Global land use impacts of U.S. ethanol:
static vs. dynamic economic modeling

by

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1. Introduction

Assessing global impacts of biofuels is a very complex task. Most of today's biofuels are produced from feedstocks traditionally used for food or animal feed, thus increased production of biofuels has a direct effect on food prices. As more agricultural land is diverted to biofuel production, demand for food, feed and fiber will likely lead to intensification on current cropland and pastures, as well as conversion of forests and other ecosystems to agricultural lands – the so called indirect land use change effect. As production of first generation biofuels expands, more co-products become available to substitute for other feed in livestock feed rations. Further, the biofuel mandates affect the price of liquid fuels, which in turn affects the overall demand for liquid fuels, as well as agricultural and nonfarm production costs.

In recent years, many economic models, including partial and general equilibrium, static and dynamic models, have been used to quantify the impacts of bioenergy on land use, food and fuel prices, and greenhouse gas emissions. One of them is a modified version of the GTAP computable general equilibrium (CGE) model nick-named GTAP-BIO (Birur et al., 2008) – the modeling framework mandated for use in California's Low Carbon Fuel Standard assessments of biofuels. GTAP-BIO is static, yet most biofuel mandates refer to some future period in time, and without an explicit baseline, it is difficult to evaluate the relative stringency of such policies. In addition, presenting biofuels-induced land use change analysis in the context of a dynamic baseline is more appealing to policy makers.

This paper discusses the development and application of a recursive dynamic version of the GTAP-BIO model – GDyn-BIO – to the analysis of expanded production of U.S. corn ethanol over 2004-2030 period. While other analyses of biofuels have been done with dynamic models (Gitiaux et al. 2009, Laborde 2011), this work builds on a broad foundation of previous research and offers potentially valuable insights for policy makers. Many structural elements of the static version of the model have to be modified to better represent land use change in the context of the dynamic analysis: responsiveness of consumer demand for food and intensification options in land using sectors and food processing. Further, in attempt to improve GTAP-BIO framework, static or dynamic, the structure of land supply is modified to reflect the greater sensitivity to relative returns amongst cropland and pasture than between forests and agriculture – where the allocation decision can be irreversible in the near term.

1. Modeling framework

Dynamic General Equilibrium Model

The model is based on two existing CGE platforms - the dynamic GTAP model nick-named GDyn (Ianchovichina and McDougall, 2001) and static GTAP-BIO (Birur et al., 2008). GDyn is a multi-sector, multi-region, recursive dynamic applied general equilibrium model that extends the standard GTAP model to include international capital mobility, endogenous capital accumulation, and an adaptive expectations theory of investment.

The GTAP-BIO (Birur et al., 2008) model is a modification of GTAP-E (GTAP-energy and environment model, Burniaux and Truong (2002) and McDougall and Golub (2007)) with standard GTAP sectors disaggregated to handle first generation biofuels and their by-products (Taheripour and Tyner 2011). Production and consumption structures of GTAP-E are modified to incorporate these new products. Grain-based ethanol, sugar cane ethanol and oilseeds-based biodiesel, substitute for petroleum products in liquid fuel consumption. In the data base used for this work, soybeans are separated from other oilseeds; soybean oil is separated from other vegetable oils and fats, and soybean biodiesel from other types of biodiesel (Taheripour et al.

2011a). Biofuels co-products (Dried Distillers Grains with Solubles (DDGS) and oilseed-meals) compete with other feedstock in livestock feed use (Taheripour et al. 2011b).

Consumer demand

The most important driver of the demand for land is the consumer demand for food. Changes in demands for staple crops, livestock products and processed foods will determine changes in the derived demand for land in each of these activities. In GTAP-BIO, as well as in the standard GTAP model (Hertel 1997), the consumer preferences are represented by constant difference elasticity (CDE) consumer demand system. The calibration of this demand system involves choosing the values of the substitution parameters to replicate the desired compensated, own-price elasticities of demand, then choosing the expansion parameters, to replicate the target income elasticities. Thus users of the model are offered flexibility to calibrate the demand system to desired set of elasticities.

In the projections from 2004 to 2030, per capita incomes are rising significantly in developing countries, and food consumption response to changes in income is an important determinant of the derived demand for land. The income elasticities provided with GTAP data base package are obtained from estimating an implicit, directly additive demand system (AIDADS) on GTAP data base (Hertel et al. 2008). Comparison of the model income elasticities of demand for food with econometric estimates reported in Muhhamad et al. (2011) is shown in table 1 for a subset of model regions. The comparison reveals that GTAP data base income elasticities for meat and dairy in developed countries are twice as large as the elasticities suggested by Muhhamad et al. (2011). For developing countries, GTAP income elasticities for both crops and meat and dairy are larger than suggested in Muhhamad et al. (2011) (table 1).

Thus, in simulations with the model, the impact of income growth on food consumption and derived demand for land may be too large. Further, one would expect that low-income countries are more responsive to changes in income and, therefore, make larger adjustments to their food consumption pattern when incomes change. For meat and dairy and processed food, this pattern, is observed in Muhammad et al. (2011), but not in the GTAP data base income elasticities. Based on this comparison, it is desirable to recalibrate the income elasticities to move them closer to the estimates reported in Muhammad et al. (2011). It is also important to take into account that over the time horizon of this analysis, per capita incomes will grow, and goods that are luxuries in 2004 at low income levels will become much less sensitive to changes in income in 2030 at higher incomes. With CDE demand system, however, consumption goods that are luxuries at the beginning of the projection period will remain luxuries as incomes grow over the time horizon of the analysis. For example, if meat consumption in a developing country is very sensitive to changes in income in 2004, it will remain very sensitive in 2030, even when per capita income improves relative to 2004. Thus, over time, as incomes grow in developing countries, initially large income elasticities for food may result in implausibly large growth in per capita food consumption in the model. To correct these problems, first, the demand system is recalibrated using elasticities reported in Muhhamad et al. (2011). Second, the income elasticities for food in rapidly growing low income developing economies are further modified so they more closely match the income elasticities for food in currently middle-income countries (a similar method is also used in Anderson and Strutt 2012).

Production structure

In standard GTAP model (Hertel 1997), the production sectors are represented by constant returns to scale, nested constant elasticity of substitution (CES) functions, which first combine primary factors into composite value-added, and imported and domestic intermediate inputs into composite intermediates, before aggregating these composites into an aggregate output. With income and population rising over the projection period, it is important to incorporate various intensification possibilities to respect historical observation and reduce pressure on scarce resources, such as land. For this purpose, standard production structure is modified in land using and food processing sectors.

In the livestock sectors we implement multilevel nested structure similar to one reported in Taheripour at el. (2011a). In the new structure, feed products are combined into a feed composite following multi-nested structure presented in figure 1. Important departure from Taheripour et al. (2011a) is that feed composite does not enter in fixed proportion with non-feed input and value-added into aggregate output. Instead, feed is combined with land to allow direct substitution between feed and grazing. Therefore, if land rents rise faster than prices of feed composite over the projection period, dairy and ruminant meat producers will shift toward feedlots and intensify their production practices.

In crop production, we allow substitution between land and other inputs to reflect the fact that producers will use more fertilizers and other factors of production to increase yields per hectare as land prices rise under the pressure of increasing demand for land. To simplify calibration of crop yield response, we follow Keeney and Hertel (2009) and represent crop sectors with a single (non-nested) CES production function. With this structure, land competes directly with all other inputs and the CES parameter and cost share of land in total crop sector costs determine the potential for substitution away from land and hence the yield response to price.

The fraction of the average consumer's food dollar devoted to the raw farm product has been continually declining over the past century (Wohlgenant 1989; Economic Research Service (ERS), US Department of Agriculture (USDA) 2006). For this reason, we introduce the possibility of substitution between farm and marketing inputs in processed ruminants, processed dairy, processed non ruminants and other processed food. When farm prices rise, or technology changes, there is potential to reduce the cost share of processed sector outputs devoted to the farm product.

In a model with many intensification options introduced in the agricultural sectors and sectors that process agricultural output, leaving forestry without an option to intensify leads to unrealistically large increases in land rents in forestry, relative to agricultural sectors, over the projection period. Representation of the forestry sector in the model follows standard GTAP production structure described above. When land rents rise, the only intensification option available to forestry produces in the model is substitution from land toward capital and labor within value added of the forestry sector. Using Global Timber Model (Sohngen and Mendelsohn, 2007), Hertel et al. (2009) observe that changes in management intensity permit substantial changes in forestry output per unit of land. Based on this observation, we increase the elasticity of substitution between land and other value added inputs in forestry sector.

Supply of land

Each model region's land endowment is disaggregated in an effort to reduce the heterogeneity of land. Following the pioneering work of Darwin et al. (1995), this is accomplished via the introduction of Agro-Ecological Zones (AEZs) (Lee et al., 2005). In each region of the model, 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). Even after introduction of AEZs, there is still considerable heterogeneity within these units, and this, in turn, is likely to limit the mobility of land across uses within an AEZ. In addition, there are many other factors -- beyond those reflected in the diverse AEZs -- that limit land mobility. These include costs of conversion, managerial inertia, unmeasured benefits from crop rotation, etc. Therefore, land mobility across uses within an AEZ is constrained by a Constant Elasticity of Transformation (CET) frontier.

In the static GTAP-BIO model, land mobility is constrained by a two-level nested CET frontier. The land owner first decides on land allocation among three land cover types. Then, based on relative returns to various cropping activities, the land owner distributes land across crops. With cropland, pasture and forests in the same nest, this structure is likely to overstate land mobility between forests and agricultural land categories (cropland and pasture). In this dynamic model, the nesting structure is revised following the approach developed in Ahammad and Mi (2005) and later incorporated in the modified GDyn model (Golub and Hertel, 2008). In the new structure (see figure 2), owners of the particular type of land (AEZ) first decide 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, based on relative returns in cropping activities, cropland is allocated to different crops.

One important limitation of the CET function is that the endowment 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. To estimate land-use changes measured in physical hectares, the static GTAP-BIO incorporates (1) an additional constraint that requires that physical hectares add up and (2) an endogenous variable which permits satisfaction of this additional constraint and represents productivity adjustment within considered nest. These two elements are introduced at each level of the CET tree. That is, there is an adjustment and adding-up constraint for the crops nest, and separate adjustment and adding up constraint for the land cover nest. The productivity adjustment within the cropland nest reflects changes in average productivity of cropland in a given AEZ due to changing mix of cropping activities. Similarly, the productivity adjustment within the land cover nest reflects changes in overall productivity of land in a given AEZ.

The magnitude of these productivity adjustments are driven by differences in per hectare land rents. In the GTAP data base, cropland rents are much larger than land rents in forests and pasture. As a result, the productivity adjustments in the land cover nest may be large and can have a significant impact on the results. Yet, with some investments, the converted pasture or forest land might be nearly as productive as current crop land (Golub and Hertel, 2012). For this reason, a model parameter that can be specified exogenously determines how many additional hectares of marginal lands are required to make up for one hectare of average crop land. Tyner *et al*. (2010) have calculated regional land conversion factors at the AEZ level using the Terrestrial Ecosystem Model (TEM) of plant growth and suggest the use of these factors to determine how many additional hectares of marginal lands are required to make up for one hectare of average crop land.

With the new land supply structure (figure 2), the adding up and the productivity adjustments should be introduced at each of the three levels of the CET tree. However, land rents per hectare in forestry are much smaller than land rents in agriculture, leading to very large productivity adjustments in the upper nest and large areas of forests converted to agriculture, contrary to what we expected when we introduce additional nest. Instead of letting the model to determine the productivity adjustment and number of forest hectares to be converted for a given expansion of agricultural land, we assume that forests converted to agricultural land, on average, are equally productive as land currently employed in agricultural activities. Given that cropland usually is much more productive than pasture, this also implies that forest land is more productive than current pasture land, but less productive than current cropland.

Moving to the next nest in Figure 2 (cropland vs. pasture), we find that cropland rents per hectare are much larger than pasture land rents in the GTAP data base. Large differences between cropland and pasture rents per hectare results in large productivity adjustment within agricultural land nest. Following the approach employed with the two-nest land supply structure of GTAP-BIO, we use TEM-based factors (Tyner *et al*., 2010) to specify ratios of marginal land productivity to current cropland productivity across AEZs and regions. Cropland expands directly through conversion of pasture, but also indirectly through expansion of agricultural land (upper nest in figure 2). Thus, TEM –based factors used to quantify ratio of productivity of natural land (forest, grasslands, and other ecosystem types) to productivity of current cropland are also applied here.

All the model features listed above help to determine the extent of land use change in the model. Below we identify some key factors that operate at a sectoral level in order to determine changes in output of the corn ethanol sector.

Ethanol and energy markets

There are two types of demand for ethanol. Until recently, the main role of ethanol was a fuel additive – aimed at allowing the fuel to burn cleaner, thereby meeting stricter air quality standards. This demand became particularly important after the primary additive (MTBE) was banned due to its role in polluting groundwater. The additive accounts for a relatively small share of total fuel use. Since it is demanded in fixed proportion to the total amount of fuel consumed, this source of ethanol demand is relatively price insensitive. The second source of ethanol demand is much more sensitive to price, as this demand is based on its energy content. This is where ethanol can potentially compete directly with petroleum products. The effectiveness of this competition depends first and foremost on the so-called 'blend wall' (Taheripour and Tyner, 2008). While it is currently legal to sell gasoline which contains a 15 percent ethanol blend, this is only approved for use in more recently produced automobiles. As a consequence, there are few gas stations selling the E-15 blend. This means that the effective constraint on aggregate ethanol use in US liquid fuels for transportation is 10% of the total – since the E-10 blend is approved for use in all automobiles. However, with time, with the turnover in the auto stock, we expect the blend wall to become less prominent. As a result, we abstract from this in the subsequent discussion.

In the absence of a blend wall, the factors determining demand for ethanol as a fuel substitute in the model include the price of petroleum products and the elasticity of substitution between ethanol and petroleum products in liquid fuel mix in private consumption. The corn price, on the other hand, is the main determinant of the cost of ethanol production, and therefore it affects the equilibrium volume of ethanol produced. Here we focus on the elasticity of substitution between ethanol and petroleum products, and discuss factors influencing the cost of ethanol and the price of petroleum products in the baseline section below.

Until recently, econometric estimates of the substitutability of biofuels for conventional fuels were unavailable due to the absence of historical data on biofuels in most parts of the world. For this reason, the substitution parameter between petroleum products and ethanol in static GTAP-BIO was determined by means of calibration. Birur et al. (2008) calibrate the substitutability of ethanol for petroleum products using general equilibrium simulation of the GTAP-BIO model over historical 2001-2006 period, taking into account drivers of demand for biofuels over this historical period. In a recent study, using 1997-2006 monthly data for ethanol (E85) and gasoline (E10) prices and sales volumes at 200 fueling stations in Minnesota, Anderson (2012) estimated elasticity of ethanol with respect to gasoline price. Anderson (2012) finds this elasticity ranges between 2.3 and 3.2. We use middle range estimate (2.75) to calibrate substitution parameter among liquid fuels in private consumption in the model. The calibration to Anderson's estimates results in 2.9 CES parameter in US, which is smaller than parameter used in earlier analysis with GTAP-BIO (3.95), suggesting in this modeling demand for ethanol is less sensitive to changes in gasoline price. The importance of the substitutability between biofuels and gasoline should not be underestimated. In our model, this parameter together with other factors (petroleum and corn prices) will determine equilibrium quantity of ethanol in the baseline simulation, and this in turn determines whether mandate is binding in the model simulations.

2. Baseline assumptions

Together with the structure of the model outlined above, baseline assumptions determine crop yields, the level of biofuels produced over the time horizon of the analysis, and the overall demand for land.

Our analysis is based on the GTAP version 7.0 data base, representing global economy in 2004, aggregated up to 36 sectors and 19 regions (regional and sectoral aggregations are presented in tables A1 and A2 in Appendix A). Projections are undertaken from 2004 to 2030. Over this period, labor force, population and productivity growth are all exogenous to the model and therefore serve to determine its dynamic path.

Historical and projected population and labor force (skilled and unskilled labor) growth rates for 2004 – 2030 are taken from Chappuis and Walmsley (2011). The population growth rates are highest in Sub Saharan Africa region, and lowest (negative) in Japan and Russia (table 2, column 3). Historical real GDP growth rates are taken from Chappuis and Walmsley (2011). The real GDP path for 2011 − 2030 is driven by assumptions about productivity growth in various sectors of the economy. Productivity growth rates in non-land using sectors are based on our assumptions about economy-wide labor productivity growth in each region (table 2, column 2). These rates are adjusted for productivity differences across sectors using estimates reported in Kets and Lejour (2003). The resulting baseline annual average real GDP growth rates are shown in table 2, column 6.

Land using sectors in the model include agricultural sectors and forestry. Agricultural sectors, in turn, include seven crops, ruminants, dairy and non-ruminants. In our model the non-ruminant livestock sector does not use land directly. However, it is a heavy consumer of feed which requires land for production. For the crops and livestock sectors, the projected productivity growth rates are taken from Fulgie (2010) and Ludena et al. (2006), respectively, and reported in table 3. TFP growth rates in forestry are assumed to be equal to the average of productivity growth rates in crops, dairy and ruminant meat sectors, weighted by their output shares in total agricultural sector output. This assumption ensures that TFP is not a major source of forest land conversion in the model.

Processed food sectors' demand for farm-produced inputs (grains, fruits and vegetables, and meat) is another important determinant of the derived demand for land. This sectoral demand depends on technological improvements in food processing: sectors equipped with better technology will require fewer inputs to produce a given amount of output. We introduce technological progress in processed food sectors according to TFP growth estimates reported in Emvalomatis et al. (2009). These authors estimated TFP growth rates for ISIC 2 digit level category of manufacturing of food products, beverages, and tobacco. These correspond to the following sectors in the model: processed dairy, processed ruminants, processed non-ruminants, beverages, processed rice and processed food. Emvalomatis et al. estimate TFP in food processing in EU to be around 0.8%/year from 2000-2005. This is similar to available estimates for US. In the absence of regionally differentiated estimates, we adopt the 0.8% annual rate of growth in TFP in food processing sectors in all regions.

In dynamic settings a policy impact is evaluated relative to baseline path over time. With respect to biofuels, there are two approaches to construction of the baseline and policy scenarios. Under the first approach, the baseline reflects the world with biofuel mandates in place, and depicts various biofuel policies implemented in EU, US and other countries over historical period, plus scenarios involving possible future developments in these policies over the time horizon of the analysis. To evaluate land use impacts of biofuel policies under this approach, one needs to create counterfactuals representing the baseline "minus" the effect of expanded production of a biofuel in question (US corn ethanol modeled in this study). Land use in the counterfactual scenario may then be compared to baseline, and any differences are attributed to expanded production of the biofuel. Under the second approach to analyzing the impact of biofuels policies in a dynamic model, the baseline is the world without biofuel policy. Quantities of biofuels produced and consumed in the baseline will change over time due to changes in supply and demand conditions (e.g. petroleum and corn prices in the case of US corn ethanol), and are not imposed exogenously. The policy scenario in this case is just the baseline "plus" expanded production of biofuels. In this analysis we adopt the second approach where in the baseline simulation quantities of US ethanol (and other biofuels produced in US and other regions) are determined endogenously in the model, while in policy simulation the ethanol mandate are imposed exogenously.

We now turn to the elements of a baseline that determine the quantity of ethanol demanded and produced in the baseline. As noted previously, gasoline and ethanol are substitutes, and the price of gasoline is an important determinant of the demand for ethanol. Accordingly, we impose an exogenous path for the crude oil price from 2004 to 2030 using historical prices and the forecast from the International Energy Agency. The price of corn is the main determinant of ethanol production costs. While historical US corn price data are readily available, the use of these prices in the model baseline is problematic because historically observed prices are those that were themselves influenced by the mandate. In fact, recent estimates suggest that corn prices were about 30 percent greater, on average, between 2006 and 2010 than they would have been if ethanol production had remained at 2005 levels (Carter, Rausser, Smith 2012). Instead of corn price, we impose historically observed U.S. corn yields. Yield outcomes in a given year are mostly driven by weather and past R&D, and are thus largely independent of the policy (ignoring the modest intensification effect which will be discussed below). Corn yields dropped in 2008 and 2011, and these are the years when corn prices were particularly high (though there are other reasons, including the presence of biofuels). With corn yields exogenously imposed in the model between 2004 and 2011, we observe higher corn prices and higher cost of ethanol production in years when yields were low, and vice versa. Post 2011, U.S. corn yields are endogenously determined and heavily influenced by the crop TFP assumptions reported in table 3.

The final element of the baseline relates to U.S. ethanol policy. Until 2011, the U.S. government paid a tax credit to the blenders for each gallon of ethanol incorporated into liquid fuels, and a tariff was levied on imported ethanol. These two instruments were eliminated in the end of 2011. Both the tax credit (modeled here as a production subsidy) and the import tariff are present in GTAP-BIO data base. To reflect these recent policy changes, we eliminate them in model simulations from 2012 onwards.

3. Results

Baseline

Assumptions about productivity improvements in crop and livestock sectors, the elasticity of demand for food with respect to changes in prices and income, as well as other structural and parameters assumptions, together determine the time path of global production of crops in the model. Overly income elastic demand and/or too high TFP growth may lead to unrealistically large increases in crops production. We conduct a simple validation exercise wherein global cereals output produced in the model over historical 2004-2010 period is compared to FAO data. In baseline simulation from 2004 to 2010, global cereal production increases by 8.3% which closely follows historical changes in global cereals production (8.8%).

Driven by the demand for food, forest products and other non-food demands, global cropland expands by 4.7% between 2004 and 2030 in the baseline. The main source of the new cropland (95%) is conversion of pasture land that is reduced by 2.5% between 2004 and 2030. Over this time horizon, 0.2% of accessible forests are converted to new cropland, contributing about 5% of the total cropland expansion. Figure 3 shows regional changes in cropland, pasture and forest area in thousands of hectares. In all regions almost all additional cropland comes from pasture – a factor driven by our land supply structure discussed above. By 2030, forest area declines in all regions except Russia. USA, Rest of South Asia (R_S_Asia), Russia and East Europe and Rest of Former Soviet Union are large contributors to global cropland expansion (figure 3). Within crop land uses, wheat and paddy rice areas experience reductions, while coarse grains and other agriculture areas (fruits and vegetables and plant based fiber) expand. Crop yields in the baseline are driven by TFP growth, endogenous yield intensification and changes in yields as marginal lands and/or land under other crops are converted. By way of example, changes in coarse grains yields are decomposed into these three components in four regions of the model (table 4). TFP is the main source of yield changes, followed by the yield drag caused by area expansion into less productive lands, which is offset to some degree by the endogenous intensification of production in response to land scarcity.

In the baseline, volumes of ethanol and other biofuels produced reflect those quantities demanded in the absence of biofuel policies. They are determined endogenously in the model and driven by petroleum prices, the ease of substitution between petroleum products and biofuels, and the cost of biofuel production. The baseline quantity of US ethanol fluctuates between 2007 and 2013 and then gradually rises to about 9 billion gallons per year in 2030 (figure 4, blue line). The increase in 2008 and subsequent reduction in 2009 are driven by fluctuations in fossil oil prices. The reduction in 2012 is due to elimination of the tax credit to the blenders and tariff on imported ethanol. This baseline indicates that, without the biofuel mandate, US corn ethanol production would not reach 15 billion gallons per year neither by 2015, nor anytime over the next 15 years. Therefore, the biofuel mandate for ethanol is always binding over this baseline.

Impacts of expanded production of US ethanol

In the policy scenario, the ethanol mandate comes into play in 2007 with the volumes of ethanol produced following the historical volumes, and then those volumes reported in the FAPRI Agricultural Outlook. After 2015, the volume of U.S. corn ethanol is fixed at the mandated level (figure 4, red line).

Globally, prices for all food categories rise, relative to baseline, due to the biofuel mandate. The largest impact is observed in coarse grains, followed by soybeans and then other cereals and food products. The cumulative deviation from baseline in the US coarse grains price index reaches 10% in 2016 and then declines to 7% in 2030 (figure 5). Consumption of all food categories falls in all regions with largest reduction observed in consumption of livestock products (0.32% reduction of non-ruminant meat consumption in US), but the impact on quantities consumed is much smaller than on prices.

Policy induced changes in global cropland, pasture and forests are shown in figure 6. These changes represent deviations from baseline and are measured in 1000 hectares. Pasture land is the main source of the new cropland with only a small fraction of forests lost due to expanded production of US ethanol. The largest changes in land use due to the mandate are observed in 2009 – about 800,000 hectares of additional cropland are brought into production. After 2013, the land use change impact gradually diminishes to about 100,000 hectares of additional cropland brought into production. Regional impacts of the expanded production of US ethanol on land use are shown in figures 7a-c in terms of absolute deviations (1000 ha) from baseline. The largest cropland expansion and reduction in pasture land are observed in US, followed by Europe (figure 7a and 7b). Regional reductions in forest area are much smaller than reduction in pasture land, and most noticeable in Africa, Asia and Europe (note change in scale in figure 7c).

The impact of the policy on land use pictured in this analysis is transitory, with land conversion due to the mandate diminishing over time (figure 6). There are two reasons for this outcome. First, given our assumptions on crop TFP growth as well as oil prices, baseline quantities of ethanol are rising over time while the mandated quantity is fixed after 2015. This results in a reduction in the additional quantity of ethanol that the mandate is forcing onto the market (the difference between red and blue lines in figure 4 is getting smaller). In addition to this, the net additional cropland requirement per unit of additional ethanol produced falls over time.

The net additional cropland requirement metric is often used as a summary measure of the impact of biofuel policies on land use. It is calculated as ratio of a net increase in global cropland, induced by expanded production of biofuels, to that additional amount of biofuels. This summary metric is plotted in figure 8. In this analysis, we started from static a version of GTAP-BIO model. In the static version, increase in US corn ethanol production from 2004 level (which is 3.41 bill gallons per year) to 15 billion gallons per year results in 0.18 ha of net additional cropland per each 1000 gallons of additional ethanol forced into the market. This result is shown by purple line in figure 8. The blue line in the same figure shows the ha/1000 gallons metric calculated with GDyn-BIO. For each year within the analytical time horizon of the dynamic analysis, the metric is calculated in similar fashion: it is a ratio of net increase in global cropland (yellow bar in figure 6) to additional ethanol forced into the market due to the mandate (the difference between red and blue lines in figure 5). For example, in 2015 the difference between policy and baseline volume is 8.7 bill gallons, and the difference between policy cropland and baseline cropland is 486 784 hectares. The metric is 486 784/(8.7*10^6) = 0.06 ha/1000 gallons in figure 8. In the dynamic analysis, the net additional cropland requirement metric shows a gradual decline from 0.15 in 2007 (the first year when policy is implemented) to 0.02 ha/1000 gallons in 2030. The implication of the gradual decline is that the average net cropland requirement depends on time horizon of the analysis. For example, over 2007-2030 period weighted average net cropland requirement per 1000 of gallons of additional ethanol produced is 0.05 ha/1000 gallons, while weighted average over 2007-2015 period is 0.08ha/1000 gall.[1]

Why is the impact of the policy pictured in the dynamic analysis so different from the static results? There are several important differences between dynamic framework developed in this study and the static framework from which we started. First, some of the structural elements of the model were modified. These include: introduction of intensification possibilities in food processing, livestock, and forestry sectors, and reduced response of yields to crop prices. Other things being equal, intensification options in livestock and forestry should increase availability of cropland: as land rents increase due to expanded production of ethanol, livestock and forestry producers will substitute away more easily from relatively more expensive land input. Intensification in food processing, on the other hand, has opposite effect making non-biofuel

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[1] The weighted average is calculated as sum over time of additional (to baseline) cropland divided by sum over time of additional ethanol forced into market.

demand more elastic and reducing amount of land conversion as a consequence of the mandate. Another modification of the model structure relates to the land supply. However, the direction of the impact of this modification on the net cropland requirement is hard to assess *a priori*. Overall, the impact of these structural changes can be assessed by implementing these changes in the static GTAP-BIO framework, estimating the net cropland requirement due to the mandated 15 billion gallons of corn ethanol, and comparing the results with those from the static model before the changes in structure. The comparison reveals that the structural changes alone do not result in reduction in the net global cropland requirement per 1000 gallons. In fact, they lead to an increase in the net global cropland requirement from 0.18 to 0.27 ha/1000 gallons.

A second important difference between the dynamic and static analyses is that the dynamic analysis captures future changes in technology. Crop yields are rising from 2004 to 2030 driven by TFP growth (as well as intensification induced by higher crop prices). These factors result in smaller gross cropland expansion for a given quantity of ethanol. For example, doubling corn ethanol production in 2004 (increase from 3.41 bill gallons to 6.82 bill gallons) at corn yield observed in 2004 (9.08 tonnes/ha) results in 3.84 mill hectares of gross cropland expansion. To increase corn ethanol production by the same amount in 2030 at projected 11 tonnes/ha yield (see table 4 for cumulative 2007-2030 yield increase), one would need just 3.17 mill hectares of gross cropland expansion.[2]

Finally, as primary factors of production (capital and labor) are accumulated over time, agents' responses become more price elastic. To isolate these adjustments from impacts of changes in productivity and population growth, we construct a diagnostic scenario where only

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[2] The calculation assumes that ethanol yield (gallons per tonne of corn) does not change over time.

capital can grow over time.[3] There are neither changes in productivity, nor labor or population growth. We also eliminate the potential for intensification in the crops sectors. In the absence of total factor productivity growth and intensification, yields on current cropland are fixed.[4] We conduct two sets of illustrative experiments. The first set compares general equilibrium (GE) demand elasticities in the beginning (2004) and end of analytical time horizon (2030) to demonstrate that demands become more elastic over time. The GE elasticity reflects adjustments in all markets and can be constructed for a commodity in a given region by shocking market price of the commodity in that region by 1% and recording the effect of the increase on the commodity output.[5] Taking coarse grains in the US as an example, the demand elasticities for this commodity in 2004 and 2030 is -0.7 and -0.9, respectively. Another example is energy intensive sector in US with elasticities -1.6 and -2.1 in the beginning and end of the analytical time horizon, respectively. These examples show that demands become more elastic over time as capital accumulates in the economy.

A second experiment with this hypothetical economy demonstrates that even in the absence of improvements in yields and diminishing stringency of the policy, net cropland requirement falls over time. In the baseline of this experiment, the quantity of ethanol is fixed at 3.41 bill gallons per year over the entire 2004 – 2030 period. In the policy scenario, the quantity of corn ethanol is increased from 3.41 to 15 billion gallons in 2005 and is fixed at this level until

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[3] Depreciation (fixed rate in this analysis) and investment determine capital stock in each period in each region. Investments are driven by disparities in rates of return to capital across regions. Over time, investors gradually reallocate capital across regions to equalize rates of return in the long run. When the hypothetical economy achieves steady state, capital does not change and investment is only sufficient to cover depreciation. See Ianchovichina and McDougall (2002) for details.

[4] Average yield, however, is not fixed due to changes in yields on extensive margin (land conversion from one crop to another and conversion of marginal lands to cropland); these cumulative 2004-2030 changes in yields are small in this experiment.

[5] In the model, under the standard closure, the market price is an endogenous variable and output tax is exogenous. To measure GE elasticity, market price is "swapped" with output tax such that the tax variable become endogenous and price become exogenous and available for shock.

2030. Thus, in this experiment, the difference between policy and baseline quantities of ethanol is the same over analytical time horizon and equal to 15-3.41 = 11.59 billion gallons. Figure 9 shows that the net additional cropland requirement per 1000 gallons of ethanol falls nonetheless. These experiments demonstrate that the general equilibrium accumulation of agents' responses becomes more elastic in the long run, with these market adjustments reducing net land conversions required for a given amount of biofuel.

4. Summary

This chapter documents a dynamic version of the GTAP-BIO model and conducts illustrative analysis of the impact of expanded production of US corn ethanol due to the US biofuel mandates. Several structural elements of the model were revised to better capture changes in derived demand for land in the medium to long run. Per capita food demand responses to changes in income in the model were calibrated to recent econometric estimates. Various intensification options in land using sectors and food processing were incorporated to reduce pressure on land resources from growing population and per capita incomes.

The impact of the ethanol mandate on land use pictured in this analysis evolves significantly over time. In particular, net global cropland brought into production due to the biofuel mandate declines over the time horizon studied here. This stands in sharp contrast to the results of static analysis where policy impacts are pictured as fixed for the next 30 years – an assumption often made to allocate the GHG emissions from land use change to the volume of biofuels produced (Searchinger et al. 2008, Hertel et al. 2010).[6] There are several forces behind

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[6] Hertel et al. (2010) attempts to overcome this "fixed" impact by conducting post simulation adjustment to reflect corn yield growth in US between 2001 and 2007.

the result. First, driven by increasing price of fossil fuels and crop yields, use of ethanol is expanding in baseline path of the global economy. Thus, baseline volumes of ethanol are rising while the mandated quantity is fixed after 2015. These factors result in falling stringency of the mandate and in diminishing over time additional quantity of ethanol the policy forces into the market. Second, net additional cropland requirement per unit of additional ethanol produced is falling. This is partly due to growing crop yields over the time horizon of the analysis in all crop sectors and regions, but also market adjustments in the long run.

Despite the fact that land use change impacts of this policy are transitory, the timing of GHG emissions is important to consider. Let us assume an extreme case when stringency of the mandate falls to zero by the end of analytical time horizon (baseline and policy ethanol volumes are the same in the end of the analytical time horizon). This would also suggest that additional global cropland brought into production by the policy is gradually falling and cumulative deviation in global cropland in policy scenario from baseline is zero. Though cumulative impact of the policy on cropland is zero, the policy, however, causes earlier conversion of forest and pasture lands to cropland than it would happen in the absence of the policy (figure 6). The earlier GHG emissions and lost carbon sequestration caused by the earlier land use changes result in GHGs to be present in the atmosphere for a longer period of time causing additional to baseline global warming effect (O’Hare et al. 2009, Kloverpris et al. 2012).

A natural next step in this analysis is to translate estimated changes in land use to GHG emissions. Ideally, one would like to measure cumulative land use change emissions due to biofuel policy as a difference between policy and baseline emissions from land use changes. Recently, Gibbs and Yui (2011) developed new geographically-explicit estimates of soil and biomass carbon stocks consistent with GTAP model region and AEZ definitions. Using this data base, Plevin et al. (2011) constructed detailed region and AEZ specific carbon fluxes by combining carbon stock estimates by Gibbs and Yui (2011) with assumptions about carbon loss from soils and biomass, mode of conversion, forgone sequestration and other assumptions. Extending this work to changes in land use modeled in dynamic settings will enable quantification of land use change GHG emissions from biofuel policies modeled with GDyn-BIO.

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Table 1 Comparison of income elasticities for food in GTAP v.7 data base and econometric study by Muhammad et al. (2011)

	USA	EU27	JAPAN	CANADA	Mala_Indo	CHIHKG	INDIA	S_S_AFR
	CGE model							
Coarse Grains and crops	0.04	0.11	0.03	0.06	0.43	0.62	0.60	0.58
Meat and dairy	0.91	0.85	0.88	0.86	0.94	0.88	1.00	0.98
Processed food	0.95	0.93	0.93	0.92	0.72	0.78	0.68	0.79
	Muhammad et al. (2011)							
Coarse Grains and crops	-0.09	0.02	0.08	0.08	0.25	0.25	0.54	0.51
Meat and dairy	0.34	0.49	0.49	0.47	0.64	0.64	0.78	0.77
Processed food	0.44	0.63	0.64	0.62	0.87	0.87	1.33	1.42

Table 2 Annual average labor productivity, population, skilled and unskilled labor, and real GDP growth rates, %

Region	Labor productivity	Population	Skilled labor	Unskilled labor	Real GDP
1	2	3	4	5	6
USA	1.1	0.99	1.61	0.15	1.61
EU27	0.9	0.39	1.50	-1.11	1.60
BRAZIL	1.5	0.93	2.99	0.58	3.05
CAN	1.1	1.04	1.34	0.45	1.83
JAPAN	1	-0.02	0.98	-1.45	0.71
CHIHKG	6 (2011-2015), 5 (2016-2030)	0.47	2.85	0.02	5.22
INDIA	5 (2011-2015), 4 (2016-2030)	1.40	4.03	1.37	4.13
C_C_Amer	1.3	1.27	3.79	1.00	2.88
S_o_Amer	1.5	1.38	3.44	0.89	3.38
E_Asia	1.5	0.49	2.38	-0.35	2.81
Mala_Indo	3	1.14	3.98	0.92	3.92
R_SE_Asia	3	0.96	3.66	0.75	3.88
R_S_Asia	3	1.66	4.75	1.88	4.19
Russia	2	-0.02	0.85	-1.04	2.16
Oth_CEE_CIS	2	0.74	1.90	-0.32	2.49
Oth_Europe	0.8	0.72	1.48	-0.58	1.89
MEAS_NAfr	3	1.86	4.07	0.70	3.65
S_S_AFR	2	2.25	5.38	2.56	4.48
Oceania	0.8	1.57	1.88	1.02	2.40

Table 3 Annual average total factor productivity growth in agriculture and forestry, %/year

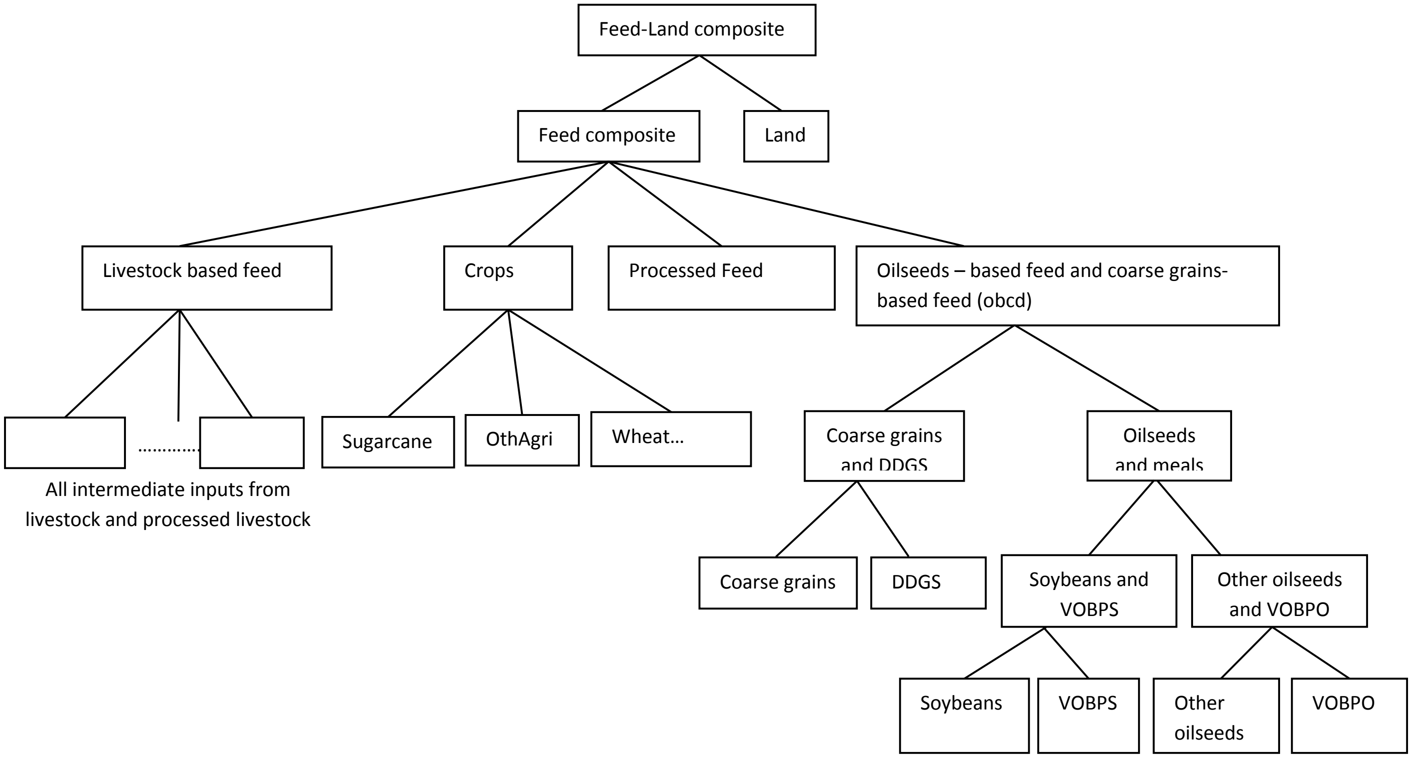
Region	Crops	Dairy Farms	Ruminant	Non Ruminant	Forestry
USA	1	0.30	0.30	0.67	0.85
EU27	1	0.30	0.30	0.67	0.86
BRAZIL	1	1.52	1.52	4.73	1.07
CAN	1	0.30	0.30	0.67	0.86
JAPAN	1	0.30	0.30	0.67	0.93
CHIHKG	1	3.27	3.27	6.90	1.14
INDIA	1	1.52	1.52	3.52	1.03
C_C_Amer	1	1.52	1.52	4.73	1.09
S_o_Amer	1	1.52	1.52	4.73	1.10
E_Asia	1	1.52	1.52	3.52	1.04
Mala_Indo	1	1.52	1.52	3.52	1.02
R_SE_Asia	1	1.52	1.52	3.52	1.02
R_S_Asia	1	1.52	1.52	3.52	1.15
Russia	1	0.54	0.54	2.13	0.84
Oth_CEE_CIS	1	0.54	0.54	2.13	0.89
Oth_Europe	1	0.30	0.30	0.67	0.70
MEAS_NAfr	1	-0.28	-0.28	-0.24	0.78
S_S_AFR	1	0.57	0.57	-0.04	0.96
Oceania	1	0.30	0.30	0.67	0.75

Note: Source for TFP growth rates in livestock is Ludena et al. (2006). 1% growth in TFP in crops is based on Fulgie (2010). TFP growth rate in forestry is weighted average of the TFP growth rates in crops and livestock.

Table 4 Coarse grains yield decomposition, 2004-2030 cumulative % change

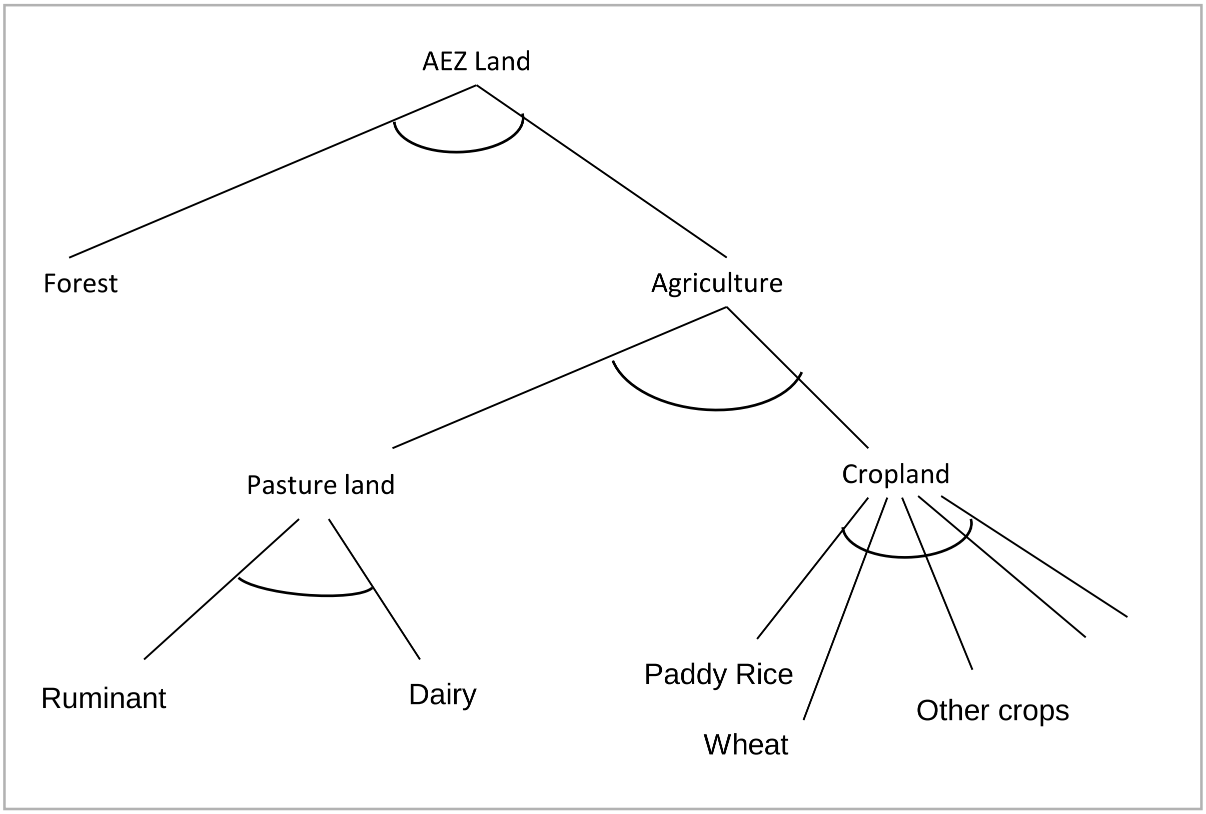
Component of yield change	USA	EU27	CHIHKG	INDIA
Driven by TFP assumption	27.2	29.5	29.5	29.5
Intensification effect	2.6	1.8	3.2	5.4
Extensification effect	-7.2	-5.8	-5.7	-0.2
Total change in yield	21.1	24.2	26.0	36.2

Figure 1 Nested structure of feed-land composite in livestock sectors



Note: Non-ruminant livestock sector does not use land. Its feed-land composite is just feed composite.

Figure 2 Land supply structure



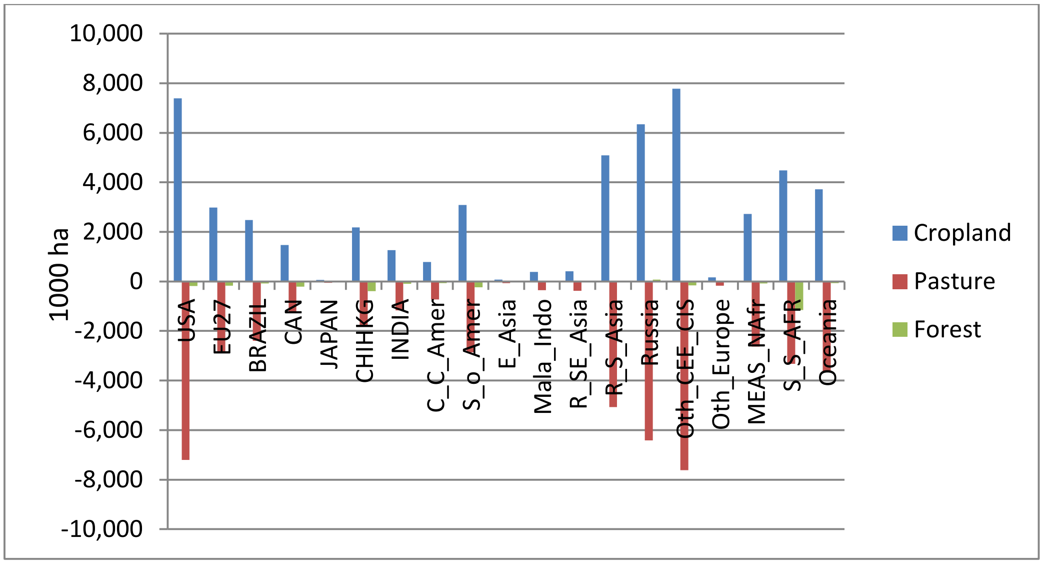


Figure 3 Regional baseline changes in land cover between 2004 and 2030, 1000 ha

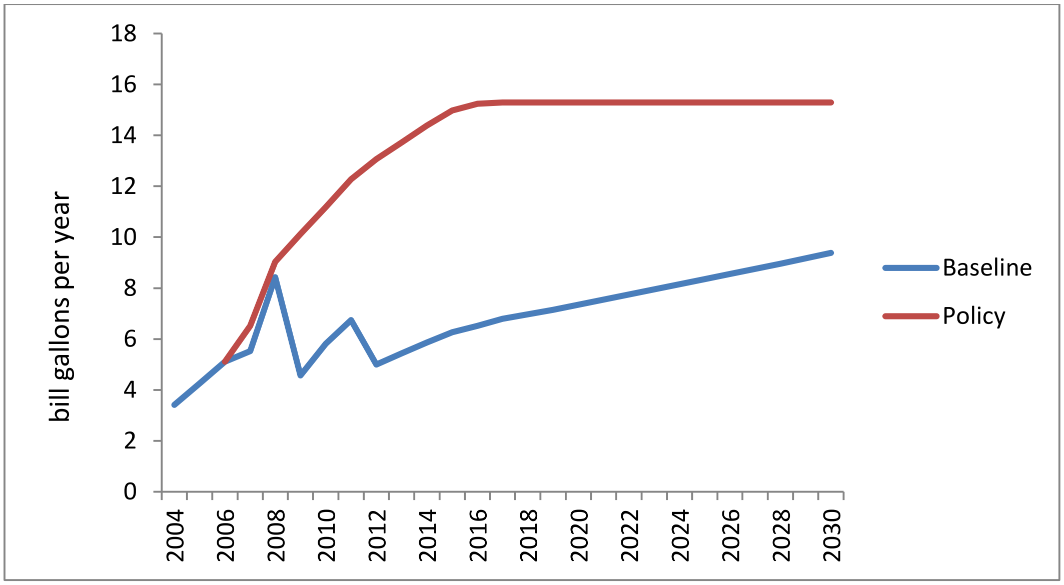


Figure 4 Mandated and baseline volumes of US ethanol, billion gallons per year

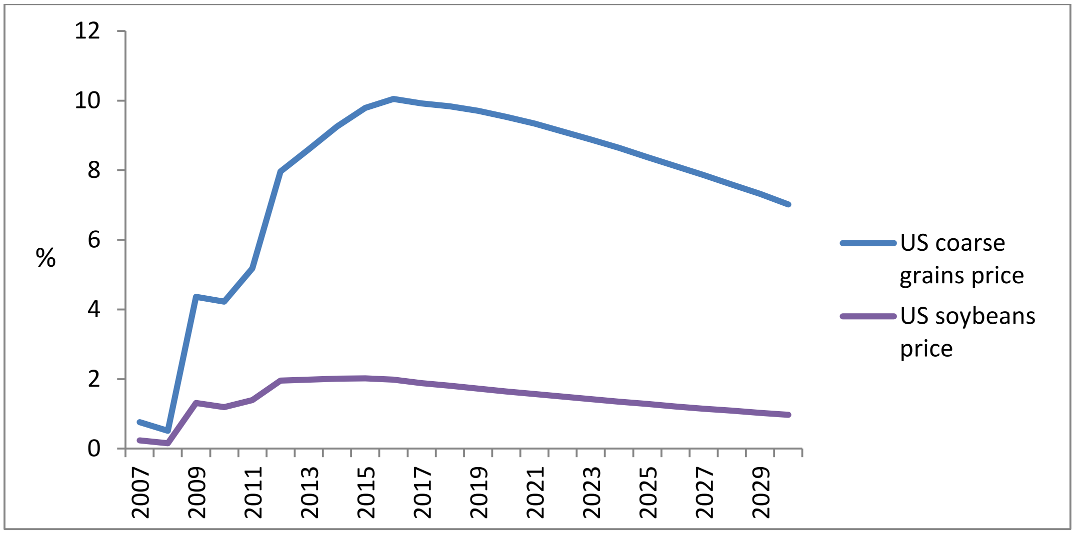


Figure 5 US coarse grains and soybeans price effects of expanded production of US ethanol, cumulative % deviation from baseline.

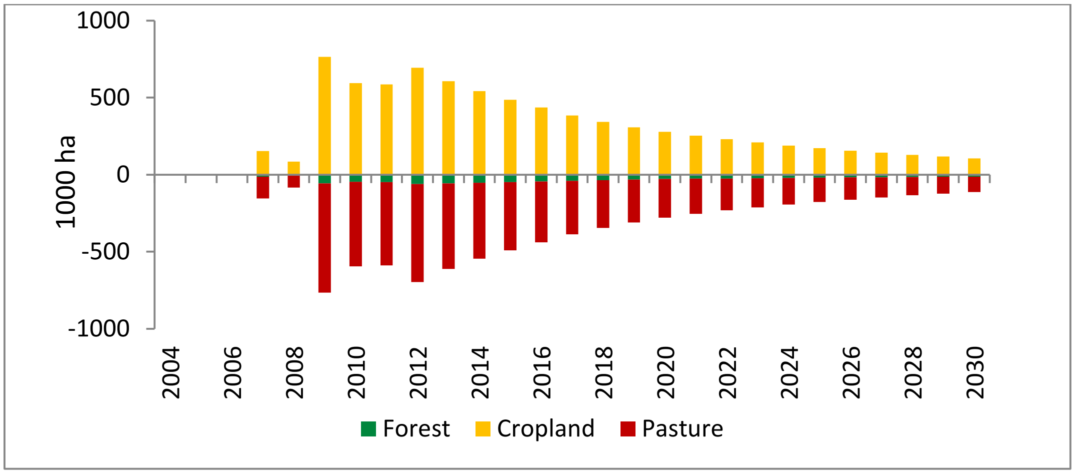


Figure 6 Global land conversion due to expanded production of US corn ethanol, 1000 ha deviation from baseline

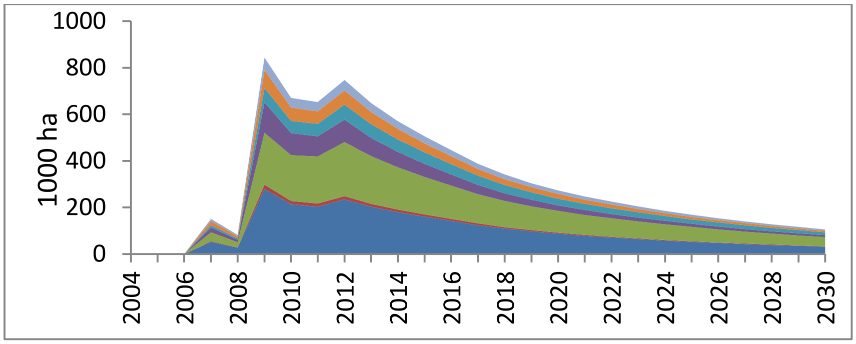


Figure 7a Regional changes in cropland due to increased production of US ethanol, 1000 ha deviation from baseline

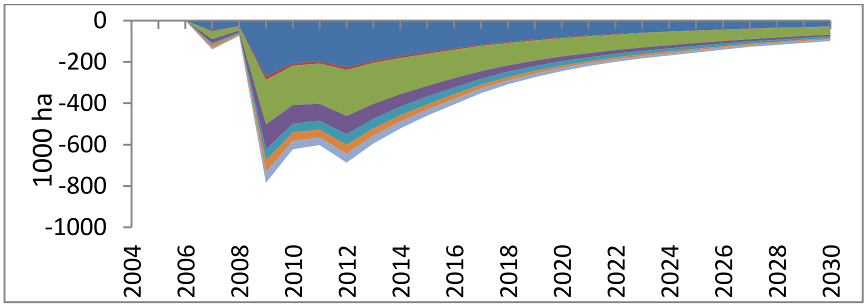


Figure 7b Regional changes in pasture due to increased production of US ethanol, 1000 ha deviation from baseline

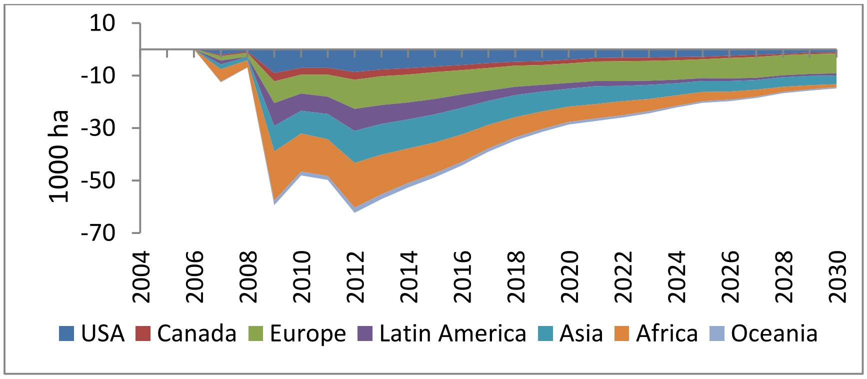


Figure 7c Regional changes in accessible forest area due to increased production of US ethanol, 1000 ha deviation from baseline

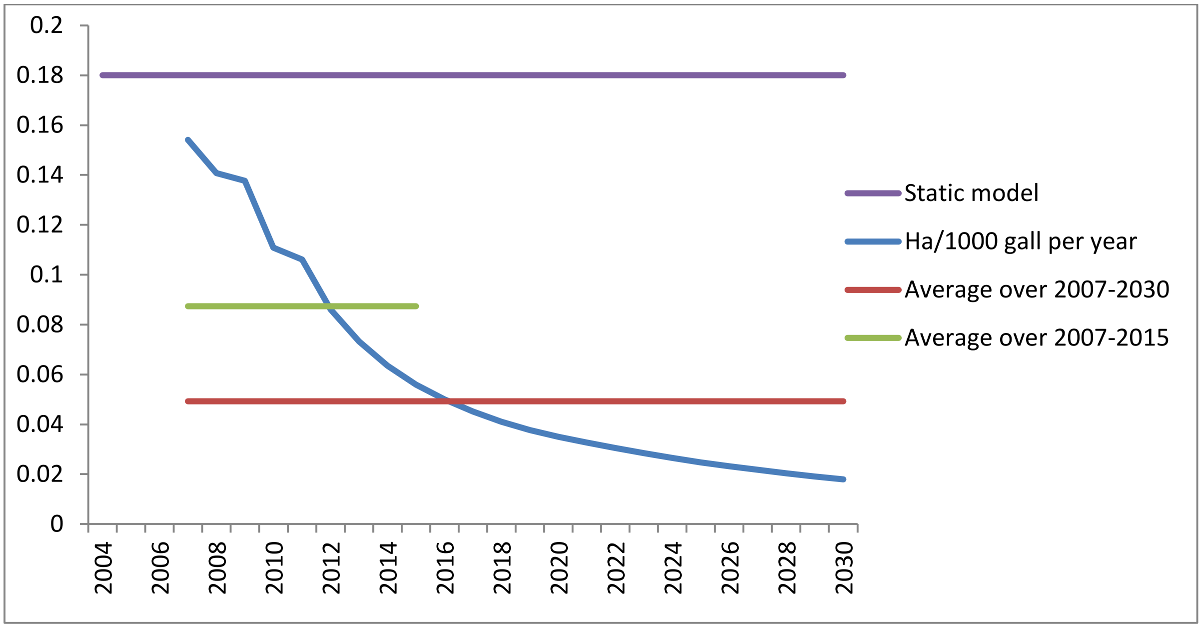


Figure 8 Global additional cropland requirement per 1000 gallons of extra US ethanol produced, ha/1000 gallons

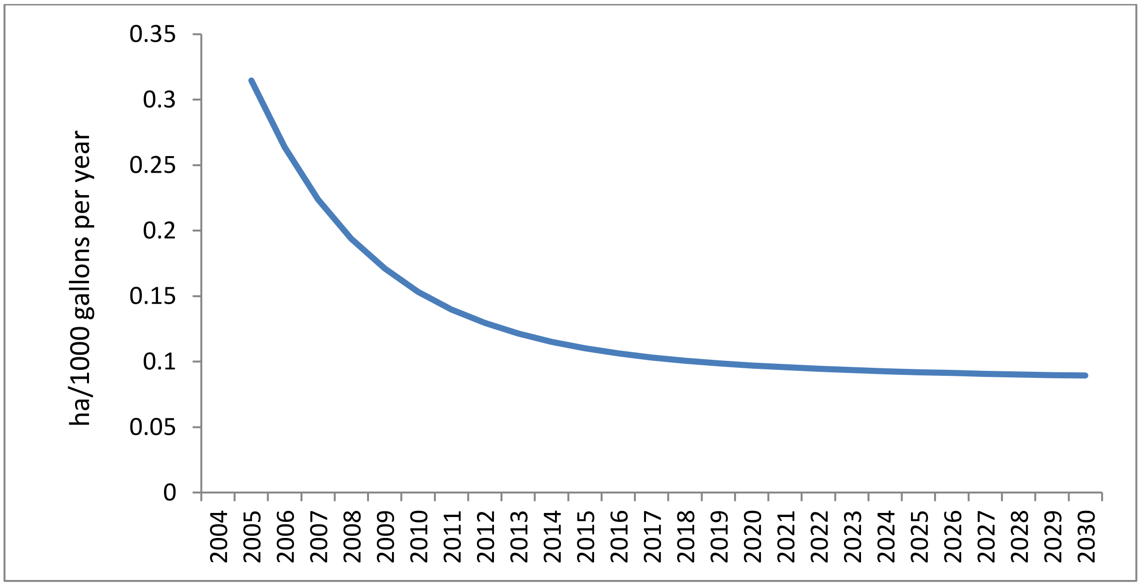


Figure 9 Global additional cropland requirement per 1000 gallons of extra US ethanol produced in the absence of total factor productivity, labor and population growth, ha/1000 gallons

Appendix A

Table A1 Aggregation of GTAP regions

Code	Region in the model	GTAP regions
USA	United States	United States
EU27	European Union 27	Austria, Belgium, Denmark, Finland, France, Germany, United Kingdom, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, Sweden, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria
BRAZIL	Brazil	Brazil
CAN	Canada	Canada
JAPAN	Japan	Japan
CHIHKG	China, Hong Kong	China, Hong Kong
INDIA	India	India
C_C_Amer	Central and Caribbean Americas	Mexico, Rest of North America, Costa Rica, Guatemala, Nicaragua, Panama, rest of North America, Rest of Central America, Caribbean
S_O_Amer	South and Other Americas	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Chile, Uruguay, Rest of South America
E_Asia	East Asia	Korea, Taiwan, Rest of East Asia
Mala_Indo	Malaysia and Indonesia	Indonesia, Malaysia
R_SE_Asia	Rest of South East Asia	Cambodia, Lao People's Democratic Republic, Myanmar, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia
R_S_Asia	Rest of South Asia	Bangladesh, Pakistan, Sri Lanka, Rest of South Asia
RUSSIA	Russia	Russian Federation
Oth_CEE_CIS	Other East Europe and Rest of Former Soviet Union	Albania, Belarus, Croatia, Ukraine, Rest of Eastern Europe , Rest of Europe, Kazakhstan, Kyrgyzstan, Turkey, Armenia, Azerbaijan, Georgia, Rest of Former Soviet Union, Rest of Europe, Rest of Eastern Europe
Oth_Europe	Rest of European Countries	Switzerland, Norway, Rest of EFTA
MEAS_NAfr	Middle East and North Africa	Iran, Egypt, Morocco, Tunisia, Rest of North Africa, Rest of Western Africa
S_S_AFR	Sub Saharan Africa	Nigeria, Senegal, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, South Africa, Rest of South African Customs
Oceania	Oceania	Australia, New Zealand, Rest of Oceania

Table A2 Aggregation of standard GTAP sectors and new biofuel-specific sectors

Code	Sector in the model	GTAP commodities
Paddy_Rice	Paddy Rice	pdr
Wheat	Wheat	wht
CrGrains	Coarse grains	gro
Soybeans	Soybeans	New commodity disaggregated from osd
Soybeans		New commodity disaggregated from osd
Sugar_Crop	Sugar cane, sugar beet	c_b
OthAgri	Other agriculture goods	v_f, pfb, ocr
Forestry	Forestry	frs
Dairy	Raw milk	rmk
Ruminant meat	Cattel, sheep, goat, horses	ctl, wol
Non Ruminant meat	Non-ruminant livestock	oap
Proc_Dairy	Processed dairy products	mil
Proc_Rum	Processed ruminant meat products	cmt
Proc_NonRum	Processed non-ruminant meat products	omt
vol	Vegetable oils and fats	vol
Bev_Sug	Beverages, tobaco, sugar	sgr, b_t
Proc_Rice	Processed Rice	pcr
Ofd	Food products n.e.c.	ofd
OthPrimSect	OtherPrimary: Fishery & Mining	fsh, omn
Coal	Coal	coa
Oil	Crude Oil	oil
Gas	Natural gas	gas, gdt
Oil_Pcts	Petroleum	p_c
Electricity	Electricity	ely
En_Int_Ind	Energy intensive Industries	i_s, nfm, fmp, crp
Other_transp	Other transport	otp
Water_transp	Water transport	wtp
Air_transp	Air transport	atp
Oth_Ind_Se	Other industries and services	tex, wap, lea, lum, ppp, nmm, mvh, otn, ele, ome, omf, cns, trd, cmn, ofi, isr, obs, ros
NTrdServices	Other services (Government), dwellings, water	osg, dwe, wtr