Lang 2002, Hettenhaus and Wooley 2000, Richey et al 1982). For the base scenario, a collection efficiency of 30% was assumed. Corn stover cost data were not incorporated into the model. There is not a separate production function for corn stover, and the model assumes a single set of costs are incurred in the joint production of corn stover and corn grain. There are no observed market prices for corn stover in the historical record or in the base scenario, and the price of

4 We do not assert that the thermochemical conversion approach will not be employed substantially. The focus of our analysis, however, is reductions in conversion costs, and the choice of the technology that we have incorporated into the model should not profoundly influence the results. DOE (2009, section 3) projects similar levels of and reductions in total costs for both the biochemical and thermochemical approaches over the next several years.
corn stover in the alternative scenarios is determined by market interactions in the model solution.

To parameterize the CES production functions for switchgrass and the different types of ethanol, engineering data relating to the production of switchgrass, ethanol from corn grain, ethanol from corn stover, and ethanol from switchgrass were reviewed. The engineering data were used to develop appropriate economic representations of current cost structures for conventional ethanol production (from corn grain) and possible cost structures that may exist for cellulosic ethanol production (from corn stover and switchgrass). These costs were then grouped into categories consistent with the CGE modeling framework. The engineering data provided a bottom-up representation of these biotechnology. The bottom-up information was translated into a top-down representation by translating the cost categories into factors of production (i.e., capital, land, labor, natural resources) and intermediate goods (i.e., feedstock, electricity, natural gas, fuel, chemicals) found in the CGE model.

Grain ethanol cost data were obtained from previous studies (Burnes et al. 2005, McAloon et al. 2000, Shapouri and Gallagher 2005, Tiffany and Eidman 2003, Wallace et al. 2005). The estimates from each of these studies were adjusted to reflect a 2001 corn price. To develop a reasonable cost structure for conventional ethanol, an average estimate based on these studies was used. The average cost plus transportation was $1.08. Following McDonald et al. (2006), cost shares for switchgrass were assigned values similar to other similar crops in the GTAP database. Various studies have estimated switchgrass production and transportation costs (Duffy 2007, Duffy and Nanhon 2001, Khanna and Chapman 2001, Mapemba et al. 2007, Perrin et al. 2008, 2004, Turhollow 2000, Vogel 2007, Walsh et al. 2003). For this study, an average estimate of $63 ton⁻¹ for switchgrass production costs was used. Average total cellulosic ethanol cost data were also obtained from previous studies (Aden et al. 2002, McAloon et al. 2000, Wallace et al. 2005, Wooley et al. 1999). These studies estimated the costs of cellulosic ethanol from corn stover. To develop a reasonable cost structure for the two cellulosic ethanol technologies, these estimates were used to calculate an average cost of cellulosic ethanol production excluding the feedstock. The cost shares were taken from McAloon et al. (2000) and the feedstock costs were adjusted for the $63 ton⁻¹ switchgrass cost. A resulting base cost of $2.08/gal was used for cellulosic ethanol, which is representative of a plant producing 25 million gal yr⁻¹. This reflects current cellulosic ethanol conversion technology, adjusted to 2001 input prices.

Cellulosic ethanol technologies are not available in the calculated base equilibrium, but the enzymatic hydrolysis technology is available at varying costs of production in alternative scenarios. It is important to note that enzymatic hydrolysis is not the only option for cellulosic ethanol production as there are other competing cellulosic conversion technologies. The use of the enzymatic hydrolysis technology represents one possible approach to cellulosic ethanol production, and it is not yet clear which conversion technology(ies) will enjoy widespread adoption.

For this analysis, reductions in cellulosic ethanol production costs are assumed to be due to input-intensive technical change. A possible source of technical change in cellulosic ethanol production is related to the enzyme input. Both Wyman (1999) and DiPardo (2000) note that the greatest potential for cost reductions in the ethanol industry are based on advances in enzymatic hydrolysis technologies. According to DiPardo (2000), the cost of producing cellulose enzymes must be reduced substantially for significant cost reductions to occur in the ethanol industry. DOE (2009) projects that cellulosic conversion costs (i.e., the cost of producing cellulosic ethanol, exclusive of feedstock costs) will fall to $0.92/gal by 2012. With significant advances in enzymatic hydrolysis, enzyme production, and fermentation, Wyman (2008) believes that cellulosic conversion costs could ultimately fall to $0.60/gal. For this study, four scenarios relating to different enzyme costs were analyzed and compared to the base equilibrium with no cellulosic ethanol production. The scenarios represent alternative values for enzyme costs and do not imply that enzyme cost reductions will occur in discrete steps over a particular time period. The scenarios include:

- scenario 1: full cost of enzymes—$0.45/gal;
- scenario 2: 25% reduction in enzyme costs—$0.3375/gal;
- scenario 3: 45% reduction in enzyme costs—$0.2475/gal;
- scenario 4: 65% reduction in enzyme costs—$0.1575/gal.

The scenario 4 enzyme costs are less optimistic than the $0.12/gal projected for 2012 by DOE (2009). Total cellulosic ethanol production costs (including the 2001 costs of switchgrass as a feedstock and all other inputs) associated with the four scenarios are $2.08/gal, $1.97/gal, $1.88/gal, and $1.79/gal. These scenarios represent possible cellulosic ethanol production costs and are not necessarily the most likely scenarios. Since cellulosic ethanol is not currently produced at a commercial scale it is difficult to predict the cost reductions that will ultimately be realized. However, since it is quite possible that production costs will be reduced, it is useful to consider the market effects that such reductions would provoke.

4. Results

The effects of the availability of cellulosic ethanol production technology on the agricultural economy were examined. Only US ethanol production is included in the model and the US import tariff on ethanol is assumed to remain effective. The US import tariff is due to expire on 31 December, 2010. However, due to its repeated renewal since it was originally established in 1980, we assume that the tariff remains in place⁵. If the tariff is eliminated in the future, more ethanol will likely be imported from Brazil instead of being produced in the US, since Brazil can produce ethanol at a lower cost. However, for the purposes of this study, the import tariff is assumed to remain effective and Brazilian ethanol is not considered in this model. The results are presented as percentage changes.

⁵ The assumption that the tariff on imported ethanol will be extended indefinitely is common in both governmental and academic economic analysis. For recent examples, see USDA (2010, p 4) and FAPRI (2009, p 50).
from the base equilibrium and reflect long-run adjustments. The focus of this study is on the changes in key variables and not the actual levels. This is consistent with related work by McDonald and Thierfelder (2004) as well as other CGE analyses, since the base year equilibrium data used in these studies is often several years old.

As cellulosic ethanol becomes cheaper to produce, production increases by a substantial amount, as expected. Production of corn grain ethanol declines as cellulosic technology improves; however total ethanol production increases (Figure 1). Switchgrass is not an economically viable feedstock in any of the scenarios. This result is similar to that of McDonald et al. (2006), in that grain ethanol production declines and cellulosic ethanol production increases, although in their model, cellulosic ethanol is produced using only switchgrass. The result that stover is a preferred cellulosic ethanol feedstock is consistent with USDA (2007). We describe in detail the general equilibrium market effects of the availability of cellulosic ethanol production technology at full cost and with 65% lower enzyme costs in turn.

The introduction of cellulosic ethanol production technology at full cost results in the production of some cellulosic ethanol as depicted in Figure 1, resulting in additional revenue accruing to producers of coarse grains. As ethanol production increases, US demand for imported crude oil is reduced, causing both the quantity of crude oil imported and the equilibrium price of crude oil to fall (Table 1). This results in a strengthening of the US dollar. These developments have two broad effects across US commodity (other than crude oil) markets. First, as US consumers spend less on foreign crude oil, they enjoy increased power to purchase other goods—schedules of domestic demand for other commodities are shifted outward. Second, export demands (in dollar terms) for US commodities are reduced as it becomes more expensive for foreign consumers to purchase US goods. The net effects on total demands for US-produced commodities are thus ambiguous apriori from a theoretical perspective.

In general equilibrium, these net demand effects interact with supply effects which differ between the coarse grain and other commodity markets, to determine market-clearing prices (Table 1) and quantities (Table 2).

In the coarse grain market, the new stover revenue enjoyed by producers in the full cost scenario causes an outward shift in the supply schedule. Prices and quantities exchanged both increase in this equilibrium, indicating that the net effect of the factors described above on total coarse grain demand is positive. This is perhaps not surprising, given that domestic use is noticeably larger than export use. In the US markets for other agricultural commodities, supply contracts as land is diverted to coarse grain production (Table 3). In these markets, equilibrium prices increase (not surprising, as demand would need to contract substantially for prices to fall, given the contracting supply), while equilibrium quantities fall. All changes are relatively modest in magnitude, which is not surprising given the long-run nature of the calculated equilibrium and the relatively modest level of cellulosic ethanol production in this full cost scenario. Lower levels of US production of most commodities, and higher equilibrium prices, are unsurprisingly associated with lower levels of US exports (Table 4).

The availability of cellulosic ethanol production technology with 65% lower enzyme costs results in a much different

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**Figure 1.** US grain and corn stover ethanol production.

**Table 1.** US commodity prices (% changes from base). (Note: 2001 base with no cellulosic ethanol production.)

| Commodity      | Full cost | 25% reduction | 45% reduction | 65% reduction |
|----------------|-----------|---------------|---------------|---------------|
| Rice           | 0.026     | 0.017         | −0.025        | −0.131        |
| Wheat          | 0.027     | 0.018         | −0.025        | −0.135        |
| Cereal grains  | 0.031     | 0.021         | −0.031        | −0.165        |
| Fruit/vegetables| 0.018    | 0.011         | −0.020        | −0.099        |
| Oil seeds      | 0.027     | 0.018         | −0.025        | −0.135        |
| Plant fibers   | 0.028     | 0.018         | −0.029        | −0.149        |
| Other crops    | 0.022     | 0.015         | −0.021        | −0.111        |
| Livestock      | 0.026     | 0.017         | −0.028        | −0.143        |
| Animal products| 0.016     | 0.010         | −0.016        | −0.084        |
| Crude oil      | −0.028    | −0.030        | −0.039        | −0.072        |
| Petroleum/coal | 0.000     | 0.000         | 0.001         | 0.002         |

**Table 2.** US commodity production (% changes from base). (Note: 2001 base with no cellulosic ethanol production.)

| Commodity      | Full cost | 25% reduction | 45% reduction | 65% reduction |
|----------------|-----------|---------------|---------------|---------------|
| Rice           | −0.032    | −0.022        | 0.022         | 0.134         |
| Wheat          | −0.042    | −0.031        | 0.026         | 0.168         |
| Cereal grains  | 0.359     | 0.240         | −0.347        | −1.836        |
| Fruit/vegetables| −0.027   | −0.019        | 0.020         | 0.117         |
| Oil seeds      | −0.033    | −0.024        | 0.023         | 0.139         |
| Plant fibers   | −0.022    | −0.015        | 0.020         | 0.107         |
| Other crops    | −0.024    | −0.017        | 0.014         | 0.092         |
| Livestock      | −0.031    | −0.022        | 0.027         | 0.147         |
| Animal products| −0.015    | −0.011        | 0.012         | 0.067         |
| Crude oil      | −0.035    | −0.038        | −0.055        | −0.113        |
| Petroleum/coal | 0.003     | 0.005         | 0.009         | 0.006         |
Finally, the US renewable fuel standard (RFS) is not imposed that are not reflected in actual changes over only a few years. This leads to long-run adjustments important to note that the results of the CGE analysis represent prices, production, exports, and land use are small, but it is likely qualitative changes that improvements in cellulosic levels. The results are best interpreted as indications of absolute terms in the base equilibrium than current production (reflecting data constraints), US ethanol production is lower in (no cellulosic ethanol production.)

| Plant fibers | Other crops | Livestock | Animal products |
|--------------|-------------|-----------|----------------|
| 0.073 -0.049 | 0.081 -0.055 | 0.082 -0.055 | 0.074 -0.049 |

Table 3. US land use (% changes from base). (Note: 2001 base with no cellulosic ethanol production.)

Table 4. US exports (% changes from base). (Note: 2001 base with no cellulosic ethanol production.)

| Rice | Wheat | Cereal grains | Fruit/vegetables | Oil seeds | Plant fibers | Other crops | Livestock | Animal products |
|------|-------|--------------|------------------|-----------|-------------|------------|-----------|----------------|
| -0.087 -0.059 | -0.073 -0.049 | 0.302 0.203 | -0.083 -0.056 | -0.087 -0.059 | 0.073 -0.049 | 0.081 -0.055 | 0.082 -0.055 | 0.074 -0.049 |

equilibrium. In this equilibrium, cellulosic ethanol production is greater than grain ethanol production, and total ethanol production is greater than in the full cost scenario. This results in even greater reductions in quantities of US crude oil imports and even greater strengthening in the US dollar. In this equilibrium, however, the ability to satisfy such a large proportion of fuel demand using stover-derived ethanol results in a substantial reduction in demand for coarse grain for use in ethanol production. This results in a reduction in the quantity of coarse grain produced, and more land is employed in the production of other agricultural commodities. Net interactions of supply and demand responses result in lower equilibrium prices for all agricultural commodities in this equilibrium. Increased production of commodities other than coarse grains in conjunction with lower equilibrium prices, is associated with increased levels of exports, despite the strengthening of the US dollar.

Some important notes and caveats regarding these results are in order. Since the base year for the CGE model is 2001 (reflecting data constraints), US ethanol production is lower in absolute terms in the base equilibrium than current production levels. The results are best interpreted as indications of likely qualitative changes that improvements in cellulosic ethanol production technology would provoke, not as exact quantitative forecasts. Overall, the changes in commodity prices, production, exports, and land use are small, but it is important to note that the results of the CGE analysis represent a long-run equilibrium. This leads to long-run adjustments that are not reflected in actual changes over only a few years. Finally, the US renewable fuel standard (RFS) is not imposed in the model. We can nonetheless infer some important information regarding this policy instrument, as discussed in the following section.

5. Discussion

Overall, the results reveal two competing broad effects: a nation-wide increase in US purchasing power as less crude oil is imported, and an expansion of the production possibilities frontier. As cellulosic technology is introduced at initially higher costs, the former effect dominates, resulting in increased coarse grain production. This is due to the fact that the US is a large importer of crude oil and a large exporter of corn, and that cellulosic ethanol production would provide even more returns to corn producers. This benefits US consumers, but is detrimental to the environment (at least to the extent that it is affected by intensive coarse grain production) and worldwide food insecurity. As cellulosic technology becomes available at a much lower cost, the latter effect comes to dominate—we are simply able to produce more with less—to beneficial effect for both US and worldwide consumers. That cellulosic conversion technology could initially exacerbate, rather than relieve, competition between food and fuel uses for agriculture’s output is a novel result.

These results have interesting implications, especially with regards to GHG emissions. As Searchinger et al (2008) concluded, the production of switchgrass or additional corn grain for ethanol may increase net lifecycle GHG emissions, relative to simply producing more gasoline. Therefore, the likely use of corn stover as a biomass feedstock and the production of less grain-derived ethanol that is found here is a favorable result, as it corresponds to an avoidance of harmful indirect changes in land use. A favorable (from a net GHG viewpoint) evolution of feedstocks employed would likely result only after significant decreases in the cost of producing cellulosic ethanol, however. As always, there are tradeoffs as well. The removal of corn stover would require more intensive chemical application with potentially negative environmental consequences. This effect is not quantified using our broad model, and deserves additional study.

The idea of eventually producing more ethanol out of the current input mix has important implications from a food insecurity point of view, which also deserves additional study. This analysis indicates that corn stover continues to be preferred over switchgrass as a biomass source, even after cellulosic ethanol costs are reduced substantially. This results in greater production of almost all food commodities, greater exports of almost all food commodities (as less land is employed in producing coarse grains), and lower market prices for all food commodities. This would result in the previously described problems with recent increases in grain ethanol production working in reverse. Low-income people would benefit from reduced food prices by increasing caloric intake and by substituting higher quality foods into their diets. Essentially, if a previously under-employed resource (corn stover) can be used in biofuel production, this greatly relieves

Table 4. US exports (% changes from base). (Note: 2001 base with no cellulosic ethanol production.)

| Rice            | Wheat           | Cereal grains   | Fruit/vegetables | Oil seeds   | Plant fibers | Other crops   | Livestock      | Animal products |
|-----------------|-----------------|-----------------|------------------|-------------|--------------|---------------|---------------|----------------|
| -0.398 -0.283   | -0.429 -0.312   | -0.018 -0.039   | -0.346 -0.253    | -0.382 -0.277 | -0.364 -0.260 | -0.317 -0.234 | -0.454 -0.322 | -0.261 -0.194 |

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the building pressure on agriculture to supply the world with both food and fuel. While RFS constraints are not incorporated into the model, we can still draw some important conclusions regarding the effects of the RFS as well as other biofuel policy instruments. As cellulosic ethanol costs decline, model results indicate that total ethanol production increases, although grain ethanol production decreases. Thus the dichotomy that is built into the current RFS (separate mandates for conventional and advanced biofuels) is likely to prove important. The existence of the advanced component of the RFS is likely to induce innovations in cellulosic ethanol production technology, which could eventually facilitate the favorable stover ethanol related market outcomes described above. Due to the conventional component of the RFS, grain ethanol will continue to be produced in significant quantities by mandate, even though market mechanisms alone might select lower levels of production in an environment of low cellulosic ethanol production costs. Results of this study should also be of interest to market participants. The results indicate that the long-run agricultural and petroleum market implications of most biofuels related activity may not be nearly as dramatic as recent experience suggests. Many grain ethanol plants are currently operating below their maximum capacity and the price of corn is now at or above its energy value. Without additional publicly-provided incentives for grain ethanol production, it is unlikely that substantial expansions of grain-based ethanol production will occur in the near future.

Public policy will clearly play a crucial role in determining the extent of both conventional and cellulosic ethanol production in coming years. It is imperative that those crafting biofuel policies have a thorough understanding of the complex tradeoffs regarding the agricultural market, food insecurity, and environmental concerns.

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