

## MODELING LAND-USE CHANGE IMPACTS OF BIOFUELS IN THE GTAP-BIO FRAMEWORK

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This paper reviews an analysis of land use change impacts of expanded biofuel production with GTAP-BIO computable general equilibrium (CGE) model. It describes the treatment of energy substitution, the role of biofuel by-products, specification of bilateral trade, the determination of land cover changes in response to increased biofuel feedstock production, and changes in crop yields – both at the intensive and extensive margins. The paper responds to some of the criticisms of GTAP-BIO and provides insights into the sensitivity of land use change and GHG emissions to changes in key parameters and assumptions. In particular, it considers an alternative specification of acreage response that takes into account the degree of land heterogeneity within agro-ecological zone (AEZ) for different AEZs and countries. The paper concludes with the discussion of alternative specifications of land mobility across uses employed in CGE models and the agenda for further research to narrow parametric and structural uncertainty to improve the model's performance.

*Keywords:* Biofuels; general equilibrium; drivers of land use change; acreage response; yields response; land supply functions.

JEL Codes: C68, Q15, Q16.

### 1. Introduction

Higher fossil fuel prices, concerns about energy security, and global warming all contributed to greater attention to biofuel policies over the past decade — particularly in Europe and the U.S. Early assessments emphasized the potential benefits of displacing fossil fuels with renewable energy (Wang *et al.*, 1999; Farrell *et al.*, 2006). However, later analysis raised concerns about indirect land-use change leading to additional greenhouse gas (GHG) emissions (Kammen *et al.*, 2007; Fargione *et al.*, 2008; Searchinger *et al.*, 2008). Additional constraints have been placed on biofuel policies — including the need to assess the likely impacts on global land-use change (e.g., California Air Resource Board, 2009). This, in turn, has led to great interest in economic models capable of eliciting the indirect land-use change impacts of biofuels.

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Biofuels production and distribution are extremely complex processes involving markets for land, crops, livestock, energy, and food. The predicted land-use change flowing from a given set of biofuel policies depends on the model assumptions about the economic structure and parameters governing each of these processes. This paper reviews a computable general equilibrium (CGE) analysis of land-use change impacts of expanded biofuel production and analyzes the sensitivity of the model outcome with respect to the key structural and parameter assumptions. The CGE model employed is a variant of the Global Trade Analysis Project (GTAP) model (Hertel, 1997) widely used for global economic analysis of trade, energy, and environmental issues. Many global CGE models have been used in the analysis of the market impacts of expanded production of biofuels. An admittedly incomplete list includes the LEITAP model (Banse *et al.*, 2008, 2011) of the Dutch Agricultural Economics Research Institute (LEI), the MIT Emissions Prediction and Policy Analysis (EPPA) Model (Paltsev *et al.*, 2005, Mellilo *et al.*, 2009), the CEPII (Centre d'Etudes Prospectives et d'Informations Internationales)/IFPRI (International Food Policy Research Institute) Mirage model (Bouet *et al.*, 2009; Al-Riffai *et al.*, 2010). Many common features of these models derive from the fact that they are all built on the GTAP global economic data base. However, models differ in their structure, and more specifically, in their treatment of energy markets, land markets, and biofuel production.

This paper focuses on a variant of the standard GTAP model nicknamed GTAP-BIO (Birur *et al.*, 2008) — the modeling framework mandated for use in California's Low Carbon Fuel Standard assessments of biofuels.

## 2. Modeling Biofuel and Energy Demands

The GTAP-BIO model is modification of GTAP-E model (Burniaux and Truong, 2002) designed for the energy–economy–environment–trade linkages analysis. With respect to biofuels, the most important feature of GTAP-E is the prominence given to energy substitution — both between alternative fuels as well as between energy and other inputs (e.g., labor and capital). Such input substitution is a key, as this represents the economy's first line of defense against higher fuel prices. If these substitution possibilities are large, then the economic costs of higher oil prices — or a carbon tax — are small. This also has important implications for the impacts of a biofuel mandate. If biofuels are a reasonably good substitute for petroleum products, then such a mandate will be less costly for the economy. And furthermore, if there are significant opportunities for conserving liquid fuel use in the economy, GHG emissions impacts of a biofuel mandate will be minimized, as the higher fuel costs flowing from the mandate will significantly curb overall fuel use. Therefore, one cannot begin to think about modeling the economy-wide and global environmental impacts of biofuels without first considering the validity of the model's treatment of energy substitution — both overall, and specifically with respect to biofuels.

## **2.1. Overall responsiveness of energy demands**

Beckman *et al.* (2011) evaluate the validity of the original GTAP-E model with respect to energy demand — specifically focusing on the price elasticity of demand for petroleum products. They use two alternative approaches. In the first, they undertake a series of stochastic simulations in which oil supplies and economy-wide demands (as measured by GDP) are perturbed, based on historic variation as evidenced in five-year moving averages. These supply-and-demand shocks in turn result in endogenously generated, medium-term price volatility from the GTAP-E model. When compared to observed oil price volatility, the authors find that the model generates far too little price variation — suggesting that the supply and demand elasticities in the model may be too large. A comprehensive literature review leads the authors to focus on the demand elasticities. After adjusting them to reflect the recent econometric literature on this topic, the authors find much more satisfactory model performance.

Beckman *et al.* (2011) also perform another type of validation exercise with GTAP-E. In this case, they undertake a deterministic simulation over the 2001–2006 period, in which they shock a variety of macro-economic drivers (population, labor force, investment and capital stock, and total factor productivity), as well as oil prices. They then compare model-generated predictions for oil consumption with observed changes, by region. With the original GTAP-E specification, predicted consumption falls in all model regions. This contrasts sharply with reality in which oil product consumption rose in all eight model regions, excepting Japan, and global consumption rose by nearly 10%. However, when the new smaller energy substitution elasticities are incorporated, the model performance is greatly improved. This indicates that the original GTAP-E parameters result in far too elastic medium-term energy demands which in turn may translate into misleading predictions of the impacts of energy price rises on fuel usage, as well as overly strong impacts of biofuel mandates on aggregate usage of liquid fuels and hence GHG emissions.

## **2.2. Biofuel–petroleum substitution possibilities**

Most first-generation biofuels are imperfect substitutes for petroleum products. For example, ethanol — the most widely used biofuel in the U.S. and Brazilian markets — has lower energy content per gallon than petroleum but it burns cleaner due to its high oxygen content and is therefore priced as a fuel additive. Indeed, the early ethanol boom (up to 2006) in the U.S. was fueled not by the demand for ethanol as an energy source but rather by the demand for its use as a fuel additive to replace the previous industry standard (methyl tertiary butyl ether) which was determined to cause groundwater pollution. So this ‘base load’ demand for ethanol is largely insensitive to price and simply varies in proportion to overall gasoline use.

Ethanol is also importantly differentiated from petroleum in that conventional automobile engines cannot use more than 10% or 15% ethanol-based gasoline without risking permanent damage. This is the so-called ‘blend-wall’, which has recently begun

to evidence itself in the U.S. When this limit is reached, it evidences itself in a price-inelastic demand for ethanol. Declines in the price of this alternative fuel can do little to increase demand — other than lowering overall fuel costs and thereby stimulating aggregate fuel use, and with it the demand for ethanol. Recently, the ethanol industry has been lobbying to increase the blend wall from its historical value of 10% to 15% — for recent model vehicles. This move has been opposed by the automobile industry, which fears an onslaught of mechanical problems, as well as gasoline distributors who do not wish to be forced to have separate pumps for old and new cars. Ultimately deeper penetration of ethanol into the U.S. market hinges on expansion of the U.S. flex-fuel fleet. And this depends in part on expansion of the number of service stations offering the higher blend, E-85 fuel. The Brazilian economy has made a major commitment to flex-fuel vehicles, and this has permitted them to dramatically increase the share of ethanol in its overall liquid fuel mix.

Econometric estimation of the substitutability of biofuels for conventional fuels has been limited to date. Outside of Brazil, the problem is one of insufficient time series. Nonetheless, this parameter is critical to any analysis of the economy-wide impacts of biofuels, as it determines the economic cost of biofuel mandates, their impact on liquid fuel prices, as well as the response of biofuel use to changes in the highly volatile oil markets. Hertel *et al.* (2010) seek to estimate the substitutability of ethanol and biodiesel for petroleum products in three key markets: Brazil, EU, and the U.S. They do this via general equilibrium simulation of the GTAP-BIO model over the historical period: 2001–2006, taking into account policy changes, oil price changes, and other economic drivers of demand. Their estimated values are 1.35 for Brazil, 1.65 for EU, and 3.95 for U.S. The relatively low value for Brazil reflects the relatively high penetration of ethanol in that market already. Further increases in market share in the face of rising oil prices over this period appear to have been difficult to attain. In contrast, the U.S. over this period was experiencing extremely strong growth in ethanol demand, and, in light of the fact that the authors deemed the additive portion of the market to be price-insensitive, the remaining 25% had to be quite price-sensitive to explain the strong growth in ethanol use for energy over this period. Looking forward, it is clear that future substitutability of ethanol for petroleum in U.S. will be severely circumscribed by the blend wall.

Having discussed how shocks to the energy market are translated into changes in biofuel production, we now consider how such changes in biofuel output affect the derived demand for feedstocks, and ultimately land-use.

### 3. Translating Biofuel Output into Feedstock Demand: The Role of By-Products

Conditional on the demand for total biofuel output, the key factors determining the derived demand for feedstock crops are conversion efficiency and the presence of by-products. Conversion efficiency, for example how many bushels of corn are needed to produce a gallon of ethanol, is a technical parameter, and this is embedded in the

GTAP-BIO data base. The reader is referred to [Taheripour \*et al.\* \(2007\)](#) for technical details on construction of the GTAP-BIO data base. However, the by-product issue is one which requires more careful thought and this has been a source of some difficulty for those modeling global land-use change due to biofuels.

The basic issue is that the production of biofuels does not exhaust the nutritional value of the feedstock. In the case of corn ethanol, for example, the production process results in both ethanol and Dried Distillers Grains with Solubles (DDGS), the latter of which can be used as a feed supplement. And so it is the case that the impact of a given increase in ethanol production on the corn market is more moderate than one might initially think due to the increased availability of a grain substitute. A similar phenomenon exists with the production of biodiesel for which the crushing of oilseeds produces both bio-oil for use in production of diesel fuel, as well as oilseed meal, which may be fed to livestock. In the case of ethanol produced from sugarcane (the dominant biofuel in Brazil) the by-product is used as a source of energy to fuel the ethanol plant. As such its benefits are subsumed in the ethanol industry production function itself.

In those cases where the biofuel by-product is fed to livestock, a critical factor in the model is the scope for substitution between the by-product and other feedstuffs — a factor which is likely to vary significantly across types of livestock ([Taheripour \*et al.\*, 2011](#)). If this substitutability is low, then massive increases in the availability of the by-product will result in severely depressed prices. Since by-products are an important revenue source for the biofuel industry, lower by-product prices will curtail expansion of the industry, which is typically viewed as being subject to zero profit conditions in the medium run. On the other hand, high substitutability — particularly for the feedstock itself (e.g., DDGS substitution for corn), the price of which is rising under such circumstances, will serve to limit the decline in by-product prices, hence bolstering revenues for the biofuel industry.

The impacts of by-products on global land-use change and agricultural markets resulting from U.S. and EU biofuel mandates are analyzed in details in [Taheripour \*et al.\* \(2010\)](#). Their analysis shows that by ignoring biofuels by-products, researchers may significantly overstate global land cover and commodity price changes. The magnitude of this impact will differ depending on feedstock considered. For U.S. corn ethanol, [Taheripour \*et al.\* \(2010\)](#) estimate that the omission of by-products in analyses of U.S. and EU biofuel policies will overstate the resulting cropland conversion by about 27%.

In the paper focusing on the impact of biofuel by-products for the global livestock industries, [Taheripour \*et al.\* \(2011\)](#) demonstrate that the global distribution of by-products can also significantly affect the pattern of livestock production worldwide, which in turn has important implications for the distribution of global land-use change. In particular, the authors conclude that EU and U.S. biofuel policies result in larger absolute reductions in livestock production overseas than in those two regions combined. This is due to the high degree of international price transmission of grains prices to these other economies (a factor which constrains livestock production), whereas the lesser degree of integration in by-product markets — particularly DDGS — means

that the associated benefits to livestock producers overseas are less prevalent. This issue of international price transmission is one that will be discussed again in the next section, where we will investigate the underlying assumptions in more detail.

#### 4. Drivers of Land-Use Change<sup>1</sup>

As we think about the drivers of land-use change due to biofuels, it is instructive to temporarily revert to a very aggregate modeling framework in order to highlight several key economic dimensions of the problem. These are encapsulated in the following expression (adapted from Hertel *et al.*, 2011) for the percentage change in global agricultural land-use ( $q_L^*$ ) in response to an outward shift in demand for agriculture-based biofuel feedstocks ( $\Delta_A^D$ ):

$$q_L^* = [(\Delta_A^D)/(1 + \eta_A^{S,I}/\eta_A^{S,E} + \eta_A^D/\eta_A^{S,E})] \quad (1)$$

The denominator of (1) highlights the key margins of economic response to the biofuel expansion. These include the elasticity of yields with respect to commodity price,  $\eta_A^{S,I}$ , the price elasticity of land supply with respect to commodity price,  $\eta_A^{S,E}$ , and the absolute value of the price elasticity of demand for agricultural output, which we write as  $\eta_A^D > 0$ . The first two terms are often referred to as the *intensive and extensive margins* of agricultural supply response — hence their superscripts *S,I* and *S,E*, respectively. By ignoring these economic margins of adjustment, pure biophysical analyses of land-use change due to biofuels will overstate the necessary expansion in land requirements, since all of the elasticity terms are defined to be positive and therefore raise the value of the denominator in (1). Another key point from (1) is that it is the *relative size* of the elasticities that matters for land-use change from biofuels growth. A large value for the intensive margin of supply response does not necessarily imply less land-use change if the extensive margin is also larger, similar is the scenario for the price responsiveness of demand. These issues will crop up as we discuss the economic drivers of land-use change in GTAP-BIO.

##### 4.1. Response of crop yields

The area of greatest controversy in GTAP-BIO is that of the yield response to commodity prices. This has been a focal point for critics — some arguing the yield response to prices (0.25) is too large, and others arguing it is too small. From Eq. (1), it is clear that this response is one of the keys to determining the indirect land-use change from a biofuels shock. If this value is too large, then the ensuing change in land area will be too small, provided one holds the extensive margin of supply response constant. The most rigorous critique of the GTAP-BIO yield specification is that provided by Berry (2011). We seek to respond to his concerns here, in addition to proposing some possible adjustments in light of his points.

<sup>1</sup>Some of the material presented in this section draws on the book chapter by Golub *et al.* (2010).

*Yield intensification:* As feedstock prices rise, with land in relatively inelastic supply, producers have an incentive to increase use of non-land inputs to boost production per unit of land. This change in implied yield did not receive a great deal of attention in the GTAP framework prior to the analysis of global land-use impacts of biofuels. Rather, the production functions in agriculture were simply calibrated to reproduce an aggregate supply response (Dimaranan *et al.*, 2006). However, with the sharp focus on land-use in GTAP-BIO, it becomes important to know whether the increased supply is resulting from more land inputs or more non-land inputs. Recognizing this, Keeney and Hertel (2009) begin their paper on assessing the land-use impacts of biofuels by reviewing the literature on yield response to corn prices and seek to calibrate GTAP-BIO to a consensus value. In their review, they note that the price responsiveness of corn yields has been diminishing in recent years. Focusing on the more recent studies, they 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/bu to \$4/bu, and the price of land substituting inputs increased by 50%, then the output-input price ratio would rise by 33% and the expected yield increase would be  $0.25 \times 33\% = 8.33\%$ .

In his critique of GTAP-BIO and the Keeney and Hertel (2009) literature review, Berry (2011) suggests that the choice of 0.25 was not truly indicative of most recent empirical evidence. He notes that, once a time trend and weather are included in a model explaining the national time series of U.S. yields, there is little room left for prices. Indeed a number of studies show a negative relationship between yields and prices. His review of the literature, combined with some economic judgment, results in a preferred yield response of 0.1. Huang and Khanna (2010) have recently produced a more sophisticated econometric analysis of the price elasticity of U.S. crop yields and report value of 0.15 for corn. Their estimated yield response for soybeans is smaller (0.06), while that for wheat is much larger. This raises a very important question which deserves further discussion: how do differences in yield response between commodities — and across regions — affect the global land-use change?

Keeney and Hertel (2009) explore the issue of differential yield response to price in the U.S. and overseas and show that higher yield response in all the crops sectors in the U.S. (not just corn) does not lead to a reduction in land-use in the U.S., as might be expected. This is because a larger yield response permits U.S. exports to remain more competitive despite increased sales to the ethanol industry. Of course global land-use is reduced under this scenario. However, the main point is that differences in the price responsiveness across regions results in a different composition of land-use expansion around the world. Regions with more price responsive yields may actually increase their share of global crop land-use.

In order to explore the issue of differential yield response in greater detail, we offer the results in Table 1. Here, we see that, if we follow the Berry suggestion and reduce the price elasticity of corn yields in the U.S. from 0.25 to 0.1, land-use in the U.S. rises

Table 1. Cropland expansion due to 1 Mtoe of U.S. corn ethanol shock under different assumptions about yield sensitivity to prices, Kha.

Scenario	Additional cropland, Kha		
	U.S.	ROW	Global
Yield parameter 0.25 for all crops in all regions	68	96	164
Yield parameter 0.1 for U.S. corn only, 0.25 for all other crops and regions	72	104	176
Yield parameter 0.1 for all crops in all regions	77	148	225

by 4,000 ha., relative to the base case for a 1 Mtoe increase in U.S. corn ethanol, while the global figure is 12,000 ha., or about 7.5% higher. This stands in sharp contrast with the increase of 61,000 ha or 37% more land-use than in the base case when yield response for all crops in all regions is reduced to 0.1. In short, the yield response of crops other than corn in the U.S. is far more important for the global land-use outcome! *We conclude that the focus on U.S. corn yields to the exclusion of other crops in other regions has been misguided.* More effort needs to be devoted to the study of yield response for other crops and other regions.

*Yields extensification:* The extensive margin is defined as the change in crop yield when land employed in other uses (other crops, pasture or forest) is converted to grow crop in question. As will be discussed below, there are two levels of land-use competition in GTAP-BIO and so there are two distinct 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 crop land (e.g., shifting from a corn–soybean rotation to continuous corn). This effect is estimated in GTAP-BIO 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.

The second extensive margin measures the change in average crop yields as aggregate cropland area is expanded into pasture, and possibly forest lands. The parameter determining this part of extensive margin is close behind the price responsiveness of yields in terms of scrutiny. The parameter can be set exogenously in GTAP-BIO to override the mechanism based solely on current land rental rates due to the extremely large disparities between cropland returns per hectare and those in grazing and forest uses. Part of this discrepancy may be due to fundamental differences in productivity, but much of it is due to conversion costs, which are not explicitly modeled in GTAP-BIO. In the original version of GTAP-BIO (Birur *et al.*, 2008), it was assumed that it took three newly converted hectares of cropland to replace two average hectares of average cropland currently in use. This value was chosen based on verbal communication with ERS-USDA staff, based on their experience evaluating the productivity of U.S. Conservation Reserve Program lands, relative to average crop land. CRP lands have proven to be marginal in the face of fluctuations in U.S. market



conditions and so this was deemed relevant — at least for the U.S. However, no pretense was made of having properly estimated the value of this parameter. The hope was that other researchers would step forward and estimate this important relationship. The effects of the alternative specification of this parameter on the resulted land-use change in the model are discussed in the Sec. 5.3.

## **4.2. Land supply and the extensive margin**

### *4.2.1. Agro-ecological zones*

In GTAP-BIO, there is an attempt to reduce the heterogeneity of land evidenced in the extensive margin of yields by disaggregating each model region's land endowment. Following the pioneering work of Darwin *et al.* (1995), this can be accomplished via the introduction of Agro-Ecological Zones (AEZs) (Lee *et al.*, 2005). In each region of GTAP-BIO, there may be as many as 18 AEZs which differ along two dimensions: growing period (6 categories of 60-day growing period intervals), and climatic zones (3 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.

Ideally, each crop/AEZ combination would have a distinct production function. Unfortunately, this results in a massive proliferation of sectors in the model. Indeed, with ten land-using sectors, this would result in  $18 \times 10 - 10 = 170$  additional sectors in each model region. If this disaggregation were critical to the results, then it should be undertaken, nonetheless, simply by using more computational time to solve the model. However, Hertel *et al.* (2009) show that, provided the crop produced on different AEZs within a given country is undifferentiated and the non-land input-output ratios are reasonably similar (i.e., they employ the same amount of labor or fertilizer per ton of output), then we can closely approximate the same outcome by simply having a single national production function and setting a very high elasticity of substitution within a national land aggregate, across AEZs, within that production function. Experience suggests that this modeling trick works pretty well and it certainly reduces model dimensions sharply. In addition, it circumvents the nearly impossible task of specifying distinct production functions for each crop/AEZ combination in the model.

### *4.2.2. Constant elasticity of transformation frontier*

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 considerations, beyond purely agronomic factors, that limit land mobility within an AEZ. These

include costs of conversion, managerial inertia, unmeasured benefits from crop rotation, etc. 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 (Ahmammad and Mi, 2005) whereby the rent-maximizing land owner first decides on the allocation of land among three economic uses/broad land cover types, i.e., 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.<sup>2</sup>

A CET parameter governs the ease of land mobility across uses within each AEZ. The parameter in the cropland, grazing land, and forest land nest determines the ease with which land is transformed across the three economic uses (e.g. from pasture to cropland). Similarly, the CET parameter in the crop nest determines the ease of 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 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 rental 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 based on their analysis of a land supply system econometrically estimated for the U.S. (Lubowski *et al.*, 2006).

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

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<sup>2</sup>Alternative CET structure could be used to reflect the fact that conversion between agricultural land and forests is more difficult than between cropland and pasture within agriculture. The modified structure will consist of three nests. First, owner of the particular type of land (AEZ) decides on the allocation of land between agriculture and forestry to maximize the total returns from land. Then, based on the return to land in crop production, relative to the return on land used in ruminant livestock production, the land owner decides on the allocation of land between these two broad types of agricultural activities. Finally, land is allocated amongst crops within cropland cover.

economic model which can pose problems when attempting to relate model results back to the physical environment” (Golub *et al.*, 2009). To estimate land-use changes measured in physical hectares, GTAP-BIO incorporates an *adjustment* 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 to total physical area. 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 pasture land (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 pasture land to fall, as the best pasture land 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, any factor leading to differences in land rents, but unrelated to fundamental productivity considerations, can result in erroneous conclusions. This is particularly true in the case of the lower-level CET nest where land cover is determined. The database shows very large differences in per hectare land rents; yet, with some investments, the converted pasture or forest land might be nearly as productive as current cropland. For this reason, the lower-level land productivity story is modified 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 crop land, as discussed earlier.

### 4.3. Consumer demand elasticities

While the intensive and extensive margins of supply response have received the most attention in the debate over land-use impacts from biofuels, Eq. (1) demonstrates that the elasticity of demand is equally important. Indeed, a small yield response can be more than offset by a large consumer demand response to higher food prices. Econometric evidence suggests that food demands are generally price-inelastic, particularly when viewed as an aggregate — and even more so when it comes to staple grains. Seale *et al.* (2003) estimate an international cross-sectional demand system and obtain own-price elasticities of demand for food, beverages, and tobacco, which may be viewed as long-run consumption responses to permanent changes in prices. Their estimates are a function of per capita income and range from  $-0.65$  in Tanzania, to  $-0.08$  in the U.S. In making long-term projections, this suggests that the global demand elasticity for food ( $\eta_A^D$ ) should be adjusted downward as one projects out into the future. In GTAP-BIO, these price elasticities of demand are governed by the

Constant Difference of Elasticities (CDE) expenditure function, which permits the user to indirectly adjust the size of the consumer demand response by manipulating the commodity-specific ‘substitution parameter’ in this function. In the base GTAP model, these parameters are set according to an estimated international demand system (Dimaranan *et al.*, 2006). However, they are often adjusted to better reflect the researchers understanding of markets, as in the case of the energy model validation work of Beckman *et al.* (2011).

Hertel *et al.* (2010) perform the following experiment to better understand the role of consumer demand response in governing the indirect land-use impacts of U.S. ethanol production. When they fix food consumption ( $\eta_A^D = 0$ ), they find that emissions from land-use change rise by 41%. Clearly, the specification of the price responsiveness of food demand is a subject which deserves more in-depth investigation.

#### 4.4. Specification of bilateral trade

Equation (1) postulates a single, global production function and a uniform stock of land. However, as noted earlier, production relationships in agriculture vary greatly across regions, as do carbon intensities of land cover. So it matters where the additional production arises. Determining the AEZ and regional distribution of increments to production is the focal point of the global trade model — precisely the reason for using GTAP to analyze this problem.

The increased area devoted to feedstock crops can come either from other crops or from expansion in total cropland area. It is the latter phenomenon which has been the focus of most of the literature, as it is the conversion of pasture land and forests which results in increased GHG emissions. The extent of such land cover conversion and the carbon intensity of the land cover which is converted to cropland depend critically on the part of the world where this conversion occurs. If this is in the tropical rainforest, the consequences can be devastating due to high carbon content of that forest. Accordingly, the specification of international trade in the economic model is critical, as this determines the extent to which an increase in biofuel demand in one part of the world (e.g., EU or U.S.) is transmitted to other markets.

There are several distinct views of how patterns of trade in commodity markets are propagated. Two views postulate that commodities are somehow differentiated, while the third ignores product differentiation, instead postulating the Integrated World Market (IWM) hypothesis. The IWM approach is the most intuitive approach and corresponds to most textbook expositions of trade in agricultural commodities. IWM postulates a single global market for these commodities, and a single market clearing price. Thus it does not matter where in the world the demand shock occurs. *Assuming neutral border policies and equal supply response across regions*, the increased production will be shared out globally according to existing production area. If, for example, India produced 10% the world’s supply of a given feedstock, then IWM would suggest that it would supply approximately 10% of the incremental production

required under a biofuels scenario. In practice, this strict proportionality does not apply, due to differences in the way border policies are modeled, as well as differences in area supply elasticities. The IWM approach was employed by [Searchinger \*et al.\* \(2008\)](#) in the analysis of land-use changes triggered by increased demand for corn ethanol. Those authors predicted that the 11 million hectare increase in global area required to meet a 56 billion liter increment to U.S. corn ethanol production would be distributed as follows: 21% U.S., 26% Brazil, 10% China and 11% India. Note that the largest area response is not in the source region. This is an important difference with product differentiation models and has important implications for the resulting GHG emissions.

Under the other two commonly employed trade frameworks, products are assumed to be differentiated. In the first, case — the so-called Armington approach — products are differentiated by origin country, and this differentiation is exogenous. In contrast, the third approach to modeling international trade assumes that products are endogenously differentiated with monopolistic firms investing in R&D in order to create new products ([Krugman, 1980](#); [Dixit and Stiglitz, 1977](#)). In the most commonly used case of monopolistic competition, firms proliferate until the excess operating profits earned by marking up their differentiated product are precisely exhausted on the fixed costs of marketing and R&D. More recently, this assumption of endogenous product differentiation has been combined with firm heterogeneity in order to come up with a richer specification of trade in which the fixed costs of trading play an important role, and average industry productivity is endogenous ([Melitz, 2003](#)).

[Berry \(2011\)](#) has criticized GTAP-BIO for not using the more ‘modern’ theories of international trade. Indeed a number of versions of the standard GTAP model have been developed which rely on monopolistically competitive behavior ([Francois, 1998](#); [Hertel and Swaminathan, 1996](#); [Zhai, 2008](#)). However, most of the empirical trade research using models of endogenous differentiation have been undertaken with data on manufactures, and it is unclear how well suited such models are to predicting changes in bulk agricultural trade volumes where there are many producers and the degree of product differentiation by firm is much less evident. In any case, the fundamental distinction in terms of patterns of global land-use change is really whether there is a unique geography to world agricultural trade, as revealed by current patterns of bilateral trade, and as embedded in the implied elasticities of substitution amongst products from different sources. If there is such a bilateral geography, whether the market structure is perfectly competitive or monopolistically competitive, the implications of biofuels expansion will differ sharply from those implied by the IWM approach.

The GTAP-BIO model utilizes the Armington approach to product differentiation. In the GTAP trade specification, the agents first decide on the sourcing of their imports, and then, based on the resulting composite import price, they determine the optimal mix of imported and domestic goods. Estimates of the import-domestic substitution elasticity are problematic due to the absence of good price series on domestic

consumption and prices for disaggregated commodities. However, by capitalizing on bilateral trade data, Hertel *et al.* (2007) are able to estimate the elasticities of substitution amongst imports from different sources. In order to avoid the type of simultaneity problems emphasized by Berry (2011) in his review of GTAP-BIO, the authors obtain their price variation across sources from a variety of fundamental determinants of price, including distance, tariffs, and bilateral shipping costs. Their estimates are all significant at the 95% level and range from 1.8 for minerals to 34.4 for natural gas. The elasticity estimate for coarse grains (including maize) is relatively small at 2.6.

With the Armington approach, the composition of trade is much more rigid than under the IWM hypothesis. For example, in the case of increased production of bio-diesel in the EU, most crop land conversion arises within the EU, followed by its dominant export competitors and trading partners. Similarly in the case of U.S. corn ethanol production, the largest area increase arises within the U.S. borders. Since the Armington approach relies on product differentiation, and product differentiation allows price differences to persist over time, some would argue that it is a better approach in the near term, but potentially problematic over longer time periods. This is the criticism of Reilly (2010), who argues that the IWM approach is more appropriate over the long run.

In the end, determining which model is appropriate for which commodities/time frames is an empirical question that is amenable to econometric investigation. Using time series data on global coarse grains area over the period 1975–2002, Villoria and Hertel (2011) formally test the null hypothesis posed by IWM against the alternative hypothesis which embraces the Armington assumption. They reject the IWM hypothesis in favor of the Armington model. Their statistical results draw special attention to the importance of third-market competition in the transmission of U.S.-generated coarse grains price changes overseas. Thus, their preferred model estimates significant land-use change in Argentina, a country which competes heavily with U.S. in import markets such as Japan. India, on the other hand, is predicted to have much less land-use change in response to the U.S.-initiated shock, than under the IWM hypothesis. This is due to the fact that India imports and exports relatively small amounts of coarse grains. Overall, these authors conclude that the IWM model may overstate GHG emissions from global land-use change in response to U.S. ethanol production by a factor of about two. This is due to the fact that the U.S. and countries more exposed to competition with the U.S. in third markets tend to have higher yields and lower average GHG emissions intensities. Clearly the specification of international trade in economic models can make a big difference for the resulting land-use and GHG impacts. Of course, the findings of Villoria and Hertel (2011) do not directly address the Reilly (2010) criticism, as they are based on annual time series data, and Reilly has decadal changes in mind. However, until further evidence is brought to bear, these findings do offer support for the product differentiation model over IWM. One way of bridging the two approaches is to reduce the degree of product differentiation

by increasing the elasticities of substitution between products from different sources, as illustrated in the Sec. 5.

## 5. Sensitivity Analysis: How Land-Use Change Depends on Key Model Parameters and Assumptions

### 5.1. Alternative specification of bilateral trade

To alter the trade specification from Armington to something approximating IWM, it is sufficient to set the elasticities of substitution among imports from different sources and elasticities between imported and domestic goods to relatively high magnitude.<sup>3</sup> Such a setting mimics the situation when goods coming from different sources, including domestic, are perfect substitutes. (Of course it does so imperfectly. To achieve a fully accurate representation of IWM, the model would need to be rewritten as a net trade model.) This is the basis for the comparison of model results presented in Fig. 1, for a one million tonne of oil equivalent (Mtoe) increase in production of ethanol in the U.S.

Figure 1 demonstrates that the trade specification affects the geographic disposition of cropland expansion. Under the Armington assumption, land conversions are concentrated in the U.S. and its dominant export competitors in Europe. When agricultural goods produced in different regions are treated as a (nearly) homogenous commodity, the effect of expanded production of U.S. ethanol is distributed more evenly across the World. Much less land conversion is observed in the U.S. and Europe, and more in other regions. Despite the fact that shock originates in the U.S., the IWM assumption results in much smaller U.S. forest land reductions and larger conversions of forest and pasture in Africa (Fig. 1). Relative contributions of global pasture and forest land to fulfill net cropland requirements are affected as well. The share of global forest

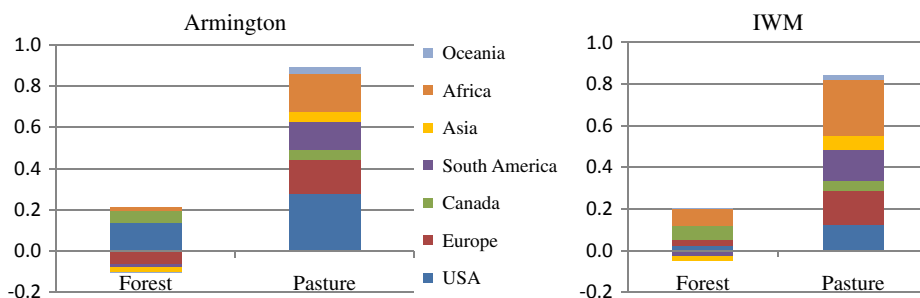


Figure 1. Composition of changes in forest and pasture land relative to net global cropland expansion under different trade specifications for 1 Mtoe increase in production of U.S. corn ethanol; numbers are expressed as shares, and add to 1.0 in both cases.

<sup>3</sup>To approximate IWM, the Armington parameters for agricultural commodities were set to 20.

Table 2. Net global land cover changes from producing an additional 1 Mtoe of biofuel in the U.S. (ethanol) and in the EU (biodiesel) under different trade specifications.

	New cropland globally, Kha	Global forest share	Global pasture share	Region of scenario forest share	Region of scenario pasture share
US Ethanol					
Armington	165	0.11	0.89	0.14	0.28
IWM	207	0.16	0.84	0.02	0.13
Change relative to IWM, %	-21	—	—	—	—
EU biodiesel					
Armington	377	0.13	0.87	0.31	0.10
IWM	363	0.18	0.82	0.17	0.05
Change relative to IWM, %	4	—	—	—	—

converted to cropland rises and the share of global pasture land converted falls as we move from the Armington specification to IWM (Table 2).

The trade specification not only determines the regions and ecosystem types from where the additional cropland comes from but also affects the size of the net global cropland requirement. This is demonstrated in Table 2. Whether the Armington structure increases or decreases net global land requirements relative to the integrated world market assumption depends on relative yields. Consider a concrete example. The U.S. corn yields are the highest in the world. When one hectare of corn grown for food is displaced by one hectare of corn for fuel in U.S., more than one hectare in the rest of the world will be needed to cover the shortage of corn for food. Under IWM, the shock originated in U.S. is more easily transmitted through the global economy. Because U.S. corn yields are higher than corn yields in other regions of the world, the net global land requirement under the Armington assumption will be 21% smaller than under the integrated world market assumption (Table 2). The situation is the opposite with EU biodiesel. EU oilseeds yields are not the highest in the world. For this reason, as we move from integrated world market assumption to Armington, the net global land requirement increases. In the considered 1 Mtoe expansion of EU biodiesel the increase in net cropland requirement is 4% (Table 2).

## 5.2. Alternative specification of acreage response within AEZs

In GTAP-BIO, the supply of land to different activities (crops, livestock, and forest) within an AEZ is constrained by the CET frontier, and land-use changes predicted by the model are sensitive to the CET parameter. While there is substantial empirical evidence on land-use choices within the U.S. (Lubowski *et al.*, 2008; Plantinga *et al.*, 2002) and some evidence in industrialized countries, less information is available for other regions of the world. One way to overcome this problem is to use estimates from the U.S. on land-use change elasticities to inform our parameter estimates for different



regions of the world. The simplest method would be to assume that elasticity of transformation is uniform across AEZs and regions. An alternative method is also based on U.S. estimates but then adjusts them to account for the degree of land heterogeneity within AEZ for different AEZs and countries. Since the CET parameter may be viewed as a proxy for the degree of land homogeneity in a region, this suggests that land mobility across uses should be greatest where land is very homogeneous and least where land within the AEZ is heterogeneous.

A heterogeneity index is constructed using five variables: growing degree days, moisture availability index, soil carbon density in the top 30 cm, soil pH in the top 30 cm and topography (elevation). For each country/AEZ the standard deviation of each of these variables is calculated. Then, the standard deviations are normalized to be in the range from 0 to 1 for each variable. Finally, the heterogeneity index for each country/AEZ is calculated as the average of the five indices. The resulting measures of AEZ heterogeneity index for 695 AEZs located in 160 countries are shown in Fig. 2.<sup>4</sup>

The index ranges from 0 (homogenous zone) to 0.64 (most heterogeneous) with mean and median very close to each other. Compared to the global mean, AEZs in the U.S., on average, are more heterogeneous, with the heterogeneity index in the range from 0.22 to 0.48. This will play role when adjusting the elasticities of transformation.

In previous work with GTAP-BIO, the CET parameter governing the ease of land mobility across cropland, pasture and forestry was uniform across all AEZs and countries. Ahmed *et al.* (2008) calibrated this parameter using econometric estimates for the U.S. documented in Lubowski (2002). In the absence of similar econometric

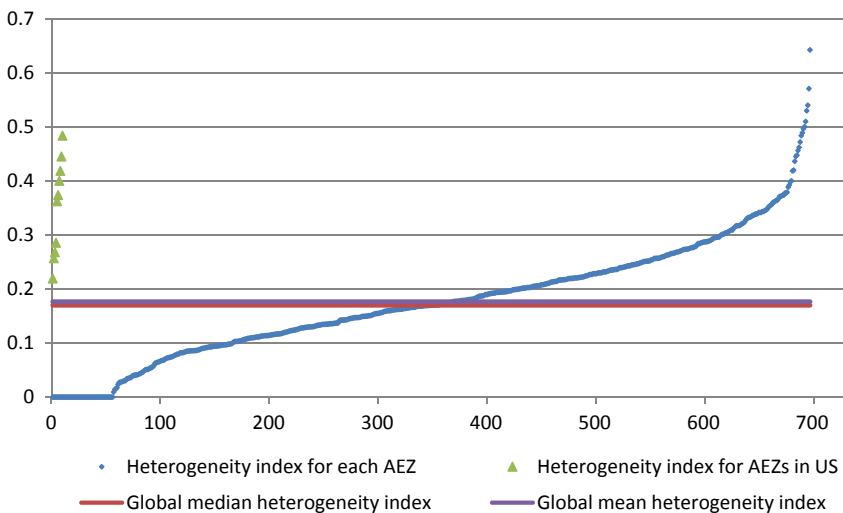


Figure 2. AEZ heterogeneity index.

<sup>4</sup>We thank Navin Ramankutty, Professor at McGill University, Department of Geography, for constructing the heterogeneity index.

analysis of supply of land in other countries, earlier studies with GTAP-BIO (Birur *et al.*, 2010; Hertel *et al.*, 2010; Tyner *et al.*, 2010) applied AEZ-generic U.S. parameter to all regions of the model. Introduction of the AEZ and country-specific heterogeneity index allows us to overcome this drawback at least to some degree. The index is able to take into account heterogeneous climatic and agronomic conditions within AEZs, however, does not reflect country-specific institutional arrangements affecting land mobility from one use to another.

To adjust the elasticities of transformation, we assume that (1) the relationship between the elasticity of transformation and AEZ heterogeneity is linear; (2) the U.S. average heterogeneity index corresponds to the unadjusted elasticity of transformation among land cover types for the U.S.; and (3) the world's most heterogeneous AEZ index corresponds to a zero elasticity of transformation. This describes a situation where the heterogeneity is so high that land is effectively immobile across uses. The resulting elasticities of transformation range from 0 (in AEZ 9 of Rest of South Asia region), suggesting no land mobility, to  $-0.503$  (AEZ3 in Colombia, AEZ10 in New Zealand and few others), suggesting land mobility is deemed to be relatively high. The elasticities of transformation adjusted for AEZ/country heterogeneity for selected regions are reported in Table 3. In U.S., the CET parameter among cropland, pasture, and forest varies considerably across AEZs around its base value  $-0.2$  in the range, from  $-0.09$  to  $-0.31$ .

Table 3. Elasticity of land transformation adjusted for AEZ heterogeneity.

	U.S.	Brazil	China	Japan
AEZ1	—	-0.40	-0.50	—
AEZ2	—	-0.37	-0.38	—
AEZ3	—	-0.31	-0.33	—
AEZ4	—	-0.30	-0.25	—
AEZ5	—	-0.32	-0.25	—
AEZ6	—	-0.33	-0.20	—
AEZ7	-0.14	—	-0.20	—
AEZ8	-0.16	—	-0.19	—
AEZ9	-0.09	—	-0.28	-0.45
AEZ10	-0.19	-0.45	-0.08	-0.36
AEZ11	-0.26	—	-0.04	-0.37
AEZ12	-0.27	-0.29	-0.05	-0.37
AEZ13	-0.12	—	-0.25	—
AEZ14	-0.18	—	-0.40	—
AEZ15	-0.28	—	—	-0.43
AEZ16	-0.31	—	—	—
AEZ17	—	—	—	—
AEZ18	—	—	—	—

In the 18-region aggregation of the GTAP database, used in the example below, the lowest absolute values of the CET parameter arise in the U.S. and China — regions with very large land areas and very heterogeneous agro-ecological endowments. The most homogeneous regions — with the highest land supply response within a given AEZ — are EU27 and High-Income Asia.

On average, AEZs in the U.S. are characterized by higher heterogeneity than most AEZs in the World (Fig. 2) — primarily due to their size (larger regions represented). When this information is incorporated in the CET parameters, the resulting elasticities of transformation for U.S. on average are relatively smaller (in absolute magnitude) than the elasticities for AEZs in other regions. This difference is reflected in Table 4, which shows land cover changes due to increase in production of U.S. corn ethanol by 15 billion gallons per year under alternative assumptions about land mobility. With the CET parameters adjusted for land heterogeneity within AEZs, land is more mobile in the Rest of the World. Thus, more land conversions are observed outside the U.S. New cropland area in the U.S. is similar under uniform and AEZ-specific elasticities of transformation (recall the assumption that the U.S. average heterogeneity index corresponds to the unadjusted elasticity of transformation among land cover types for the U.S.). Globally, the adjusted CET parameters result in slightly larger new cropland from U.S. ethanol shock. This change also alters the sources of new cropland: more pasture, and less forestry land are converted. While the former effect leads to an increase in total emissions from land cover change, the later moderates this effect because the emission factors for pasture conversions are smaller than for forest conversions. The net effect of introducing the adjusted CET parameters is to reduce emissions from land cover changes in the case of U.S. ethanol mandate (875 g/MJ in the base case versus 773 g/MJ with AEZ heterogeneity, assuming no amortization).

This finding cannot be generalized for other feedstocks. Indeed, in the case of expanded production of EU biodiesel, because the EU AEZs are relatively more homogenous, the introduction of AEZ/region-specific parameters results in larger conversions within EU. Moreover, in the model EU new cropland comes mostly from forestry, which results in higher emissions when heterogeneous acreage response is introduced into the model.

Table 4. Comparison of land cover changes due to increase in U.S. corn ethanol production by 15 billion gallons under alternative assumptions about land mobility, Kha.

	Uniform parameter		Heterogeneous parameter	
	U.S.	ROW	U.S.	ROW
Cropland	1,593	2,598	1,579	2,918
Pasture	-1,054	-2,350	-1,309	-2,833
Forest	-539	-247	-270	-85

Finally, it is important to realize that the heterogeneity adjustment in both cases, U.S. ethanol and EU biodiesel, is tied to the assumed global linear relationship between the CET parameter and land heterogeneity index. Ideally, the elasticity of land supply to different activities should be estimated for each country/region of the world, and then adjusted to reflect land heterogeneity within each AEZ.

### 5.3. Alternative specification of response of crop yield on the extensive margin

As pasture and forest lands are converted to fulfill cropland requirements for expanded biofuel feedstock production, crop yields on new cropland are likely to be different from current crop yields. In GTAP-BIO this change in yields is set exogenously by specifying model parameter, which determines how many additional hectares of marginal lands are required to make up for one hectare of average cropland. In the absence of strong empirical evidence, a value of 0.66, uniform across all regions and AEZs, was assumed in earlier work (Hertel *et al.*, 2010). This suggests that it takes three additional acres 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 calculated regional land conversion factors at the AEZ level using the Terrestrial Ecosystem Model (TEM) of plant growth. Those authors employed TEM to calculate Net Primary Production (NPP) at  $0.5^\circ \times 0.5^\circ$  spatial resolution for all grid cells across the world. NPPs are then converted to AEZ and region-specific ratios of the average yield on the new cropland to the average yield of existing cropland. These are ordered from least to greatest, with the maximum bounded at 1.0, and reported in Fig. 3.<sup>5</sup>

The ratios reported in Fig. 3 fall in the range between 0.42 and 1, with only 6% of AEZs with ratio below 0.66 and 37% of AEZs with ratio equal to 1. This suggests that, according to TEM in 37% of AEZs, yields on newly converted pasture and forests are as high (or higher — since values in excess of 1 were truncated at 1.0) as the on cropland currently employed in agricultural production. In these AEZs, it will take only one hectare of marginal cropland to offset one hectare of current cropland diverted to biofuel production. Of course, when incorporated in GTAP-BIO model, this set of ratios results in much smaller requirement for new cropland globally. To produce 1 Mtoe of U.S. corn ethanol, global cropland expands by 164 Kha when “0.66” assumption is employed. With TEM AEZ/region-specific ratios, the same amount of ethanol requires 124 Kha globally, 25% less.

The TEM model offers considerable appeal from the viewpoint of bringing a great deal of biophysical detail to bear on the question of land productivity. Reilly *et al.*

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<sup>5</sup>In Tyner *et al.* (2010) analysis, there are 19 regions and there may be as many as 18 AEZs in each region that would result in total number of  $18 \times 19 = 342$  AEZs. Of course, due to specific agronomic and climate conditions, not all 18 AEZs are present in each region. For example, in Canada none of tropical AEZs 1–6 are present, and boreal AEZs 13–18 cannot be found in Central America. For this reason, total number of AEZ/region combinations shown in Fig. 3 is 195.

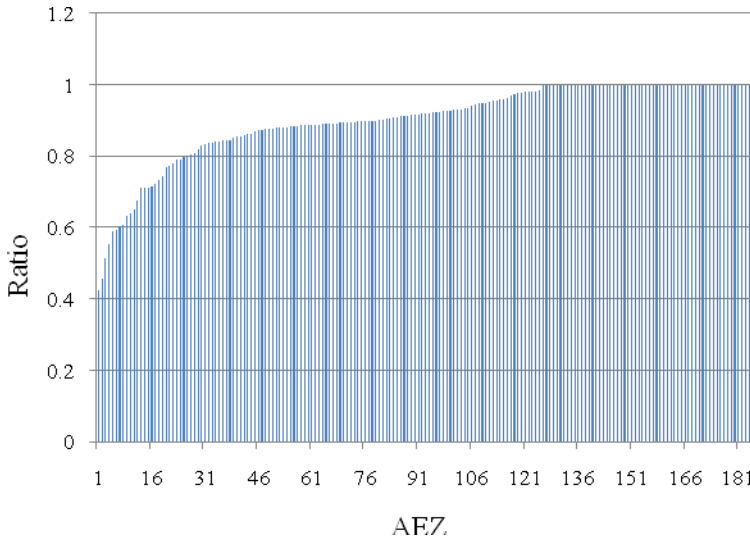


Figure 3. AEZ/region-specific ratios of the average yield on the new cropland to the average yield of existing cropland. The figure is constructed using information reported in [Tyner \*et al.\* \(2010\)](#).

([forthcoming](#)) also utilize TEM to estimate the productivity of new lands brought into production. It should be noted, however, that these biophysical simulation models are focused on net primary productivity, which is quite different from the yield for a specific crop under local management conditions. The large number of AEZs showing evidence that the unused land is equally as or more productive than the land currently used for crops begs the question: If this land is so productive, why is not it already in use? Possible explanations include existence of the conversion costs, as well as the TEM model overestimation of the yield potential on these new lands due to local crop management specifics. There is a great need for econometric estimates of the extensive margin of yields. [Keeney \(2010\)](#) has outlined one possible approach to this problem, which involves examination of time series data on yields, as a function of area, while controlling for technological change via a pre-determined time trend. Keeney focused on the behavior of wheat yields over time in a set of eight different countries. Overall, his findings suggest that the TEM-base approach may be overstating the yield potential of these new lands. Keeney does find that, for the case of Brazil, new lands have higher productivity than existing croplands — a point that is consistent with casual observations. Clearly much more work is required before a definitive assessment of the extensive margin of crop yields is possible.

#### **5.4. Relative importance of acreage, yield and bilateral trade responses as sources of parametric uncertainty**

Economic model outcomes regarding land-use changes and GHG emissions are sensitive to changes in key parameters/assumptions. As the models are increasingly used

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 (2009) undertake a sensitivity analysis of land-use changes triggered by increased production of U.S. corn ethanol. They identify the CET parameters describing land supply to alternative uses, Armington elasticities and responsiveness of yield to crop prices as main sources of uncertainty in land cover changes predicted by the GTAP-BIO model.

The uncertainty in CET parameters determining land supply to crops, pasture, and forestry are drawn from Lubowski *et al.* (2008) and Ahmed *et al.* (2008). The distribution for acreage response across various crops within cropland is defined as  $\pm 80\%$  of around central estimate. Keeney and Hertel (2009) only conduct sensitivity on the trade elasticities for crop sectors and draw directly from the point estimates and standard errors provided by the earlier econometric analysis documented in Hertel *et al.* (2007). The yield intensive margin parameter (the elasticity of crop yield to own price) 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.<sup>6</sup> The authors then conducted systematic sensitivity analysis via the Gaussian Quadrature (GQ) approach of DeVuyst and Preckel (1997) as implemented by Pearson and Arndt (2000) to solve the model under the assumption of independent triangular distributions for each of the key sources of parametric uncertainty determining land-use change.<sup>7</sup>

Key findings of Keeney and Hertel (2009) are summarized in Fig. 4, which reports 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. Reporting the CVs in Fig. 4 in ratios highlights which sources of parameter uncertainty are most influential in driving the land cover change results.

There are two sets of bars in Fig. 4; each measures the CV of one source of uncertainty relative to the base uncertainty which is driven by uncertainty in the trade elasticities. Specifically, the darker columns in this figure shows 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. The figure demonstrates that for broad land 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 coefficients of variation much larger than those from the acreage and trade elasticity assumptions. For land-use changes within the

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<sup>6</sup>To conduct systematic sensitivity analysis for yield response, the authors included not only parameter determining sensitivity of yield to crop price, but also specified distributions of labor and capital factor supply elasticities. Parameter determining how many additional hectares of marginal lands are required to make up for one hectare of average crop land is not included in the uncertainty analysis in Hertel and Keeney (2009).

<sup>7</sup>For large models, the GQ method is more tractable than a full Monte Carlo analysis. This model solves in approximately 12 minutes. A Monte Carlo analysis using just 1,000 simulations, would take more than 8 days.

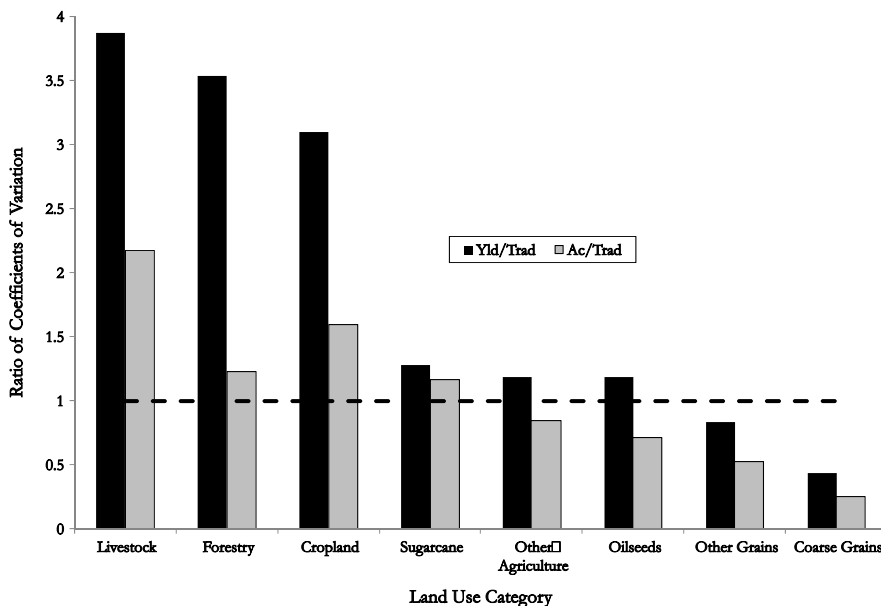


Figure 4. The relative importance of supply response versus bilateral trade response assumptions in uncertainty about land-use changes. Systematic sensitivity analysis for yield response includes factor supply and substitution parameters. Acreage response includes both levels of land allocation. Bilateral trade response includes all trade elasticities for commodities featured in Fig. 4 using the confidence intervals from Hertel *et al.* (2007).

Source: Keeney and Hertel (2009).

crop sectors, 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.

### 5.5. Sensitivity to economic parameters and emission factors

In policy analyses where a particular estimate, say the grams of CO<sub>2</sub> equivalent GHG emissions per mega joule (MJ) of biofuel produced, is of critical importance, one wants to establish a comprehensive confidence interval on the findings. Hertel *et al.* (2010) estimated the GHG emissions from indirect land-use change associated with U.S. corn ethanol mandate and quantified parametric uncertainty of the resulted land-use changes and emissions. As with Keeney and Hertel (2009), those authors specified distributions of their parameters. However, in addition to uncertainty in the economic behavioral

parameters, those authors included uncertainty in the physical GHG emission factors associated with land-use change as well. The authors then sampled from these distributions following the GQ approach to estimate means and standard deviations of model results.<sup>8</sup> Hertel *et al.* (2010) find that the CV associated with global additional cropland to be 0.37. The CV associated with global emissions from the land-use change is 0.46, with a mean value of 27g/MJ of corn ethanol produced annually. The associated 95% confidence interval, which ranges from 2g/MJ to 52g/MJ suggests considerable uncertainty in this key value. It also suggests that the critical value of zero emissions from land-use change (such that the issue can be safely ignored) is highly unlikely.

## 6. Conclusions

This paper describes the treatment of biofuels demand and supply, the resulting derived demand for land, and the key drivers of land-use change in the GTAP-BIO model. It responds to some of the most important criticisms of GTAP-BIO and seeks to provide insights into the sensitivity of the model outcomes regarding land-use change and GHG emissions to changes in key parameters and assumptions. For the analysis of implications of biofuels policies for land-use and GHG emissions (both, emissions from fossil fuel combustion and land-use related) key elements include: energy substitution parameters, including the potential for biofuels to substitute for fossil fuels; the treatment of biofuel by-products — particularly their substitutability for other feedstuffs; the specification of global 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 increased demand for feedstocks.

Assumptions about yield response on the extensive and intensive margins are certainly critical in determining land-use change outcome of the model. Indeed, uncertainty of the yield response on intensive margin dominates uncertainty in the acreage response and trade elasticity (Keeney and Hertel, 2009). We also show that yield response for other commodities (other than the focus feedstock) and other regions are even more important than the yield response of the specific feedstock/

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<sup>8</sup>The SSA as a method has certain limitations. First, the SSA allows parametric uncertainty to be represented with only two distributions: uniform or triangular, and the distributions must be symmetrical. Second, the output distribution is assumed symmetrical; however the posterior distribution from a set of symmetrical priors is not necessarily symmetrical. Third, the implemented SSA does not account for correlated variables, though very recently Horridge and Pearson (2011) developed SSA with respect to correlated variations in parameters and shocks. Finally, while the GQ method of propagating uncertainty is much more efficient computationally than a Monte Carlo simulation, it is valid only for continuous functions (Arndt, 1996). While this restriction is thought to apply to the economic model, it's unclear whether the ecosystem carbon calculations satisfy this constraint. There are indications that ILUC emission distributions may be strongly right skewed. Hertel *et al.* (2010) point out that the generated distributions were asymmetric. The implementation of the SSA in Hertel *et al.* (2010) also has certain limitations as it does not include all the parameters, but only those known to be most important in determining land-use change results. See Hertel *et al.* (2010) and Supporting Online Materials available at <https://www.gtap.agecon.purdue.edu/resources/download/4606.pdf>.



region under examination (U.S. corn in this case). Far too little attention has been paid to these other margins of response. In addition to the intensive margin of yield response, changes in the assumption about crop yield response at the extensive margin can also have a dramatic impact on the resulting net global cropland requirement. As more data become available, econometric estimation of both margins using country-specific data should be high priority. And the same is true for the consumer demand elasticity for food products, which is shown to play a critical role in determining the necessary expansion in global land-use following expansion of ethanol production.

In the GTAP-BIO model, land mobility across uses is constrained using the CET frontier. While CET parameters are critical in determining the ease with which forests and pasture can be converted to cropland, previous versions of the model used a single parameter, calibrated based on U.S. data, for all AEZs and regions. This paper attempts to overcome this shortcoming by introducing adjustments for within-AEZ heterogeneity. The method of adjusting the elasticity of transformation allows us to capture heterogeneous biophysical conditions and highlights the importance of AEZ- and region-specific parameters but does not reflect region-specific institutional arrangements affecting land mobility across uses. Again, more econometric work is needed in this area, in addition to a fundamental rethinking of the modeling approaches used for land supply.

While the CET approach is widely used in CGE modeling to represent land mobility across uses (Darwin *et al.*, 1995; Ianchovichina *et al.*, 2001; Ahammad and Mi, 2005; Golub and Hertel, 2008), alternatives to the CET structure need also be considered. One alternative is to employ more flexible functional forms, such as the CRETH function, which would allow the supply response to different uses to vary. This would be useful, since we know, for example, that in the U.S., the movement of land between pasture and crops is greater than that between forests and crops (Ahmed *et al.*, 2008). Beyond the choice of functional form, other approaches to modeling land mobility across uses available in CGE literature include conversion costs and transition matrices. Gurgel *et al.* (2007) propose an alternative to the CET approach to explicitly include a cost of converting land from one use to another. The approach implies that intensively managed land (i.e., cropland) can be “produced” from less intensively managed or unmanaged land. Gurgel *et al.* (2007) retain consistency between the physical land accounting and the economic accounting in the general equilibrium setting by assuming “that 1 hectare of land of one type is converted to 1 hectare of another type, and through conversion it takes on the productivity level of the average for that type for that region.” In comparison, in GTAP-BIO the consistency is achieved via introduction of AEZ-wide productivity adjustment. Another important element of the conversion structure of Gurgel *et al.* (2007) is “that in equilibrium the marginal conversion cost of land from one type to another should be equal to the difference in value of the types”. Of course this kind of a supply structure can result in very large swings in land area unless some other factor is introduced to limit the extent of land conversion. Those authors also only have a single crops sector and so do not face the

problem of restricting land mobility across different crop types — it is effectively infinite.

Ferreira-Filho and Horridge (2011) incorporate a transition matrix of land-uses into their CGE model of the Brazilian Economy. They take advantage of detailed land-use change data available for each of 15 regions within Brazil. Three broad types of managed land-use are identified: crops, pasture, and plantation forestry. In their model, land can move from one use to another according to Markov probabilities that are modified endogenously in the model according to the average unit rentals of each land type in each region. Unmanaged land can also be converted to one of three managed uses. Both Ferreira-Filho and Horridge (2011) and Gurgel *et al.* (2007) are dealing with an issue of value of unmanaged lands. In contrast to Gurgel *et al.* (2007), conversion costs are not modeled. The Ferreira-Filho and Horridge (2011) representation of land mobility among different crops within cropland and between pasture and dairy within pasture land is similar to one employed by GTAP-BIO. It is CET-like rule with endogenous productivity adjustments to ensure that physical hectares add up to total. Both, the MIT approach of modeling land conversion (Gurgel *et al.*, 2007) and the transition matrix approach of Ferreira-Filho and Horridge (2011) are appealing. More testing and evaluation of these competing approaches within the context of well-defined and replicable analyses is needed.

Additional work aimed at discriminating between competing models of key components of the analytical framework is also important. 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.

While reduction of these parametric and structural uncertainties is important, there are also other points that have not been seriously addressed although they are likely important in terms of improving model performance. The first of these has to do with the discrepancy between harvested area and cropland cover. Crop production functions in GTAP-BIO are applied to harvested area, and double-cropping effectively doubles the amount of area available for production while keeping cropland cover constant. So the fact that we do not explicitly model the choice to undertake multi-cropping (e.g., switching from one to two harvests per year on the same cultivated area in warm climatic zones) is a significant drawback. Presumably higher prices will encourage intensification of production on this margin as well, thereby reducing overall cropland area requirements. Of course, working in the opposite direction are crop failures, which result in less harvested area, as well as the practice of fallowing cropland or temporarily grazing this land. Finally, in the U.S., a significant portion of cropland cover is set aside for environmental purposes under the Conservation Reserve Program. Changes in enrollment rates in response to increased commodity prices is a critical element of the resulting land-use change in the face of biofuels expansion.

Explicit modeling of these other ‘margins’ is potentially important. Recent work by **Birur (2010)** using the GTAP-BIO model has taken a step in this direction.

Another important element of the response to biofuel policies which has received too little attention to date is the potential for ruminant livestock production to become more, or less, feedlot intensive in the wake of biofuels expansion. Clearly higher grains prices encourage a shift to more grazing — except when grazing land rents are also rising. Incorporating an explicit response of the livestock sector to changes in the relative price of grazing versus feedlot production would be an important improvement as well.

In the current version of GTAP-BIO, there is no scope for conversion of unmanaged land, including access of currently inaccessible forests. Golub and Hertel (2007) introduce access of unmanaged land into the dynamic GTAP model, which can be incorporated into GTAP-BIO model. This brings us to the question of dynamics. The current version of GTAP-BIO is static, yet most biofuel mandates refer to some future period in time. Without an explicit baseline, it is difficult to evaluate the relative stringency of such policies. This is an area where the partial equilibrium modelers are far ahead of those working in general equilibrium. And, while it may not change the final answer, presenting biofuels induced land-use change analysis in the context of a dynamic baseline is far more appealing to policy makers. Accordingly, a dynamic version of GTAP-BIO is now under construction.

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