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A Prospective Analysis of Brazil and the U.S. Biofuel Trade

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Biofuel use has been considered globally as part of the solution to mitigate greenhouse gas (GHG) emissions and to guarantee energy security in many fossil-fuel importer countries. The U.S. and Brazil are the world's first and second largest biofuel producing countries, respectively, with Brazil as the biggest biofuel exporter. The U.S. Renewable Fuel Standard (RFS) has established a goal of 36 billion gallons (B Gal) of biofuel production in 2022, of which 21B Gal must be "advanced biofuels", defined as biofuels with at least 50% GHG emission reduction (sugarcane ethanol included) relative to fossil-fuel emissions, of which in turn, 16B Gal must be cellulosic ethanol. Sugarcane ethanol from Brazil is eligible for both the "advanced" and conventional renewable fuel categories in the U.S. However, as part of the incentive to increase national production, the U.S. government has imposed a 2.5% ad valorem tariff per Gal to the imported biofuel. Likewise, the U.S. energy policy provides a Volumetric Ethanol Excise Tax Credit (VEETC) of $0.45 per Gal for the blending of pure ethanol (regardless of the feedstock) with gasoline, charges a per unit tariff of $0.54 on imported biofuels, and makes available a tax credit of $1.01 per Gal to cellulosic ethanol producers.

On the other hand, Brazil implements a mandate for blending ethanol into gasoline at 25% ratio. Brazil consumes most of its ethanol production to fuel its passenger vehicles fleet which was converted into a flex fuel system over the last decade through government energy policies and incentives provided to car manufacturers. Due to recent shortfalls in the domestic ethanol supply, the blending rate has been reduced to 20%, ethanol market price increased and although historically Brazil has been a net biofuel exporter the country had to import now cheaper corn ethanol from the U.S.

This complex policy climate leaves the public with unclear conclusions about the prospects for biofuels; hence, several important questions are raised: If U.S. removes the current trade policies can sugarcane ethanol imported from Brazil be a more economical alternative to corn ethanol in the

U.S. to satisfy the RFS blending requirements? If all subsidies and trade policies are removed what would be the economically optimum transportation fuel mix without biofuel mandates? How would the increased demand for sugarcane ethanol affect consumers and producers welfare, land uses in Brazil and U.S., and aggregate GHG emissions?

Brazil has a vast amount of agricultural land most of which is used for beef cattle production using an extensive grazing system. It has been argued that at a reasonable investment cost it is economically feasible to convert a substantial portion of those lands into cropland and expand the current sugarcane plantation to meet the increased demand for ethanol including both the domestic and export demand. Removal of the U.S. trade policies would further intensify the conversion process. Direct and indirect land use change implications, particularly in Brazil, have become a central theme surrounding the economic analysis of bio-fuels. Yet, there is little previous research that considered the potential for transition (intensification) in the livestock production practices in Brazil and impacts of this on the growth of the bio-fuel sector and agricultural lands use. In this paper we develop a spatial, multi-market, multi-product partial equilibrium framework regionally disaggregated both for Brazil and the U.S. agricultural, livestock and biofuel sectors to facilitate the analysis of trade policy distortions in the international biofuel economy, the impact of long-run of domestic and foreign biofuels policies, as well as the resulting implications on land use change and total GHG emissions. In particular, the potential for livestock intensification of Brazilian pasture land grazing systems is considered as a prospective pathway for releasing new land and expanding sugarcane, corn, and soybean cultivation, while taking into account Brazil's role in the world beef market.

Literature Review

A fast growing literature on biofuels economics discusses the extent of land use changes and policy distortions. Hochman, Sexton, and Zilberman (2008) summarize the intuition of these policies with

an illustration of the economics underlying the domestic policies in the bio-fuel economy. They claim that the effect of a binding bio-fuels mandate functions domestically as a deficiency payment to the cereal market supplying biofuel feedstock, while internationally the world price increases due to fewer exports. Additionally, combining the mandate with a subsidy (VEETC) increases total demand for biofuel crops, with less being consumed as food domestically and a sharper decline in exports, raising world prices further. de Gorter and Just (2008) develop a general theory analyising the effect on fuel markets arising from ethanol import tariffs in the presence of bio-fuel mandates and tax credits. They find that ethanol exporters benefit mostly from the elimination of both the biofuel tax credit and the import tariff in the presence of a binding mandate, despite the result that a mandate reduces total fuel consumption.

Birur, Hertel, and Tyner (2008) employ a computable general equilibrium (CGE) framework to examine the impact on world agricultural markets from changes in the demand for biofuels in response to increases in the price of crude oil, the phasing out of MTBE (methyl tertiary butyl ether) in the U.S., and the EU and U.S. subsidies to bio-fuels. While excluding the role of trade policy distortions, the authors find that significant land use changes will occur in Brazil and in the U.S. as the demand for ethanol increases, with more pronounced growth of sugar crops in Brazil. They report that greater expansion in Brazil results in other agricultural sectors experiencing more rapid declines in land use. However, omitting trade distortions from the analysis may obscure the constricting impact of U.S. import tariffs on ethanol demand.

Elobeid and Tokgoz (2008) employ a partial equilibrium econometric model to analyze the effects of removing the distortions in the U.S. ethanol sector that arise from ethanol trade restrictions and domestic subsidies. The authors model the ethanol demand from the perspective of U.S. refiners and final consumers in Brazil to reflect the different elasticity of substitution between gasoline and ethanol in each country, and the contrast in demand behavior. Their study finds that

removing the VEETC and the import tariffs on ethanol in the U.S. reduces domestic ethanol production and increases domestic ethanol consumption accompanied with a sharp decline in domestic price. In Brazil, trade liberalization was found to increase ethanol production and net exports to the U.S.

Both Elobeid and Tokgoz (2008) and Birur, Hertel, and Tyner (2008) capture only the land use changes at an aggregate level, which does not provide much insight into the interregional allocations within the two countries. Disaggregation enhances precision and enables the model to more closely replicate the behavior of regional producers. Additionally, the role of technological change in the infrastructure of the domestic biofuel economy remains unexplored in the current literature. This paper contributes to the literature by developing a framework for analyzing the impact of policy and technological change on the biofuel economy and subsequent land use changes disaggregated at the U.S. Crop Reporting Districts (CRD) level and Brazil mesoregion level.[1]

The next three sections are devoted to describe the beef-cattle and fuel sectors, and the transportation infrastructure capacity in Brazil, which constitute central parts of the model along with the U.S. commodity markets, transportation fuels market, and the biofuel policy mandates. We also discuss another important constraint in the model, namely the Agro-Ecological Zoning for sugarcane, which legally restricts the boundaries for the sugarcane expansion in Brazil. The remaining sections discuss the results and conclusions. We present the mathematical programming model used in the analysis in Appendix 1.

Brazilian Beef-cattle producing system

[1] According to the IBGE (2011c) mesoregions are geographic units defined as "subdivisions grouping by the social process as determinant, the natural setting as conditioning, and the communication and place network as an element of space articulation"

Brazil is the largest exporter of beef and has the world's largest commercial beef cattle herd (FNP, 2008a). Given that a substantial amount of land is currently being used by the beef cattle industry, to analyze potential land use changes in Brazil and simulate the sector properly in the economic model it is necessary to understand the beef-cattle production systems.

Brazil's pasturelands cover approximately 171 million hectares, of which 91.5 million hectares are planted pastures, 57 million hectares are native pastures, 9.8 million hectares are pastures planted but degraded, and the rest is fodder for court and area planted with forest species (IBGE, 2006). Approximately 80 percent of this area is used by the beef-cattle herd (IBGE, 2006), which ranges between 137 (IBGE, 2006) and 165 million (IBGE, 2011b) heads (excluding dairy cattle). This implies a stocking rate between 1 and 1.2 heads per hectare, which could be increased by providing supplemental feed rations to the animals.

More than 40 percent of the cattle ranches raise their animals for complete cycle from weaning to fattening; whereas the remaining ranches are devoted to one or two of the weaning, post-weaning, and fattening stages. The weaning ranches sell their calves to post-weaning and fattening ranches (IBGE, 2006). For modeling purposes, we restrict ranching activities to three categories: complete cycle, weaning, and finishing (post-weaning and fattening together), which represent more than 81 percent of the beef-cattle production activities in Brazil (Martins et al. 2005).

With respect to the land use for beef-cattle production, Brazil has 97 percent of its beef-cattle grazing pasture land allocated to an extensive livestock system (IBGE, 2006), under which animals spend their life entirely in the pasture areas with minimal use of feed supplements (such as silage, corn grain, and soymeal). This lowers the annual beef cost and makes the industry competitive in the world beef market. On the other hand, only about 3 percent of the beef cattle herd is subject to some kind of intensification by either feeding the cattle during the post-weaning and fattening stages and planting improved pasture varieties (semi-intensive systems) or confinement

of the animals for 3 months during the fattening stage (feedlots or intensive systems) (FNP, 2008 and IBGE, 2006). As mentioned before, here we aim to explore alternative intensification pathways for releasing new lands to expand the cropland and sugarcane plantation. By transitioning to a more intensive system, average livestock productivity would increase, less grazing would take place, and hence less land is required. However, there are trade-offs. Besides the increased operating costs, fixed costs of conversion, and cost of feed, some additional cropland has to be allocated to feed crops production, particularly corn and soybeans, to feed the animals under a confined feedlot system. We incorporate the interactions between food, fuel and feed sectors in a simultaneous framework in our model.

Fuel sector and ethanol trade

Currently the U.S. is the world's largest ethanol producing country; in 2010, its production exceeded 13B Gal (RFA, 2011). Meanwhile, Brazil, the world's second largest producing and the first exporter country, reached a production of 6.9B Gal and exported more than 0.5B Gal, of which 0.12 was exported to the U.S. (MAPA, 2011). Sugarcane and corn are the main feedstocks in Brazil and the U.S., respectively However, in recent years, the U.S. has made considerable effort and allocated substantial amount of research funding to develop alternative technologies for commercial cellulosic ethanol production from biomass, including dedicated perennial grasses (such as switchgrass and miscanthus), crop residues (such as corn stover and wheat straw), and forest residues aiming to achieve the RFS advanced biofuel targets.

On the demand side, ethanol consumption in the two countries is driven by different factors such as availability of vehicle technology, relative prices of ethanol and gasoline, and fuel efficiency.[2] In the case of Brazil, biofuel economy is fully integrated to the fuel sector. Sugarcane ethanol

[2] Fuel efficiency refers to the energy content of ethanol and gasoline as transportation fuels, which is approximately one-third less for ethanol compared to gasoline.

maintains roughly 50% of the market share in the fuel market, and most of the conventional vehicles are designed to run with up to 25% of anhydrous ethanol blended with gasoline. Additionally, during the period 1979-2007, Brazil manufactured and sold pure hydrous ethanol vehicles, and since 2003 most of the vehicles in the market are designed for any proportion of gasoline and hydrous ethanol (flex-fuel vehicles). In U.S., according to the Energy Information Administration (2007), the ratio of biofuel in the use of petroleum-based transportation fuels was approximately 2.5%, and the flex-fuel vehicles, which can run with up to 85 percent ethanol, represent only about 4 percent of the total vehicle miles traveled.

Agro-Ecological Zoning for Sugarcane

The increase of sugarcane production during the last years has generated environmental concerns in many areas of Brazil. The Agro-ecological Zoning for Sugarcane (ZAE-CANA) production was elaborated by EMBRAPA and other state agencies and approved in 2009 (Decree 6961), aiming to control this process by defining the most suitable areas for sugarcane production considering physical (soil and climate), biological, socioeconomic and institutional-regulatory conditions (Zacamoto, 2009). As a result, the legislation restricts the sugarcane production in 81.5% of the Brazilian agricultural lands, including Amazonia, Pantanal and other sensible eco-systems. To reflect this restriction, in the model we do not allow any expansion of sugarcane on the pasture areas beyond the ZAE-CANA boundaries, and allow any amount of expansion on the pasture areas that are legal and suitable for sugarcane expansion.

Ethanol transportation infrastructure in Brazil

The current capacity of Brazil to transport and to export ethanol in Brazil is about 9.5B Gal (Tolmasquim, et al, 2008). Brazil has projected high investments in infrastructure for ethanol

production and transportation. On the transportation side, three pipelines are projected to transport ethanol from the Central-West and South-East Regions to four seaports in the states of Rio de Janeiro, Sao Paulo and Parana. If these pipelines are built, domestic transportation cost of ethanol for exports could decrease by 50% (Scandiffio, 2010). For the 2022 projections, we calculate ex-ante the minimum transportation costs to and from all mesoregions and export ports taking into account the pipelines.

The Model

In this section, we describe briefly the methodology used and overall structure of the model. A complete algebraic representation of the model is presented in the Appendix 1.

We develop a multi-market, multi-product, spatial partial equilibrium model employing the well-known social-surplus maximization approach (Takayama and Judge, 1971; McCarl and Spreen, 1980) of the international biofuel economy to solve for a market equilibrium given resource constraints, trade policy parameters, and the RFS targets. The social welfare function is represented by the sum of producers' and consumers' surpluses, where the relevant arguments correspond to the agricultural and fuel markets in the U.S., Brazil, China, and the Rest-of-the-World (ROW). We aggregate the consumer surpluses derived from consumption of agricultural commodities and vehicle-miles-traveled (VMT) in both countries. For demand functions we assume linear price-quantity relationships, which imply additive quadratic utility functions.

The total cost of producing agricultural commodities in each country is expressed as a linear function of areas planted assuming fixed production costs and yields for individual crops. On the other hand, the fuel supply component assumes a constant elasticity supply function. The model also incorporates commodity export demands, the total costs of trade including the relevant trade margins (i.e. transportation costs, trade policy, etc.). When modeling the ethanol trade between the

U.S. and Brazil we take into account the trade barriers and policies including taxes and tariffs. In the objective function we also include the domestic policies such as subsidies (tax credits on blended fuels) and fuel taxes. Additionally, revenues from co-products, such as Distiller's Dried Grains with Solubles (DDGS) produced from corn during conversion to ethanol and the value of energy produced from bagasse during ethanol production from sugarcane, are taken into account.

The supply side of the model is regionally disaggregated, at CRD level in the U.S. component and at mesoregion level in the Brazil component.

The model includes eleven major temporal crop commodities produced in the U.S., namely corn, sugarcane, sugar beets, soybeans, wheat, barley, sorghum, oats, peanuts, cotton and rice. For Brazil, we consider nine major crops, namely sugarcane, soybeans, corn, wheat, sorghum, cassava, beans, cotton and rice. We include various intra-year and inter-year crop rotation activities that are commonly practiced by farmers in each country. In the U.S., the main intra-year crop rotation is planting second soybean crop after wheat. In Brazil, second corn after soybeans or beans, and second and third beans after beans or corn are most common. The main inter-year crop rotation is soybean-corn in both countries. The land allocated to all crops and pasture uses is constrained to the total land availability in each country. The competition between crops and livestock activities in each region is modeled explicitly based on the national and world prices, costs of production, processing costs, costs of transportation, and regional yields all of which together determine the comparative advantages. Additionally, in the 2022 projections for U.S., we include advanced biofuel production from corn stover, wheat straw, and from two perennial grasses, miscanthus and switchgrass, produced on unused and marginal lands. Crop production is modeled using Leontief production functions, where land is the primary input and crop yields are the output. Land is considered as the only input whose availability is limited, while the availability of all other inputs (e.g.

fertilizers, chemicals, seed, credit, labor, machinery services) is assumed to be unlimited at constant prices.

A difficulty that is often encountered when working with programming models is that optimum solutions generated by the model may involve extreme specialization in crop production where each region allocates all the land available in that region to a few (even a single) crops, which is not realistic. This difficulty is addressed here by considering the 'crop mix' approach (McCarl, 1982; Önal and McCarl, 1991), where feasible solutions for total land allocation in a given region are restricted to be a convex combination (weighted average) of the historically observed crop patterns in that region.

In the Brazil component of the model, we include three pasture land categories: planted in good conditions, planted but degraded, and native pastures. Each type of pasture can hold any of the three beef-cattle ranches activities (i.e. complete cycle, weaning, and finishing), but we restrict semi-intensification systems only to planted pastures in good conditions. The model assumes that regional representative producers determine the optimal pasture land allocation to each activity and livestock production system based on the beef-cattle costs in the region, including the cost of planting improved seed varieties and feeding the animals. A demand for feed is generated implicitly depending on the intensification level.

The optimal output levels based on the land allocations at regional level are aggregated to determine the national supply of agricultural commodities that can be consumed either in the domestic market as food, feed or biofuel feedstock, or exported, all of which are driven by downward-sloping demand functions. Besides primary commodity demands, the model includes four processed commodities: soymeal and soy oil from soybean, sugar from sugarcane and sugar beets, and beef from cattle grazing in pasture lands in Brazil.

Data and Assumptions

We use 2007 as the base year to calibrate and validate the model. The data inputs include the base year domestic and global commodity prices and quantities demanded, historical crop mixes (areas planted to individual crops), crop yields, crop budgets (production costs), cost of processing, cost of transportation, and crop yields. We use the historical land use data from 2003 to 2009 to restrict the feasible land use allocations. We obtain these data from various sources, including NASS (2011), FAS (2011) and Chen et al. (2011) for the U.S., China, and ROW, and from IGBE (2006, 2011a), CONAB (2011), FNP (2008a and 2008b), CEPEA (2011), PECEGE (2009), Scandiffio (2010) and EMBRAPA for Brazil.

Beef production is the result of converting heads of adult live animals to animal units times the Brazilian slaughtering rate, expressed in terms of carcass weight. Base on the beef-cattle budget figures from FNP (2008a), we calculate parameters for each type of ranch (i.e. system and activity) to convert the heads of adult live animals to pasture area required in each region. As mentioned before, by transitioning to a more intensive system, average livestock productivity would increase. Based on the reports of Martins et al. (2005) and Lopes and Marques (2006), we calculate the feed rations neccesary to finish the cattle in a semi-intensive system.

The miles demand function is specified for each vehicle type (conventional, flex-fuel, and pure ethanol) using a price elasticity of miles driven, the price per mile and the total miles generated in the base year. The price is obtained by dividing the total cost of fuels consumed by the miles generated. The price and quantity data are obtained from EIA (2010). The price elasticities used in the model for the U.S., Brazil, China and the ROW were obtained from various sources, including ERS (2009), Marsh (2007), Adams et al. (2005), Carley and Fletcher (1989), Gao, Wailes, and Cramer (1995), Piggott and Wohlgenant (2002), FAPRI (2011), Fortenbery and Park (2008), Bredahl,

Meyers, and Collins (1979). Using this formulation, we calculate the price of miles for U.S. and Brazil based on information in EIA (2007, 2008, and 2010) and (FNP, 2010),

The ROW and China are included in the model to close the trade flows for ethanol and agricultural commodities in the global economy.

Policy Scenarios and Results

We design three trade and biofuel policy scenarios and use the model to analyze their implications with particular emphasis on U.S.-Brazil bilateral trade and welfare of producers and consumers.

We apply the RFS biofuel blending mandates to replicate the 2022 projected market conditions. As mentioned at the outset, the RFS goal is 36B Gal of biofuel production in 2022, of which 21B Gal must be "advanced biofuels". The latter must include 16 B Gal of cellulosic biofuels. The VEETC was set at US$0.45 per Gal of ethanol and applied towards ethanol from both domestic and international sources for domestic fuel distributors and $1.01 per Gal of cellulosic ethanol produced. The per unit import tariff on ethanol imports originating from sources other than the countries within the Caribbean Basin Initiative (CBI) is US$0.54 per Gal of ethanol. There is also an ad valorem tariff of 2.5 percent placed on all ethanol imports.

The baseline scenario reflects the 2007 policy conditions for the purposes of model validation. Since the actual ethanol consumption in 2007 exceeded the RFS mandate for that year, we do not apply a mandate in the baseline scenario. The import tariffs and subsidies remain in place. For the sake of space and given the purpose of the analysis, we only present the results for more relevant crop-commodities. Maps 1-2 illustrate land use results for sugarcane and pasture planted in good conditions in Brazil. The maps show a very small deviation in the regional distribution of cropland allocation.

[Insert Map 1 here]

[Insert Map 2 here]

Tables 1-2 summarize the market equilibrium solution in the modeled baseline. The baseline results for the land use and crop production in both countries are usually within a 10 percent margin of error (Table 1). Fuel markets deviations are also at tolerable levels (Table 2). These deviations notwithstanding, the model appears to reasonably replicate the market equilibrium in the base year, both for Brazil and the U.S., and we proceed with the scenario analysis.

[Insert Table 1 here]

[Insert Table 2 here]

In the 2022 scenarios, we shift in average every year the supply curves of ROW and demand curves upward by 1.5 percent, yields by 0.05 percent and corn yield by 0.065 percent, and China's soybean and corn demand by 5 percent. These assumptions approximately reflect the historical trends and some projections in ERS (2011). The VMT's in U.S. are set to the levels projected by EIA (2010) and Brazilian kilometers driven are assumed to increase in the same proportion.

Tables 3-5 summarize the model simulation results for the agricultural and fuel markets under the 2022 projected scenarios. The scenario in the first column refers to a business-as usual (BAU) case and it is defined as one without any biofuel policy, which for our case works as the 2022 baseline scenario. Here it is important to underscore that the U.S. ethanol demand corresponds to minimum oxygenate amount added to gasoline (3.5%).

The scenario in the second column in tables 3-5 maintains the RFS mandates, tariffs and subsidies. It shows that under the current policy, most of the domestic ethanol demand is supplied by the U.S. producers, including both corn and cellulosic ethanol, the latter is above the "advanced" ethanol mandate and represents 76% of the U.S ethanol market, whereas sugarcane ethanol imports are about 7%, which is the maximum quota of the CBI countries (Table 4). Agricultural consumers in both countries decrease net benefits with respect to BAU, as well as U.S. fuel sector. The highest

welfare gains are in the agricultural sector in both countries. GHG emissions decrease by 10% (Table 5). In general, however, there are not dramatic changes relative to BAU with the exception of the agricultural producer's surplus (Tables 3-5).

[Insert Table 3 here]

The scenario in the third column shows the results when all ethanol subsidies are removed, but barriers to imported ethanol remain. The U.S. corn ethanol production increases to 15B Gal, cellulosic ethanol binds the mandate amount (16B Gal), and imported sugarcane ethanol fills the advanced category required (Table 4). However, this policy scenario results in a large amount of corn production in Brazil and export into the world market, substituting the U.S. supplier role (Table 3). U.S. fuel sector and agricultural producers in both countries increase significantly their gains, whereas agricultural consumers face high losses (Table 5).

[Insert Table 4 here]

The fourth scenario (fourth column in tables 3-5) maintains the RFS mandates and removes all tariffs and producer subsidies applied to biofuel trade and domestic production. In this case, imported sugarcane ethanol increases its participation by filling the remaining "advanced" category and taking a significant portion of the conventional ethanol (Table 4). Thus, sugarcane area and production increases dramatically, and greater intensification take place since sugarcane areas increase and the total pasture area remains the same (Table 3). In this scenario, the agricultural producers in Brazil face the highest gains (Table 5).

[Insert Table 5 here]

Map 3 shows the sugarcane regional land allocation across all four scenarios including the projected pipelines. The most intensive sugarcane land becomes that around them, mainly in the state of Mato Grosso do Sul and in the southeast region. Map 4 shows the livestock intensification and the new crop land. In the first three scenarios intensification occurs in the states of Mato

Grosso and Mato Grosso do Sul, whereas in the last scenario, which requires significantly more sugarcane land, intensification is extended to the Southern states.

[Insert Map 3 here]

[Insert Map 4 here]

The reported results are consistent with intuition regarding the respective comparative advantages between the two countries. Implementing the U.S. biofuel policies subsequently reduces the amount of U.S. corn placed on the world market. The U.S. diverts its corn supply towards domestic ethanol production and meets the RFS upper bound for corn ethanol. This result supports the theoretical explanation made by de Gorter & Just (2008), where it was demonstrated that U.S. producer of ethanol would benefit the most from a mandate combined with a tariff and a subsidy, while leaving the mandate and removing tariffs and subsidies provides enormous benefits to fuel and agricultural producers in the ethanol exporting country (Table 5).

Furthermore, we also observe that by comparing our model baseline results with the 2022 scenarios, an increased ethanol supply and increased sugarcane production could be effectively facilitated by intensifying the livestock production systems in Brazil. We observe that transition towards a semi-intensive livestock system would release the land required to increase both corn and sugarcane production, while maintaining Brazil's share in the world beef market (Table 3).

Conclusions

Projecting the market conditions in 2022, we find that a free U.S. - Brazil trade regime would substantially reduce the domestic ethanol production in the U.S. Implementing the RFS and Brazil mandates and maintaining the current U.S. biofuel policies in the form of trade tariffs on ethanol and the tax credits reduces the aggregate consumer welfare in U.S., while increasing the aggregate

welfare of producers in the U.S. Here we find further evidence that the multi-market effects of biofuel policy are quite far-reaching.

With regards to land use, we find that under trade liberalization and removing the tax credits intensifying the current livestock systems, particularly in the central-west Brazil, particularly in the *Cerrado* region, would release a significant amount of land for corn production. Sugarcane planted area would expand in these area and the southeastern states, where soybean and corn are produced. The competition for land between these crops depends on their own demands and also on the increased demand for supplemental feed demand resulting from livestock intensification. Hence, we find that the livestock semi-intensification through feeding the animals in the finishing stage will dominate the land conversion process in Brazil rather than deforestation and savannah conversion, which ultimately implies reduced GHG emissions.

Our analysis provides insight into the multi-market dimensions of the biofuel economy, in particular, the cycle of direct and indirect land use change due to the policy climate in the U.S. and the resource base in Brazil. Through our framework, we are able to identify the key linkages between land use, GHG, agricultural commodities, and fuel. It is evident that the U.S. and Brazil biofuel policies do exert influence over global agricultural markets.

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Appendix 1

========== Algebraic representation of the Model ==========

Main sets:

BR: Brazil

ROW: Rest of the World, China

COU: U.S., Brazil, ROW, China

XCOU: COU by exports origin

DOM: U.S., Brazil

REG: 137 Mesoregions in Brazil & 295 CRD in the U.S.

VT: Vehicle Conventional, Vehicle Flex-Fuel, Pure Ethanol (Only in Brazil)

Com: Barley, Beans, Cassava, Corn, Cotton, Oats, Peanut, Rice, Soybean, Soy oil, Soymeal, Sorghum, Sugar, Wheat, Beef

Processed: Sugar, Soymeal, Soy oil, Beef.

Cellulosic: Miscanthus, Switchgrass, Corn stover, Wheat Straw

Perennials: Miscanthus, Switchgrass

Pasture: Planted Pasture, Native Pasture, Degraded Pasture

Crop: Barley, Beans, Cassava, Corn, Cotton, Oats, Peanut, Rice, Soybean, Sorghum, Sugarbeets, Sugarcane, Wheat

Act: Finishing, Complete cycle, Weaning

System: Extensive, Semi-intensive

========== OBJECTIVE FUNCTION ==========

Maximize

========== Miles Demand of Brazil and U.S. consumers ==========

$$\sum_{DOM,VT} \int_{0}^{Milesdemand_{DOM,VT}} \left(\alpha_{DOM,VT} + \beta_{DOM,VT} * MD\right) dMD$$

========== Gas Demand of China & ROW consumer ==========

$$+\int_0^{GasdemandROW}(\alpha_{GasdemandROW}+\beta_{GasdemandROW}*GD)dGD$$

========== Ethanol Demand of China & ROW consumer ==========

$$+\int_0^{ETHdemand_{ROW}}\left(\alpha_{ETHdemand_{ROW}}+\beta_{ETHdemand_{ROW}}*ED\right)dED$$

========== Gas supply of Brazil, U.S., ROW, and China ==========

$$-\sum_{COU}\int_0^{Gassupply_{COU}}\left(\alpha_{Gassupply_{COU}}+\beta_{Gassupply_{COU}}*GS\right)dGS$$

========== Ethanol production costs and subsidies in Brazil and U.S. ==========

$$-\sum_{DOM}\left(ETHcost_{DOM,FEEDSTOCK}-ETHsubsidy_{US}\right)*ETHSupply_{US}$$

$$+(CellulosicETHsubsidy_{US})\sum_{Cellulosic}ETHyield_{Cellulosic}*FEEDSTOCK_{US,Cellulosic}$$

===== Ethanol transportation costs, transp. subsidies, and import tariffs in Brazil and U.S. ====

$$-\sum_{COU}\Bigg((ETHShipCost_{COU}+ETHShipInternalcost_{COU}-ExportCredits_{COU}+Tariff_{COU}+advaloremTariff_{COU})*\sum_{XCOU}ETHExports_{XCOU,COU}\Bigg)$$

========== Coproducts revenue ==========

$$+\sum_{DOM,COM}\left(PriceCoproduct_{DOM,COM}\;CoproductFactor_{DOM,COM}\right)*FEEDSTOCK_{DOM,Com}$$

========== Agricultural Commodities demand ==========

$$+\sum_{COU,COM}\int_0^{ComDemand_{COU,COM}}\left(\alpha_{ComDemand_{COU,COM}}+\beta_{ComDemand_{COU,COM}}*CD\right)dCD$$

===== Agricultural Commodities production costs. Crop includes perennials in crops lands ====

$$-\sum_{DOM,REG,CROP}CropCost_{DOM,REG,CROP}*\left(Cropland_{DOM,REG,CROP}+NewCropland_{BR,REG,CROP}\right)$$

========== Perennial crops in marginal lands ==========

$$-\sum_{REG}CropCost_{US,REG,Perennial}*MarginalLand_{US,REG,Perennial}$$

========== Costs of converting pasture land to cropland in Brazil ==========

$$- \sum_{REG,CROP} CroplandConversionCost_{REG,CROP} * NewCropland_{BR,REG,CROP}$$

========== Processed Commodities production costs ==========

$$- \sum_{COU,PROCESSED} ProcessedComCost_{COU,PROCESSED} * ProcessedCom_{COU,PROCESSED}$$

========== Commodities supply of the ROW ==========

$$- \int_0^{CommoditiesSupplyROW} \left(\alpha_{CommoditiesSupplyROW} + \beta_{CommoditiesSupplyROW} * CS\right) dCS$$

========== Internal and external transportation costs of the exports ==========

$$- \sum_{COU,COM} \left(ComShipCost_{COU,COM} + ComShipInternalcost_{COU,COM}\right) * \sum_{XCOU} ComExports_{XCOU,COU}$$

==== Beef Cattle costs per AU in Brazil depending on the system, activity, and pasture type ====

$$- \sum_{\substack{REG,System,\\ Act,Pasture}} CostBeefCattle_{\substack{REG,System,\\ Act,Pasture}} * AUbyPastureArea_{\substack{REG,System,\\ Act,Pasture}} * PastureArea_{\substack{REG,System,\\ Act,Pasture}}$$

======= Transportation costs of calves from weaning ranches to finishing ranches ========
======= depending on the system, activity, and pasture type ==========

$$- \sum_{\substack{REG,REG',System,\\ Act,Pasture}} CostTransportCattle_{\substack{REG,REG',System,\\ Act,Pasture}} * Distance_{REG,REG'} * Calveshipped_{\substack{REG,REG',System,\\ Act,Pasture}}$$

========== CONSTRAINT SET ==========

Subject to

========== Miles demand by Vehicle type ==========

$$Milesdemand_{DOM,VT} = MPG_{DOM,VT} * \left(ETHEfficiency * ETHDemand_{DOM,VT} + GasDemand_{DOM,VT}\right) \quad \forall DOM, VT$$

========== Ethanol maximum and minimum by Vehicle type ==========

$$ETHDemand_{DOM,VT} \leq ShareETH_{VT} * (ETHDemand_{DOM,VT} + GasDemand_{DOM,VT}) \quad \forall DOM, VT$$

$$ETHDemand_{DOM,VT} \geq MinimumETH_{VT} * (ETHDemand_{DOM,VT} + GasDemand_{DOM,VT}) \quad \forall DOM, VT$$

========== Gasoline Balance ==========

$$\sum_{VT} GasDemand_{DOM,VT} \leq GasSupply_{COU} + \sum_{XCOU} GasExports_{XCOU,COU} \quad \forall COU$$

========== Ethanol Balance ==========

$$ETHDemand_{ROW} + \sum_{VT} ETHDemand_{DOM,VT} \leq ETHSupply_{DOM} + \sum_{XCOU} ETHExports_{XCOU,COU} \quad \forall COU$$

======= Ethanol Supply. Yields depend on the feedstock. ==========
======= Crops for ethanol include perennial in croplands and crop residues ==========

$$ETHSupply_{DOM} = \sum_{FEEDSTOCK} ETHyield_{FEEDSTOCK} * FEEDSTOCK_{DOM,CropsandOtherforEthanol} \quad \forall DOM$$

$$FEEDSTOCK_{DOM,CropsandOtherforEthanol} = yield_{DOM,REG,CropsforEthanol} * Cropland_{DOM,REG,CropsforEthanol} + yield_{DOM,REG,Perennial} * MarginalLand_{US,REG,Perennial} \quad \forall DOM, CropsandOtherforEthanol, Perennial$$

========== Land for crop residues restriction ==========

$$Cropland_{US,REG,CornStover} \leq Cropland_{US,REG,Corn}$$

$$Cropland_{US,REG,WheatStraw} \leq Cropland_{US,REG,Wheat}$$

========== Ethanol RFS Mandates ==========

$$\sum_{VT} ETHDemand_{US,VT} \geq RFSmandate$$

$$\sum_{Cellulosic} ETHyield_{Cellulosic} * FEEDSTOCK_{US,Cellulosic} \geq RFScellulosicmandate$$

$$ETHExports_{BR,US} + \sum_{Cellulosic} ETHyield_{Cellulosic} * FEEDSTOCK_{US,Cellulosic} \geq RFSAdvancedmandate$$

========== Agricultural Commodity Balance ==========

$$ComDemand_{COU,COM} + FEED_{BR,COM} + \sum_{XCOU} ComExports_{XCOU,COU} \leq ComSupply_{COU,COM} + \sum_{XCOU} ComExports_{COU,XCOU}$$

===== Agricultural Crop-Commodities Supply. Yield includes the processed commodities ====

$$ComSupply_{DOM,COM} = \sum_{REG} Yield_{DOM,REG,COM} * Cropland_{DOM,REG,Crop} + \sum_{REG} YieldNewLand_{BR,REG,COM} * NewCropland_{BR,REG,CROP} \quad \forall DOM, COM$$

=== Beef Supply in Brazil. Heads Cattle finished include cattle received from weaning farms. ===

$$ComSupply_{BR,BEEF} = \sum_{REG,System,Act,Past} CarcassWeight * Slaughtredrate * AUfactor * HeadsCattleFinished_{REG,System,Act,Pasture}$$

========== Cattle beef Feed requirements ==========

$$FEED_{BR,COM} = \sum_{REG,System,Act,Pasture} FEED_{COM,System,Act,Pasture'} * AUbyPastureArea_{REG,System,Act,Pasture} * PastureArea_{REG,System,Act,Pasture} \quad COM = Corn\ \&\ Soymeal$$

========== Land Use. Crop includes perennials in crops lands ==========

$$\sum_{Crop}\left(Cropland_{DOM,REG,Crop} + NewCropland_{BR,REG,Crop}\right) + \sum_{\substack{System,\\ Act,Pasture}} PastureArea_{\substack{BR,REG,System,\\ Act,Pasture}} \leq$$

$$ALLCroplandAvailable_{DOM,REG} + \sum_{Pasture} ALLPasturelandAvailable_{BR,REG,Pasture} \qquad \forall DOM, REG$$

========== Land use including Perennial crops in marginal lands in the U.S. ==========
========== Crop includes perennials in crops lands ==========

$$Cropland_{US,REG,Crop} + MarginalLand_{US,REG,Perennial} \leq$$

$$ALLCroplandAvailable_{US,REG} + AllMarginallands_{US,REG} \qquad \forall REG$$

$$Cropland_{US,REG,Perenial} \leq 0.25 * ALLCroplandAvailable_{US,REG} \qquad \forall REG$$

========== Pasture Land & Converted land in Brazil ==========

$$\sum_{\substack{System,\\ Act,Pasture}} PastureArea_{\substack{BR,REG,System,\\ Act,Pasture}} + AllConvertedland_{BR,REG} \leq \sum_{Pasture} ALLPasturelandAvailable_{BR,REG,Pasture} \qquad \forall REG$$

$$\sum_{Crop} NewCropland_{BR,REG,Crop} \leq AllConvertedland_{BR,REG} \qquad \forall REG$$

========== Agro-Ecological Zoning for Sugarcane on Pasture ==========

$$NewCropland_{BR,REG,Sugarcane} \leq ZAECanaPasture_{BR,REG} \qquad \forall REG$$

========== Historical Mixes ==========

$$Cropland_{REG,Crop} \leq \sum_{Year} \lambda_{REG,Year} * LandPlantedObserved_{REG,CROP,YEAR}$$

$$Year = 2003, \ldots, 2009 \ \forall REG, Crop$$

$$\sum_{Year} \lambda_{REG,Year} \leq 1 \qquad Year = 2003, \ldots, 2009 \ \forall REG$$

==== Cattle production. Heads Cattle finished include cattle received from weaning farms. ====

$$PastureArea_{\substack{BR,REG,System,\\ Act,Pasture}} = PastureAreabyHeads_{\substack{System,\\ Act,Pasture}} * HeadsCattleFinished_{\substack{REG,System,\\ Act,Pasture}}$$

$$\forall REG$$

========== Pasture availability ==========

$$\sum_{\substack{System,\\ Act}} PastureArea_{\substack{BR,REG,System,\\ Act,PasturePlanted}} \leq ALLPasturelandAvailable_{BR,REG,PasturePlanted}$$

$$\forall REG$$

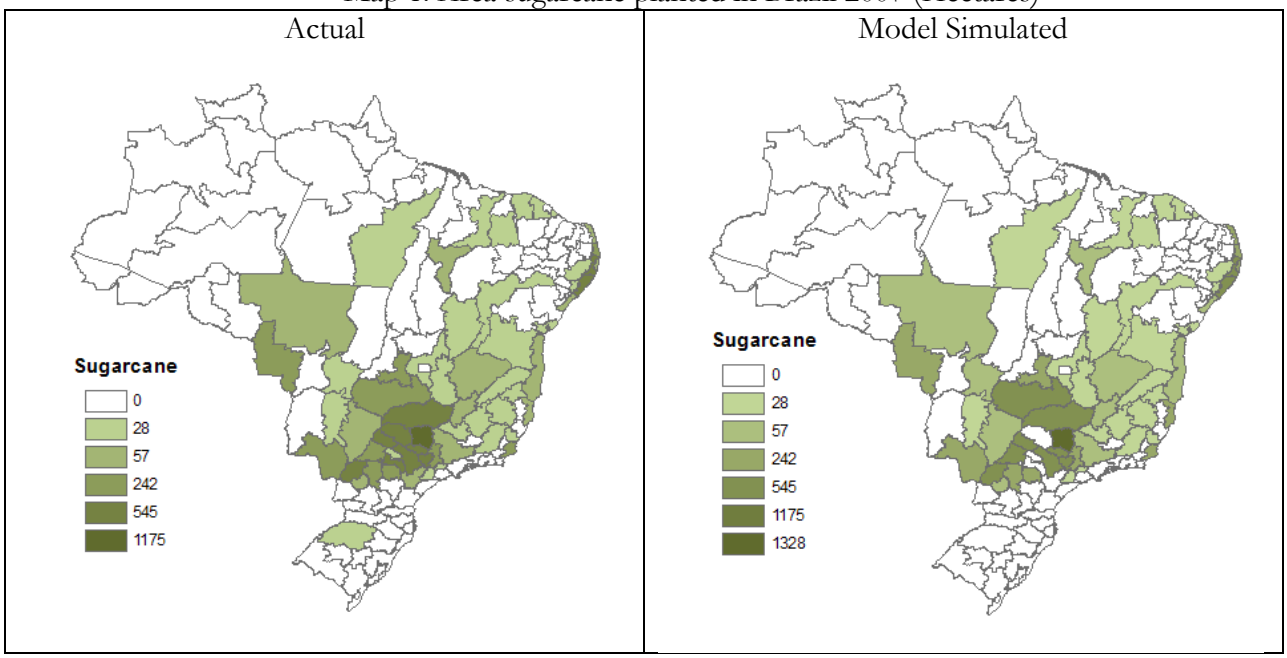
$$\sum_{\substack{System,\\ Act}} PastureArea_{\substack{BR,REG,System,\\ Act,PastureNative}} \leq ALLPasturelandAvailable_{BR,REG,PastureNative}$$

$$\forall REG$$

$$\sum_{\substack{System,\\ Act}} PastureArea_{\substack{BR,REG,System,\\ Act,PastureDegraded}} \leq ALLPasturelandAvailable_{BR,REG,PastureDegraded}$$

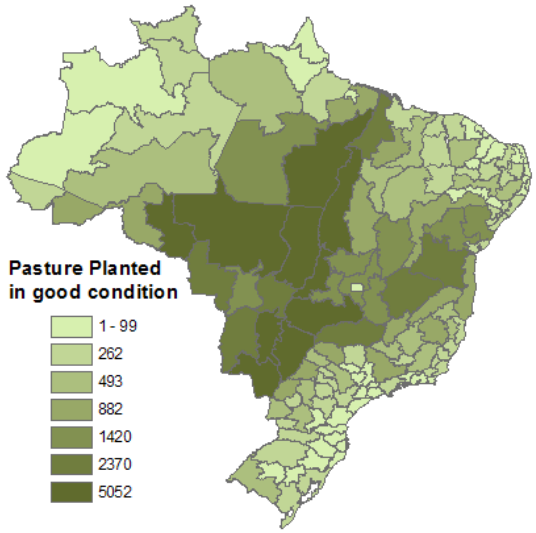
$$\forall REG$$

Map 1. Area sugarcane planted in Brazil 2007 (Hectares)

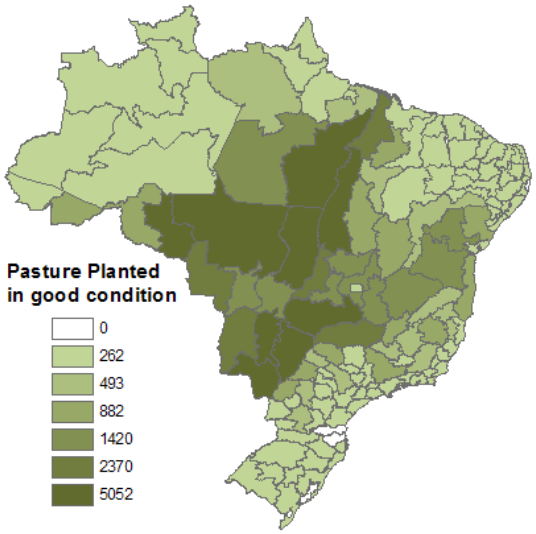


Map 2. Area pasture planted in Brazil 2007 (Hectares)

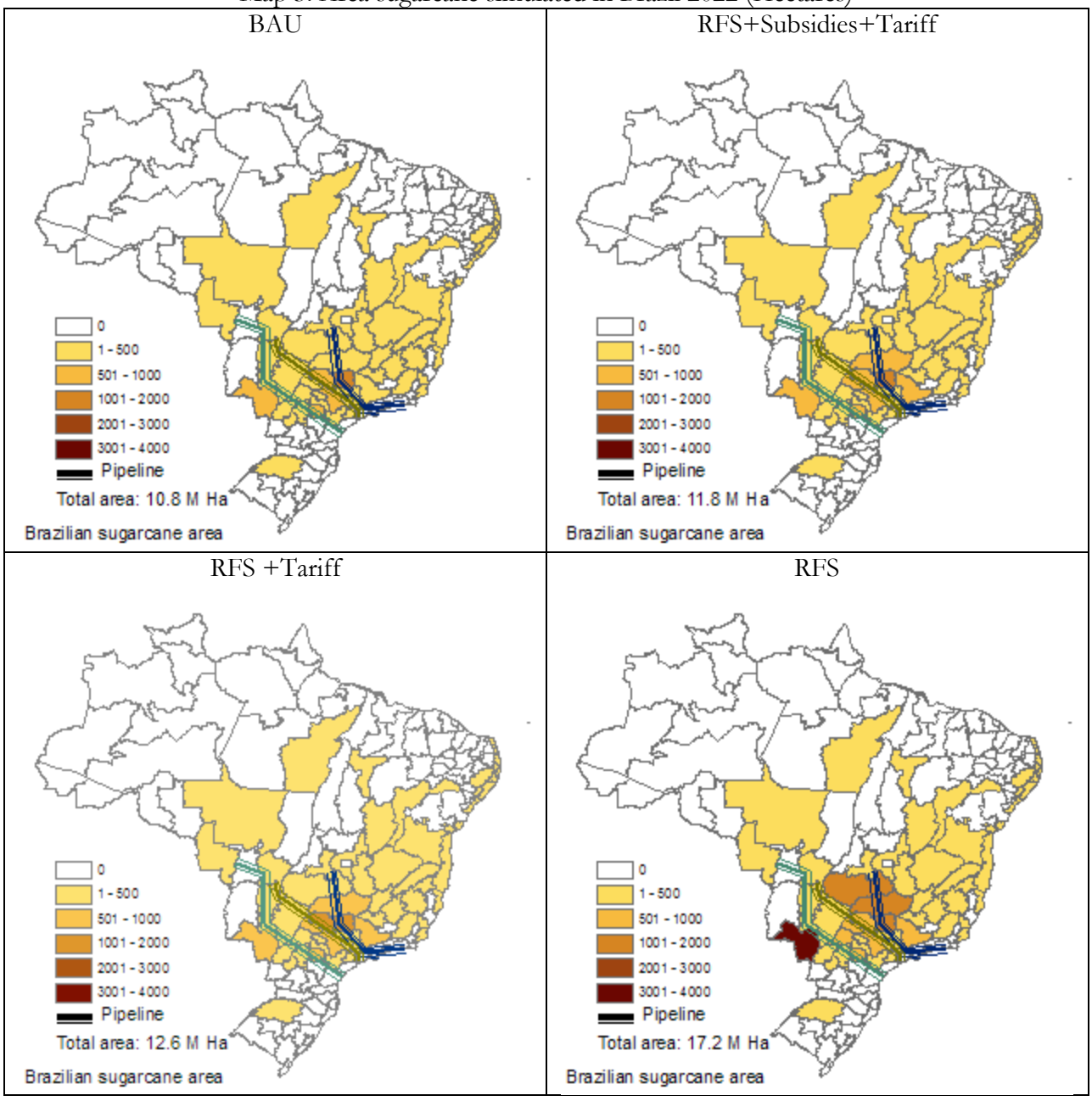
Actual



Model Simulated

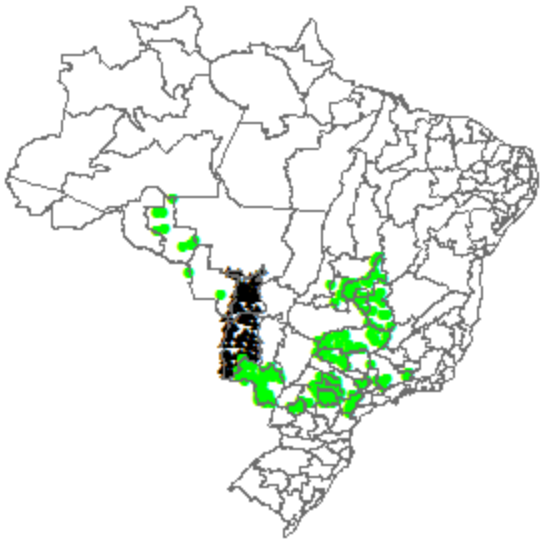


Map 3. Area sugarcane simulated in Brazil 2022 (Hectares)



Map 4. New Cropland and beef-cattle intensified pastures in Brazil 2022 (Hectares)

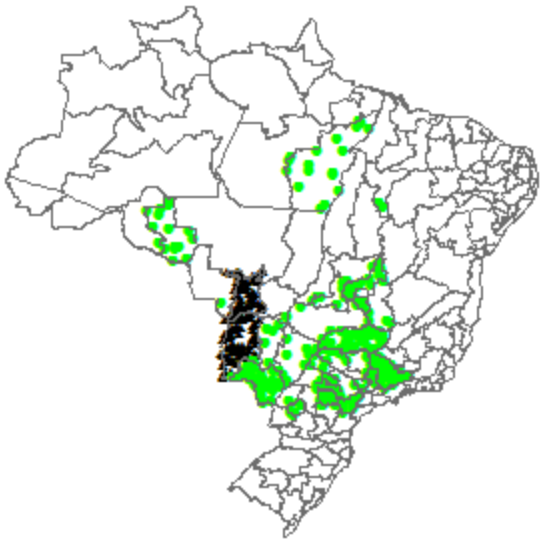
BAU



▲ Pasture intensified.

● New Cropland

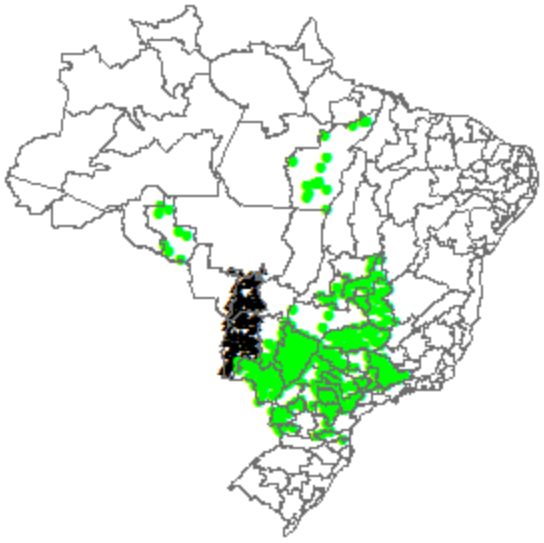
RFS+Subsidies+Tariff



▲ Pasture intensified.

● New Cropland

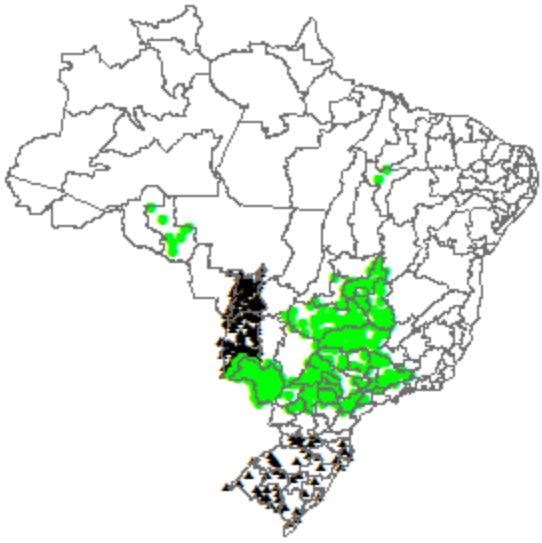
RFS +Tariff



▲ Pasture intensified.

● New Cropland

RFS



▲ Pasture intensified.

● New Cropland

Table 1. Model Validation: Agricultural Sector

			US		Brazil	
Crop	Item	Units	Year 2007	Model 2007	Year 2007	Model 2007
Corn in U.S.	Area	M Ha	37.3	36.3	13.9	12.2
	Production	M Tons	318.4	315.8	52.0	54.3
	Consumption	M Tons	185.7	182.4	40.1	41.1
	Exports	M Tons	54.2	54.6	7.8	13.2
	Ethanol Feedstock	M Tons	73.2	78.7	0.0	0.0
	Price	$/ton	165.1	173.0	150.2	197.1
Sugarcane	Area	M Ha	0.3	0.2	6.9	6.3
	Production	M Tons	25.5	18.9	543.4	511.7
	Ethanol Feedstock	M Tons			280.8	278.4
	Sugar Feedstock	M Tons	25.5	18.9	262.5	233.3
	Price Sugarcane	$/ton	266.8	245.5	282.7	237.9
Perennials	Area	M Ha	0.0	0.0		
Pastures	Area	M Ha			127.0	124.2
	Beef Production	M Tons			7.8	7.2

Table 2. Model Validation: Fuel Sector (B Gal)

	US		Brazil	
	Year 2007	Model 2007	Year 2007	Model 2007
Corn Ethanol	7.84	8.43		
Cellulosic Ethanol	0.00	0.00		
Sugarcane Ethanol			5.96	5.91
Hydrous			3.78	3.85
Anhydrous			2.18	2.06
Exports to US			0.47	0.63
Exports to ROW			0.46	0.50
Gasoline consumption	135.17	120.33	5.47	4.93
Distance driven (B Km)	4,714.06	4,220.54	353.00	358.90
Ethanol Price ($/Gal)	2.31	2.64	2.93	2.60
Gasoline Price ($/Gal)	2.74	3.97	4.74	3.91

Table 3. Simulation Results under Policy Scenarios: Agricultural Sector

			US				Brazil			
Crop	Item	Units	BAU	RFS + Tariff + Subsidies	RFS + Tariff	RFS	BAU	RFS + Tariff + Subsidies	RFS + Tariff	RFS
Corn	Area	M Ha	35.0	34.8	36.6	35.4	12.1	12.3	17.9	12.1
	Production	M Tons	335.3	335.5	350.3	339.3	57.4	58.7	104.1	57.3
	Consumption	M Tons	213.3	207.9	187.7	208.1	48.3	47.9	46.4	48.4
	Exports	M Tons	76.6	73.8	22.6	75.7	9.1	10.8	57.7	9.0
	Ethanol Feedstock	M Tons	45.4	53.7	140.1	55.6	0.0	0.0	0.0	0.0
	Price	$/ton	188.1	200.9	249.5	200.6	212.2	225.0	273.6	224.7
Sugarcane	Area	M Ha	0.3	0.3	0.3	0.3	10.8	11.8	12.6	17.2
	Production	M Tons	26.6	26.0	26.6	26.6	948.0	1040.1	1110.7	1547.3
	Ethanol Feedstock	M Tons					677.5	770.2	842.4	1279.1
	Sugar Feedstock	M Tons	26.6	26.0	26.6	26.6	270.6	269.9	268.4	268.2
	Price Sugar	$/ton	294.7	300.2	305.3	308.2	313.6	319.1	324.2	327.1
Perennials	Area	M Ha	0.0	7.6	4.7	4.8				
Pastures	Area	M Ha					120.4	118.4	112.9	114.3
	Beef Production	M Tons					7.0	6.9	6.6	6.7
	Beef Price	$/ton					10906.0	11238.3	12521.7	12137.2

Table 4. Simulation Results under Policy Scenarios: Fuel Sector (B Gal)

	US				Brazil			
	BAU	RFS + Tariff + Subsidies	RFS + Tariff	RFS	BAU	RFS + Tariff + Subsidies	RFS + Tariff	RFS
Corn Ethanol	4.87	5.75	15.00	5.95				
Cellulosic Ethanol	0.00	26.80	16.00	16.00				
Sugarcane Ethanol					14.41	16.41	17.89	26.91
Hydrous					9.88	11.87	11.81	11.79
Anhydrous					4.53	4.53	6.08	15.13
Exports to US					0.37	2.45	4.00	13.05
Exports to ROW & China					2.83	2.82	2.82	2.82
Gasoline consumption	144.28	126.67	126.67	126.67	5.10	5.12	5.14	5.14

Table 5. Simulation Results under Policy Scenarios: Distance, Price, GHG & Welfare

			US				Brazil			
		Units	BAU	RFS + Tariff + Subsidies	RFS + Tariff	RFS	BAU	RFS + Tariff + Subsidies	RFS + Tariff	RFS
Ag. Sector	Welfare	B $	258.7	279.3	278.2	270.5	306.6	311.7	319.5	332.1
	Consumers	B $	142.7	138.9	128.6	138.8	169.0	166.4	157.8	161.8
	Producers	B $	116.0	140.4	149.6	131.6	137.6	145.3	161.7	170.4
Fuel Sector	Distance driven	B Miles	3.14	3.19	3.19	3.19	0.37	0.37	0.37	0.37
	Distance price	$/Miles	0.21	0.20	0.20	0.20	0.18	0.18	0.18	0.18
	Ethanol Price	$/Gal	2.94	2.80	2.80	2.80	3.12	3.18	3.22	3.24
	Gasoline Price	$/Gal	4.41	4.22	4.22	4.22	4.69	4.78	4.84	4.86
	Welfare	B $	2,180.6	2,013.7	2,182.9	2,053.8	798.2	801.4	804.3	818.7
	Consumers	B $	1,620.9	1,607.9	1,654.2	1,650.7	726.8	725.6	724.9	724.6
	Producers	B $	559.7	405.8	528.7	403.1	71.4	75.7	79.5	94.1
	GHG	M Tons CO2-eq	1,731.1	1,540.8	1,561.3	1,539.1	106.9	111.4	125.4	130.1