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The potential for renewable fuels under greenhouse gas pricing: The case of sugarcane in Brazil

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Abstract

We develop a supply model for ethanol production in Brazil with spatially disaggregated potential yield, freight costs, and pasture land available for conversion. We show that, under the assumptions of free capital markets, constant prices, and a modest increase over the current oil-equivalent price, a non-trivial amount of future global liquid fossil fuel can be profitably displaced by Brazilian ethanol production using existing pasture land. Along with policies to encourage the intensification of existing beef production, the dominant current land use, this new production can occur without the use of additional agricultural land, assuaging concerns about indirect land use change. At the current ethanol price, which includes the subsidizing effect of the mandate, the model predicts a substantial expansion of sugarcane ethanol, indicating that real-world considerations, such as capital controls and institutional, policy, and price uncertainty, are considerable barriers to investment in this context.

Oil accounts for 33% of global greenhouse gas (GHG) emissions (International Energy Agency 2015). It is crucial to examine the scaling potential of alternative fuels as ambitious climate mitigation action is considered around the world, since the costs of possible policies, such as cap and trade programs and carbon taxes, must be evaluated. In the 1970s, Brazil established the first large-scale alternative transportation fuel sector under the Pró-Álcool program, demonstrating the commercial viability of the ethanol industry. The sector expanded aggressively in the 2000s; however, in recent years, a constellation of factors has

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contributed to slowing investment in new capacity. These include an unfavorable policy environment, particularly restrictions on the ownership of land that discourage the entry of foreign capital, energy policies that encouraged expansion of the oil sector, especially by investing in deepwater production (Azanha Ferraz Dias de Moraes and Zilberman 2014), and decreasing energy prices. Today, ethanol is mandated to be blended into domestic fuel in Brazil at a proportion of 27%, providing an implicit subsidy to producers.

Three features of the Brazilian ethanol context make it particularly attractive to consider the expansion of low-carbon fuels on a large scale. First, the Brazilian climate allows for high yields of sugarcane (both in potential and reality), which is readily convertible into ethanol using a production process that emits relatively little GHG, when compared to gasoline or US corn ethanol (State of California 2009). Brazil also has a large amount of pasture land that is appropriate for growing this sugarcane (approximately 170 Mha, compared to around 10 Mha in use today), which emits a relatively small amount of carbon dioxide when converted to sugarcane, compared with forest or savanna systems (Mello et al. 2014). Further, Brazilian pasture land is primarily used for low-intensity ranching of beef cattle, which can plausibly be intensified with low or no cost. An appropriate suite of policies that achieves sugarcane ethanol expansion into pasture land, along with matching intensification in the beef industry, can assuage concerns about indirect land-use change (Cohn et al. 2014), as would enforced restrictions on deforestation.

This paper presents an optimization model of the Brazilian sugarcane industry that is used to simulate the effects of a range of assumptions about future variables. In particular, our main research question is: assuming free markets and a constant price, what would be the quantity and net present value (NPV) of the additional ethanol that would be produced in Brazil over the next 30 years. Further, we explore the impacts on this supply function of a global GHG price (or a policy that similarly affects the price of ethanol), aggressive technology investments resulting in high yield increases, evaluating the investment decisions in the model using a “social” discount rate, and different levels of available construction resources.

We set up and solve a mixed integer linear program which allocates both new refineries and new sugarcane land over space and time to optimize total profits, depending on spatial variation in potential yield and freight cost to port and constrained by the available construction resources and pasture for conversion.

There are several novel features of this paper as a contributor to the literature on the potential for renewable fuels and agricultural land-use change. We are the first to examine the supply of sugarcane ethanol in Brazil explicitly in an optimal investment framework. We use spatially disaggregated data on potential yield, freight costs, and available pasture land. We also explicitly account for the limits to investment over time due to finite construction resources.

Our approach is in stark contrast to the majority of the literature on land-use change in that it focuses on the investment in the processing facility and the change in the use of the land simultaneously, rather than simply the land conversion stage (see Khanna, Dhungana, and Clifton-Brown (2008), for example). Consideration of the simultaneous adoption of several production technologies (i.e. a processing unit as well as feedstock units), as opposed to the adoption of an atomistic element of a supply chain, is particularly important for industries where a downstream subindustry depends on specific units of an upstream subindustry. In the case of sugarcane, the feedstock inputs are highly perishable and must be processed quickly, restricting the size of the catchment area for any given refinery. The sugarcane land would not be profitable without the nearby refinery, and vice versa. Essentially, the important industry feature is a high ratio of input to output freight costs, per-unit value. This is a feature of almost every agricultural supply chain, in addition to many mining supply chains.

In our primary results that assume recent oil-equivalent prices, our simulation model suggests that expansion of sugarcane ethanol over the coming decades would be unprofitable in Brazil. However, as we add more optimistic assumptions, the outlook improves. In our most optimistic scenario, which assumes aggressive technology investments that result in high yield increases, evaluates investment decisions using a social discount rate, uses a GHG price, and allows for a large construction capacity, we calculate that 11% of global fuel liquids will be produced by Brazilian ethanol on 1.8% of global agricultural land, yielding $2859 billion in value. We believe that these more optimistic assumptions are safely in the space of reasonable parameters.

Background

Ethanol has been both produced and consumed on a large scale in Brazil for many decades. In 2012, sugarcane for both ethanol and sugar production occurred on 9.8 Mha of land, and domestic production of ethanol amounted to 23.2Mm^3 (Brazilian Sugarcane Industry Association 2014). Lifecycle emissions of modern Brazilian sugarcane ethanol, absent land conversion, are just 13% of those associated with gasoline on an energy basis (State of California 2009). Mello et al. (2014) find that conversion from pasture to sugarcane in Brazil results in a cumulative reduction in soil organic carbon of 31.8Mg/ha over 20 years which, in our most optimistic scenario, is 5% of gasoline emissions, when averaged over 30 years of ethanol production. Estimates of emissions associated with indirect land-use change vary widely from -5 to 159 g CO_2-eq/MJ (Ahlgren and Di Lucia 2014), or -5.2% to 166% of gasoline emissions.

For a review of the numerous studies of global bioenergy potential, see Slade, Bauen, and

Gross (2014). The majority of these studies do not examine any economic incentives; they just assess the physical potential of bioenergy production. To our knowledge, one paper attempts to evaluate the global economic supply of biofuels; de Vries, van Vuuren, and Hoogwijk (2007) use the IMAGE model to estimate global bioenergy supply curves; however, the cost estimation is simple and, other than differences in yields, appears not to be spatially explicit beyond world regions (Hoogwijk 2004).

Two papers have performed more straightforward analyses of the physical potential of biofuel in Brazil in particular; Somerville et al. (2010) discuss the prospects for several biofuel crops, including Brazilian sugarcane, and Cerqueira Leite et al. (2009) ask what proportion of pasture land in Brazil would be required to displace 5% of world gasoline consumption. Both simply extrapolate existing yields to new sugarcane regions, and perform a very simple analysis.[1] Accounting for the spatial variation in potential feedstock yields is crucial. Simple extrapolation based on empirical yields is inappropriate, as optimizing farmers will choose the land most appropriate for sugarcane first, so expansion areas will likely be lower yielding than existing sugarcane land. For this reason, estimates of biomass potential that simply extrapolate using empirical yields will be biased upwards.

In the economics literature, Holland et al. (2014) employ a similar simulation model to ours in the US context. Their paper examines the costs and benefits of various fuel policies and the correlation of these costs and benefits over space with voting on a cap-and-trade bill. The underlying biofuel supply model is described in Parker (2011). Like ours, it also solves a spatially explicit optimization problem designed to calculate the supply of biofuels; however, it does not account for the limited construction industry capacity to build new refineries, making it interpretable as a "long run" supply model. A model that does not account for supply over time can adequately answer questions relating to differences in profitability across space, as in Holland et al. (2014), but is not able to answer questions relating to the scale of potential production in the near to medium term. Considering the medium term potential is especially important in the biofuel supply context as it's likely that it will never become a dominant global energy source, due to the higher energy potential per-unit land that can be extracted from solar photovoltaics (e.g. Nelson (2010)).

The paper proceeds as follows: the following section presents our high-level modeling framework, then describes our optimization model in detail. Next, we outline our full list of data sources then discuss our main results. The final section concludes.

Conceptual Framework

In this section, we describe the conceptual pieces that make up our larger simulation model. Firstly, to model the refinery investment decision, we use the standard NPV method, first formalized in Fisher (1907), where the refinery operator invests if the NPV is positive, and otherwise does not invest.[2]

To obtain indicative price changes for ethanol over time under a greenhouse price, we use a simple partial equilibrium model of the global energy market with constant elasticity demand and supply functions. The key assumptions we employ are: oil supply, ethanol supply, and energy demand are constant elasticity functions of price, oil and ethanol are perfect substitutes in the energy market, BTUs are the only valued component of either fuel, and oil BTUs are adjusted using a scalar multiplier to equate the prices of the two fuels on a per-BTU basis, before adjustments due to GHG pricing. We use the central parameter values from Holland et al. (2014). The model is fully described in the appendix.

Both price expectations and constraints on refinery construction are not explicitly modeled but are of first order importance to our results. We assume price expectations, before the effects of GHG pricing, to be constant and explore sensitivities to generate a full supply curve; in our specifications that calculate more outputs than just quantity, we assume a recently observed oil-equivalent price. The limit on refinery construction is estimated by doubling the historical maximum annual capacity installed and we explore sensitivity in several specifications by tripling this limit.

Finally, we combine these elements in an optimization model, presented in full in the following subsection. Our model is similar in spirit to the classic models of von Thünen, or Alonso (1964), Mills (1967), and Muth (1969), with a monocentric destination for output and spatial allocation of firms driven by output freight costs and spatial variability in yields. A complete model would also expressly incorporate input freight costs and economies of scale in processing; firms would locate in resource rich areas due to the trade-off between input and output freight costs, when the former are much larger than the latter per-unit value, as is the case in our context. Economies of scale would then prevent processing units from simply being so small that input freight costs are driven to zero. However, for computational tractability, we make simple restrictions to account for each of these features.

To account for input freight costs, we assume these to be fixed per unit of sugarcane and limit input land to only come from nearby areas. To account for economies of scale in processing, we assume all refineries built have the same capacity, on the order of that for recently-built large refineries.[3] The amount of input land is then chosen to match this capacity.

Optimization model

In this section, we describe our main simulation model, which we parameterize to the Brazilian sugarcane context. In this model, the unit of analysis is a municipality-year. The model chooses the number of refineries that are built in each municipality-year, and the amount of pasture, potentially from neighboring municipalities, that is purchased by each refinery operator, so that it operates at capacity.

The sugarcane cycle in Brazil is typically six years long, beginning with an initial planting that takes 12-18 months to produce a first harvest, followed by 4 subsequent annual harvests with declining productivity, finishing with a fallowing period prior to the beginning of the next cycle. To account for this behavior, we assume the investor staggers her purchases of land over six periods. At the time each production unit is built, the investor plants 1/6 of the total land that will ultimately be allocated to the refinery. This initial land purchase is first harvested in the following period.[4] The investor then continues to purchase and plant land for a total of six periods. Five periods after the initial building period, the refinery operates at its capacity of 250ML/year, the size of a typical large ethanol refinery in Brazil. In the sixth period, the land that was initially purchased is replanted and the cycle restarts. Absent yield increases, this planting pattern allows the refinery to operate at a constant rate from the period 5 years following construction to the period 30 years following construction, after which we assume the project is abandoned and the land is sold at the initial purchase price. We allow for yield increases in the model by allowing for simultaneous capacity upgrades, with costs proportional to the initial construction costs.

Refineries send all production to Paulínia in São Paulo state, currently a delivery hub for both domestic consumption and export. We restrict the analysis to the Central-West, Southeast, and South regions, as well as Bahia state, to encapsulate all high-yielding areas that have pasture land available, to keep our freight destination assumption reasonable, and to keep the model computationally tractable.

We set up the supply model as a mixed integer linear program (MILP). For each run, the problem is solved to within 1% of the best objective bound using the optimization software Gurobi.

The basic procedure is as follows:

- Calculate the net present value (NPV) of revenue, per-hectare operating costs, per-unit-ethanol operating costs, construction costs, freight costs, and upgrade costs for a refinery located in each municipality i, and built at each time t.
- Calculate the NPV of land conversion and purchase costs for a hectare located in each municipality i, and for each time t.
- Choose the (integer) number of refineries built in each municipality i and year t, and the (continuous) pasture land in municipality j that is used by refineries in each municipality i, where $j \in \text{Neighbors}(i)$. Neighbors($i$) denotes i itself, i's direct spatial neighbors, and neighbors of neighbors.

The formal model setup is as follows. The objective function is

$$OBJ: \qquad \max_{K,H} \sum_{i=1}^{N} \sum_{t=0}^{T} (NPV_{NoLand,it} k_{it} - \sum_{j \in J_i} NPV_{Land,jt} h_{ijt}), \tag{1}$$

where $k_{it} \in K$ is the integer number of new refineries built in municipality i at time t, $h_{ijt} \in H$, $j \in J_i$ is the amount of pasture (in hectares) used in municipality j by a refinery located in municipality i at time t; J_i is the set of municipalities which have pasture land available to i. $NPV_{NoLand,it}$ is the NPV per refinery in municipality i built at time t, excluding land purchase and conversion costs.[5] $NPV_{Land,jt}$ is the NPV of conversion and land costs per hectare in municipality j.[6]

There are several constraints for this problem; firstly, we must ensure that the total pasture used does not exceed some maximum allowable limit $\bar{P}$. For example, in all our scenarios, we do not allow the total pasture converted to be more than 50% of what remains in Brazil; this acts as a constraint on the total eventual expansion of ethanol. In notation, this is:

$$\text{s.t.} \qquad \sum_{i=1}^{N} \sum_{t=0}^{T} \sum_{j \in J_i} h_{ijt} \leq \bar{P}. \tag{2}$$

Next, we must ensure that the pasture land used in a municipality does not exceed the total amount in that municipality, which we denote $\bar{P}_i$:

$$\sum_{t=0}^{T} \sum_{j \in J_i} h_{jit} \leq \bar{P}_i \qquad \forall i, \tag{3}$$

where h_{jit} is the pasture used in i by a refinery in j at time t. Next, we must ensure that the sugarcane production from land, used by refineries in municipality i, built at time t, matches the sugarcane production required by these refineries in the first period in which they are fully operational.

$$\sum_{j \in J_i} h_{ijt} Y_{j,t+5} = k_{it} F \qquad \forall i, t, \tag{4}$$

$Y_{j,t+5}$ is the yield of sugarcane per hectare of pasture in municipality j at time $t + 5$ (recall that the refinery is at capacity after five years), and F is the sugarcane required for a refinery to operate at capacity. To substitute for explicit modeling of the supply curve of refinery construction, the final set of constraints limit the total number of refineries that can be built in each year. These constraints act as the main limit on the expansion of ethanol over time.

$$\sum_{i=1}^{N} k_{it} \leq K \qquad \forall t \tag{5}$$

where K is the maximum refineries built in a year.

Because yields vary across municipalities, the total hectares required for a refinery can vary depending on the configuration of land chosen by the optimization algorithm. Because we assume linear yield trends, *along with matching increases in refinery level capacity*, the change in production of a refinery over time (part of the NPV calculation) can depend on the specific allocation of land between neighboring municipalities as there can be different numbers of hectares allocated, which is chosen by the MILP. Since explicitly accounting for this interaction in the calculation of $NPV_{NoLand,it}$ would make the optimization problem nonlinear, we simplify by assuming that, when calculating $NPV_{NoLand,it}$, the production increases for a refinery in municipality i are the same as what would result from a refinery that used only land within municipality i.[7] If, in the solution, a refinery were to use a neighboring municipality's land, which was lower yielding than the land in its own municipality, this assumption would have the effect of lowering production increases over time, as the number of hectares per refinery would be lower than what is chosen in the optimization.

Data

This section describes the input data for our optimization model, along with sources. Our general aim is to incorporate all readily available information for accuracy and to be conservative when making assumptions (i.e. biased against investment in ethanol).

Yield data and calculations

The FAO-GAEZ dataset (IIASA and FAO 2012) uses agronomic modeling, based on climate, soil and terrain data, to provide global gridded datasets of potential yields for many important crops, including sugarcane. The relative spatial arrangement of the yield assumptions in our analysis is taken from these data. All scenarios presented in this paper use the yield values predicted for the 2020s using the Hadley CM3 A1F1 scenario (the SRES A1F1 scenario corresponds closely in predicted temperature increases to the RCP8.5 scenario (Rogelj, Meinshausen, and Knutti 2012)), assuming "high" input levels[8] and rain as the water supply.[9] The grid is then aggregated up to the municipality level on an area weighted basis. Figure 1 displays the FAO-GAEZ yields for the areas in our analysis.

Empirical yields for São Paulo are obtained from the Brazilian Sugarcane Industry Association (UNICA), which provides a long time series of state-level yields. We collect municipality-level planted areas for 2012 from the Brazilian Institute of Geography and Statistics (IBGE).

Potential yields derived from the FAO-GAEZ data are somewhat higher than empirical yields in the regions of Brazil with already developed sugarcane land. To correct for this, we scale down the FAO-GAEZ yields so that the planted-area-weighted, São Paulo (the most developed sugarcane area) empirical average yield matches the FAO-GAEZ average for the same region. This ensures that the yield assumptions are initially at status quo levels, and that the arrangement of yields across space reflects variation in climate, soil, and terrain.

In the empirical data, only the average of rain-fed and irrigated yields is reported, whereas the FAO-GAEZ data separates these. We back out separate empirical estimates by assuming that the empirical ratio is equal to the ratio between the irrigated and rain-fed yields in the FAO-GAEZ dataset. That is, we solve the following equations for $\bar{y}_R$ and $\bar{y}_I$:

$$\begin{aligned} \bar{y} &= \rho_I \bar{y}_I + (1 - \rho_I)\bar{y}_R \\ \frac{\bar{y}_R}{\bar{y}_I} &= \frac{\bar{y}_{R-GAEZ}}{\bar{y}_{I-GAEZ}}, \end{aligned}$$

where $\bar{y}$ is the empirical planted-area weighted sugarcane yield, taken from the UNICA data, $\rho_I = 0.39$ is the proportion of sugarcane land irrigated,[10] $\bar{y}_R$ is the empirical planted-area weighted sugarcane yield for rain-fed plots, $\bar{y}_I$ is the empirical planted-area weighted sugarcane yield for irrigated plots, $\bar{y}_{R-GAEZ}$ is the planted-area weighted FAO-GAEZ predicted potential yield for rain-fed plots, and $\bar{y}_{I-GAEZ}$ is the planted-area weighted FAO-GAEZ predicted potential yield for irrigated plots. The two unknowns in the above are $\bar{y}_R$ and $\bar{y}_I$ and all yield averages here are for São Paulo. Municipality level planted areas, used for aggregating the GAEZ data up to the the state level, are taken from the IBGE data.

Next, we scale the municipality level FAO-GAEZ yields for all municipalities to get our period 0 yield assumptions:

$$y_{iR0,Final} = \frac{\bar{y}^{SP}_{R0}}{\bar{y}^{SP}_{R-GAEZ}} * y_{iR,GAEZ}$$

where i indexes municipalities, $\bar{y}^{SP}_{R0}$ denotes the empirical yield in SP in 2014.

Finally, in order to incorporate expected yield increases, we estimate the yield trend with ordinary least squares (OLS) for São Paulo, using the UNICA data, and predict for all years in our analysis (2014–2068 in the reference run; $\bar{y}_{R0}^{SP}$ above is calculated in this prediction.).[11] Because São Paulo is the Brazilian state with the best developed sugarcane industry, these figures represent a reasonable point prediction of ongoing yield increases given normal to good production practices.

$$y_{iRt,Final} = y_{iR0,Final} + 0.3243t$$

In an alternative scenario, we also assume high yield increases that could eventuate from more aggressive investment in yield improving technology, which we assume to be annual increases of 2 Mg/ha. Near the end of our study period, some areas' assumed yields would then be close to recent experimental maxima reported in Waclawovsky et al. (2010). [12]

Land Prices

Because Brazilian land price survey data is proprietary, we simply use a recent academic paper which reports averages for 2002, 2006, and 2010 (Richards, Walker, and Arima 2014). Because the values have trended slightly downwards in real terms, instead of extending the trend, we conservatively assume pasture prices average to the most recent value, 2014R$1514/ha. We then assume land prices can be expressed as a linear function of the period 0 rain fed yield as calculated in the previous subsection. Because land prices comprise a small fraction of total costs in our model, the qualitative results are insensitive to reasonable adjustments to these assumptions. Importantly, the land prices we use were originally derived from sales data, which is indicative of land values conditional on the land being sold. If sold land is systematically higher or lower value than average, our land price assumptions may be biased. However, as aforementioned, because land prices comprise such a small fraction of total costs, this bias would have to be large in order to materially affect our results.

In addition to the land purchase price, we obtain land conversion costs from Bonomi et al. (2012). These costs cover roads construction, terraces construction, agricultural area systematization, and roads maintenance. Again, these costs are small in comparison to total costs, so results are insensitive to reasonable adjustments to this input.

Refinery construction, upgrade costs, and construction industry capacity

Refinery construction costs are estimated using data obtained from the Bloomberg New Energy Finance (BNEF) database. This database includes construction costs of several ethanol refineries built in Brazil. We simplify our model by assuming each refinery has a capacity of 250ML/year. We estimate the cost of each of these plants by regressing cost in 2014$R against capacity and a trend line, and predicting for 250ML/year and 2014[13]. Refineries included in this estimation are those that are ethanol-only, located in Brazil, and use sugar crops as the feedstock.

Upgrade costs are assumed to be equal to construction costs on a per-unit-of-capacity basis.

The same dataset is used to obtain a reasonable assumption of how many refineries might be able to be constructed during any year. We assume that the industry is able to construct twice the capacity that was built in the highest construction year, which was 4548ML. We observe a total of 3735.6ML nameplate capacity for 23 refineries built in 2009 in the BNEF data, of 28 total (Barros 2014). We estimate total new capacity in 2009 using the product of the total capacity observed in the BNEF data and the ratio of total refineries built to the number observed in the BNEF data.[14]

Operating Costs

Typical annual operating costs are obtained from both PECEGE (2012) and Bonomi et al. (2012). In the model, we collapse these costs into a per hectare component, which does not increase with yields, a per-unit of sugarcane component, and a per-unit of ethanol component.

The per hectare component covers all expenses after land conversion costs and before transportation costs from the field to the refinery, not including rent. These include costs related to planting, fertilizer, and harvesting. The number is obtained by taking total operating expenses less land rent and sugarcane transportation, for refinery operated sugarcane operations in the expansion region, from PECEGE (2012).[15]

The per-unit of sugarcane component accounts for the cost of sugarcane transport from field to refinery per tonne cane from Bonomi et al. (2012).

The per-unit of ethanol component captures all refinery processing and maintenance costs. It is calculated as the total cost less feedstock cost, depreciation, cost of capital, working capital.

In all specifications, we keep these operating costs constant in real terms.

Ethanol Freight Costs

For simplicity, we assume all ethanol freight goes to Paulínia, SP, the delivery destination for the BM&F Bovespa ethanol futures contract, and the location of a major hub delivery location in Brazil.

Empirical intercity ethanol freight costs per m^3 are obtained from ESALQ-LOG (2013). Because the municipalities we allow in our analysis are far more numerous than those observed in the empirical data, we use a simple predictive model for freight costs, based on distance by road. The Google Maps API is used to obtain roading distances between all origin-destination pairs in ESALQ-LOG (2013). We then estimate the following predictive relationship using OLS:[16]

$$F_{ij} = \alpha + \beta_1 D_{ij} + \beta_2 D_{ij}^2 \tag{6}$$

Finally, we use the Google Maps API to obtain the roading distance to Paulínia, SP for all municipalities and predict the freight costs using (6).

Pasture Location Data

A shapefile containing pasture data is obtained from IBGE (2013). This file contains the locations of pasture farms in Brazil as of 2012. We calculate the pasture land available in each municipality by spatially aggregating this shapefile up to the municipality level and computing the total area.

Output Prices

In our results, we calculate supply curves over many assumed output prices. For comparison to status quo prices, we collect output prices for ethanol from BM&F Bovespa (2015). We use a recently collected futures prices for hydrous ethanol delivered in São Paulo (delivery October, 2016, collected October 25, 2016).[17].

Because ethanol has traded at a premium over oil on an energy basis, we also compare our supply curves to an oil-equivalent price. The ethanol BTU premium/discount is due to a number of factors, including oil refining costs, the value of ethanol as an oxygenate/octane enhancer, the lower energy density of ethanol (meaning transport and storage costs are higher for ethanol), short run market conditions, and relative policy support for ethanol versus gasoline. As of October 25, 2016, the ethanol premium, adjusted only for the lower energy density of ethanol, is 209%. After accounting for refining costs, calculated using the United States Energy Information Administation's (EIA) decomposition of the gasoline price for September, 2016, the premium becomes 123%. When accounting for a further USD$0.25/gallon value to account for ethanol's value as an oxygenate (as suggested in Hurt, Tyner, and Doering (2006)), ethanol has an implied premium of 98%. When we explore model outputs in addition to quantity, we assume an oil-equivalent price, that accounts for ethanol's lower energy density, oil's need to be refined, and ethanol's value as an oxygenate.

To generate indicative price changes that may result from a global greenhouse price, we simulate a simple global oil and ethanol market with GHG pricing, discussed further in the appendix. Oil prices for this exercise (and for calculating the above oil-equivalent price) are collected from CME Group (2015), and we use all available futures prices that do not appear stale.[18]

Greenhouse Gases

In the aforementioned oil and ethanol market exercise, we use the values for the social cost of carbon (SCC) emitted in different years, as calculated by the Interagency Working Group on Social Cost of Carbon of the United States Government (**us˙epa˙social˙2013**), to calculate a total social value of the GHG emissions of oil and ethanol respectively.[19] We use the values reported using a 3% discount rate and linearly interpolate between years.

The lifecycle GHG emissions of sugarcane ethanol are obtained from California's Low Carbon Fuel Standard (LCFS) documentation. We make use of the estimate that does not take account of indirect land-use emissions. The LCFS implicitly assumes that carbon fluxes directly arising from changes in land-use are zero, so we also account for changes in soil organic carbon due to the permanent conversion of land from pasture to sugarcane using Mello et al. (2014).

We obtain lifecycle GHG emissions of conventional oil from Chavez-Rodriguez and Nebra (2010).

Results

We present results for six scenarios. The first is the "Reference" scenario, where we assume free and efficient land markets, constant prices, and otherwise make assumptions that reflect the status quo.[20] Second, we present a "GHG price" scenario that features an increasing profile of global GHG prices over time (or equivalent domestic policy), resulting in immediately higher and further increasing ethanol prices over time. Third, we show a "Social discount rate" scenario where we assume a 3% real discount rate, versus the reference 6.08%,[21] which some argue is more appropriate than financial investment rates when evaluating the impacts of government policies. Fourth, in our "High yield increase" scenario, we assume aggressive investments in sugarcane technology that produce an annual yield increase of 2 Mg, versus the reference 0.32 Mg. Fifth, our "High construction capacity" scenario substantially relaxes the constraint on building by allowing 108 refineries to be built per year, versus the reference 36.[22] Finally, in our "All" scenario, we assume all the changes in the "GHG price", "Social discount rate", "High yield increase", and "High construction capacity" scenarios.

Profitability over space

In this section, we present maps that show how the profitability of refineries changes over space, using the "GHG price" scenario.[23] The price we use, before adjustments due to GHG pricing, is a recent BRL-denominated oil-equivalent price, which is the oil price adjusted downward to remove the premium ethanol receives per-unit-energy and adjusted upward to account for both oil refining costs (Energy Information Administration 2014) and the value of ethanol as an oxygenate (Hurt, Tyner, and Doering 2006). The mapped output variable is the NPV per refinery in each municipality, built in period 0, assuming only pasture land from within that municipality is used. Using the notation from the Optimization model section, this is $NPV_{NoLand,i0} - NPV_{Land,i0}h_{ii}$, where h_{ii} is the amount of pasture land in i required, at time 0, to operate a refinery in i at full capacity. Figure 3 maps this quantity for each municipality, left censoring at the negative of construction cost, as this excludes areas where operating profit is negative.

Comparing this to Figures 1 and 2, which, respectively, show the variation in yields and freight rates over space, one can see that the differences in profitability over space are closely related to these two input variables. The yield variation generates differences in both land prices and the cost of sugarcane production across space, as we assume this is a fixed per-hectare value. However, because land prices are such a small proportion of total cost, the primary source of spatial variation in profitability, due to yield differences, is the cost of feedstock. To demonstrate this, Figure 4 removes the land price component from the model; clearly, the main pattern of spatial heterogeneity is preserved, when compared with Figure 3.

Figure 5 displays the effect of removing ethanol freight costs from the model. The map shows that many areas in the western and southern parts of Brazil become profitable, showing that transportation costs are an important determinant of the spatial heterogeneity in profitability. However, the variation in profitability due to differences in sugarcane costs is still larger.[24]

Supply Curves

Figure 6 displays the calculated supply curves for each of our six scenarios. The quantity variable plotted is the total production of ethanol in Brazil after 30 model-years. In each plot, we include a recent observation of the Brazilian ethanol price and the aforementioned oil-equivalent price.

First, we can see that in the "Reference" scenario, the model predicts no expansion of the ethanol sector in Brazil under the subsidy-free price. We also see that the model predicts such large production growth that the refinery building constraint binds for *all years* at the current ethanol price. This price increase is reasonably large (98%); however, only an 18% increase is required for the model to predict enough expansion to meet the construction capacity constraint for all periods. The modest slope is mostly driven by the small variation in yields and freight costs over the space that's initially invested in (i.e. near Paulínia), and the low pasture land prices we see in Brazil. As aforementioned, because our cost model includes a substantial per-hectare cost component, the largest contributor to the spatial variation in profitability is differences in yields.

In the "GHG price" scenario, we plot the ethanol price *before* adjustments due to GHG pricing on the vertical axis. Recall that the GHG price, and thus the ethanol price, is increasing over time in these scenarios. The ethanol price faced by the refineries in these scenarios is substantially higher than in the "Reference" scenario, resulting in investment taking place at much lower initial ethanol prices. Here, the supply curve shifts down and becomes less elastic.[25]

Assuming aggressive investments in technology that result in high yield increases generates both a supply curve that is somewhat less elastic, and extends to much higher quantities of total ethanol production when the building constraint binds, as each refinery eventually upgrades by a larger amount, when compared to the previous scenarios.

Upweighting more distant cash flows by utilizing a social discount rate likewise shifts the curve down. However, the relative importance of this variable, when compared to GHG pricing, is small.

The importance of the refinery building constraint is highlighted in the "High construction capacity" scenario. While not substantially changing the supply curve in the region of total production where the limits on refinery construction do not bind for all periods, relaxing this constraint considerably increases the total potential production.

In our "All" scenario, which combines the adjustments from all of the previous four scenarios, we see a combination of the shifting down and extending the supply curve. What is striking here is the scale of production implied at today's oil-equivalent price. The model suggests that Brazil can eventually economically produce levels of sugarcane ethanol energy at a similar level of that which Saudi Arabia and Russia produce in oil energy today.

Because we find such small slopes on the supply curves, the construction capacity constraint binds at many different reasonable prices, even in the scenarios that partially relax this. An improvement to this modeling exercise would be to directly model the construction supply curve to reflect increasing scarcity of human and physical capital inputs into this process. While beyond the scope of the current project, this improvement is an important avenue for future research that would move further towards a complete characterization of the supply function for ethanol.

Various model outputs

For each scenario, Table 1 presents each of total NPV, investment cost (excluding land purchases), and the amount of pasture converted, again using the oil-equivalent price. Before the discussion, note well that the analysis in our model abstracts from both taxation and the increases in land prices that would likely result from the prospect of large investment in the sugarcane industry. As such, the NPV numbers should be interpreted as the amounts to be shared between refinery/sugarcane investors, government revenue, and current land owners.

In our “Reference” and “High construction capacity” scenarios, the model finds that no new refineries are profitable. Using a social discount rate or assuming fast-growing yields increases the profitability somewhat, so that the model predicts aggregate NPVs of $4.4 and $18 billion for these scenarios respectively. These both represent substantial expansions over current production.

Introducing a GHG price greatly increases the profitability of sugarcane ethanol to yield a model-predicted NPV of $272 billion. Production, in this scenario, is limited by the refinery construction constraint.

However, the most interesting result from this table is that the combination of all the optimistic deviations from the “Reference” scenario results in investments totaling almost $3 trillion in present value. This massive increase in profitability, when compared with the “GHG price” scenario, arises from the combination of several complementary effects. First, much more production occurs due to a tripling of the allowed number of refineries built in the model. Next, large increases in both production and profit per-unit arise due to high yield-growth; the latter occurring as we have a large per-hectare cost component. Lastly, future cash flows are up-weighted when using the social discount rate. Table 2 decomposes the NPV by scenario into several categories, allowing the reader to further explore how the components change by scenario.

Table 3 presents two measures of aggregate production predicted by the model in each of the scenarios; these are total production in 30 years, both expressed as a level and as a percentage of world liquids production in 30 years, and the proportion of land employed in sugarcane in Brazil.

In the "Reference" and "High construction capacity" scenarios, no new production occurs so we report only existing production, which we assume will continue as is. In the "Social discount rate" scenario, many areas become profitable and investments are made to increase production to almost 1% of world liquids production.

When we assume high yield increases, many more areas become profitable and, because those areas are also more productive, total production increases to around 3% of global liquids production. This is a scale of production similar to that of a top 10 oil producing country today. The "GHG price" scenario, where the refinery construction constraint binds, yields a similar level of production on a larger amount of land.

Again, it is the optimistic scenario that contains the most striking result here. When allowing for highly profitable production through a GHG price, a large amount of construction resources, and high yield increases, we calculate that Brazil would produce more liquids energy than the USA does today. When adding Brazil's current oil production, this would make it the largest liquids producer globally.

Limitations

Our model predicts large levels of investment *today*, at current ethanol prices. There are several real-world barriers to investment that can account for this disconnect from the relatively low levels of sugarcane ethanol investment we have observed empirically in recent years.

Firstly, due the mandate, the current ethanol price includes an observed premium over oil, even when adjusting for refining costs and ethanol's value as an oxygenate. So, the current ethanol price does not reflect the prevailing energy price. However, the implicit subsidy in Brazil is highly unlikely to be reduced substantially in the near term, so real-world price expectations should likely be formed with this premium for several years to come.

Capital controls and general uncertainty over the stability of institutions in Brazil can partially account for low investment. These capital controls basically manifest in restrictions on the amount of land that can be controlled (including leasing) by foreign interests. However, our discussions with local experts indicate that no such restrictions exist on contracts with local farmers, so presumably the development of this institutional arrangement, in this context, could be a path forward for would-be investors. However, it is also plausible that long term production contracts with local landholders could be viewed by the government as a form of leasing. The magnitude of the effect of general institutional instability cannot be known, but it surely non-zero.

We do not model yield variability, which could reduce capacity utilization below what it is in the model. We do not model any land market frictions, essentially assuming eminent domain. Uncertainty over sugarcane production in the refinery catchment area would reduce investment.

Our model makes the simplifying assumption that real ethanol prices will remain the same over the investment period. As ethanol production expands, obviously demand will also have to increase in order to keep prices constant. While this is simply an assumed scenario, it is important for the reader to keep in mind the type of world this imagines. For example, a scenario in which ethanol blending and E85 are progressively adopted globally would be consistent with our more optimistic results, as we project up to 11% of global energy liquids supply will come from Brazilian biofuel.

We know of no study that examines the effect of price volatility on investment in ethanol refineries specifically, through the mechanism of utilizing the option value of investment delay (Dixit and Pindyck 1994). Kellogg (2014) uses data on Texas drilling operations to indicate the effect of uncertainty on investment in an empirical context. Extending Kellogg's result to the full certainty case indicates that uncertainty can account for approximately a 25% reduction in investment rates, in that circumstance. However, the effect of uncertainty in any given context is highly dependent on the level of profitability of the investment, so a parametrization for the Brazilian ethanol context would be required to better get a sense of how large the magnitude of this effect is.[26] This would be a fruitful avenue for future research.

We also do not directly model the supply curve for refinery construction, choosing to make the simplifying assumption that the number of refineries built is limited to 36 per year in most scenarios and 108 in the "Low Building Constraint" and "All" scenarios. There are several reasons why direct modeling of the refinery construction supply curve is difficult in our context. Firstly, an increasing construction cost curve would make our optimization model nonlinear, increasing an already large computational burden. Secondly, even simple empirical estimation of this supply curve is limited by the few observations of ethanol refineries constructed in Brazil. Thirdly, careful modeling of the refinery construction process is outside the scope of this paper. Doing so would be another avenue for future research.

Another potentially important omission is any modeling of the sugar market. However, because our paper is primarily focused on scenarios in which sugarcane production for ethanol is vastly expanded, the relative importance of the sugar market will be much diminished.

There are also several limitations of our model that may bias us against investment in ethanol. Of first order concern is the relative future cost reductions in ethanol vs other transportation fuels. For example, plant growth technologies, such as CRISPR (Doudna and Charpentier 2014), could potentially vastly reduce the cost of producing sugarcane, and decrease conversion costs if sugar density increases. Cost reductions in second generation biofuels could similarly vastly improve the profitability of ethanol. Of course, these cost reductions have to out pace reductions in the costs of production of other fuels in order to bias our results against investment in ethanol.

We also do not account for revenue associated with the sale of electricity from burning bagasse at refineries. Additionally, restricting refinery size to be fixed removes a dimension of optimization, also biasing the model against ethanol investment. We also do not allow for any second generation ethanol production, so in the event that this technology becomes economic, our model would underestimate refinery values.

Conclusion

This paper develops a supply model for ethanol production with a view to demonstrating the economic potential of biofuel in Brazil under a variety of future scenarios. We show that, with free capital markets, constant prices, and a GHG price, a non-trivial amount of future global liquid fossil fuel can be profitably displaced by ethanol production using existing pasture land. Because the GHG price increases profitability by so much, our model predicts that incorporating high yield increases and a large capacity for constructing refineries would increase production further so that 11% of global liquids production would come from Brazilian ethanol, using 1.8% of global agricultural land.

References

Ahlgren, S., and L. Di Lucia. 2014. “Indirect Land Use Changes of Biofuel Production – a Review of Modelling Efforts and Policy Developments in the European Union.” *Biotechnology for Biofuels* 7:35.

Alonso, W. 1964. *Location and Land Use.* Cambridge, MA: Harvard University Press.

Azanha Ferraz Dias de Moraes, M., and D. Zilberman. 2014. *Production of Ethanol from Sugarcane in Brazil.* Cham: Springer International Publishing.

Barros, S. 2014. *Brazil Biofuels Annual,* GAIN Report BR14004. Washington DC: USDA.

BM&F Bovespa. 2015. “Settlement Prices.” Accessed January 9, 2015. http://www2.bmf.com.br/pages/portal/bmfbovespa/boletim2/Ajustes2.asp.

Bonomi, A., A. P. Mariano, C. D. Farias de Jesus, and H. C. J. Franco. 2012. *Technological Assessment Program (PAT) The Virtual Sugarcane Biorefinery (VSB) 2011 Report.* Technical Report. Campinas, Brazil: Brazilian Bioethanol Science and Technology Laboratory (CTBE).

Brazilian Institute for Geography and Statistics. 2013. *Technical Manual on Land Use [Portuguese: Manual Técnico de Uso Da Terra].* Rio de Janeiro: Brazilian Institute for Geography and Statistics.

Brazilian Securities, Commodities and Futures Exchange. 2014. “Settlement Prices.” Accessed January 5, 2015. http://www2.bmf.com.br/pages/portal/bmfbovespa/boletim2/Ajustes2.asp.

Brazilian Sugarcane Industry Association. 2014. “Unicadata.” Accessed October 8, 2014. http://www.unicadata.com.br/.

Cerqueira Leite, R. C. de, M. R. L. Verde Leal, L. A. Barbosa Cortez, W. M. Griffin, and M. I. Gaya Scandiffio. 2009. “Can Brazil Replace 5% of the 2025 Gasoline World Demand with Ethanol?” *Energy* 34 (5): 655–661.

Chavez-Rodriguez, M. F., and S. A. Nebra. 2010. “Assessing GHG Emissions, Ecological Footprint, and Water Linkage for Different Fuels.” *Environmental Science & Technology* 44 (24): 9252–9257.

CME Group. 2015. “Brent Crude Oil Futures Quotes.” Accessed January 6, 2015. `http://www.cmegroup.com/trading/energy/crude-oil/brent-crude-oil.html`.

Cohn, A. S., A. Mosnier, P. Havlík, H. Valin, M. Herrero, E. Schmid, M. O’Hare, and M. Obersteiner. 2014. “Cattle Ranching Intensification in Brazil Can Reduce Global Greenhouse Gas Emissions by Sparing Land from Deforestation.” *Proceedings of the National Academy of Sciences* 111 (20): 7236–7241. eprint: `24778243`.

De Vries, B. J. M., D. P. van Vuuren, and M. M. Hoogwijk. 2007. “Renewable Energy Sources: Their Global Potential for the First-Half of the 21st Century at a Global Level: An Integrated Approach.” *Energy Policy* 35 (4): 2590–2610.

Dixit, A. K., and R. S. Pindyck. 1994. *Investment under Uncertainty.* Princeton University Press. eprint: `j.ctt7sncv`.

Doudna, J. A., and E. Charpentier. 2014. “Genome Editing. The New Frontier of Genome Engineering with CRISPR-Cas9.” *Science* 346 (6213): 1258096. eprint: `25430774`.

Energy Information Administration. 2014. *Annual Energy Outlook 2014.* Energy Information Administration.

ESALQ-LOG. 2013. *Sifreca: Sistema de Informações de Fretes.* Yearbook. Piracicaba, São Paulo: ESALQ-LOG.

Fisher, I. 1907. *The Rate of Interest: Its Nature, Determination, and Relation to Economic Phenomena.* New York: The MacMillan Company.

Holland, S. P., J. E. Hughes, and C. R. Knittel. 2009. “Greenhouse Gas Reductions under Low Carbon Fuel Standards?” *American Economic Journal: Economic Policy* 1 (1): 106–46.

Holland, S. P., J. E. Hughes, C. R. Knittel, and N. C. Parker. 2014. “Some Inconvenient Truths about Climate Change Policy: The Distributional Impacts of Transportation Policies.” *Review of Economics and Statistics* 97, no. 5 (March 21): 1052–1069.

Hoogwijk, M. M. 2004. “On the Global and Regional Potential of Renewable Energy Sources.” Ph.D Dissertation, Utrecht University.

Hurt, C., W. Tyner, and O. Doering. 2006. *Economics of Ethanol,* Purdue Extension Working Papers ID-339. Lafayette: Purdue University.

IIASA and FAO. 2012. *Global Agro-Ecological Zones (GAEZ v3.0).* Laxenburg, Austria and Rome, Italy: IIASA/FAO.

International Energy Administration. 2015. “Oil Market Report.” Accessed January 6, 2015. `https://www.iea.org/oilmarketreport/omrpublic/`.

International Energy Agency. 2015. *CO2 Emissions From Fuel Combustion.* Paris: International Energy Agency.

Kellogg, R. 2014. “The Effect of Uncertainty on Investment: Evidence from Texas Oil Drilling.” *The American Economic Review* 104 (6): 1698–1734.

Khanna, M., B. Dhungana, and J. Clifton-Brown. 2008. “Costs of Producing Miscanthus and Switchgrass for Bioenergy in Illinois.” *Biomass and Bioenergy* 32, no. 6 (June): 482–493.

Mello, F. F. C., C. E. P. Cerri, C. A. Davies, N. M. Holbrook, K. Paustian, S. M. F. Maia, M. V. Galdos, M. Bernoux, and C. C. Cerri. 2014. "Payback Time for Soil Carbon and Sugar-Cane Ethanol." *Nature Climate Change* 4, no. 7 (July): 605–609.

Mills, E. S. 1967. "An Aggregative Model of Resource Allocation in a Metropolitan Area." *The American Economic Review* 57 (2): 197–210. eprint: `1821621`.

Muth, R. F. 1969. *Cities and Housing.* Chicago: University of Chicago Press.

Nelson, G. C. 2010. "Are Biofuels the Best Use of Sunlight?" In *Handbook of Bioenergy Economics and Policy,* edited by M. Khanna, J. Scheffran, and D. Zilberman, 15–25. Natural Resource Management and Policy 33. Springer New York.

Parker, N. C. 2011. "Modeling Future Biofuel Supply Chains Using Spatially Explicit Infrastructure Optimization." Ph.D., University of California, Davis.

Programa de Educação Continuada em Economia e Gestão de Empresas. 2012. *Production Costs of Sugarcane, Sugar, and Ethanol in Brazil: 2011/2012 Season Report - South-Central [Portuguese: Custos de Produção de Cana-de-Açúcar, Açúcar E Etanol No Brasil: Acompanhamento Da Safra 2011/2012 - Centro-Sul].* São Paulo: University of São Paulo.

Renewable Fuels Association. 2014. "Annual Industry Outlook." Accessed January 7, 2015. `http://www.ethanolrfa.org/pages/annual-industry-outlook`.

Richards, P. D., R. T. Walker, and E. Y. Arima. 2014. "Spatially Complex Land Change: The Indirect Effect of Brazil's Agricultural Sector on Land Use in Amazonia." *Global Environmental Change* 29 (November): 1–9.

Rogelj, J., M. Meinshausen, and R. Knutti. 2012. "Global Warming under Old and New Scenarios Using IPCC Climate Sensitivity Range Estimates." *Nature Climate Change* 2 (4): 248–253.

Slade, R., A. Bauen, and R. Gross. 2014. "Global Bioenergy Resources." *Nature Climate Change* 4 (2): 99–105.

Somerville, C., H. Youngs, C. Taylor, S. C. Davis, and S. P. Long. 2010. "Feedstocks for Lignocellulosic Biofuels." *Science* 329 (5993): 790–792. eprint: `20705851`.

State of California. 2009. *Low Carbon Fuel Standard,* April 28.

Waclawovsky, A. J., P. M. Sato, C. G. Lembke, P. H. Moore, and G. M. Souza. 2010. "Sugarcane for Bioenergy Production: An Assessment of Yield and Regulation of Sucrose Content." *Plant Biotechnology Journal* 8 (3): 263–276.

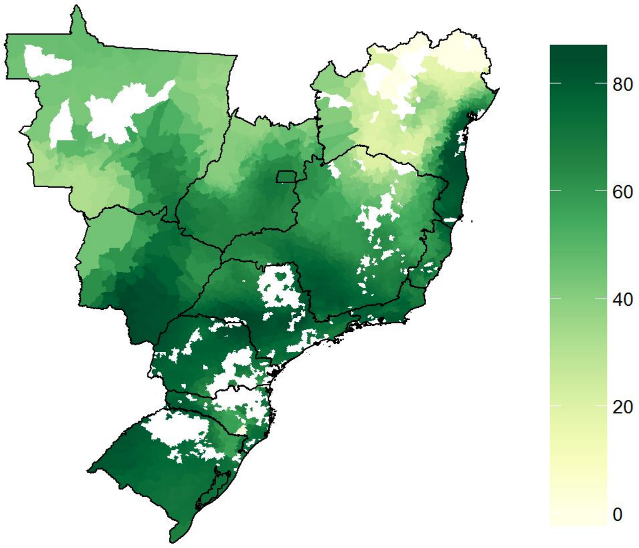

Figure 1: Municipality-level potential yield predictions

Note: Obtained from IIASA and FAO (2012). Results displayed for the Central-West, Southeast, and South regions, as well as Bahia state. Predictions are for the 2020s using the Hadley CM3 A1F1 scenario, and rain fed systems. Omitted municipalities have either zero potential yield or zero pasture land available.

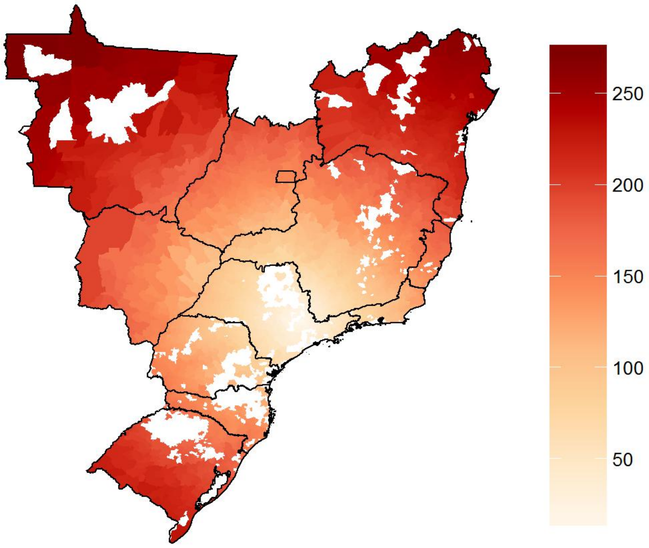

Figure 2: Model predicted freight rates per m^3 of ethanol

Note: Raw data obtained from ESALQ-LOG (2013). Unobserved routes are extrapolated using a quadratic predictive relationship between freight rates and roading distances.

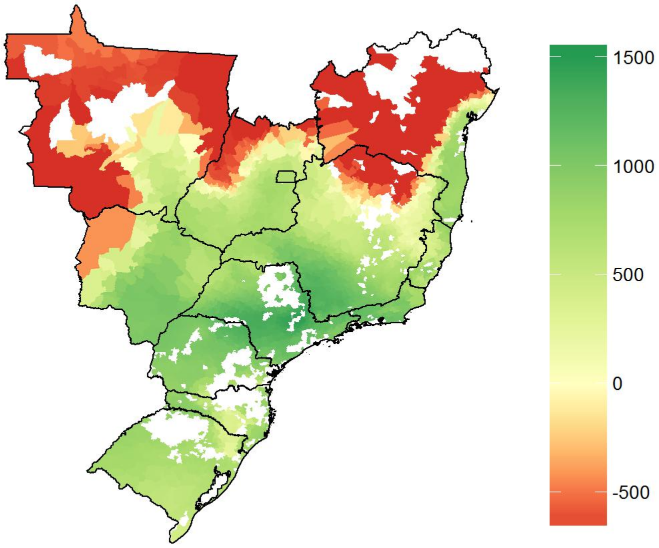

Figure 3: NPV per refinery in the "GHG price" scenario

Note: Values are for refineries constructed at time 0 and are censored at the negative of the refinery construction cost.

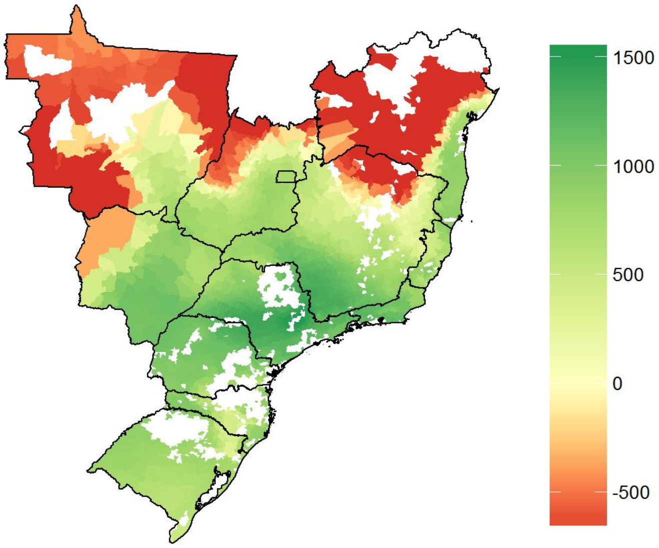

Figure 4: NPV per refinery in the "GHG price" scenario with free land purchase/conversion

Note: Values are for refineries constructed at time 0, are censored at the negative of the refinery construction cost, and assume land conversion and purchase costs are 0.

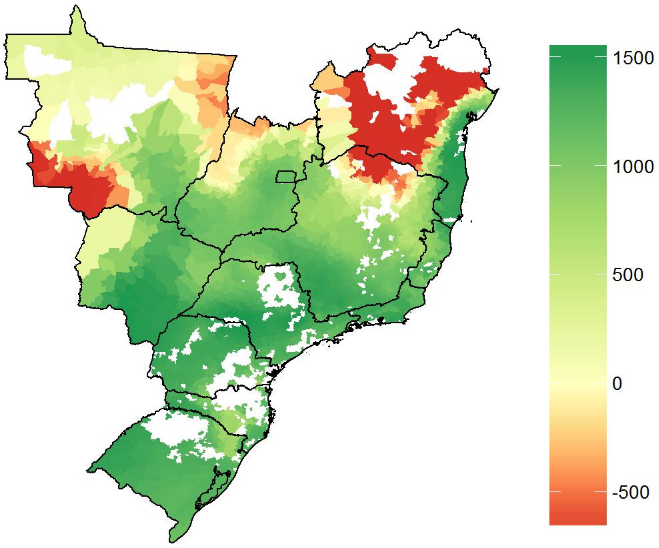

Figure 5: NPV per refinery in the "GHG price" scenario with free freight

Note: Values are for refineries constructed at time 0, are censored at the negative of the refinery construction cost, and assume freight costs are 0.

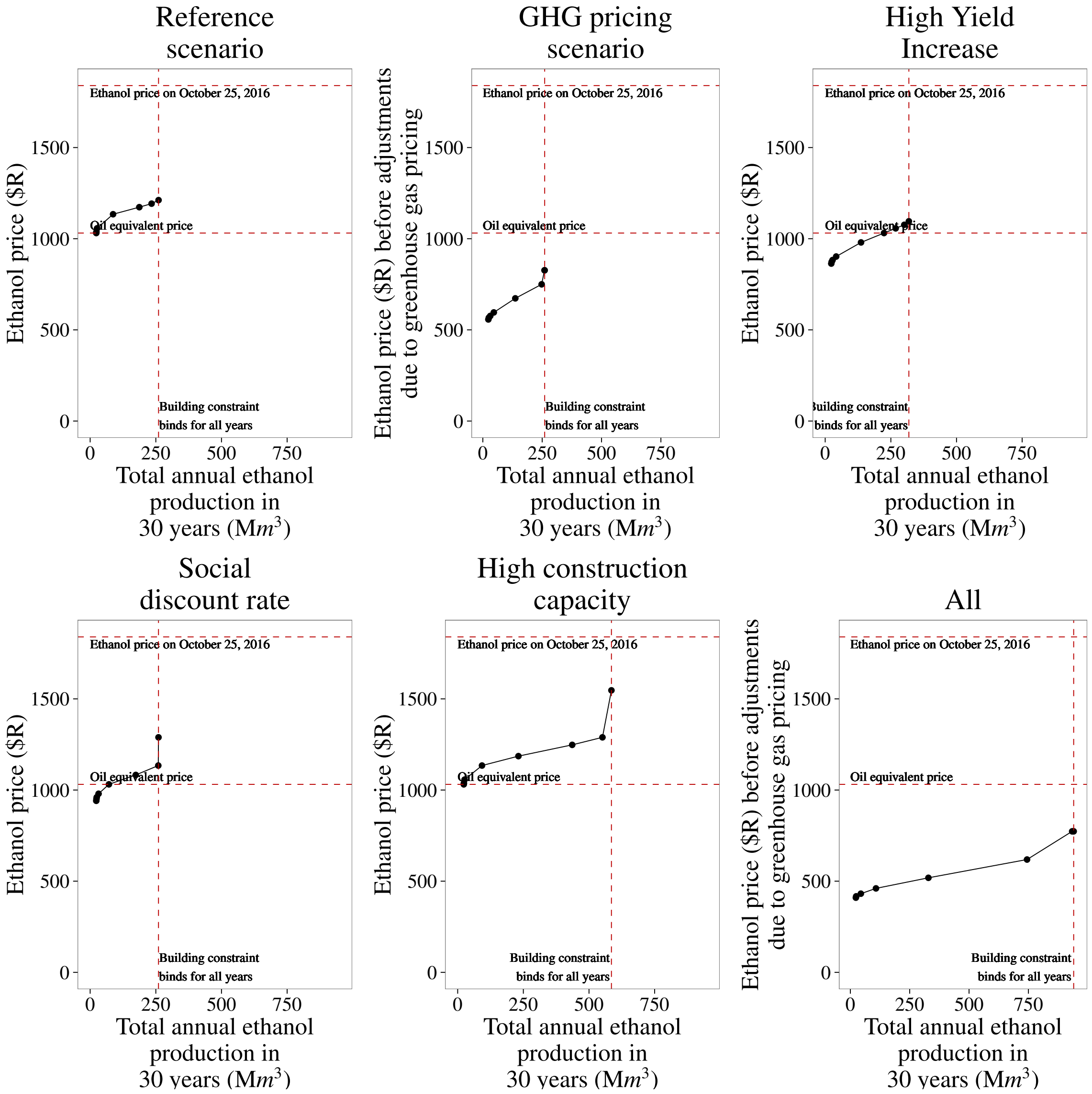

Figure 6: Calculated supply curves for Brazilian ethanol production in 30 years

Note: Total production is the sum of existing ethanol production and new model-predicted ethanol production. World crude oil supply in 30 years is projected to be energy equivalent to 5765 Mm^3 of ethanol. Optimization is performed to within a 1.5% MILP gap to reduce the computational burden. Oil equivalent price removes the ethanol BTU premium but retains the premiums associated with ethanol's value as an oxygenate and oil's need for further costly refining.

Table 1: Aggregate Profit, Investment Cost, and Land Used by Model Scenario

Scenario	Total NPV ($ billion)	Investment Cost NPV (Land Conversion and Refinery) ($ billion)	Pasture Converted (Mha)
Reference scenario	0	0	0
GHG price	271.7	115.7	31.51
Social discount rate (3%)	4.411	23.35	6.178
High yield increase (2 tonne/year)	17.52	74.04	16.35
High construction capacity (108 refineries/year)	0	0	0
All	2859	672.6	84.4

Note: Total NPV is the sum of the NPV of refinery construction costs, land purchase costs, land conversion costs, feedstock costs (production and transport), refinery operating costs, and ethanol freight costs. Investment Cost includes land conversion, refinery construction costs, and refinery upgrade costs. There is approximately 4,912 Mha of agricultural land and 3,359 Mha of pasture land globally. There is approximately 281 Mha of agricultural land and 172 Mha of pasture land in Brazil.

Table 2: Decomposition of NPV by Scenario

Scenario	Revenue	Refinery Operation	Land Operation	Construction/ Upgrade	Freight	Other
Reference/High construction capacity	0.00	0.00	0.00	0.00	0.00	0.00
GHG price	824.97	131.78	211.62	109.40	42.21	58.23
Social discount rate (3%)	152.23	41.10	60.58	23.17	7.69	15.28
High yield increase (2 tonne/year)	319.95	86.39	88.01	73.69	21.58	32.76
All	6588.36	1015.09	1121.54	641.63	557.47	393.45

Note: Revenue accounts for all receipts at the delivery point. Refinery operation accounts for all operating expenses at the refinery. Land operation accounts for all operating expenses in sugarcane fields, including capital depreciation, and excluding rent. Construction/Upgrade accounts for all capital expenditure at the refinery. Freight accounts for transportation costs from the refinery to the delivery point. Other includes the cost of transporting sugarcane from the field to the refinery, land purchases, and land conversions.

Table 3: Aggregate Output and Percentage of Global Agricultural Area by Model Scenario

Scenario	Percentage of Global Agricultural Area	Total Production in 30 Years (million m^3/year)	Total Brazil Ethanol as Percentage of World Liquids in 30 Years
Reference scenario	0.1%	26.66	0.3%
GHG price	0.74%	264.2	2.9%
Social discount rate (3%)	0.23%	74.8	0.83%
High yield increase (2 tonne/year)	0.43%	245.1	2.7%
High construction capacity (108 refineries/year)	0.1%	26.66	0.3%
All	1.8%	997.1	11%

Note: Total production includes both current production and the model-predicted new production. 30 year projection of world liquids is linearly extrapolated from the BP world energy outlook. World crude oil supply in 30 years is projected to be energy-equivalent to 5765 Mm^3 of ethanol.

Parameter values

Table A1 presents all parameter inputs into the refinery-level NPV calculation.

Table A2 presents all parameter inputs into refinery and pasture allocation optimization model.

Oil and Ethanol Market Equilibrium

In this subsection, we describe the simple energy market equilibrium model we use to generate the effect of a global GHG price, or equivalent policy, on the producer prices for oil and ethanol. Because we use these equations exactly, we also provide our particular parametrization.

The key assumptions we employ are: oil supply, ethanol supply, and energy demand are constant elasticity functions of price, oil and ethanol are perfect substitutes in the energy market, BTUs are the only valued component of either fuel, and oil BTUs are penalized using a scalar multiplier to equate the initial prices of the two fuels on a per-BTU basis.

The equilibrium equations are given below. We use subscript t's to denote variables that potentially change over time in our later simulation.

$$P^s_{ot} = P^d_{BTU,t} BTU^*_o - P_{GHG,t} GHG_o \tag{7}$$

$$P^s_{et} = P^d_{BTU,t} BTU_e - P_{GHG,t} GHG_e \tag{8}$$

$$Q_{BTU,t} = A_d (P^d_{BTU,t})^{-r} \tag{9}$$

$$Q_{BTU,t} = Q_{ot} BTU^*_o + Q_{et} BTU_e \tag{10}$$

$$Q_{ot} = A_o (P^s_{ot})^{\eta_o} \tag{11}$$

$$Q_{et} = A_e(P^s_{et})^{\eta_e} \tag{12}$$

In the above, P^s_{ot} is the price per barrel of oil to suppliers, P^s_{et} is the price of ethanol per m^3 to suppliers, $P^d_{BTU,t}$ is the price of world energy demanded in ethanol-equivalent quadrillion BTUs,[27] BTU^*_o is the energy content of oil per barrel, scaled to equate the initial prices of the fuels on a per-BTU basis, BTU_e is the energy content of ethanol per m^3, $P_{GHG,t}$ is the price of GHGs emitted, GHG_o is the GHGs emitted per-unit oil, GHG_e is the GHGs emitted per-unit ethanol, $Q_{BTU,t}$ is the world supply of ethanol-equivalent BTUs supplied across both fuels, $P^d_{BTU,t}$ is the price of an ethanol-equivalent BTU, Q_{ot} is the world supply of oil in barrels, Q_{et} is the world supply of ethanol in m^3. Prices and quantities are the endogenous variables in this system; the calculation of the remaining parameters is summarized in Table A5:

The results using GHG prices from **us˙epa˙social˙2013**, oil prices from CME Group (2015), and a recent ethanol price are presented in

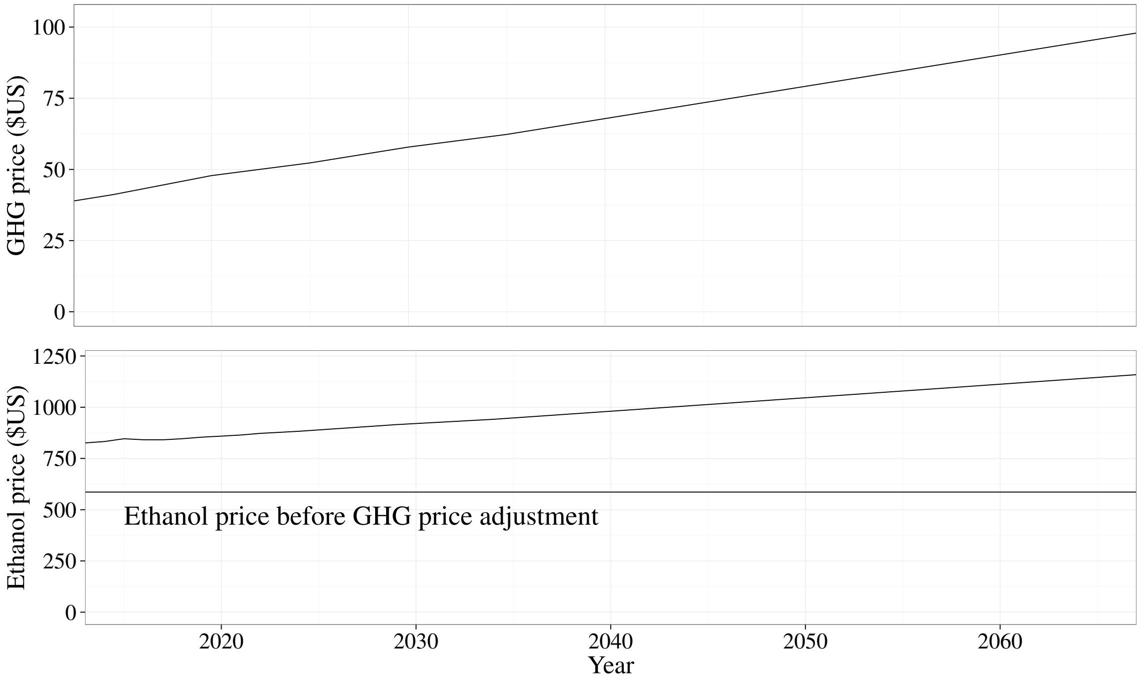

Figure A1: Greenhouse gas and ethanol prices produced using energy market equilibrium model

Table A1: Sugarcane Investment Model Parameter Values

Parameter	Value	Source
Refinery capacity (m^3/year)	250,000	Assumed.
Construction costs per refinery ($R million)	680.9	Bloomberg New Energy Finance. Predicted value for 2014 from a regression of construction cost on capacity and a linear trend using 22 ethanol-only refineries built in Brazil from 2005-2014.
Real discount rate (%)	6.1%*	Petrobras' WACC from wikiwealth.com, less expected inflation from tradingeconomics.com
Sugarcane cycle length (years)	6	Assumed.
Lifespan of each refinery (years)	30*	Assumed.
Additional maintenance costs as a proportion of initial construction costs (%)	0*	Assumed. Note that maintenance costs are explicitly accounted for in the refinery operating costs.
Construction period (year)	1	Assumed.
Ethanol price	R$1840/m3*	Nearest upcoming hydrous ethanol futures price on BM&F Bovespa (Collected October 25, 2016) (Brazilian Securities, Commodities and Futures Exchange 2014)).
Oil price	US$48.8-US$53.3 (2015-2088)	Nymex futures prices, averaged for each year. Unobserved years take the latest value. (Collected October 25, 2016 (CME Group 2015)).
Refinery operating costs	R$278/m3	PECEGE expansion region costs of refinery production less capital costs, depreciation, and rent (2012)
Feedstock costs	R$3189/ha	PECEGE expansion region costs of cane production less capital costs, depreciation, rent, and transportation costs (2012).
Feedstock transport costs	R$8.2/Mg Cane	Sugarcane transportation costs from Bonomi et al. (2012).
Pasture to sugarcane conversion cost	181	Conversion cost used in IBGE (2013).
Annual yield increases	0.32	Projected from historical trend using Brazilian Sugarcane Industry Association (2014).
Ethanol yield per Mg sugarcane stalk	0.086	Calculated from Somerville et al. (2010).

Table A2: Optimization Model Constraint Values

Parameter	Value	Source
Maximum number of refineries built per year	36	Assumed to be equivalent to 50% more than on a production capacity basis.
First year in the model	2014	Assumed.
Final potential build start year	2038	Assumed.
Proportion of total pasture available for conversion.	0.5	Assumed.

Table A3: GDP deflators for USD and BRL

USD		BRL	
2000	89.02	2000	100.00
2001	91.05	2001	108.09
2002	92.45	2002	118.80
2003	94.29	2003	135.38
2004	96.88	2004	145.91
2005	100.00	2005	156.84
2006	103.07	2006	167.34
2007	105.82	2007	178.05
2008	107.89	2008	193.83
2009	108.71	2009	208.09
2010	110.04	2010	225.91
2011	112.31	2011	244.69
2012	114.33	2012	259.04
2013	116.03	2013	275.90
2014	117.72	2014	294.93

Note: Collected from the World Bank Development Indicators.

Table A4: Miscellaneous Parameter Values

Parameter	Value	Source
Soil carbon change when converting from pasture to sugarcane (Mg/ha)	31.8	Mello et al. (2014)

Table A5: Oil and ethanol market parameter calculations

Parameter	Formula	Value	Explanation
$P_{GHG,t}$		$\$38.94\text{–}\$96.79$ (2014–2068)	US federal social cost of carbon, linearly interpolated/extrapolated (**us˙epa˙social˙2013**).
GHG_o		0.657	Lifecycle GHG content of a barrel of crude oil (Chavez-Rodriguez and Nebra 2010).
GHG_e		0.256	Lifecycle GHG content of an m^3 of ethanol.[28]
A_d	$\frac{Q_e^0 BTU_e + Q_o^0 BTU_o^*}{(P_e^0/BTU_e)^{-r}}$	$\frac{2.24 + 203 * BTU_o^*}{(26.2)^{-0.072}}$	Equation (9) rearranged using 2014 values. World oil supply in 2013Q4-2014Q3 (International Energy Administration 2015), Brent oil futures price in 2014 dollars for year t (CME Group 2015) (unavailable years are taken to be the final price in this list), r is the central value from (Holland, Hughes, and Knittel 2009).
A_{ot}	$\frac{Q_o^0}{(P_o^t)^{\eta_o}}$	$\frac{33.9}{(P_o^t)^{0.5}}$; $P_o^t \in \{\$48.8\text{–}\$53.3\}$	World oil supply in 2013Q4-2014Q3 (International Energy Administration 2015), Brent oil futures price in 2014 dollars for year t (CME Group 2015) (unavailable years are taken to be the final price in this list), η_o is the central value from (Holland, Hughes, and Knittel 2009).
A_e	$\frac{Q_e^0}{(P_e^0)^{\eta_e}}$	$\frac{99.9}{(1840)^1}$	World ethanol supply in 2013 (Renewable Fuels Association 2014), Ethanol futures for February 2015 delivery to SP (BM&F Bovespa 2015), η_e is the central value from (Holland, Hughes, and Knittel 2009).
BTU_{ot}^*	$BTU_o \frac{P_{ot}^0/BTU_o}{P_e^0/BTU_e}$	$\frac{49.8}{1840/22391726}$	Scales the BTU content of a barrel of oil in the model to equate the initial prices of the (scaled) oil BTUs and ethanol BTUs. P_o^0 (Energy Information Administration 2014; CME Group 2015; Brazilian Securities, Commodities and Futures Exchange 2014).
BTU_e	$\frac{BTU_e}{boe_e} * \text{bbl/m}^3 * 10^6$	$3.560 * 6.29 * 10^6$	BTUs per m^3 ethanol. Standard measure from (Energy Information Administration 2014).