Long-term Effects of Increasing Ethanol Production on Agricultural Markets and Trade, Land Use, and Food Insecurity

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Abstract

We examine the long-run effects of an increase in U.S. ethanol production on the agricultural economy and on worldwide food insecurity. Overall, we find that moderate increases in ethanol production would result in relatively modest changes after a (potentially lengthy) adjustment period. Significant improvements in cellulosic ethanol production technology would substantially reduce the magnitude of such changes, as increases in ethanol production could be fueled by previously unutilized ag wastes. Changes in food insecurity caused by increasing ethanol production would tend to be most painful in Africa, the Far East, and Central and South America (excluding Brazil).

1 Introduction

This paper analyzes the long-run economic effects of increasing U.S. ethanol production. Ethanol production has increased dramatically in recent years, and the ambitious new Renewable Fuel Standards (RFSs) ensures that this trend will continue. The "conventional biofuel" (i.e., ethanol from grain) RFS calls for annual production of 15 billion gallons by 2015, and the "advanced biofuel" (probably including biodiesel and cellulosic ethanol) RFS calls for annual production of 21 billion gallons by 2022. These large increases in biofuel production will have profound effects on the agricultural economy, as the dramatic ag market conditions of recent years suggest. However, the high level of short-run

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variability in ag markets, combined with the inherently long-run nature of the adjustments that increasing biofuels production will provoke, make extrapolation of recent events a poor guide to long-run equilibrium outcomes.

This paper characterizes these long-run effects, with particular emphasis on the effects of increasing biofuels production on agricultural markets. Key questions of interest include the extent to which production of various types of biofuels are likely to increase, the changes land use that will result, and the effects of these increases on worldwide food insecurity. Potential effects on food insecurity have raised tremendous concern for obvious reasons, and potential effects on land use are of interest due to their implications for green house gas emissions and climate change.

This paper employs a computable general equilibrium (CGE) model of world trade to determine changes in agricultural economic variables, and uses those results as an input into the UN Food and Agricultural Organization (FAO) methodology for estimating numbers of under-nourished people. The use of CGE modeling for this analysis is especially attractive, as it not only allows us to discern long-run effects without being distracted by short-run noise, but also allows us to thoroughly consider the growing general equilibrium entanglements between agricultural and energy markets. That is, we can address likely equilibrium levels of cellulosic ethanol production and their effects, not just potential levels of production that have been calculated from biomass resource surveys.

This project's results should be of keen interest to policy makers, as they debate the merits of maintaining, extending, or eliminating the current production mandates and incentives. The relatively high level of disaggregation in the agricultural sectors will help policy makers and industry participants consider the effects of increasing ethanol production on various stakeholders (i.e., crop producers, livestock producers, consumers). NGOs should be keenly interested in the food insecurity and land use results.

2 Methods

This paper employs an existing static computable general equilibrium (CGE) model of world trade. The model uses the Global Trade Analysis Project (GTAP) database, and employs a high level of disaggregation in the agricultural sectors relative to other large-scale CGE models. The model currently features extensions of the GTAP data which allow inclusion of grain, switchgrass, and corn stover-based ethanol production sectors. Changes in equilibrium levels of market variables and land use are determined for alternative scenarios, and food insecurity implications stem from a second stage analysis. This second stage employs a method developed by the UN-FAO. Changes in aggregate consumption of food commodities in different world regions from the CGE results will be used to calculate changes in average daily caloric intake in each region. The means of estimated distributions of daily caloric intake within each region will then be shifted commensurately, and changes in the proportions of each regions' population that fall to the left of the level of minimum caloric needs will be calculated.

2.1 Computable General Equilibrium (CGE) Model

We use a static comparative, multi-region, computable general equilibrium (CGE) trade model, based on Global Trade Analysis Project (GTAP) data. This model is described in (Bryant and Campiche, 2009). Model structure is similar to that of McDonald et al. (2005) and McDonald et al. (2006), but with more detailed representations of agricultural and biofuels-related activities. In this model, the primary factors of production are fully mobile across production activities, and the calculated equilibria are therefore long-run, and would be achieved after (potentially lengthy) periods of adjustment to technology and policy shocks.

This model facilitates analysis of the general equilibrium effects of biofuels policy. Partial equilibrium methods are certainly helpful for analyzing the effects of marginal increases in biofuels production on agricultural markets and trade. However such methods are less appropriate for considering other very interesting questions, such as the effects of very large changes from the status quo, the likely effects of new technologies for which no historical data exist, and the increasing influence of biofuels production on fossil energy market equilibria. Computable general equilibrium methods can overcome these limitations.

Interesting model features relate to biofuels production. The GTAP database does not contain information on biofuels production, and data from other sources, including USDA reports, and agronomic and engineering studies are used to calibrate and incorporate production sectors related to biofuels. New production sectors relate to feedstock production and production of biofuels themselves. Additionally, the existing petroleum and coal products sector is modified to reflect the incorporation of biofuels into the energy products distribution stream. Each of these enhancements is now described in turn.

A switchgrass production sector is added to the model, as switchgrass is a leading candidate cellulosic ethanol feedstock. Switchgrass is a summer perennial grass that is native to North America and is a dominant species of the remnant tall grass prairies in the United States. Switchgrass is resistant to many pests and plant diseases and has the potential to produce high yields with low fertilizer application rates. Switchgrass can be grown on marginal land with fairly moderate inputs and can also protect the soil from erosion problems (Duffy and Nanhou, 2002). The two main types of switchgrass are upland types (grows to 5 or 6 feet tall) and lowland types (grows to 12 feet tall). Switchgrass planting and harvesting is very similar to other hay crops and the same machinery can be used for harvesting. When switchgrass is produced for biomass, it can be cut once or twice a year. Switchgrass is currently grown as a forage crop on limited acreage in the Conservation Reserve Program (CRP), and on various test plots throughout the United States.

Adding a dedicated switchgrass sector follows the approach taken by McDonald et al. (2006), and contrasts with the approach of Raneses et al. (1998) who considered switchgrass an output of an existing "other hay" sector. As in McFarland et al. (2004), we calibrate the production technology for this sector using cost share and total cost information. Following McDonald et al. (2006), cost shares for the inputs into switchgrass production are set to levels similar to those of similar crops in the GTAP database. The total cost of switchgrass production in the base year is based on a broad literature review (Duffy, 2008; Duffy and Nanhou, 2002; Khanna and Chapman, 2001; Mapemba et al., 2007; Perrin et al., 2003, 2008; Turhollow, 2000; Vogel, 2007; Walsh et al., 2003; Ugarte et al., 2003). Individual estimates from these sources were adjusted based on their varying assumptions, and a average price of approximately $63 per ton is used in calibrating this sector. This cost is exclusive of transportation costs, which are borne by the consumer. In contrast to standard practice in CGE model calibration, we use actual price per ton for switchgrass, and model quantities are therefore measured in standard physical units (c.f., physical units that are implied by a base year price of unity).

Corn stover is a byproduct of corn grain production and consists of the stalk, leaf, husk, and cob remaining in the field after the corn grain harvest. The main component of corn stover is cellulose. Corn stover composition and moisture content varies due to several factors such as region, soil type, weather, corn variety, and harvesting methods (Aden et al., 2002). Half of the corn crop yield by weight is corn stover, but it is generally left in the field after harvest. A portion of the 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 avoid soil erosion. Less than 5% of corn stover production is generally used presently (Hettenhaus and Wooley, 2000).

Given that large quantities of corn stover are currently produced, yet little is utilized, they are likely the lowest cost biomass source as cellulosic ethanol production begins (Gallagher et al., 2003). Consideration of corn stover is therefore critical to ensuring that an unrealistic level of dedicated energy crop production is not provoked by increases in cellulosic ethanol production. We incorporate stover as a fixed proportions joint product of cereal grain production (Figure 1). Costs for producing corn stover are therefore not separately modeled, but are instead shared with the cereal grains production activity. Collection and transportation costs for stover in this model are borne by the consumer.

A portion of the corn stover can be collected and used as a biomass source for cellulosic ethanol production. The amount that can be removed varies by region, soil conditions, and harvest activities. Corn stover is very important in preserving the organic matter and nutrients in the soil following corn grain harvesting and preventing soil erosion. It is difficult to establish a corn stover removal rate that is ideal for all regions due to variations in soil and weather conditions. Additionally, stover collection is restricted by several constraints relating to available collection technologies. For the purposes of this model, we assume a stover collection rate of 30%, which is consistent with available collection technology and is believed sustainable from an erosion standpoint.

Three ethanol production sectors are incorporated into the model, reflecting three possible feedstocks: cereal grain, switchgrass, and corn stover. Fuel ethanol production from grain feedstocks is a mature technology, and numerous estimates of production costs and their structures are available. Calibration of

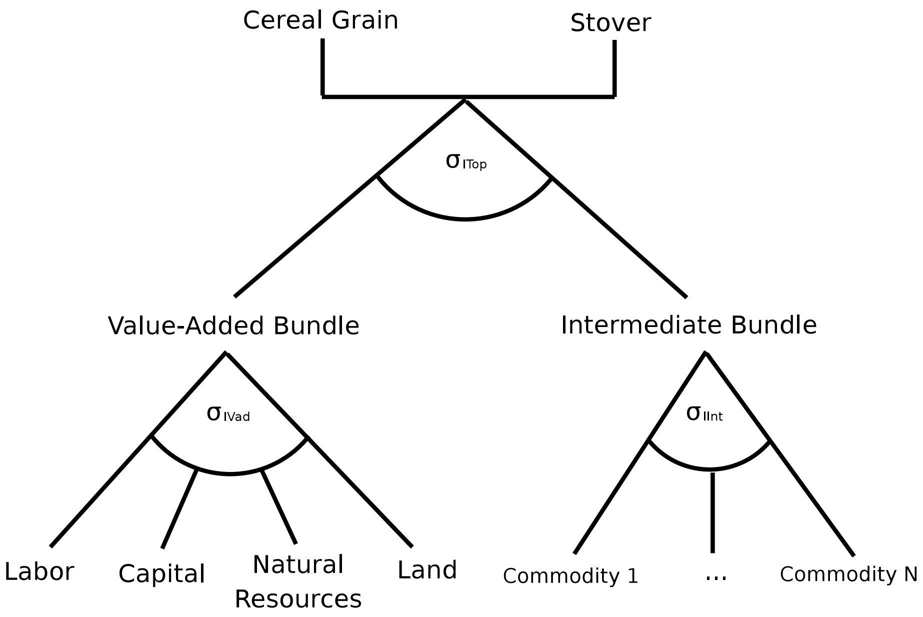

Figure 1: Joint Production of Coarse Grains and Stover

the production function is again accomplished by calibrating cost shares and total cost to available cost studies, as described above for switchgrass production. Numerous such studies were reviewed (Tiffany et al., 2008; Environmental Protection Agency, 2007; Eidman, 2007; Burnes et al., 2005; Shapouri and Gallagher, 2005; Wallace et al., 2005; Tiffany and Eidman, 2003; McAloon et al., 2000), and the individual unit cost estimates were adjusted to reflect a 2001 corn price (corresponding to our base year). The average adjusted unit cost estimate of about \$1.08 is employed in calibration. Cost shares for individual inputs were averaged over available studies as well, and those averages were used for calibration.

So-called cellulosic ethanol is widely viewed as a promising avenue for development of sustainable, domestically produced liquid fuel. Cellulosic ethanol is produced by converting cellulose from plants into sugars which can then be fermented and distilled using standard technology. Enzymatic hydrolysis is the technology being most actively pursued for cellulosic conversion, and this is the technology against which we calibrate cellulosic ethanol production sectors. This technology is much less mature than that for grain-based ethanol, and production on large commercial scales has yet to commence. Cost estimates therefore reflect a fair amount of uncertainty. Available cost studies vary widely in their assumptions, particularly regarding production scale, feedstock costs, and enzyme costs.

We incorporate both corn stover and switchgrass-based ethanol production

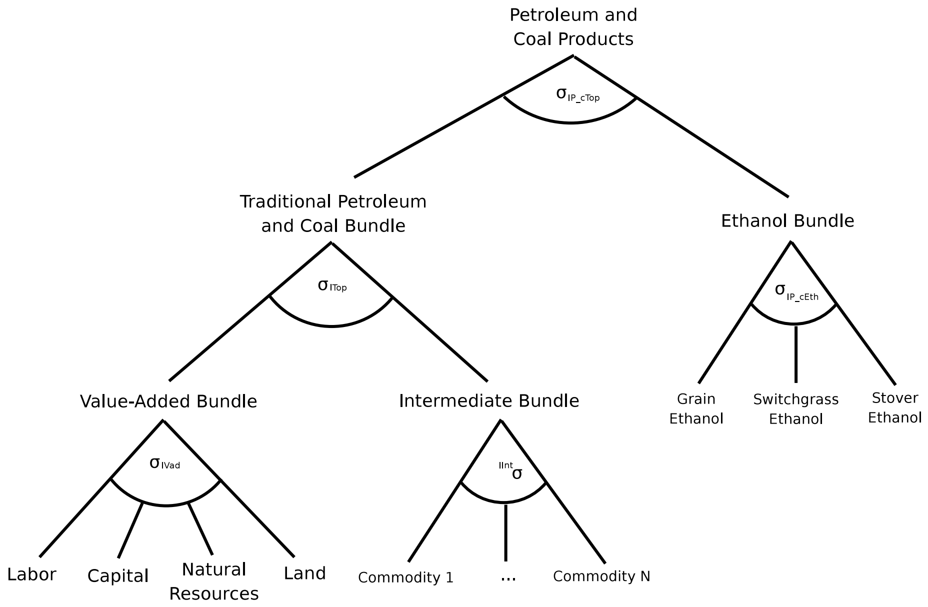

Figure 2: Petroleum and Coal Products Sector

sectors in the model. All available cost estimates concern producing cellulosic ethanol from switchgrass (Aden et al., 2002; McAloon et al., 2000; Wallace et al., 2005; Wooley et al., 1999), and these cost data are used for calibrating both cellulosic ethanol production sectors. The different cost estimates are normalized to reflect identical biomass costs, and to reflect the cost of biomass collection and transportation. The resulting average normalized estimate of total unit cost of $2.08 is used in the calibration. Individual costs from the studies reviewed were categorized and aggregated as appropriate, and the these categorized costs were mapped to the primary factors and commodities employed in the model. As with the biomass and grain ethanol production sectors, actual unit costs are used as the base year price rather than unity, and the corresponding quantity variables are therefore measured in standard physical units.

All biofuels are consumed by a petroleum and coal products production sector. This arrangement is similar to Reilly and Paltsev (2007), who assume that the output of their “bio-oil” sector is a perfect substitute for refined oil products. The arrangement is also somewhat similar to McDonald et al. (2006), who consider switchgrass as a substitute for crude oil in the production of refined petroleum products. More generally, the use of biofuels as an input into production of petroleum products is consistent with the nature of actual biofuel marketing, which typically involves the distribution of blends of biofuels and traditional petroleum-based fuels.

The petroleum and coal products production sector is depicted in Figure 2. Traditional petroleum and coal products are produced in a sub-tree structured like all other commodity production functions in the model. Ethanols produced using grain, switchgrass and stover are used to produce a composite ethanol good. A high degree of substitutability among ethanol varieties is assumed. Finally, the composite ethanol good and the composite traditional coal and petroleum-based products good are used in the production of the new, more broadly defined petroleum and coal products commodity. The top nest is calibrated using the value of production of the traditional coal and petroleum products, the value of production of fuel ethanol in 2001, and the 2001 grain ethanol cost of production of about \$1.08. A moderately high degree of substitution is specified for this top nest.

2.2 Estimation of Food Insecurity

We adopt the UN Food and Agriculture Organization (FAO) method for estimating changes in the numbers of food insecure people (Naiken, 2002) as aggregate consumption of food commodities changes. The FAO measure endeavors to capture those whose food consumption level is insufficient for body weight maintenance and work performance, focusing on the phenomenon of hunger rather than poor nutrition. The FAO measure of food insecurity is based on a probability distribution framework. Given the distribution of dietary energy consumption $f(x)$, the percentage of undernourished people is estimated as the proportion of population below the minimum per capita dietary energy requirement r_L. This arrangement is illustrated in Figure 3. r_L is derived by aggregating the estimated gender and age-specific minimum dietary energy requirements, using the relative proportions of a population in the corresponding sex-age group as weights. The estimates are calculated on a country-by-country basis and are reported periodically by FAO.

The distribution $f(x)$ is estimated based on household surveys, which collect data on the quantities of food product consumed by individuals in a representative sample of households in the population. However, the methodology and concepts applied in the surveys are not sufficiently precise to provide an accurate and reliable estimate of the distribution, and FAO therefore employs a theoretical distribution. The frequency distributions suggested by the food survey data are generally unimodal, and FAO considered a specific group of appropriate distributions.

FAO initially employed the Beta distribution, as it enabled fixing the lower and upper limits of the range as determined by the physiological lower and upper limits of intake in individuals. However, researchers found this distribution was appropriate only when dealing with the true intake of individuals. In most of the surveys, the data refer to the food available to, or acquired by, the household and thus include household wastage, food fed to pets, etc. Since 1987, FAO has instead employed the two-parameter log-normal distribution. The short lower tail and long upper tail better reflect the richer and more affluent households, who are more likely to have wastage, food fed to pets, etc.

The log-normal distribution can be specified by two parameters, the coefficient of variations $CV(x)$, and the mean $(\overline{x})$. Given these two parameters, the

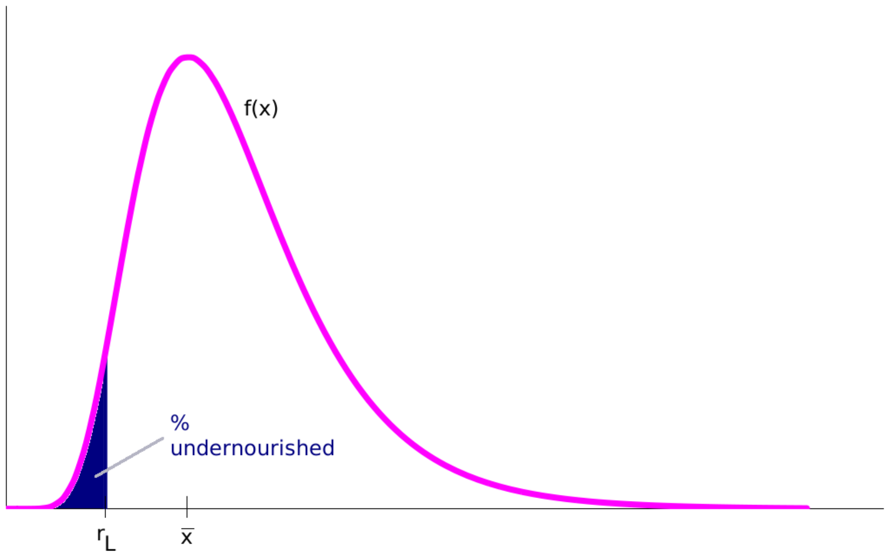

Figure 3: FAO Method of Calculating the Number of Undernourished People in a Region.

mean and variance of the corresponding normal distribution can be determined as

$$\sigma^2 = ln\left(CV^2(x) + 1\right)$$

and

$$\mu = \frac{ln(\overline{x}) - \sigma^2}{2}.$$

The $CV(x)$ is estimated as

$$CV(x) = \sqrt{CV^2(x|v) + CV^2(x|r)}$$

where $CV(x|v)$ is variation owing to household per capita income, v, and $CV(x|r)$ is variation due to the energy requirement r. A detailed procedure of estimation is documented in (Naiken, 2002). Because the inequality of income distribution for a number of developing countries varied little over last three decades, and the inequality in the distribution of household per capita food consumption is much smaller than the inequality in the distribution of household income, and $CV(x)$ is assumed to be constant.

The mean $\overline{x}$ represented by the per capita dietary energy supply refers to the energy available for human consumption, expressed in kilo-calories (kcal) per person. It is derived from the food balance sheets (FBS) compiled every year by FAO on the basis of data on the production and trade of food commodities. The total dietary energy supply is obtained by aggregating the food component of all commodities after being converted into energy values.

Energy requirements are different for different individuals. The most influential factors are age, sex, body weight, and activity level. The r_L for a country is derived by aggregating the minimum sex-age-specific energy requirement with information on the composition of the population.

The sex-age-specific energy requirement is derived in two procedures. For adults and adolescents, the energy requirements are calculated with the basal metabolic rate (BMR). For children below age ten, the energy requirements are expressed as fixed amounts of energy per kilogram of body weights. The lower limits of the requirements for each sex-age group were derived with the lowest acceptable body weight and lowest acceptable activity allowance. r_L is around 2,000 kcal per day for each country, and is updated by FAO periodically as the composition of population changes over time.

FAO provides caloric intake distributions for a much larger number of countries/regions than are featured in the CGE model. To estimate the daily calorie intake distribution for each of nine aggregate regions that correspond to the regions of the CGE model, we adopted a two-step Monte Carlo simulation method. First we randomly draw a country i within the region with probabilities equal to the population weights. We then randomly draw a number from the specific country's distribution $f_i(x)$. We employ 65,500 trials for each aggregate region to estimate its empirical aggregate caloric intake distribution $f(x)$. While we take care to accommodate the possibility of complex aggregate caloric intake distributions, all nine of the simulated aggregate distributions appeared unimodal with an approximate log-normal shape. Within each region, the per capita dietary energy supply for each country was aggregated by the population weights, using the 2001 Food Balance Sheets. Per capita dietary energy supply from each food group in our model is also aggregated in the same way.

Similarly, the lowest energy requirement level r_L is aggregated with population weights of the countries within the specific region. With the daily calorie intake distribution $f(x)$ and the lowest energy requirement level (r_L) for each region, we can update the mean $\overline{x}$ corresponding to the results from the CGE model, and calculate the proportion of undernourished people within each region for different scenarios.

3 Scenarios Analyzed

We use a base solution corresponding to the 2001 base year equilibrium with ethanol production of 10 billion gallons imposed as a constraint. This approximately corresponds to the current level of U.S. ethanol production. In this equilibrium, the cellulosic ethanol technologies are present, but at full cost, and very little cellulosic ethanol is produced. Using that solution as a base, we then compute two alternative scenarios for future ethanol production levels. In the first scenario, we calculate an equilibrium with a constraint that at least 15 billion gallons of ethanol are required, and cellulosic ethanol is produced at current full costs. In the second scenario, we again require at least 15 billion gallons of ethanol production, but we assume that input-intensive technical change results in a reduction of 55% in the cost of the enzymes required to produce a fixed quantity of cellulosic ethanol.

These scenarios do not correspond to the long-run levels of ethanol production required by the revised Renewable Fuel Standard (RFS). However the RFS contains provisions that allow relaxation of the standards under unfavorable market conditions, and the RFS may undergo revision (as has already happened once) before the higher production levels are reached. In short, while the RFS may seem to establish immutable minimum levels of future ethanol production, things could easily change. This is especially true with respect to the "advanced biofuel" provisions. In the event that large-scale production of cellulosic ethanol proves very expensive, pressure to relax advanced biofuel requirements will surely swell.

The selection of a 55% reduction in the cost of producing cellulosic ethanol (via improved enzyme technology) is somewhat arbitrary. Estimates for reductions in enzyme costs currently vary widely, and there is obviously no certainty regarding time frames for achieving particular levels of reductions.

We therefore do not assert that the two future scenarios considered here are the likely future courses of events. The scenarios merely represent interesting "what-if" cases which serve to illustrate the changes in variables of interest under two plausible future longer-run trajectories of ethanol production.

4 Results

Results are presented in two stages. We first describe changes under the two scenarios of some general ag-related market variables, ethanol production, land use, and fossil energy use. We then present the effects of increasing ethanol on global food insecurity.

4.1 Changes in Ag Economy

Under the expensive enzyme scenario, only about 1.25 billion gallons of the total 15 billion gallons is produced using cellulosic feestocks (Figure 4), and this is essentially all stover. Stover prices remain below the cost of switchgrass production in both scenarios. It is therefore the preferred feedstock, and the switchgrass production activity is operated at zero intensity in both scenarios. With a 55% percent reduction in enzyme costs, almost 4 billion gallons of ethanol is produced using stover. A likely predominance of stover over switchgrass as a cellulosic ethanol feedstock is consistent with the findings of Milbrandt (2005) and U.S. Department of Agriculture (2007).

Unsurprisingly, these increases in ethanol production influence equilibrium production levels for other ag commodities. Since the two ethanol feedstocks employed in computed equilibria, grain and stover, are the two joint products of the coarse grain production activity, revenue to this activity increases significantly and it is operated at greater intensity in both scenarios (Figure 5). In the cheaper enzyme scenario, however, less grain is produced as greater quantities of

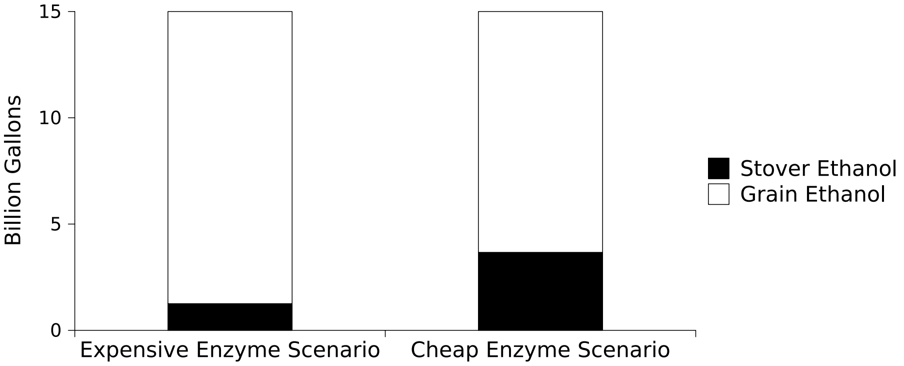

Figure 4: U.S. Production of Grain and Cellulosic Ethanol Under a 15 Billion Gallon Mandate in Alternative Cellulosic Cost Scenarios.

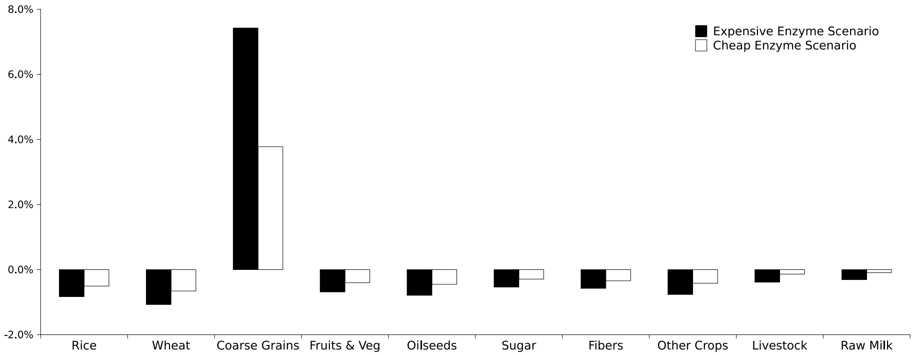

Figure 5: Changes in U.S. Production of Agricultural Commodities Under Increased Ethanol Production.

stover can be employed in satisfying the ethanol production mandate. Smaller quantities of other ag commodities are produced as the coarse grains sector consumes greater quantities of available inputs, especially land. Decreases in the production of other ag commodities are fairly modest, however, around 1% at most.

Prices of agricultural commodities generally increase as greater proportions of ag output are consumed in ethanol production (Figure 6). These increases are more pronounced in the expensive enzyme scenario, however, as more resources must be devoted to production of coarse grain for ethanol production. Under the cheap enzyme scenario, a greater proportion of ethanol is produced using a heretofore unused resource (stover), resulting in a smaller increase in coarse grain production relative to the base scenario. Interestingly, this actually results in lower grain prices, as more new-found stover revenue accrues to the coarse grain production activity under this scenario. Again, changes are fairly

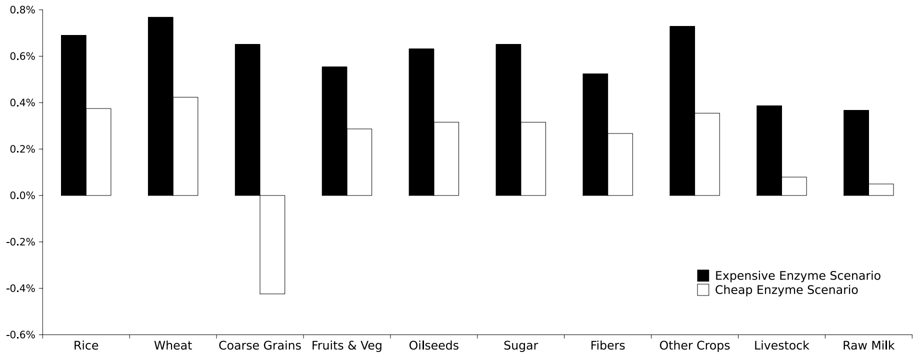

Figure 6: Changes in U.S. Prices of Agricultural Commodities Under Increased Ethanol Production.

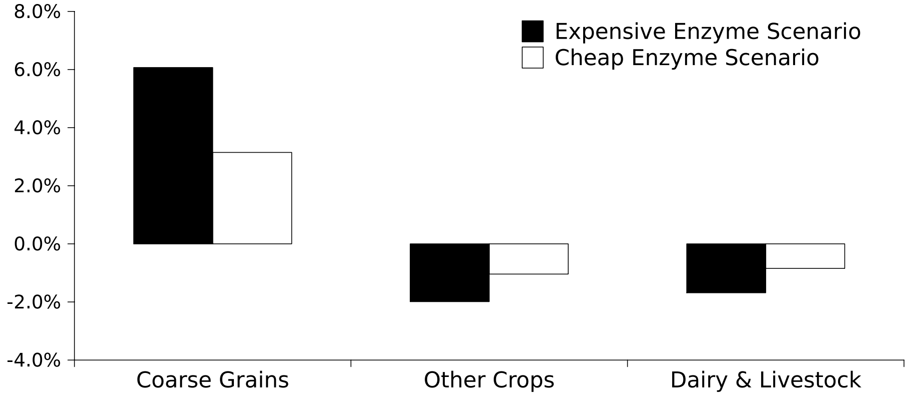

Figure 7: Changes in U.S. Land Use Under Increased Ethanol Production.

modest in magnitude, with all price changes being less than 1%. This reflects the long run nature of computed equilibria, as factors of production are fully mobile across sectors. The short run adjustment process may well involve more dramatic price swings.

Land use changes are consistent with the increased levels of coarse grain production under the two scenarios, relative to the base. Again, however, more resources are devoted to coarse grain production under the expansive enzyme scenario then under the cheap enzyme scenario (Figure 7).

Reduced dependence on fossil energy is a commonly stated benefit of increasing biofuels production. Under both scenarios we consider here, ethanol production is required to increase to 15 billion gallons from the base level of 10 billion gallons, and changes in fossil energy use are very similar under both.[1] U.S. fossil energy use declines more than 3% with the increased ethanol pro-

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[1] These numbers reflect coal and crude oil use, but not natural gas.

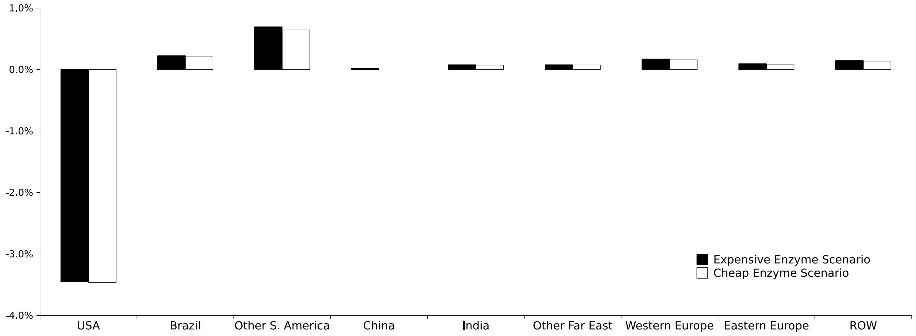

Figure 8: Changes in Fossil Energy Use Under Increased U.S. Ethanol Production.

duction, and the resulting decrease in fossil energy prices results in greater consumption in other world regions.

4.2 Changes in Food Insecurity

The relatively modest changes in long-run equilibrium prices for food commodities under the increased ethanol production scenarios result in relatively modest changes in average per capita caloric consumption (Table 1). The largest changes in caloric intake occur in the U.S., where the ethanol production occurs. The U.S. population also consumes relatively large quantities of cereal grains indirectly via livestock production relative to other world regions, and increased grain prices thus lead to lower consumption of high-calorie meat products. Higher world prices for commodities influence other regions' caloric intake as well, with regions' reliance on ag imports heavily influencing relative results. Brazil, a major exporter of ag commodities enjoys higher income following an increase in U.S. ethanol production, and therefore increases consumption of food commodities. Many Far East countries other than China (e.g., Japan), by contrast, rely heavily on agricultural imports and consume fewer calories as food prices increase. In all regions with reduced caloric intake, the reductions are smaller under the cheap enzyme scenario, wherein less food (i.e., grain) is used to fuel increased ethanol production.

Changes in the percentage of the population in each region that is food insecure are determined by the interaction of the magnitude of the shift in mean caloric intake described above and by the percentage of the each region's population that was food insecure under the base scenario. While the largest declines in caloric intake were in the U.S., only a very small proportion of the U.S. population is food insecure, with a large majority of consumers enjoying a significant daily caloric surplus. Thus shifting the distribution of caloric intake, as described in subsection 2.2, only shifts a very small area to the left of the minimum caloric need (Table 2). In short, Americans can easily afford to eat less.

Table 1: Changes in Mean per Capita Daily Caloric Intake

	Expensive Enzymes	Cheap Enzymes
USA	-7.12	-3.88
Brazil	0.13	0.15
China	-0.75	-0.69
India	-0.04	-0.02
Other Far East	-1.00	-0.43
Western Europe	-0.35	-0.24
Eastern Europe and FSU	0.02	0.02
Central and South America	-1.05	-0.42
Rest of the World	-0.74	-0.57

Table 2: Percentages of Populations that are Food Insecure

	Base	Expensive Enzymes	Cheap Enzymes
USA	0.134%	0.142%	0.137%
Brazil	8.933%	8.928%	8.928%
China	11.557%	11.582%	11.579%
India	25.733%	25.736%	25.734%
Other Far East	8.762%	8.794%	8.774%
Western Europe	0.354%	0.356%	0.354%
Eastern Europe and FSU	7.177%	7.176%	7.176%
Central and South America	11.160%	11.195%	11.171%
Rest of the World	24.611%	24.643%	24.635%

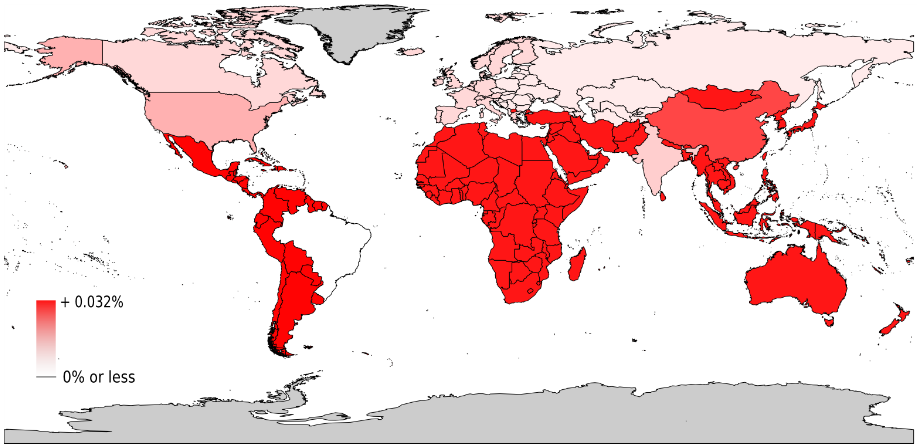

Figure 9: Changes in Percent of Population that is Food Insecure as Ethanol Production Increases, Full-cost Enzyme Cost Scenario.

Changes in other regions vary. Among regions with significant food insecure population (i.e., regions other than the U.S. and Western Europe), the largest increases in the percentages of food insecure people occur in the Other Far East, Central and South America, and Rest of the World regions. The changes in these percentages for the two scenarios relative to the base solution are depicted graphically in Figures 9 and 10. Brazil (a significant food exporter) and regions that minimally rely on food imports fair better.

The numbers of people in each region multiplied by the percentage changes reported in Table 2 imply the absolute numbers of people that become (or cease to be) food insecure. These absolute numbers are depicted in Table 3. Almost all of the increase in food insecure people occurs in the Far East (China and Other Far East regions), Central and South America (excluding Brazil), and the Africa (comprises a large portion of the Rest of the World region). Overall, however, the net change in the number of food insecure people worldwide is relatively modest, at about 1.2 and 0.8 million people in the expensive and cheap enzyme scenarios, respectively. This reflects the minimal changes in food prices reported in Table 6.

4.3 Caveats

Several caveats apply to this work. First, the calculated equilibria are long-run, and would occur after potentially lengthy adjustment periods. Short-run results may well be more painful in terms of food insecurity, as the agricultural economy gropes with the shock of increasing diversion of its output into fuel production. Second, the enzymatic hydrolysis of non-woody biomass reflected in our model is but one among many competing cellulosic feedstock-technology pairs, although this combination seems to have the most momentum. Third,

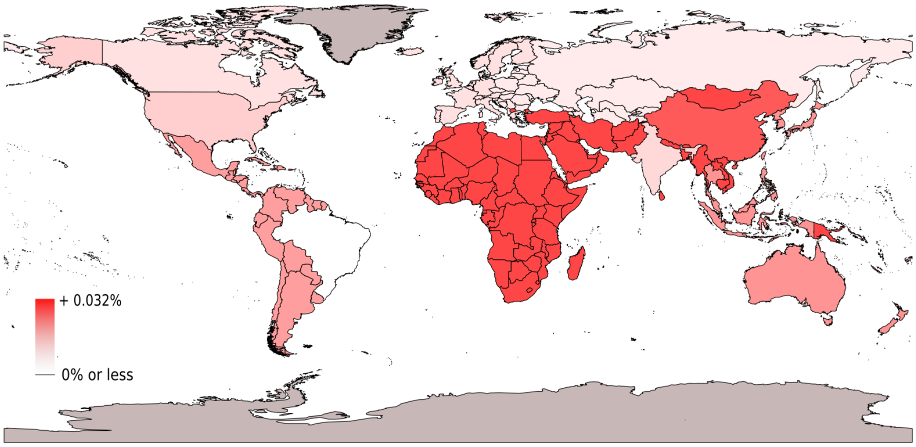

Figure 10: Changes in Percent of Population that is Food Insecure as Ethanol Production Increases, Lower Cost Enzyme Cost Scenario.

Table 3: Changes in Numbers of Food Insecure People (millions)

	Expensive Enzymes	Cheap Enzymes
USA	0.023	0.009
Brazil	-0.008	-0.008
China	0.316	0.276
India	0.032	0.016
Other Far East	0.184	0.070
Western Europe	0.006	0.000
Eastern Europe and FSU	-0.006	-0.006
Central and South America	0.122	0.037
Rest of the World	0.514	0.391
Total	1.182	0.786

the eventual extent of cost reductions for the enzymatic hydrolysis technology are clearly uncertain, and our assumption of a 55% reduction in enzyme costs merely reflects one possibility. Fourth, we are not accounting for improvements in coarse grain productivity, which would tend to overstate the net increase in food insecurity. We are using 2001 population numbers and FAO calorie distributions, which would tend to understate net increases in food insecurity. Finally, and perhaps most importantly, we are not presently accounting for increases in biofuel production in regions other than the U.S., and the RFS calls for much larger increases in ethanol production than the 5 billion gallons that we consider here. Larger increases in worldwide biofuel production would also tend to understate net increases in food insecurity.

5 Conclusions

Overall, we find that moderate increases in U.S. ethanol production would result in modest changes in agricultural economies and net food insecurity, after a (potentially lengthy) adjustment period. Significant improvements in cellulosic ethanol production technology would substantially reduce the magnitude of such changes, as increases in ethanol production could be fueled by previously unutilized ag wastes.

Increases in cellulosic ethanol production are likely to be fueled by ag waste rather than dedicated energy crops. Production of coarse grains is certain to increase as ethanol production increases, as both the grain and associated stover represent current and likely feedstocks for future ethanol production. Changes in food insecurity caused by increasing ethanol production would tend to be most painful in Africa, the Far East, and Central and South America (excluding Brazil), although such changes would likely be modest in the long run for moderate increases in ethanol production.

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