The Indirect Land Use Impacts of U.S. Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses

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Abstract

Recent analysis has highlighted agricultural land conversion as a significant debit in the greenhouse gas accounting of ethanol as an alternative fuel. Perhaps the most controversial element of this debate has to do with the role of crop yield growth as a means of avoiding significant cropland conversion in the face of biofuels growth. We examine the agricultural land use impacts of mandate-driven ethanol demand increases in the United States in a formal economic equilibrium framework which allows us to evaluate the importance of yield-price relationships. We find that the standard assumption of trend yield growth is unduly restrictive. Furthermore, we identify both the acreage response and bilateral trade specifications as critical modeling considerations for predicting global land use change. Sensitivity analysis reveals that each of these (yield, acreage, and bilateral trade) are important sources of parametric uncertainty.

Keywords: Biofuels, yield response, indirect land use, international trade, general equilibrium.

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1. Introduction

Longstanding U.S. policies promoting ethanol as a fuel substitute have arrived at the forefront in the agricultural economy. As improved ethanol technology has brought its net energy production as a fuel to acceptable levels, detailed accounting of the greenhouse gas (GHG) mitigation possibilities of carbon sequestration by ethanol feedstock crops has been noted as a source of potential benefit in the carbon accounting of energy production and use (McCarl and Schneider, 2000).

The prospect of generating environmental benefits from corn ethanol production, combined with rising oil prices and uncertain supply sources, led policymakers to consider aggressive mandates for biofuel production in the coming years (Farrell et al., 2006). These mandates and the associated governmental support fostering the development of renewable fuel capacity represent a dramatic change in the economic landscape of agricultural commodity markets. How domestic and international producers and consumers adjust to a new long run equilibrium has now become a critical question facing economists with an interest in both the incidence of biofuels policies, as well as the efficacy of renewable fuel mandates as a source of environmental benefit (Searchinger et al., 2008).

Environmental scientists continue to point to the significant gains in GHG mitigation that are foregone from not preserving and restoring forests while noting that economic and policy incentives are encouraging deforestation (Righelato and Spracklen, 2007; del Carmen Vera-Diaz et al., 2008). Recent multidisciplinary work on the potential GHG changes arising from mandate driven increases in agricultural land use has received considerable attention as the results indicate an increase in the global carbon debt that will take lengthy periods to recoup given the meager GHG emission advantages of current biofuels (Searchinger et al. 2008; Fargione et al., 2008; Searchinger and Heimlich, 2008). Underlying each of these projections are some highly sensitive and uncertain assumptions regarding economic and technological adjustment (Schneider and McCarl, 2006). In particular, the extent to which ethanol grain demands can be met with improved yields has become a focal point of the debate over biofuel policy (Tannura, Irwin, and Good, 2008; Dhuyvetter, Kastens, and Schroeder, 2008). Searchinger et al. (2008) and Searchinger and Heimlich (2008) inherit the assumption of negligible yield response to price from the Food and Agricultural Policy Research Institute (FAPRI) modeling framework.[1] This stance contrasts starkly with that of many biofuel proponents who claim that yield growth can be accelerated to meet additional energy demands with only modest long run acreage reallocation.

The objective of this paper is to strengthen the analytical underpinnings of projected land use changes (and thus GHG mitigation) of biofuel programs. We focus our attention on agricultural supply response, highlighting the own-price yield elasticity and length of run assumptions embodied in competing views of this measure. We adapt a model of the global economy to study the agricultural commodity and factor markets implications of increased biofuel production in the U.S. focusing on the use of existing crop land, as well as potential conversion from pasture and forestry. Our findings highlight the sensitivity land use impacts to the yield price elasticity, as well as another factor that has received little attention to date – namely the responsiveness of bilateral trade in crops to changes in relative prices.

2. Background

Producer theory tells us that changes in relative prices lead to changes in input demands. For agricultural crops, these input demands reflect both changes at the extensive margin (when acreage devoted to a crop is expanded) as well as intensive changes arising when more inputs are used to increase yield per unit area. Despite these well known principles, it has become commonplace to attribute intensive increases of agricultural output to technological gains disembodied from the producer or market signals while ascribing year to year variations solely to weather.

The preponderance of research on supply response looks only to acreage movements, adopting the assumption that any yield change in response to commodity price movements is insignificant. Houck and Gallagher (1976) challenge the dominance of acreage response in agricultural supply studies, offering empirical estimates of yield response to commodity prices on par with those for acreage response to the same price changes. Induced innovation studies in the spirit of Hayami and Ruttan (1971) regularly find empirical support for the notion that the supply of technological advance is also responsive to changes in agricultural prices. Aggregate studies of agricultural technology find significant potential for non-land inputs to substitute for land in response to changes in prices as well (Abler, 2000). Hertel, Stiegert, and Vroomen (1996) show that substantial, econometrically estimated, aggregate input substitution possibilities can be reconciled with input substitution at the farm level through entry and exit (and thereby turnover in the land market) by producers of heterogeneous managerial ability (and hence heterogeneous input intensities). In addition to price changes, changes in agricultural policy incentives have been shown to generate dramatic changes in trend yield growth (Foster and Babcock, 1993).

The increasing use of computational models for analyzing the impact of shocks to the agricultural economy has perhaps clouded the question of the response of agricultural output to price, as supply assumptions are tied up in complex assumptions of interacting markets applied to disaggregate data with calibrated parameters. Keeney and Hertel (2005) identify the set of assumptions on factor supply and substitution in primary crop and livestock agriculture as well as food processing that contribute significantly to differing supply and demand responses to policy changes in a general equilibrium context.

The emphasis on factor supply and substitution in determining the response to different policies and the impact on farm incomes was first detailed in Floyd (1965). Since then the approach has been extended to analysis of agricultural trade (Hertel 1989; Gunter, Jeong, and White 1996) and a multi-sector setting for analysis of agricultural liberalization (OECD 2001). The attraction of the factor market approach for generating agricultural supply response in policy models arises from several factors. First of all, as will be seen below, direct estimation of yield response has met with limited success. Secondly, this factor-based approach ties nicely into the determination of farm incomes. Finally, it allows assumptions about the mobility of productive factors to contribute directly to the determination of length of run in the analysis, thereby giving a more precise analytical underpinning to supply response.

3. Supply Response in Agricultural Policy Models

To understand the implications of price and yield relationships in policy models we consider the simple model of factor supply and demand, expressed in terms of elasticities and percentage changes in price and quantity (denoted p and q). An agricultural producer operating under locally constant returns to scale earns zero economic profits and faces perfectly elastic demand (exogenous commodity prices: $p = 0$) as in equations (1) through (3) below. Percentage changes in input and output prices (r, p), commodity output (q) and factor supplies and demands (x^s, x^d) are determined by the equilibrium model, following an output price shock. Factor mobility is captured by the supply elasticity of input i to a particular crop in response to a change in the factor returns and is denoted η_i, while substitution between two factors is captured by $\sigma_{i,j}$, the Allen-Uzawa elasticity of substitution (AUES). Initial cost shares of inputs are represented by c.

(1) $$x_i^s = \eta_i r_i$$

(2) $$x_i^d = \sum_j \sigma_{i,j} c_j r_j + q$$

(3) $$p = \sum_i c_i r_i$$

In factor market equilibrium, we have: $x_i^s = x_i^d$ so we may solve (1) through (3) for the change in q from an exogenous shock to p. This provides the own-price supply elasticity. For finite values of the factor supply elasticities, η_i, the commodity supply elasticity is given in (4) where 1_n is a summation vector, Σ is the symmetric matrix of AUES for the quasi-fixed factors of production, and Ω is a diagonal matrix with elements $\eta_i c_i^{-1}$ (Hertel, 1989):

(4) $$\varepsilon = -\left[1_n' [\Sigma - \Omega]^{-1} 1_n\right]^{-1}$$

From (4), we can see that the assumptions on factor mobility are critically important in determining response to price changes. If we assume a fixed land base for the particular crop in question ($\eta_{land} = 0$) then the sole source of supply response is the yield gains which depend on the ability of non-land inputs to substitute for land, as well as the supply elasticity of those inputs.

In our subsequent analysis, we will use (4) combined with the assumption that $\eta_{land} = 0$ to define the yield elasticity for any particular combination of technology (Σ) and factor supply assumptions (Ω). If we define the long run as the period over which non-land factor prices are set by the non-farm economy, so that $\eta_{i \neq land} = \infty$ then land remains as the only quasi-fixed factor and the long run yield elasticity is given by $-\sigma_{land,land}$, the own AUES for land (see Hertel 1989). This is a natural vehicle for calibrating the technology of our model to an assumption on long run yield response. From there, we can make use of varying assumptions on factor mobility to coordinate our analysis with the appropriate length of run or to understand the sensitivity of land use changes to different time perspectives on yield response.

Table 1 presents seven separate estimates of the corn yield to price elasticity in the United States. These estimates range from 0.22 to 0.76 and were estimated from various data sets, collectively covering the period 1951-1988. Taken as a group, the seven estimates in table 1 provide solid evidence to reject the assumption of zero yield response in the long run. Evidence on response of yields to prices for crops other than corn is reviewed in Keeney and Hertel (2008). We restrict our reporting here to studies of U.S. corn for two reasons. Firstly, this is the main feedstock for biofuels in the U.S. at present; and secondly, the availability of repeated studies of yield response for this crop gives us some confidence that we might be able to arrive at viable estimate of long run yield response given the changing structure of U.S. agriculture. The vintage of these studies precludes their direct adoption for use in our 2006 oriented study. As noted in Hertel, Stiegert, and Vroomen (1996), significant yield response emerges through growth in farm size by best managers, which given the size of farms today relative to the time of these econometric estimates would surely shrink the gap between realized and potential yields.

The corn yield-price elasticities in Table 1 can be broken into two broad groups: which we might call "high response" ($\varepsilon = 0.76; 0.69; 0.61$) and "low response" ($\varepsilon = 0.22; 0.24; 0.27; 0.28$). We choose to focus on the "low response" estimates at the exclusion of the three largest values in table 1. The attraction of the "low response" estimates rests on the issue of relative modernity (Choi and Helmberger use the most recent data) and the fact that the four "low response" estimates arise from three independent studies using distinct approaches and different data sets in the estimation[2] while arriving at quite similar values. This is in stark contrast to the three "high response" values in table 1, which come from only two studies, the second one (Menz and Pardey) being a replication of the first (Houck and Gallagher). Additionally, these high response estimates incorporate a non-linear trend variable calibrated to adoption patterns (of high yielding varieties) observed in the mid-20th century. This aspect of the estimation distinctly dates these estimates more so than the general estimation approaches giving rise to the "low response" estimates. Averaging the four low response estimates we arrive at a value for the yield elasticity of 0.25.[3]

4. Modeling Framework and Experimental Design

In this section we provide an overview of the global economic model, including detailed discussion of the yield, acreage, and trade framework and parameter specification, and outline the biofuels scenario.

Overview of Global Modeling Framework

In order to evaluate the role of factor mobility and yield response in determining the indirect land use impacts of a U.S. biofuels program, we embed the analytical framework outlined above within a larger model of global trade capable of predicting land use change in the rest of the world as well as in the U.S. Given our theory of yield response, we require a model in which factor markets are explicit (as opposed to simply being implicit in reduced form, commodity supply equations). In addition, it is critical to be able to predict the change in bilateral trade patterns resulting from U.S. biofuels growth, as this will determine the pattern of land use change within the non-U.S. regions. Finally, it is desirable to utilize a framework in which the biofuels issue has already been explored, so that we can build on earlier work developing a biofuels mandate scenario. For purposes of this paper, we choose the GTAP-BIO framework outlined in Birur, Hertel and Tyner (2008). This framework is a modified version of the widely used, GTAP-E model. The latter was originally designed for analysis of fossil fuels consumption and climate mitigation policy.

Birur, Hertel and Tyner (2008) modify the model in order to incorporate the potential for biofuels to substitute for petroleum products. They also disaggregate land endowments by Agro-Ecological Zone (AEZ) following the work of Lee et al. (2008) and Hertel et al. (2008). This is critical to the analysis, as the indirect land use impacts hinge critically on the direct competition of biofuel feedstocks for other crops, pasture, and forests in particular ecological zones. If a given crop is not grown in the same AEZ as corn, for example, it will be less affected by the corn ethanol program than a crop which is grown predominantly in the same AEZ as corn. Birur, Hertel and Tyner (2008) validate their model over the 2001-2006 period. It is their updated, 2006 data base from which we embark in the present study. Thus, we start from a benchmark wherein the U.S. was producing about 5 billion gallons of corn-based ethanol per year.

Yield Response, Factor Supplies and Trade Elasticites

For purposes of simulating the impacts of a biofuels program on land use, we need to incorporate the long run yield elasticity assumption discussed previously, into the modified global model. The latter utilizes a nested CES production structure as shown in figure 1. The parameters of this function ultimately determine the own-AUES for land, $-\sigma_{land,land}$, which in turn, determines long run yield response. Abstracting from the lower level elasticity of substitution between capital and energy which plays no role in this calculation, and setting $\sigma^{T} = \sigma^{VA}$ to reduce our parameter space to a single scalar, we can choose this elasticity of substitution in each region to give the desired *long run* yield response. By definition, the long run yield response reflects the potential for substituting non-land inputs for land, when these non-land inputs are in perfectly elastic supply. Table 2 below presents the calibrated matrix of AUES that is consistent with this outcome. Note that homogeneity implies that the own-AUES for land (-0.25) equals the sum of the cost-share weighted off-diagonal substitution elasticities in the land row, divided by the cost share of land.

Having pinned down the long run yield response, we also wish to characterize yield response over shorter lengths of run. For a given technology (i.e. long run substitution possibilities), lesser yield response will be characterized by limited potential for non-land input levels in agriculture to be adjusted. This suggests introduction of a single, length of run parameter governing agricultural factor mobility. Accordingly, we further modify the GTAP model following Keeney and Hertel (2005) who introduce imperfect mobility of labor and capital between these sectors using Constant Elasticity of Transformation (CET) functions in which factor supplies are a function of returns in a given use, relative to an index of economy-wide returns for labor, or for capital.[4]

We draw on Abler's (2000) review of factor supply in the U.S. for parameterizing these CET supply equations for labor and capital. He concludes that medium run (five year) supply elasticities for labor and capital supply to agriculture could be reasonably set to 0.7 and 1.0, respectively – thereby suggesting relatively higher supply elasticity for capital, as opposed to labor. Holding the ratio of labor and capital supply elasticities constant, we can vary the length of run by multiplying both supply elasticities by a common factor, λ. When $\lambda = 0$, we obtain the very short run featuring minimal yield response. For $\lambda = 1$, this formulation incorporates Abler's medium run elasticities, and as $\lambda \to \infty$ we approach the long run yield response of 0.25. We make particular use of this length of run parameter in our analytical discussion of how yield response affects the demand for land in both the U.S. and rest of world.

Of course the potential for varying the quantity of land in U.S. corn production is also a critical factor in such an analysis. In this study, we follow many others in conceptualizing the land owner's problem as one of maximizing total returns from land, subject to limitations on transforming land from one use to another (see e.g., Hertel and Tsigas, 1988). Acreage response in the model is governed by Constant Elasticity of Transformation (CET) revenue functions. The general form of the CET revenue maximization problem faced by landowners is given in equation (5) in levels form (upper case letters), and with an additional index *l* representing land using sectors.

$$
(5) \quad \max_{X_{land,l}} \sum_l R_{land,l} X_{land,l} \quad s.t. \quad A = \left[\sum_l \theta_{land,l} X_{land,l}^{\rho} \right]^{\frac{1}{\rho}}
$$

$R_{land,l}$ is the return to land supplied by the land owner to sector *l*. The revenue maximizing allocation of land to sector *l*, $X_{land,l}$, is determined as the solution to (5), with this particular supply accounting for a share of total land rental revenue equal to $\theta_{land,l}$. The constant elasticity of transformation $\nu = (1-\rho)^{-1}$ describes the ease with which land may be shifted between alternative uses. Thus, for example, the (absolute value of the) elasticity of transformation amongst alternative cropping activities is larger than that describing the mobility of land between crops and forestry. This translates the following partial equilibrium supply elasticity of land to a given use: $\eta_{land,l} = -(1-\theta_{land,l})\nu$ so that the upper bound on the supply elasticity ($\theta_{land,l} \to 0$) is given by $-\nu$ and the lower bound is zero, as $\theta_{land,l} \to 1$ and all land is devoted to a single use. A key point about this land supply function is that the total endowment of land is measured in productivity-weighted terms, such that the rental-share-weighted change in sectoral land use is constrained to be constant.[5] This contrasts sharply with a model that fails to differentiate land by quality and simply constrains total physical acres to remain constant.

We make the assumption of homothetic weak separability in land supplies and divide the allocation problem into two parts. In the first, the landowner allocates land cover across three different types—crop, pasture, and accessible forestry. Conditional on the total availability of land for crop production, the next CET nest determines its allocation across crops.

For land cover, we draw on Lubowski, Plantinga, and Stavins (2006), who report land use elasticities consistent with a 5 year land cover transformation parameter of -0.11 (Ahmed, Hertel and Lubowski, 2008). A transformation parameter of -0.5 for the crop frontier is obtained by taking the maximum acreage response elasticity from the FAPRI model documentation (FAPRI, 2004) for corn acreage response across the different regions of the United States.

Finally, we turn to the critically important elasticities of substitution in international trade. These parameters will determine the ease with which diminished U.S. exports can be displaced by competing exporters in the import markets. Here, we draw on the recent econometric estimates of Hertel et al. (2007), who utilize variation in bilateral trade costs in order to estimate the elasticity of substitution amongst products supplied by different exporters. Those authors estimate this elasticity for coarse grains to be 2.6 with a standard error of 1.1. The elasticity of 2.6 is low relative to their estimated elasticities of substitution for rice, wheat and oilseeds (see table 1 in Hertel et al., 2007).

Biofuels Scenario

For analytical purposes, we focus our attention on a modest perturbation to total corn ethanol production in the U.S. Other studies have examined the impacts of ambitious renewable fuel mandates as laid out by the U.S., e.g., the 15 billion gallon target laid out in the 2007 Energy Act (e.g., Searchinger et al., 2008). Our goal is to complement these scenario-based studies with a rigorous analysis of the fundamental determinants of indirect land use associated with biofuel mandates. Accordingly, we choose to model the impacts of a one billion gallon increase in U.S. ethanol demand, which works out to about a twenty percent increase from the 2006 benchmark. (We assume that imported sugarcane ethanol increases in proportion to the total rise in ethanol use.)

5. Results and discussion

Our ultimate goal is to understand the changes in land use across countries following U.S. biofuel demand increases, both with respect to types of cover (forest, pasture, cropping) and the movement of harvested area across crops. To initiate this investigation, we begin with a focus on the coarse grain sector in the U.S., where the initial impact of the ethanol mandate arises. This demand shock, and its impact on coarse grain production, alter both demands for agricultural land in the U.S. and abroad because the U.S. is an important source of coarse grains exports in the world. Thus, supply response in the U.S. will have important impacts both on U.S. and rest of world (ROW) demands for land by the coarse grains sectors. It is this interplay that begins our discussion of results as presented in table 3.

The percentage change in coarse grains output q_{US} can be decomposed into the sum of the percentage changes in land use and yield, i.e. $q = x^{d}_{land,US} + y_{US}$ as is seen in the first three rows of table 3. In the first column of table 3 we restrict factor mobility to examine the scenario of minimal (short run) yield response and see that coarse grains output rises by 1.25 percent following ethanol mandates with nearly all of the output gain coming from expanded land use. The increase in domestic sales (nearly 3% of total output) is accommodated by a sharp decline in exports. In column two, we relax the factor mobility assumption in the U.S. to allow labor and capital to move between uses in accordance with the medium run ($\lambda = 1$). Here, we see that the output response to the ethanol demand shock is nearly twice as large (2.49% vs. 1.25%). About half of the increased responsiveness (i.e. 0.62% - 0.02% = 0.60% as a proportion of the 1.24% total increase in output) is attributable to yield growth relative to the short run assumption of perfectly immobile non-land primary factors in the U.S. Exports obviously decline much less under this scenario.

In the last column of table 3, we level the playing field between the U.S. and her competitors by increasing ROW non-land factor mobility to the medium run response as well. Here we see that this dampens U.S. output growth in both the yield and acreage components relative to the case where only the U.S. yield response is non-zero. Not surprisingly, ROW is able to displace U.S. coarse grain exports to a greater degree in this case and ROW coarse grains acreage (bottom row of the table) is increased relative to the second column. However, it is still far below the increase in acreage when neither U.S. nor ROW yields respond to price (0.46%).

Following on the results given in table 3, figure 2 traces out the changes in responsiveness to the U.S. ethanol demand shock over the factor mobility range: $\lambda = [0,2]$. In this figure, we see the importance of length of run in predicting total output response. Beginning from the short run assumption (i.e. immobile primary factors of production), output response (the top line) rises rapidly with increased factor mobility, tracking closely the increased impact on yields (the lowest line). The rapid rise of yields over the range of factor mobility assumptions indicative of the short run (e.g. $\lambda = [0.0, 0.4]$) points to the extreme nature of the commonplace zero yield response assumption.

A rather surprising result in figure 2 is the continued increase of land use by the coarse grains sector, even as yield response rises (middle line in figure 2). This stands counter to the conventional wisdom emerging from biofuel policy analysis, which suggests that adding greater yield response in a region will necessarily lead to less land use (Searchinger et al., 2008). The continued expansion of coarse grains acreage as non-land factors more readily replace it is due to the price-responsiveness of exports. As yields respond to higher prices, U.S. export prices fall (relative to the initial levels) and these exports recoup some of their competitiveness in foreign markets. The lesson is that increased yield response in the US does not necessarily result in less US acreage devoted to the biofuel feedstock.

To sharpen our analysis of export markets, we can decompose q_{US}, the equilibrium change in coarse grains output, by expressing it as the volume-share weighted sum of the percentage changes in domestic and export sales, $\delta q_{US}^{dom} + (1-\delta)q_{US}^{\exp}$ where δ is the share of total production sold to domestic uses. Rows four and five of table 3 report these two terms and we confirm that while price-inelastic domestic demand changes little in the wake of yield response, U.S. losses in grain export volume are only about one half of the amount realized when we assume no yield response (i.e. comparing column one to column three of table 3). The last row of the table indicates that, at the same time, use of land by ROW coarse grain sectors is around one half of the increase that was reported under the perfect immobility assumption (column one in table 3).

We trace the results of the last four rows in table 3 over the λ = [0, 2] length of run domain in figure 3. The top line in the top panel shows the share-weighted percentage change in domestic sales of coarse grains. Given the fact that the biofuels mandate is unchanging across these different factor mobility assumptions, as well as the relative inelasticity of domestic demands, this top line is relatively flat. The second line in figure 3 shows the output response in the wake of increased factor mobility. It follows quite closely the weighted percentage change in exports shown at the bottom of this panel which diminishes as yield response rises. The increased potential to dampen losses in export volume via domestic yield response is mirrored by the reduced demands for coarse grain acreage in ROW bottom panel). Thus, we see that the implications of U.S. yield responsiveness to price do indeed play a key role in determining ROW coarse grains acreage.

Of course, from the point of view of Greenhouse Gas emissions, it is very important to know where the increased production and land use occurs. If it occurs in Brazil, for example, there is the potential for the increased demand for land to infringe on savannah grasslands or rainforest, in which case the CO2 emissions associated with land use change might be substantial. Accordingly, we turn to an analysis of the consequences of U.S. biofuels production for international trade patterns. Table 4 reports the change in global coarse grains export volumes, in $US thousands (2001), valued at initial equilibrium prices. From this table, it is clear that U.S. coarse grain exports decline across the board following biofuel mandate implementation, with the largest volume declines tending to occur in the largest markets (East Asia and Japan, Latin America, the Middle East). However, much of the decline in U.S. exports is offset by increased exports from third countries. For example, the $29.8 million decline in coarse grain exports to Japan are largely offset by increased exports from Latin America, China and the Pacific Rim, and South Africa. Thus, determining where the increased land use will occur is actually quite complex.

The first column of table 5 reports the regional changes in coarse grains acreage, as a result of the one billion gallon rise in ethanol use in the U.S. Not surprisingly, the largest percentage increase comes in the U.S. itself, followed by Japan (a major import market, but a very minor producer) and Canada – the largest bilateral coarse grains exporter to the U.S. Some of this increased acreage is diverted from other crops, as reported in table 5. Thus, for example in the U.S., soybean acreage falls by about one percent. This, in turn, leads to increased demand for land in these competing crops in the rest of the world as well. As a consequence, there is a strong incentive to convert pasture and forest lands to cropland. Table 6 reports the changes in the three broad land cover categories. The largest percentage change in accessible forest land arises in the

U.S., followed by Brazil, where sugarcane production is also stimulated by the increased demand for ethanol. Outside the U.S., the largest percentage changes in pastureland arise in Brazil and Canada.

Of course the land use change results depend critically on a few key parameters in the model -- in particular, the yield elasticity, the acreage response elasticities, and the bilateral trade elasticities. We use 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.

The CET transformation parameters describing factor supply drawn from Lubowski, Plantinga, and Stavins (2008) and Ahmed, Hertel, and Lubowski (2008) is judged to range over the interval [-0.03, -0.19] with mean -0.11. We use this same range (plus or minus eighty percent of the point estimate) to define the distribution for acreage response across crops implying an interval of [-0.10, -0.90] about the -0.5 point estimate. For non-land factor supplies, we maintain the ratio of labor and capital supply elasticities and consider a distribution symmetric about the base assumption of $\lambda = 1$. A reasonable lower bound for this value is assumed to be zero, indicative of the short run. With this lower bound assumption a symmetric treatment for the upper bound implies an interval for λ of [0.00, 2.00] and hence a labor and capital supply elasticity range of [0.00, 1.40] and [0.00, 2.00] respectively.

As previously discussed, the substitution component of the yield elasticity is derived from the literature estimates for corn with a range of [0.00, 0.50] surrounding the 0.25 point estimate for the long run yield response to price. The trade elasticities are drawn from Hertel et al. (2007) each of which is estimated with a standard error. We only conduct sensitivity on the trade elasticities for crop sectors and draw directly from the point estimates and standard errors provided by those authors.

The results in tables 5 and 6 are the mean percentage changes in demand for land across regions. These mean results are accompanied by coefficients of variation (in parentheses) reflecting the uncertainty in the model result from the solution that considers the respective distributions on acreage response, yield response (factor substitution), non-land factor mobility, and import-import substitution. *A coefficient of variation that is larger than 0.51 is indicative of a confidence interval inclusive of zero* under the assumption that the model variables follow a normal distribution.

From table 5, we see the significant reallocation of land into coarse grains in the United States away from other crops, with both land use in oilseeds and other grains falling by more than one percent as land in coarse grains rises by 1.66 percent. In Brazil, we see both the direct impact of the U.S. ethanol demand increase via the increased demand for land to produce sugarcane and the impact of reduced coarse grains exports as Brazil expands production in that sector as well. In Canada, we see increased land demand in both coarse grains and oilseeds in response to increased bilateral import demand by the U.S., their dominant trading partner.

Across all regions, we see increased demand for coarse grains in response to the reduction in US exports. With most of the increased U.S. coarse grains land coming from oilseeds, we also see many regions shifting acreage into this crop. In the majority of cases, these results are qualitatively robust as indicated by the coefficients of variation implying confidence intervals that do not encompass zero, but large enough that predictions on land use change (and thus any analysis of the GHG emissions tied to land conversion) can be seen as critically tied to the parametric assumptions. Recall that the variability indicated by these coefficients of variation is with respect to uncertainty in all three of the acreage response, yield response (factor substitution and mobility), and trade substitution parameters.

In table 6, we find a similar pattern of change occurring across types of land cover (accessible forest, pasture, crop land) across regions. Again reporting both means and coefficients of variation, we note the robustness of the results in a qualitative sense (i.e. we can be certain of the direction of change) but note for example that the coefficient of variation for U.S. forest cover change could be reported as a ninety-five percent confidence interval of [-0.55, -0.15]. The more dramatic changes in the U.S., Brazil, and Canada result from the direct influence of the shock in the U.S. (coarse grains) and Brazil (sugarcane) sectors (recall that we increase the use of Brazilian ethanol in the US in proportion to corn-based ethanol use) as well as the dominant trade relationship between the U.S. and Canada. For results on land cover in these three regions we see comparable coefficients of variation relaying the uncertainty around predicting the magnitude of impact.

Our mean results indicate that U.S. pastureland and forest cover are reduced by -0.35 and -0.53 percent respectively leading to a 0.10 percent increase in cropland use (all adjusted by their relative productivity, see footnote 5 and equation (5)). In Brazil and Canada, the expansion of crop land is responsive to the world market impacts of the U.S. domestic market for coarse grains. In Brazil, productivity-weighted land for crops increases by 0.08 percent with productivity-weighted forest and pasture lands declining by about twice this percentage. Canada has the largest percentage expansion of crop land of any region with a 0.14 percent increase, with this shift leading to -0.10 and -0.17 percent changes in forest and pasture cover respectively. Other agricultural exporters such as the European Union, Oceania, and Latin America similarly shift land in to crops at the expense of forest and pasture, but to a smaller magnitude.

Finally, in figure 4 we highlight the relative importance of our assumptions on economic response for specific sectors by examining the uncertainty of model results when only one set of parameters are allowed to vary at a time. (The darker column shows the ratio of CVs associated with yield vs. trade elasticities, while the lighter columns report the ratio CVs stemming from acreage response, vs. trade elasticities.) In figure 4, we see that for broad categories of forestry, livestock, and crops it is indeed 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 agricultural sector, we find that in general the trade elasticities, yield, and acreage assumptions all make comparable contributions to uncertainty in model predictions, with the exception of the two grain 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.

6. Conclusion

As research into the potential impacts of biofuels policies in the U.S. moves forward, increased attention to the characterization of economic response is needed. The analysis presented here highlights the complexity inherent in large scale models used for predicting global land use changes from a marginal shock to U.S. ethanol demand. Indeed, the set of assumptions on supply response in the U.S. and bilateral trade response in the rest of the world are critical for understanding the greenhouse gas emissions impacts of indirect land use change.

For example, differing treatments of yield response will generate markedly different results in the expansion of U.S. coarse grains, and thereby differences in the need for land conversion in other countries. Using a plausible distribution on the yield elasticity reflective of past work and current agricultural economic conditions, we find that nearly thirty percent of the medium run (five year) output response to a marginal ethanol demand shock is expected to be due to yield gains (see table 3). This stands in sharp contrast to assumptions made in Searchinger et al. (2008) where only trend yield growth is considered in the main, or even that work's *best case* yield expansion scenario of a twenty percent contribution of yield growth to meeting increased corn demand.

Differing treatments of the economic allocation of acreage among uses and the determination of bilateral trade patterns in international commodity markets will similarly have strong impacts on any predicted land conversion as well as the predicted impacts of any cross-country emissions trading scheme considered. Moving forward into the more concrete assessments required to forecast environmental impacts as required by the U.S. Energy Independence and Security Act of 2007 and the associated regulatory agencies will depend both on the careful consideration of model formulation as well as the stock of empirical knowledge on supply and demand response.

Footnotes

[1] More specifically, they assume that any increase in yields due to higher corn prices will be offset by yield reductions as acreage is expanded.

[2] Houck and Gallagher directly estimate the effect on yield of changes in the corn to fertilizer price ratio while Choi and Helmberger estimate jointly the derived demand for fertilizer and the response of yield to fertilizer in deriving their estimate. Both of these studies use U.S. data only. The final estimate by Lyons and Thompson uses a cross-country panel to estimate directly the yield impact of price changes.

[3] By way of example, it is useful to consider the implications of such a yield response in the context of contemporary US corn production. Assume initial corn yields of 150 bushels per acre. Now consider the impacts of a long run doubling in corn prices from $2 to $4/bushel as has been seen in recent years. Of course, this price rise has been accompanied by a rise in variable input costs as well. If we assume that input prices rise by half as much as corn prices (i.e. 50%) then the rise in cost-deflated corn prices is just 33.33%. Coupled with a yield elasticity of 0.25, this gives rise to an 8.25% yield increase, or just over 12 bushels per acre. This amounts to a little more than one bushel per annum over a 10 year time horizon.

[4] In addition to restricting mobility between the two sectors, we restrict mobility across uses within agriculture to more closely match the approach used in OECD (2001).

[5] Following the notation used in equation (5) this constancy of the rental share weighted quantity of land implies that $\sum_l \theta_{land,l} x_{land,l} = 0$ where the lowercase $x_{land,l}$ indicates percentage change in the level of *l's* land demand.

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Table 1. Literature estimates of yield elasticities, corn in the U.S.

Authors	Time Period	Data/Estimation Notes	Elasticity	T-Statistic
Houck and Gallagher	1951-1971	Time series with calibrated non-linear trend	0.76	6.33
Houck and Gallagher	1951-1971	Time series with calibrated non-linear trend (acreage control program variable)	0.69	6.32
Houck and Gallagher	1951-1971	Time series with linear trend	0.28	3.59
Houck and Gallagher	1951-1971	Time series with linear trend (acreage control program variable)	0.24	3.11
Menz and Pardey	1951-1971	Time series with calibrated non-linear trend (acreage control program variable); replicates Houck and Gallagher	0.61	5.61
Choi and Helmberger	1964-1988	Time series of fertilizer demand and yield response to fertilizer joint estimation	0.27	2.80
Lyons and Thompson	1961-1973	Pooled time series (14 countries)	0.22	3.13

Notes: T-statistics are for linear coefficient from original estimation rather than the calculated elasticity for each study except for Lyons and Thompson. Menz and Pardey elasticity for 1951-1972 is calculated here using the relationship between elasticity and partial derivative implied in Houck and Gallagher's equation (1.4).

Table 2. Calibrated (long-run) technology matrix for coarse grains in the U.S.

Input	Substitution Elasticities				Cost Share
	Land	Labor	Capital	Other	
Land	-0.250	0.048	0.048	0.048	0.16
Labor	0.048	-0.203	0.048	0.048	0.19
Capital	0.048	0.048	-0.190	0.048	0.20
Other	0.048	0.048	0.048	-0.058	0.45

Notes: Cost shares are from the GTAP database for U.S. coarse grains. Matrix of substitution elasticities is calibrated to long run yield response estimate. Elasticities are rounded off at the third decimal point so adding up may not be exactly satisfied in the values given in the table. Simulations are conducted using the six decimal off-diagonal AUES of 0.047619.

Table 3. Model results for coarse grains under varying factor mobility assumptions following a one billion gallon increase in ethanol demand in the U.S.

Variable		Factor Mobility		
		$\lambda^{US} = 0$, $\lambda^{ROW} = 0$	$\lambda^{US} = 1$, $\lambda^{ROW} = 0$	$\lambda^{US} = 1$, $\lambda^{ROW} = 1$
Land use	$x^{d}_{land,US}$	1.23	1.87	1.68
Yield	y_{US}	0.02	0.62	0.53
Output	q_{US}	1.25	2.49	2.21
Domestic sales	$\delta\, q^{dom}_{US}$	2.94	3.05	3.04
Exports	$(1-\delta)q^{exp}_{US}$	-1.69	-0.56	-0.82
ROW land use	$x^{d}_{land,ROW}$	0.46	0.13	0.21

Notes: Source is authors' simulations. All variables are specific to the coarse grains sector in a given region. Lambda parameter is a proportional adjustment to the medium run assumption on labor and capital supply elasticity to a particular crop sector (labor = 0.7, capital = 1.0). Domestic sales and exports are volume weighted contributions to total disposition of output.

Table 4. Bilateral export volume (2001 US$$10^3$) changes in coarse grains following a one billion gallon ethanol demand shock in the United States

Exporting Region	Importing Region: USA	Canada	Eur. Union	Japan	Lat. Amer. Ex	R. Lat. Amer.	R. High Inc. Asia	M. East & No. Afr. Ex	Other Regions
USA	0	-8,899	-6,779	-32,733	-38,530	-15,933	-40,454	-47,795	-15,232
Brazil	19	0	-691	2,790	58	340	2,995	4,869	7
Canada	8,419	0	-325	1,299	1,200	145	30	314	-457
China (HK)	42	9	41	4,483	7	3	9,542	9	2,830
Eur. Union	3,854	46	6,914	1,929	2,034	534	14	11,510	3,056
India	92	18	41	40	13	14	15	174	270
Japan	1	0	0	0	0	0	0	0	-2
E. Eur. & FSU Ex.	235	113	1,312	33	11	77	83	7,701	1,226
Lat. Amer. Ex.	601	20	-2,163	3,516	1,105	5,426	1,242	3,130	-1,403
M. East & No. Afr. Ex.	223	37	-9	104	43	11	12	1,348	37
Oceania	6	6	-44	6,115	420	84	320	948	-914
R. Africa	97	17	-12	6,238	55	5	121	327	110
R. Asia	42	9	7	277	7	2	215	54	651
R. Europe	17	3	34	33	136	1	5	1,209	190
R. High Inc. Asia	32	2	-1	6	1	0	0	0	2
R. Lat. Amer.	3,177	761	-630	617	1,250	709	84	84	-16
So. Asia Ex.	42	9	7	277	7	2	215	54	651
Sub-Saharan Ex.	457	73	235	199	247	23	32	177	736

Notes: Source is authors' simulations. Countries aggregated under 'Other Regions' (last column) have an aggregate absolute change in imports less than one million dollars.

Table 5. Percent changes in land demand following 1 billion gallon increase in ethanol demand in the United States

Region	Coarse Grains	Oilseeds	Sugarcane	Other Grains	Other Agriculture
USA	1.66	-1.14	-0.64	-1.31	-0.34
	(0.15)	(0.16)	(0.15)	(0.22)	(0.13)
Brazil	0.33	0.09	0.55	-0.18	-0.15
	(0.41)	(0.77)	(0.05)	(0.19)	(0.12)
Canada	0.84	0.32	-0.09	-0.08	-0.05
	(0.28)	(0.43)	(0.33)	(0.60)	(0.45)
China (HK)	0.24	0.18	-0.02	-0.01	-0.02
	(0.40)	(0.33)	(0.17)	(0.67)	(0.20)
Eur. Union	0.15	-0.03	-0.03	-0.02	-0.01
	(0.47)	(1.38)	(0.42)	(1.49)	(2.10)
India	0.00	0.02	-0.02	0.01	0.00
	(2.33)	(0.42)	(0.22)	(0.61)	(0.81)
Japan	1.28	0.20	-0.02	0.04	-0.01
	(0.20)	(0.32)	(0.24)	(0.50)	(0.35)
E. Eur. & FSU Ex.	0.09	0.18	-0.01	0.03	0.00
	(0.48)	(0.31)	(0.46)	(0.62)	(15.55)
Lat. Amer. Ex.	0.42	0.11	-0.14	-0.11	-0.08
	(0.27)	(0.85)	(0.17)	(0.39)	(0.24)
M. East. No. Afr. Ex.	0.43	0.13	-0.04	0.06	-0.02
	(0.33)	(0.33)	(0.15)	(0.52)	(0.32)
Oceania	0.63	0.21	-0.01	-0.03	-0.02
	(0.22)	(0.50)	(1.28)	(0.66)	(0.41)
R. Africa	0.39	0.14	-0.04	0.00	-0.01
	(0.32)	(0.49)	(0.41)	(17.56)	(1.17)
R. Asia	0.08	0.10	-0.03	0.00	-0.01
	(0.53)	(0.33)	(0.18)	(2.63)	(0.33)
R. Europe	0.30	0.10	0.00	0.07	0.01
	(0.34)	(0.37)	(11.91)	(0.48)	(0.94)
R. High Inc. Asia	0.54	0.22	-0.01	0.00	-0.01
	(0.34)	(0.39)	(0.30)	(1.58)	(0.36)
R. Lat Amer.	0.50	0.12	-0.06	0.00	-0.03
	(0.29)	(0.47)	(0.15)	(28.95)	(0.26)
So. Asia. Ex.	0.13	0.16	-0.03	-0.01	-0.01
	(0.48)	(0.34)	(0.16)	(0.32)	(0.35)
Sub-Saharan Ex.	0.03	0.16	0.00	0.07	0.02
	(0.93)	(0.35)	(2.75)	(0.41)	(0.44)

Notes: Source is authors' simulations. Coefficients of variation are in parentheses. Land-use changes reported are productivity (rental) weighted changes in land use: $\sum_{j \in AEZ} \Omega_{j,l} x_{j,l}$ where $\Omega_{j,l}$ is the share of land rents in AEZ j in total land rents for crop type *l*.

Table 6. Percent changes in land cover following 1 billion gallon increase in ethanol demand in the United States

Region	Forest Cover	Pasture Cover	Cropland Cover
USA	-0.35	-0.53	0.10
	(0.29)	(0.27)	(0.28)
Brazil	-0.16	-0.17	0.08
	(0.25)	(0.26)	(0.26)
Canada	-0.10	-0.17	0.14
	(0.27)	(0.29)	(0.27)
China (HK)	-0.01	-0.02	0.00
	(0.46)	(0.44)	(0.44)
Eur. Union	-0.09	-0.11	0.03
	(0.34)	(0.34)	(0.34)
India	-0.01	-0.01	0.00
	(0.57)	(0.52)	(0.52)
Japan	-0.03	-0.07	0.02
	(0.43)	(0.28)	(0.36)
E. Eur. & FSU Ex.	-0.03	-0.07	0.02
	(0.33)	(0.32)	(0.30)
Lat. Amer. Ex.	-0.08	-0.08	0.04
	(0.31)	(0.34)	(0.33)
M. East. No. Afr. Ex.	-0.04	-0.06	0.02
	(0.37)	(0.32)	(0.34)
Oceania	-0.04	-0.04	0.03
	(0.27)	(0.37)	(0.34)
R. Africa	-0.06	-0.10	0.06
	(0.30)	(0.30)	(0.30)
R. Asia	-0.01	-0.02	0.00
	(0.43)	(0.48)	(0.46)
R. Europe	-0.04	-0.05	0.03
	(0.29)	(0.31)	(0.29)
R. High Inc. Asia	0.00	-0.04	0.00
	(2.70)	(0.25)	(0.28)
R. Lat Amer.	-0.04	-0.06	0.02
	(0.32)	(0.34)	(0.34)
So. Asia. Ex.	0.00	-0.01	0.00
	(5.33)	(0.53)	(2.11)
Sub-Saharan Ex.	-0.02	-0.04	0.03
	(0.33)	(0.30)	(0.32)

Notes: Source is authors' simulations. Coefficients of variation are in parentheses. Land-use changes reported are productivity (rental) weighted changes in land use: $\sum_{j \in AEZ} \Omega_{j,l} x_{j,l}$ where $\Omega_{j,l}$ is the share of land rents in AEZ j in total land rents for land cover type *l*.

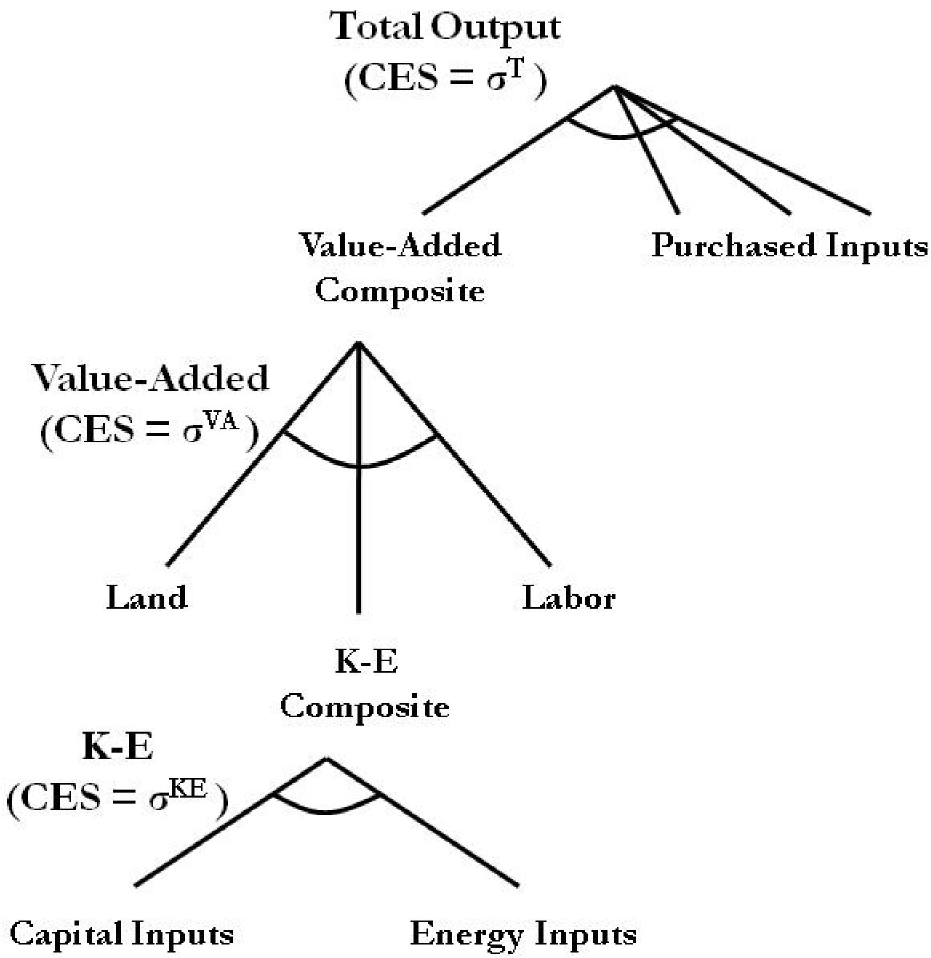


Figure 1. Nested CES production function for crop output

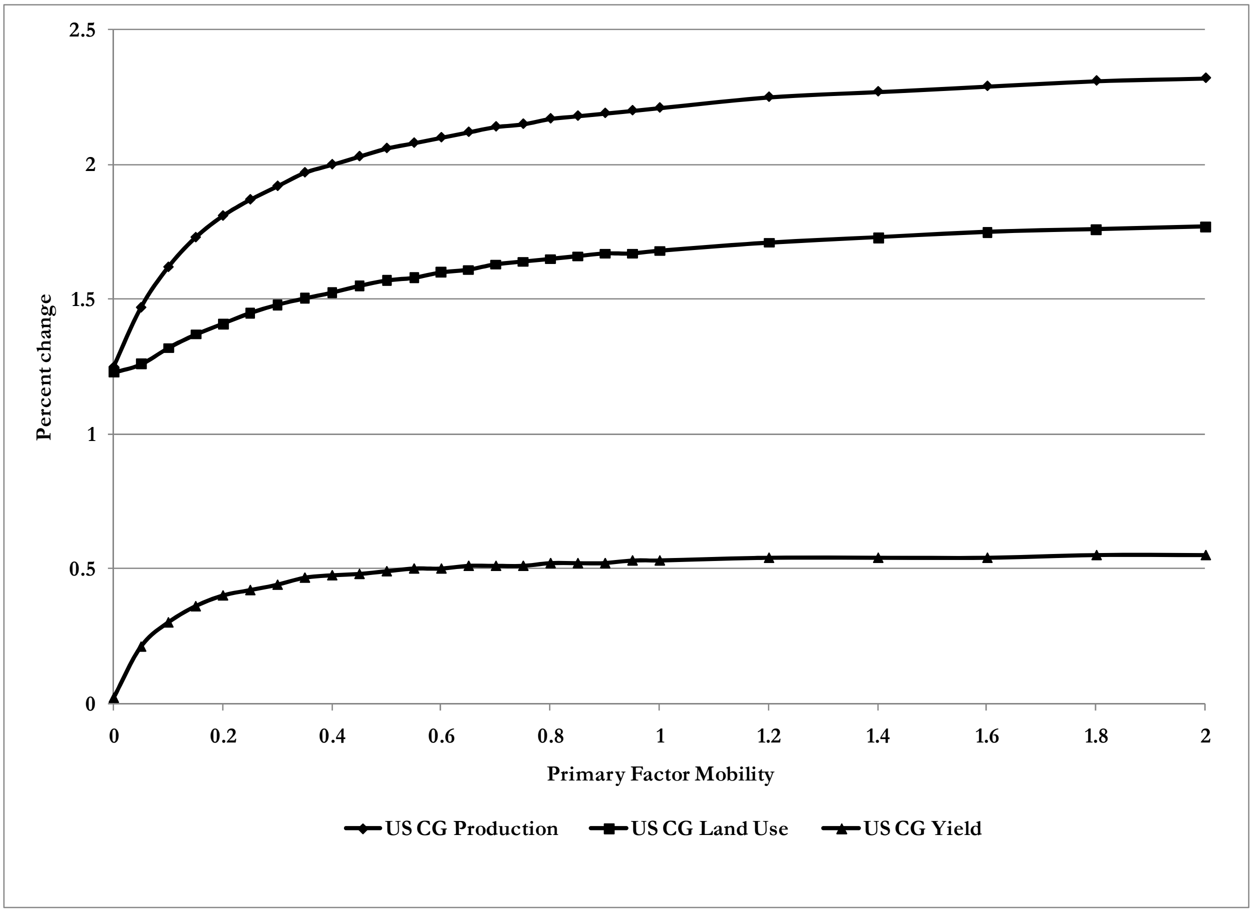
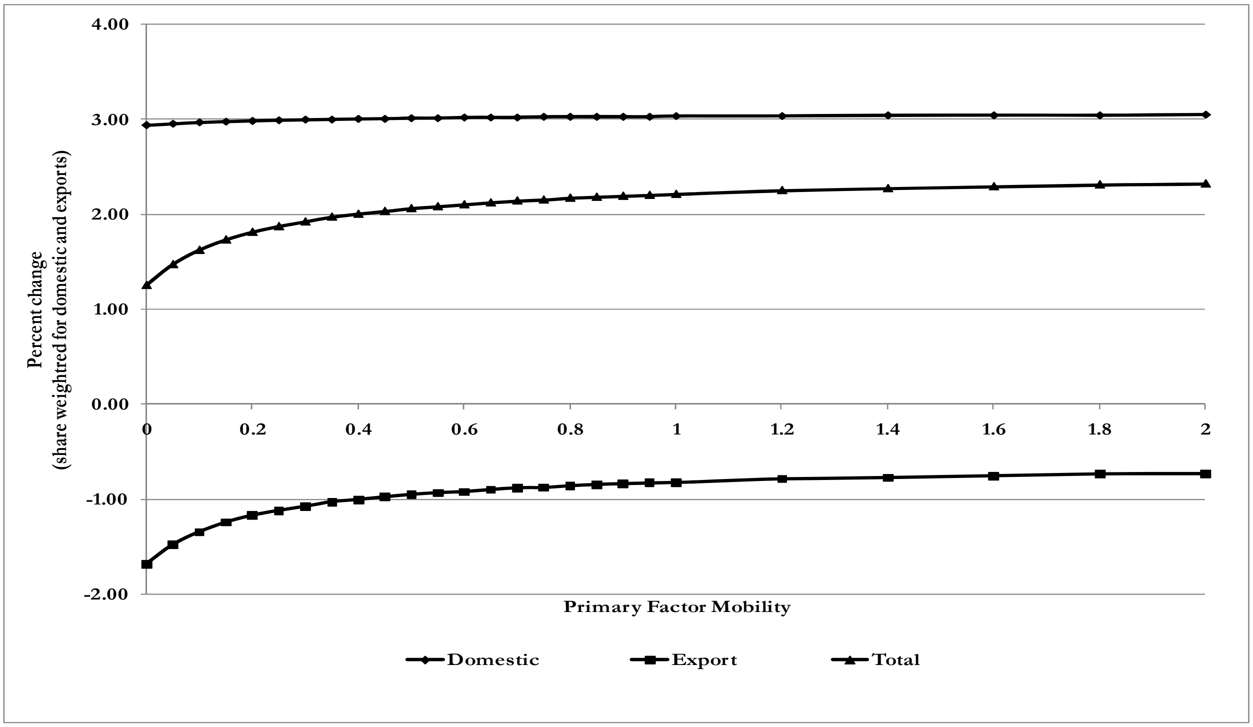


Figure 2. Yield and acreage decomposition of U.S. coarse grains output following a one billion gallon increase in ethanol demand for different assumptions on factor mobility

Notes: Source is authors' simulations. X-axis is the lambda parameter which determines the proportion of the medium run factor mobility assumption in the United States. Factor mobility (thus yield response) is held at zero for non-U.S. regions.



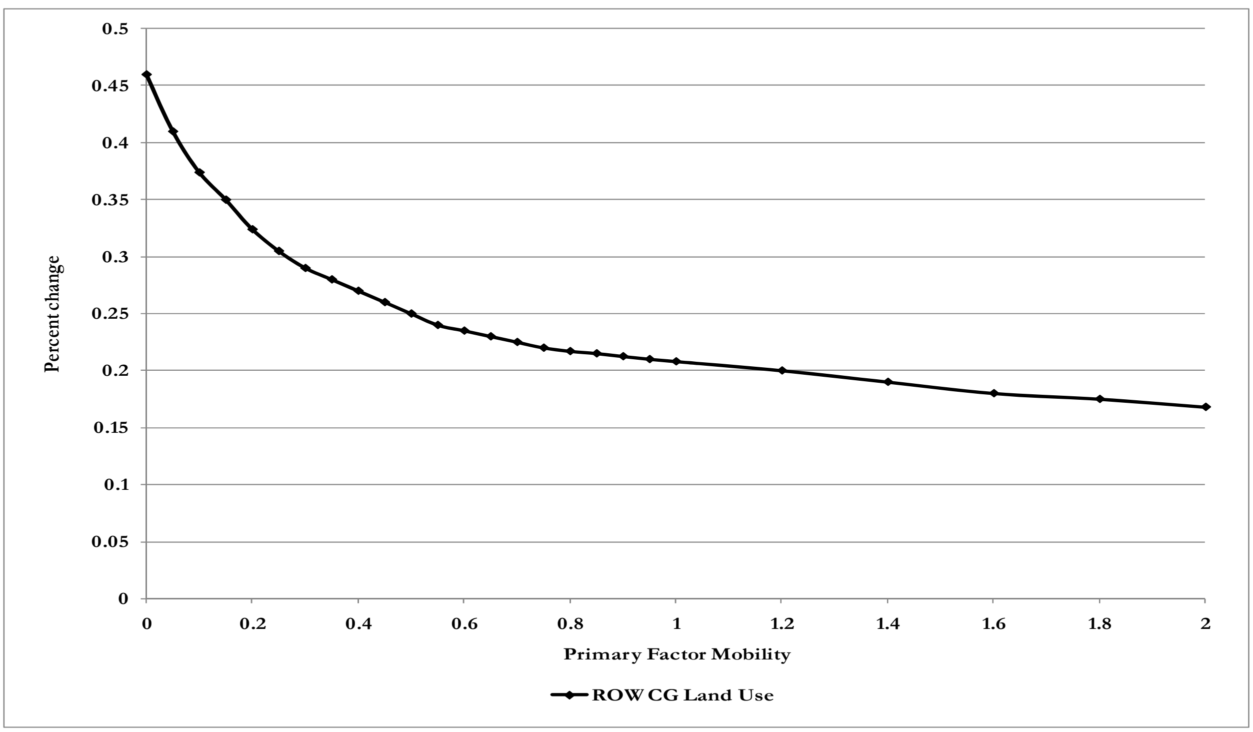


Figure 3. U.S. coarse grains disposition and ROW coarse grains acreage following the one billion gallon increase in ethanol demand under varying factor mobility assumptions

Notes: Source is authors' simulations. X-axis is the lambda parameter which determines the proportion of the medium run factor mobility assumption in the United States. Factor mobility (thus yield response) is held at zero for non-U.S. regions.

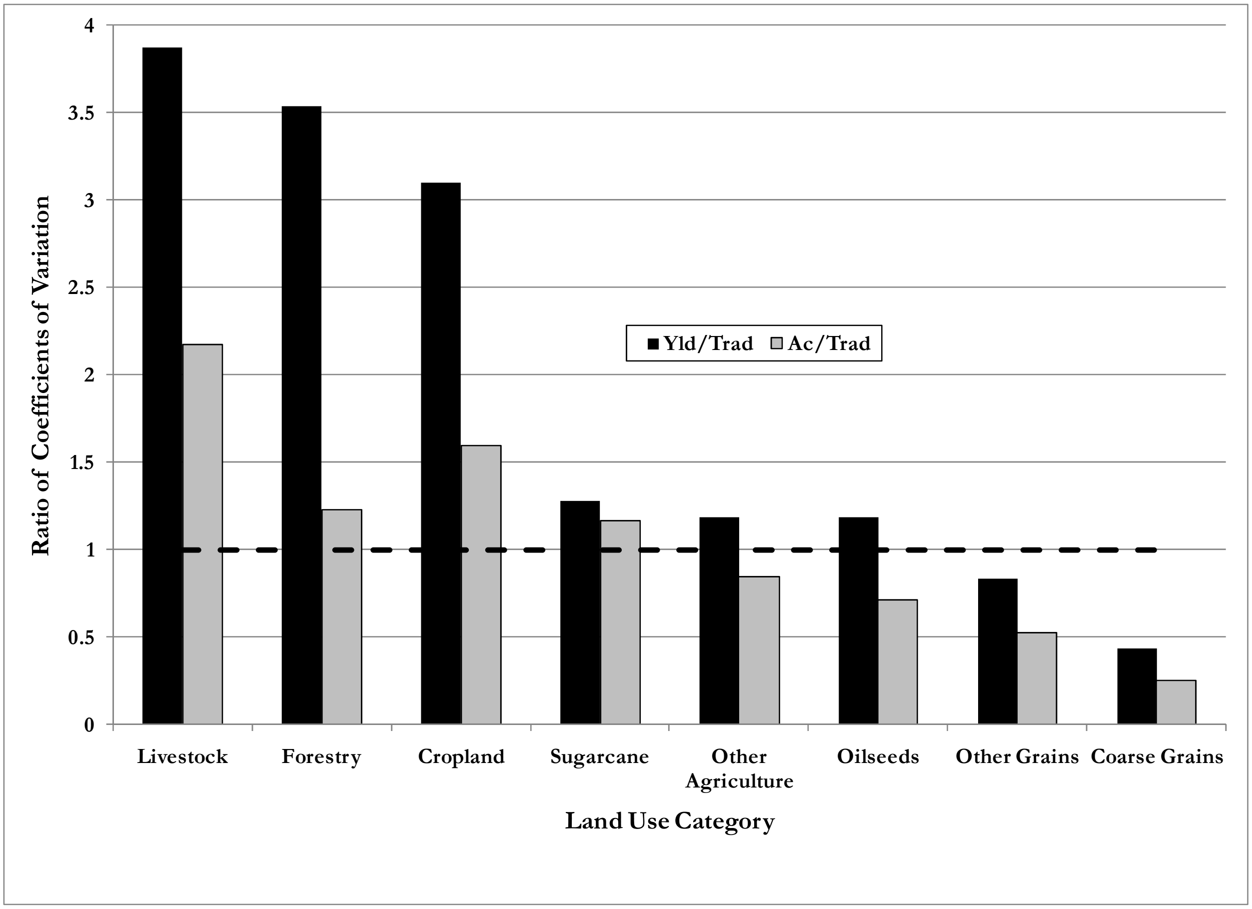


Figure 4. The relative importance of supply response versus bilateral trade response assumptions in uncertainty about land use changes

Notes: Source is authors' simulations. Systematic sensitivity analysis for yield response includes factor supply and substitution parameters. Acreage response includes both levels of land allocation (see equation 5). Bilateral trade response includes all trade elasticities for commodities featured in figure 4 using the confidence intervals from Hertel et al. 2007.