ABSTRACT

Demand is growing worldwide for alternatives to fossil fuel energy sources. Ethanol produced from sugarcane is receiving attention as a viable fuel source, especially in Brazil where production has doubled from 2002 to 2008 in response to a strong domestic market and rapidly growing demand for exports. This paper presents an analytical model which uses continuous approximation to relate the costs and greenhouse gas emissions associated with the logistics of transporting raw sugarcane and distributing ethanol based on the properties of the land, infrastructure, vehicles, and production facilities. The model provides insights into the design of the logistics system and the associated greenhouse gas emissions if companies seek only to minimize costs. Model outputs are compared to existing sugarcane ethanol production in Brazil, and their implications for developing new production regions in different parts of Brazil are explored.

Keywords: biofuels, Brazil sugarcane ethanol, ethanol logistics, greenhouse gas emissions, continuous approximation
INTRODUCTION

Demand is growing worldwide for liquid fuel alternatives. Ethanol produced from sugarcane is receiving attention as a viable fuel source, especially in Brazil where production doubled from 2002 to 2008 in response to a strong domestic market and rapidly growing demand for exports (UNICA, 2009). In 2008, 27.5 billion liters of ethanol were produced from sugarcane in Brazil, which is the energy equivalent of 95 million barrels of oil. Although Brazil has long been supplying ethanol domestically to consumers with flex-fuel vehicles, exports have increased dramatically since 2000 as shown in Figure 1. The primary foreign markets are the United States, Europe, and Japan (Ribeiro, 2008). In 2008, over 100 billion MJ (5.1 billion L) of ethanol were exported from Brazil making up 70% of the global trade, and some estimates suggest that Japanese demand for Brazilian ethanol could reach 10 billion MJ (500 million L) in 2010, increasing more than 12 times by 2030 (Bryant and Yassumoto, 2009).

The motivation for modeling costs and global warming potential of sugarcane ethanol logistics in Brazil is to understand the greenhouse gas impacts of future growth in sugar cane production. To include the effects of all greenhouse gases (e.g., carbon dioxide, methane, nitrous oxide, etc.), this analysis focuses on global warming potential (GWP) which measures radiative effects of all emitted gases over a 100 year time period expressed as an equivalent mass of carbon dioxide (Houghton et al., 2001). A logistics model is developed in this paper to help quantify greenhouse gas emissions from the production of sugarcane ethanol and indirect greenhouse gas effects of sugarcane ethanol use. Though small relative to other life-cycle greenhouse gas emissions of sugarcane ethanol, logistics emissions are large enough to merit measurement. Moreover, logistics constitute an important portion of agricultural costs in Brazil and can strongly influence the greenhouse gas impacts of sugarcane use. Their magnitude will influence the cost competitiveness of sugarcane ethanol relative to other liquid fuels thereby influencing the global warming potential of the liquid fuel mix. In addition, agricultural logistics costs have been shown to strongly influence the geography of agricultural expansion in Brazil. This too has important greenhouse gas implications.

Sugarcane in Brazil

The logistics model developed in this paper has been constructed based on data from Brazil, but the form is general and can be applied to other crops and other parts of the world by changing the input parameters accordingly. Figure 2 shows the primary sugarcane production regions in Brazil as of 2008, and areas where growth in sugarcane production is likely to expand. São Paulo state dominates the production of sugarcane and is also the primary center for ethanol production in Brazil (UNICA, 2009). This is likely due to the fact that this region gets strong sugarcane crop yields and it is close to the major population and economic centers of the south. There is also a smaller production region in the northeast part of Brazil which has historically developed to produce refined sugar but due to the drier climate has lower crop yields.

Due to climate, soil properties, and cost competitiveness, much growth in Brazilian sugarcane production is expected to be primarily toward the north and northwest of São Paulo State and into Mato Grosso and Goiás in Brazil’s center-west (Cortez, 2007). With investments in irrigation, expansion might also arise in the arid interior of the Northeast. The GWP associated with converting existing land uses to sugarcane production in these regions are very different, as explored in Farigione et al. (2008), and new production and transportation infrastructure will have to be designed.
A logistics model for production and distribution of sugarcane ethanol in Brazil

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Figure 1 – Total production and exports of sugarcane ethanol from Brazil (UNICA, 2009).

Figure 2 – Current and potential regions for sugarcane production (Sources: Cortez, 2007; Goldemberg, 2008)
and constructed in any case. Although sugarcane production is not likely to occur directly in the Amazon, there is also concern that displaced land uses from other parts of Brazil could encroach on the forest. This is the land use and climate models which seek to predict hot spots for crop expansion and are thereby used to plan infrastructure expansion, combat deforestation, and design greenhouse gas mitigation policies. The logistic model presented in the following sections can generate inputs for these models by providing estimates for costs and greenhouse gas emissions associated with logistics of ethanol production.

**Modeling Approach**

The logistics of transporting raw sugarcane to ethanol distilleries, and then distributing the final product to consumers is an important component of ethanol production costs and also influences GWP. Some research summarizes the performance of some existing systems in São Paulo State (Macedo et al., 2004, 2008), but these findings cannot be easily generalized to different production scenarios. Existing models in Brazil and elsewhere have also sought to identify the minimized cost of production and distribution of ethanol using linear or mixed integer programs, but these require extensive data collection for detailed outputs (Kawamura et al., 2006; Paiva and Morabito, 2007). Thus, in order to plan for future growth in ethanol production, a model is needed which can describe the ethanol logistics system structure, costs, and GWP with as few data inputs as possible.

This paper presents an analytical model which uses the continuous approximation methods introduced by Newell (1973). The simple model relates the costs and greenhouse gas emissions associated with the logistics of transporting raw sugarcane and distributing ethanol based on the properties of the land, infrastructure, vehicles, and production facilities. By approximating all parameters as continuous values, logistic cost functions are developed to show how the transport systems for sugarcane and ethanol would be most cost effectively structured. These models provide estimates of the costs and emissions associated with these systems.

Continuous approximation models have several benefits over more detailed integer programs, as described in Daganzo (1999). Concise data summaries are used in place of detailed data, and analytical models are developed instead of numerical solutions. As a result, trade-offs that drive logistic costs and system structure are clearly revealed and properties of solutions near the global optimum can be identified. This physical understanding of the logistics system also provides insights so that the effects of changing input parameters or the limitations of simplifying assumptions can be easily traced to final solutions. Dasci and Verter (2001) shows that for logistics system solutions in the vicinity of the optimum, the total costs estimated from continuous models are insensitive to changes in model parameters. This data is often not available in great detail for preliminary planning or forecast studies. Thus, the simple approximate models presented in this paper are ideally suited for large scale analysis where the goal is to identify basic system structure as well as aggregate costs and emissions which are the desired inputs for assessment and planning models.

These models could be integrated with GIS for more spatially detailed results, however the proposed models are developed by approximating parameters with averages that applied over an entire production region. More precise numerical approaches based on detailed data are better suited for finalizing decisions, so the proposed model which accurately solves the logistics optimization using approximate data complements other approaches to solve precise models approximately. The simplicity of the approximate macro model also makes it well-suited for cross
checking the results of analyses using more detailed data sets and methods.

The following sections describe the steps of the logistics process included in this analysis. The scope of the study begins from transporting the raw harvested cane to local distilleries where ethanol is produced. In each stage of the production and distribution process, a logistic cost function and emissions model is developed based on the underlying structure of the existing ethanol production system in Brazil. There are typically several distilleries in a region making up a production cluster, and the ethanol from these distilleries is transported over long distances to fuel bases near population centers or ports. At the fuel base, the ethanol for domestic use is blended with gasoline and then distributed to individual retail service stations. The ethanol for export is loaded directly onto tanker ships to be carried around the world as far away as Japan.

PRODUCTION LOGISTICS

The production of ethanol begins with the cultivation of sugarcane which grows in tropical climates. The annual crop yield of the land depends on properties of the soil and the amount of water available. In southern Brazil, the land is very productive, averaging 82 tons of sugarcane per hectare, while in the Northeast, irrigation is required and each hectare typically yields 55 tons per year (Cortez, 2007). Further details on the costs and environmental impacts of growing sugarcane have been described by other researchers (e.g., Macedo et al., 2004), and the cost of resources such as fertilizer can vary greatly and have significant effect on the costs of agricultural production. Mature cane is harvested annually either mechanically or by burning and cutting by hand. The harvested cane must be transported to a distillery quickly before the sugars begin fermenting in order to maximize the production of ethanol, and this is done with large trucks that often have multiple trailers. The sugarcane is processed at the distillery to produce ethanol, and this process can usually get 86 L for each metric ton of raw sugarcane (Macedo et al., 2008). By-products of ethanol production may be burned to generate electricity.

As illustrated in Figure 3, each distillery typically processes sugarcane from fields up to a distance, \( r \) (km), away. This creates a roughly circular catchment region, and the size of this region is a consequence of the cost trade-off between transporting sugarcane and constructing and operating a distillery. The size of the region also depends on the land’s sugarcane yield. A model of this system is developed both for costs and greenhouse gas emissions.

Cost Model

The logistic cost of sugarcane is the sum of the cost of transporting the raw cane and building and operating the distillery. Assuming that fields are uniformly distributed across the land, the average distance that sugarcane must be transported from field to distillery is \( \frac{2}{3}r \). The transport cost then depends on the operating cost per distance for a cane truck, \( z_{ct} \) ($/truck-km), the capacity of each truck, \( c_{ct} \) (ton cane/truck), and in order to express the cost per unit of energy, the ethanol energy yield of the sugarcane, \( y \) (L ethanol/ton cane). The cost of the distillery includes a fixed annual cost \( z_{d,1} \) ($/yr), and a marginal cost per unit of capacity \( z_{d,2} \) ($/L). The transportation and distillery cost per MJ of ethanol produced (field to distillery), \( Z_p \) ($/L) is:

\[
Z_p = \frac{4r z_{ct}}{3 y c_{ct}} + \frac{z_{d,1}}{\pi r^2 a Y y} + z_{d,2}
\]

(1)
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where \( a \) is the fraction of land within the distillery's catchment region that has sugarcane growing on it and \( Y \) (ton cane/km\(^2\)-yr) is the annual sugarcane yield of the land.

This expression illuminates a trade-off in the choice of radius of the region which a distillery should serve. While increasing \( r \) improves the efficiency of the distillery by processing more sugarcane in one facility, the transportation cost increases as well. Since the cost of production logistics is a convex function of \( r \), the optimal radius, \( r^*_z \), which minimizes the cost can be found by solving for \( r \) when \( \frac{dZ_p}{dr} = 0 \):

\[
r^*_z = \frac{3}{2} \sqrt{\frac{3c_{ct} 2d_{1}}{2c_{ct} \pi a Y}}.
\]

(2)

Note that value of \( r^*_z \) depends on the cost of transporting sugarcane relative to the fixed cost of building and operating a distillery and the annual yield of the land.

**Greenhouse Gas Model**

The model of the greenhouse gas emissions associated with the production logistics for sugarcane ethanol is similar to the cost model presented above. These emissions are expressed in units of equivalent grams CO\(_2\) (g CO\(_2\) eq) which includes carbon dioxide as well as the global warming effect of other greenhouse gases (conversion rates are available in Houghton, 2001). The transportation of sugarcane to the distillery is associated with greenhouse gas emissions for the road infrastructure, \( g_{ct,1} \) (g CO\(_2\) eq/truck-km), and truck operation, \( g_{ct,2} \) (g CO\(_2\) eq/L-km). There are also emissions associated with the fixed infrastructure component of the distillery, \( g_{d,1} \) (g CO\(_2\) eq/yr), and for each additional unit of production, \( g_{d,2} \) (g CO\(_2\) eq/L). Thus, the GWP associated with ethanol production, \( G_p \) (g CO\(_2\) eq/L), is:

\[
G_p = \frac{2r}{3} \left( \frac{2g_{ct,1}}{c_{ct} Y} + g_{ct,2} \right) + \frac{g_{d,1}}{\pi r^2 a Y} + g_{d,2}
\]

(3)
Just as with the cost model, there is an optimal radius of production region which minimizes the GWP,

$$r_g^* = \sqrt[3]{\frac{3g_{d,1}}{2g_{c,1} + g_{c,2}}} \cdot \pi a Y_y.$$  (4)

A comparison of $r_z^*$ and $r_g^*$ would show the difference between the design of the production system to minimize cost or to minimize global warming potential. Note that in both (2) and (4), the trade-off weighs truck transportation against distillery infrastructure, and the expression is a cube root, so the optimal radius is insensitive to changes in the values of the input parameters.

**Application to Production in Brazil**

Costs and emissions associated with sugarcane transport and ethanol production in Brazil are compiled in Table I. Typical parameter values for São Paulo state have been estimated based on data in the sources indicated. On the basis of cost, the optimal production region extends 21 km from the distillery, whereas the radius which minimizes global warming potential is 16 km. These are similar, and this is not so surprising because the resource requirements that are correlated with cost (infrastructure, fuel, etc.) are also correlated with emissions of greenhouse gases. The cost-minimizing radius is compatible with the average distance from field to distillery reported by Macedo et al. (2004). The annual ethanol production of a distillery in a region of this size would be 250 million liters which is more than the 170 million liters of an average distillery (Cortez, 2007), but this is compatible with the size of newer facilities being planned and constructed.

Furthermore, the design radius is insensitive to inputs, so the radius of production regions in the Northeast, where annual crop yields are about 67% that of São Paulo, increase to only 24 km. The difference between the optimal radius due to cost and the optimal radius is due to the difference between the relative costs of production components and their relative GWP intensities. Note that the difference in cost between the cost-minimizing and GWP-minimizing radii is 5%, and the difference in GWP is only 3%. This means that changing crop yields do not have much impact on the structure of the production system because the costs of cane transport make larger areas uneconomical.

**DOMESTIC TRANSPORT OF ETHANOL**

From the distilleries which are located in the region where the sugarcane is grown, the ethanol is transported to fuel bases in the region where the ethanol will be consumed or to ports on the coast for export. Ethanol is usually shipped in its pure form from the distillery, and it is blended to the appropriate concentration with gasoline at the fuel base prior to distribution to retail service stations. For this part of the distribution system, a variety of modes may be used. In Brazil, the most likely modes are truck, railroad, and pipeline, so these are the focus of the analysis in this section. The logistics model is general, however, and can be modified to describe other modes with different cost characteristics. The structure of the most cost effective distribution system depends on the modes used, the quantity of ethanol produced in the region, and the distance to the fuel base.

The general structure of the system to transport ethanol is illustrated in Figure 4 where the production region is within a distance $d$ from the fuel bases. When trucks are used, they can be
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane field coverage, $\alpha$</td>
<td>%</td>
<td>0.25</td>
</tr>
<tr>
<td>Cane truck capacity, $c_{ct}$</td>
<td>ton cane/truck</td>
<td>38</td>
</tr>
<tr>
<td>Sugarcane yield per area, $Y$</td>
<td>ton cane/km$^2$-yr</td>
<td>8200</td>
</tr>
<tr>
<td>Ethanol yield of sugarcane, $y$</td>
<td>L ethanol/ton cane</td>
<td>86</td>
</tr>
<tr>
<td>Fixed annual cost of distillery, $z_{d,1}$</td>
<td>$/yr</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Marginal annual cost of distillery capacity, $z_{d,2}$</td>
<td>$/L</td>
<td>0.021</td>
</tr>
<tr>
<td>Cane truck operating cost, $z_{ct}$</td>
<td>$/truck-km</td>
<td>1.40</td>
</tr>
<tr>
<td>Radius of production region to minimize cost, $r^*_z$</td>
<td>km</td>
<td>21</td>
</tr>
<tr>
<td>Cost of cost-minimizing radius, $Z_p(r^*_z)$</td>
<td>$/L</td>
<td>0.039</td>
</tr>
<tr>
<td>GWP of cost-minimizing radius, $G_p(r^*_z)$</td>
<td>g CO$_2$ eq/L</td>
<td>36.5</td>
</tr>
<tr>
<td>Fixed GWP per vehicle distance, $g_{ct,1}$</td>
<td>g CO$_2$ eq/truck-km</td>
<td>780</td>
</tr>
<tr>
<td>Marginal GWP per unit ethanol, $g_{ct,2}$</td>
<td>g CO$_2$ eq/L-km</td>
<td>0.42</td>
</tr>
<tr>
<td>Fixed GWP of distillery, $g_{d,1}$</td>
<td>g CO$_2$ eq/yr</td>
<td>680,000,000</td>
</tr>
<tr>
<td>Marginal GWP per unit ethanol, $g_{d,2}$</td>
<td>g CO$_2$ eq/L</td>
<td>21</td>
</tr>
<tr>
<td>Radius of production region to minimize GWP, $r^*_g$</td>
<td>km</td>
<td>16</td>
</tr>
<tr>
<td>Cost of GWP-minimizing radius, $Z_p(r^*_g)$</td>
<td>$/L</td>
<td>0.041</td>
</tr>
<tr>
<td>GWP of GWP-minimizing radius, $G_p(r^*_g)$</td>
<td>g CO$_2$ eq/L</td>
<td>35.4</td>
</tr>
</tbody>
</table>

$^a$ Goldemberg (2008)  
$^b$ Macedo et al. (2008)  
$^c$ Cortez (2007)  
$^d$ Shapouri et al. (2006)  
$^e$ Barnes and Langworthy (2004)  
$^f$ Macedo et al. (2004)  
$^g$ Facanha and Horvath (2007)
loaded and carry ethanol directly point to point. High capacity modes have economies of scale, however, so some consolidation of ethanol loads is necessary in the production region. This can be done either by trucking ethanol from distilleries to transshipment points, building spur lines of high capacity infrastructure, or some combination of the two. A model of the costs and GWP is described in the following subsections. Such a model can be used to compare mode performance.

Cost Model

In order to account for the complete cost of transport modes, all of the components of infrastructure and vehicle operation must be accounted. For the cost of a mode \( i \), these components can be grouped into three cost coefficients:

- Annual cost per distance, \( z_{i,1} \) ($/km) – infrastructure construction
- Cost per unit of ethanol per distance, \( z_{i,2} \) ($/L-km) – infrastructure maintenance, vehicle maintenance, labor and fuel for operation
- Cost per unit of ethanol, \( z_{i,3} \) ($/L) – vehicle purchase, ethanol loading and unloading

These costs vary significantly from mode to mode reflecting the necessary infrastructure investments, the cost of vehicle capacity, and the incremental cost of transporting each additional unit of cargo. These are the fewest variables to capture the effects of both production quantity and distance on the logistics of transporting ethanol. Although approximate, the model based on these parameters provides insights for which modes can transport ethanol most cost effectively.

Consolidating Loads

Although truck transport of ethanol can operate point to point because every distillery must be connected by roads, other modes require the consolidation of loads for the line haul portion of the trip in order to exploit the economies of scale of high capacity infrastructure. There is a trade-off between connecting the distilleries in the production cluster with trucks to a transshipment facility and building spur lines of the line haul infrastructure to each distillery. Therefore, when the primary transport mode for ethanol is not by tank truck, consolidation of loads as described in this section should be considered.

A production cluster in a region is composed of \( n \) distilleries each producing \( P = \pi r^2 a Y y \) MJ of ethanol per year based on the radius of the production region \( r \) and crop yield \( Y \) as described in the previous section. In order to model the trade-off between trucking ethanol to transshipment locations (as shown by dotted lines in Figure 4) and the construction of spur lines of the higher capacity mode (solid lines in Figure 4), suppose the production cluster is divided into subclusters each with \( m \) distilleries.

Within each subcluster, trucks are used to transport ethanol to one distillery where it can be loaded onto rail cars or into a pipeline. If the road infrastructure required is structured as a branching tree connecting distilleries at distances \( 2r \) apart, then \((m - 1)\) links of this length must be constructed in each subcluster. Assuming roughly circular subclusters with area \( m \pi r^2 \), the average distance that ethanol must be transported to the center of the subcluster is \( \frac{2}{3} r \sqrt{m} \). The first three terms of (5) expressing cost per unit of ethanol of consolidating loads, \( Z_c \) ($/L), are the contribution of trucking (denoted by subscript \( t \)). Truck infrastructure requirements are associated with the cost of roads per distance, \( z_{t,1} \), the average trucking distance with the cost per distance
per unit of ethanol, \( z_{t,2} \), and the cost of loading and unloading each unit of ethanol, \( z_{t,3} \). The last two terms of (5) are associated with the high capacity mode \( i \). Of the \((n-1)\) links between adjacent distilleries in the production cluster, \( \frac{n}{m}(m-1) \) are connected with roads for trucks, so this leaves \( \left( \frac{n}{m} - 1 \right) \) links which cost \( z_{t,1} \). The average distance from the transshipment center in each subcluster to the main line is a function of the radius of the entire production region, and is multiplied by the cost per distance per unit of ethanol transported, \( z_{i,2} \).

\[
Z_c = \frac{2rz_{t,1}(m-1)}{mP} + \frac{2}{3}rz_{t,2}\sqrt{m} + z_{t,3} + \frac{2rz_{i,1}\left( \frac{n}{m} - 1 \right)}{nP} + \frac{2}{3}rz_{i,2}\sqrt{n}
\]  

(5)

Note that the loading and unloading cost is not counted for the high capacity mode during consolidation because it is considered as part of the line-haul calculation, and a rail car or pipeline loaded at any of the transshipment points will not be unloaded until the ethanol reaches the fuel base.

The amount of infrastructure that should be built for the high capacity mode and the number of distilleries that should be served by trucks headed to transshipment points can be described by the choice of subcluster size, \( m \). The value of \( m \) which minimizes the cost per unit of ethanol in (5) is:

\[
m^*_z = \left( \frac{6(z_{i,1} - z_{t,1})}{z_{t,2}P} \right)^{\frac{2}{3}}
\]

(6)

which depends on the cost of infrastructure for trucks and mode \( i \), the operating cost for a tank truck, and the annual productivity of each distillery in the region.

Although in reality \( m, n, \) and \( \frac{n}{m} \) are integer values, we can approximate by allowing them to be continuous which allows us to gain insights about the impacts of key parameters while contributing minimal errors to the analytical estimates of the costs of ethanol transportation (less than 1% using typical numbers for Brazil). This approximate error is less than the effect of errors in the input parameter values on cost estimates.

**Line-Haul Transport**

The line-haul is the component of the transportation of ethanol from the production cluster to the fuel base at a distance \( d \) (km) away, as shown by the long solid line in Figure 4. The expression for the line-haul cost per unit of ethanol, \( Z_l \) ($/L), is a straightforward sum of each of the mode cost coefficients multiplied by the appropriate combination of travel distance and ethanol production:

\[
Z_l = \frac{z_{i,1}d}{nP} + z_{i,2}d + z_{i,3}.
\]

(7)

This expression captures the main trade-off between modes like trucking which require relatively cheap infrastructure but have high operating cost and modes such as pipelines which can move large quantities of ethanol efficiently but require expensive infrastructure investments.

**Greenhouse Gas Model**

The greenhouse gas model for the transportation of ethanol from distilleries to fuel bases is very similar in structure to the cost model presented above. In this case, the GWP intensity of each component of the logistics system are expressed by the \( g \) coefficients. The infrastructure for mode
is associated with $g_{i,1}$ (g CO$_2$ eq/km), and the full extent of vehicle operation and maintenance is associated with $g_{i,2}$.

Using the same structure for consolidating loads in terms of subclusters of distilleries within a production cluster as described above, (5) can be rewritten for the global warming potential of consolidation, $G_c$ (g CO$_2$ eq/L), as

$$G_c = \frac{2rg_{t,1}(m - 1)}{mP} + 2\frac{rg_{t,2}\sqrt{m}}{mP} + 2\frac{rg_{i,1}(n - 1)}{nP} + 2\frac{rg_{i,2}\sqrt{n}}{n}.$$  

This expression can also be minimized through the choice of $m$, and (6) becomes

$$m^*_g = \left(\frac{6(g_{i,1} - g_{t,1})}{g_{t,2}P}\right)^{\frac{3}{2}}$$

which similarly captures the trade-off between the impact of infrastructure and truck operations, taking into account the productivity of each distillery. Note the similarity of the functional forms of $m^*_g$ and $m^*_z$. These values differ only because of the difference between the relative costs and relative GWP intensity of the various components of the consolidation and line haul logistics.

The GWP associated with the line-haul component of the transportation system, $G_l$ (g CO$_2$ eq/L), is also similar in structure to (7) for the cost model.

$$G_l = \frac{g_{i,1}d}{nP} + g_{i,2}d$$

A trade-off exists between the emissions associated with the length of infrastructure and the distance and quantity of ethanol transported.

**Comparison of Mode Performance**

Estimates for the cost coefficients for transporting ethanol by truck, railroad, and pipeline have been compiled and summarized in Table II. These estimates are based, where possible, on data from Brazil. However, more published data are available for the United States, so in cases such as characterizing the costs of railroad transport, sources outside of Brazil were relied upon. Note that across modes, improvements in the efficiency per distance per unit of ethanol are countered by more expensive fixed investments per distance. Pipelines do not even involve vehicles, and the cost per unit of ethanol is an order of magnitude less than that of truck or railroad, but this is offset by the cost of building the infrastructure.

Table III displays a comparison of GWP coefficients for the same modes. Most sources for estimates of the emissions associated with freight transportation focus on the operation of vehicles, and for these components emissions have been estimated based on Facanha and Horvath (2007) and are consistent with the weight of a full vehicle load of ethanol. Estimates of the life-cycle GWP associated with infrastructure per distance were made using an economic input-output life-cycle assessment tool which relates monetary expenditures and consequent economic activity associated with various sectors of the economy to GWP (Carnegie Mellon University Green Design Institute, 2010). Although these numbers are almost exclusively based on sources outside Brazil, they provide estimates to make general comparisons between modes.

To show the effect of distance on the cost of using different line haul modes, Figure 5 displays a comparison of the 3 modes used in this paper. For a large hypothetical production cluster in
a region with a crop yield of sugarcane comparable to São Paulo state, this figure shows how the cost per unit of ethanol increases with distance from the production region to the fuel bases. Tank trucks are cost effective for short distances where the cost of consolidating loads outweighs the greater economies of scale exhibited by railroads or pipelines. In this scenario, the pipeline outperforms railroad at all distances because the fixed cost per unit of ethanol is lower.

The distances over which each mode transports ethanol most cost effectively depends not only on how far the production region is from the fuel base, but also on the total quantity of ethanol produced in the region annually. Figure 6 shows the ranges of production and distance for which truck transport has the lowest cost versus pipeline transport.

The figure on the left side of Figure 6 is constructed considering the full infrastructure construction costs along with vehicle operations. Notice that truck transport makes sense for short distances when the benefits of consolidating loads cannot outweigh the costs and for low production quantities when insufficient ethanol is transported to pay for the cost of infrastructure. The tipping point between truck and pipeline transport is insensitive to the crop yield. Since most of the potential sugarcane production regions are more than 500 km from ports and markets on the coast, the large increase in ethanol production expected in Brazil is likely to be carried by pipelines. This is consistent with reports of plans to invest billions of dollars in building ethanol pipelines into the interior of the country.

The right side of Figure 6 is the same plot of distance and production, but this time the truck and rail models omit the cost of infrastructure construction (still including the infrastructure maintenance associated with passing loads). In most cases there is existing road capacity for ethanol
Figure 5 – Comparison of transport costs per unit of ethanol for producing 84 billion MJ (4 billion L) per year on land yielding 82 tons sugarcane per hectare.

Figure 6 – Range of regional ethanol production quantities and line haul distances served most cost effectively by each mode when the cost of infrastructure is included (left) or only operations and maintenance of truck and railroad are considered (right) assuming an annual sugarcane yield of 82 ton/ha.
transport by trucking, because roads will have to be built to access distilleries regardless of the mode of ethanol transport. Railroads in Brazil do not currently extend to all sugarcane production areas, but where excess railroad capacity is available, the right side of Figure 6 shows how rail might be able to compete with pipelines for smaller scale production. Brazil is expected to increase exports of the ethanol in the coming year by amounts great enough that investments are likely to be funneled into pipeline construction projects. This is further discussed in last section of this paper.

**DISTRIBUTION TO CUSTOMERS**

Once the ethanol arrives at the port or fuel base it can either be loaded onto a ship for export or distributed locally. Ethanol is exported in large tankers loaded at coastal facilities. For local consumption, the ethanol is blended with gasoline at the fuel base to appropriate concentrations for sale at retail service stations. In order to account for the cost and GWP of distributing ethanol, only the costs associated with the ethanol component of the fuel is computed, and these values are also reported per MJ of ethanol for consistent comparison.

**Cost Model**

The costs of distribution are considered in two categories. Domestic distribution is the transportation from fuel bases to service stations by truck over relatively short distances as illustrated in Figure 7. The structure is based on the assumption that fuel bases are distributed roughly proportionally with ethanol demand around the country such that the area served by each fuel base and the average distance to service stations within this region can be easily estimated. The other category of distribution is exporting by ship which depends on the cost of operating large tank ships across vast distances to foreign markets in the United States, Europe, and Asia.

![Figure 7 – Ethanol is mixed to appropriate concentration with gasoline at fuel bases and then transported by truck to individual service stations](image)
**Domestic Distribution**

Fuel bases are located around the country and serve as distribution stations from which tank trucks carry blended fuel to individual service stations. If a fuel base serves retail fueling stations in a roughly circular region of size \( A_f \) (km\(^2\)), the average distance that blended ethanol must be transported is \( \frac{2}{3} \) the radius of the region. So the cost of distributing ethanol to service stations around the fuel base, \( Z_d \) ($/L), is

\[
Z_d = 2\frac{2}{3} \sqrt{\frac{A_f}{4\pi}} z_{t,2} + z_{t,3}.
\]

The model for the distribution of ethanol in Brazil could be further extended to incorporate the cost trade-off between the size of regions served by each fuel base and fuel delivery. Since these fuel bases are also a part of the petroleum distribution system, the design does not rely only on the costs associated with the ethanol industry.

**Export**

Most of the new ethanol production in Brazil is for export which means that it must be transported to ports where it can be loaded onto ships. For the majority of export destinations, tank ships are the only viable transport modes. The expression for cost of ethanol shipping, \( Z_e \) ($/L), as a function of the shipping distance, \( d_e \) (km), is

\[
Z_e = z_{s,2} d_e + z_{s,3}
\]

where \( z_{s,2} \) is the cost per unit of ethanol per distance transported, and \( z_{s,3} \) is the cost associated with loading and unloading each unit of ethanol. Expression (12) provides an estimate for how shipping biofuels over long distances across the world contributes to their price.

A typical value for \( z_{s,2} \) based on the capacity and operating costs of oil tankers and the properties of ethanol is \( 3.2 \times 10^{-7} \) $/L-km (Reynolds, 2002; Rodrigue et al., 2009), and an estimate for \( z_{s,3} \) is \( 4.0 \times 10^{-3} \) $/L, based on America’s Energy Future Panel on Alternative Liquid Transportation Fuels (2009). With these values, even if ethanol is shipped to as far as Japan, the cost of logistics is not more than doubled (see Table IV).

Upon delivery in the destination country, the ethanol will still need to be distributed to local service stations. In simple cases where demand for fuel is near the port, the domestic distribution model described above can be applied to provide an estimate.

**Greenhouse Gas Model**

The GWP associated with distributing ethanol from fuel base to service station, \( G_d \), follows the same structure as (11):

\[
G_d = 2\frac{2}{3} \sqrt{\frac{A_f}{4\pi}} g_{t,2}
\]

where the GWP of the tank truck operations includes incremental effects of infrastructure and vehicle maintenance in addition to regular operations.

The exports of ethanol by ship are also associated with greenhouse gas emissions because tank ships burn petroleum-based bunker fuel for power. The GWP of shipping can be roughly
estimated by

\[ G_e = g_{s,2}d_e \]  

(14)

where a typical value of \( g_{s,2} \) for a tank ship is approximately \( 5.5 \times 10^{-3} \) g CO₂ eq/MJ-km as a consequence of burning bunker fuel (Weber and Matthews, 2008). Although this is a rough approximation, this simple calculation can give us an idea of how the order of magnitude of GWP from exports compares with keeping ethanol in Brazil for domestic consumption.

**DISCUSSION**

A comparison of 3 hypothetical production clusters in Brazil is shown in Figure IV. Each region is assumed to produce the same total amount of ethanol, but with different sugarcane crop yields and distances to the coast where fuel bases and ports are located. The first scenario is based on the existing production in São Paulo state where the land produces the greatest yield of cane and is near the major consumer markets and ports of southern Brazil. The second scenario in Mato Grosso corresponds to the possible expansion to the north and west of São Paulo state as indicated in Figure 2 where crop yields are slightly less and production areas are far from the coast. Finally, expansion of production across the northeast provinces (also shown in Figure 2) has lower yields, but also shorter transportation distances.

For each of the regions in Table IV, the logistics of production, consolidation, line-haul transportation, and distribution are modeled to minimize costs as described in the preceding sections. Due to the quantity produced, and the fact that all likely production regions are far from the coast, all three scenarios fall in similar locations on the plot in Figure 6 and would be served most cost-effectively by pipelines. The breakdown of costs attributable to each of the components of the logistic system is summarized in the table, and we can see that the cost does not vary greatly between different production regions, although distance to ports does have an effect. The total cost of domestic logistics, which omits the cultivation and harvest as well as other company facilities and overhead, makes up about half of the reported production cost of ethanol in Brazil which is about 0.17 $/MJ (Henniges and Zeddies, 2004). The cost of shipping ethanol to as far away as Japan roughly doubles the logistics cost. Although these costs are not very sensitive to the specifics of the production scenario they are a major component of the cost of producing ethanol.

The GWP of the logistics systems in each of the production scenarios is also compared in Table IV. Crop yield and distance have similar effects on the relative magnitudes of emissions and costs, and the contribution from petroleum-powered tank ships is evident in the effect on export GWP. The difference from the cost model is that these few g CO₂ equivalent are small compared with the total GWP associated with the ethanol production life-cycle. Fargione et al. (2008), Searchinger et al. (2008), and other researchers have shown that the effect of land conversion from other uses (e.g., forests, grasslands, abandoned farmland) to the cultivation of sugarcane or any other biofuel has a much bigger role in the total GWP associated with it. To compare ethanol with other fuels, it is more reasonable to compare the costs and GWP per unit of energy rather than volume. Since ethanol has an energy density of about 21 MJ/L, the GWP of sugarcane ethanol logistics per energy lies in the range 3–10 g CO₂ eq/MJ depending on the production scenario and destination. This is very small compared to the 94 g CO₂ eq/MJ associated with gasoline (Brandt and Farrell, 2007), however this can easily be outweighed by the GWP associated with land use conversion and deforestation.
Table IV – Comparison of Potential Growth in 3 Regions of Brazil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>São Paulo</th>
<th>Mato Grosso</th>
<th>Northeast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual sugar cane yield, $Y^a$</td>
<td>ton cane/km^2</td>
<td>8200</td>
<td>7500</td>
<td>5500</td>
</tr>
<tr>
<td>Annual ethanol production, $nP$</td>
<td>Billion L/year</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Distance from region to market, $d$</td>
<td>km</td>
<td>400</td>
<td>1500</td>
<td>700</td>
</tr>
<tr>
<td>Radius for distillery, $r^z$</td>
<td>km</td>
<td>21</td>
<td>22</td>
<td>24</td>
</tr>
<tr>
<td>Size of production cluster, $n$</td>
<td>distilleries</td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Size of subcluster, $m^z$</td>
<td>distilleries</td>
<td>6.5</td>
<td>6.6</td>
<td>7.1</td>
</tr>
<tr>
<td>Cost of production, $Z_p$</td>
<td>$/L</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Cost of consolidation, $Z_c$</td>
<td>$/L</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Cost of line-haul transport, $Z_t$</td>
<td>$/L</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Cost of distribution, $Z_d$</td>
<td>$/L</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Cost of export, $Z_e$</td>
<td>$/L</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Total logistic cost in Brazil</td>
<td>$/L</td>
<td>0.09</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>Total logistic cost to Japan</td>
<td>$/L</td>
<td>0.16</td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td>GWP of production, $G_p$</td>
<td>g CO₂ eq/L</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>GWP of consolidation, $G_c$</td>
<td>g CO₂ eq/L</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>GWP of line-haul transport, $G_t$</td>
<td>g CO₂ eq/L</td>
<td>10</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>GWP of distribution, $G_d$</td>
<td>g CO₂ eq/L</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>GWP of export, $G_e$</td>
<td>g CO₂ eq/L</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Total GWP of logistics in Brazil</td>
<td>g CO₂ eq/L</td>
<td>60</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>Total GWP of logistics to Japan</td>
<td>g CO₂ eq/L</td>
<td>120</td>
<td>220</td>
<td>190</td>
</tr>
</tbody>
</table>

\(^{a}\) Cortez (2007)  
\(^{b}\) Line-haul transport is by pipeline for all cases.  
\(^{c}\) Export with large tank ship 22,000 km to Japan.

**CONCLUSIONS**

The model presented in this paper is intended to provide insights for the costs that determine the structure of the logistics system for the production and distribution of sugarcane ethanol in Brazil. A similarly structured model was developed to provide estimates of the greenhouse gas emissions associated with these systems, because this is a major interest among researchers and decision-makers who are looking at how sugarcane production will expand in Brazil and what the impacts of this growth will be. The contribution of this paper is a generic, analytical model of costs and GWP of biofuel production. The developed models have been applied to the production of Brazilian sugarcane ethanol.

Although the continuous approximation approach does not incorporate detailed data about the transportation network and geography of Brazil, the results show analytically how different factors regarding land productivity, transport modes, and production facilities are likely to affect the structure of the logistics system and the associated costs and greenhouse gas emissions. In most cases, large volumes of ethanol will be transported by pipeline as production in Brazil increases, and the bulk of costs and greenhouse gas emissions will be associated with the transport of raw sugarcane and the production of ethanol in distilleries. The line-haul movement of ethanol...
to ports and transshipment points makes some regions like São Paulo and the Northeast more economically competitive than other regions of Brazil, but this does not take into account the global warming effects of land use conversion which can easily outweigh the environmental impacts of the logistics system.

The logistics models presented are ideal for studying the future growth in sugarcane ethanol production when estimates of the total costs and environmental effects are needed. Such models can be used as an input for existing spatially explicit integrated assessment models which used to plan infrastructure expansion and prevent deforestation. Logistics modeling of raw sugarcane also has implications for other biofuels and bioenergy crops which are grown worldwide, so this simple model provides insights for studying ethanol production scenarios when data is scarce or the future is uncertain. The main structure of the model is generic, so this approach can also be used to estimate costs and impacts associated with other biofuels by making minor adjustments to reflect the nature of the materials and landscape used.

REFERENCES


