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Estimated reduction in greenhouse gas emissions resulting from the use of intermodal transportation in sugarcane industry: An application of linear programming

Maria Andrade Pinheiro and José Vicente Caixeta-Filho*

Titular Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ), Universidade de São Paulo, Av. Pádua Dias, 11 CEP 13418-900 - Piracicaba, SP - Brasil.

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ABSTRACT

The level of concern about global warming is increasing worldwide, leading governments and environmentalist organizations to intensify research and take measures aimed at minimizing the effects of greenhouse gas emissions. In Brazil, the transportation sector is the second most energy-intensive sector. Although most goods are delivered to the ports by rail, a combination of transportation modes could be employed. Among the overland modes, road transportation produces the most CO_2 emissions, followed by transport via railway, waterway and pipeline. The sugarcane industry is a major generator of foreign exchange for the country. In 2010, revenues, were R$50 billion and exports were R$24.3 billion. Given the significant contribution that the transportation sector makes to greenhouse gas emissions and the important role that a change in transportation mode may play in reducing those emissions; this study was aimed at estimating the reduction in CO_2 emissions achieved by changing the transport network used in the sugarcane industry and to determine the impact of infrastructure projects implemented by the Brazilian government. The findings of this research indicate that, over a 3-year period, such a change could reduce CO_2 emissions by 6.6 million tons of CO_2 and result in a savings of approximately R$3.3 billion.

INTRODUCTION

The debate over global warming has intensified in the international arena and, increasingly, countries are reaching agreements on targets for reducing greenhouse gas emissions. There have been a series of intergovernmental meetings to discuss and define those targets.

In December 1997, during the 3rd Conference of the Parties to the Climate Convention, the Kyoto Protocol was put forth and was signed by representatives of 170 countries, who pledged to reduce greenhouse gas emissions to 5.2% below that observed in 1990 by the 2008-2012 quadrennium. The countries were divided into developed countries (Annex I parties) and countries with economies that are in transition (non-Annex I parties) (Costa, 1998). The report submitted by the United Nations Framework Convention on Climate Change (UNFCCC) (2011), in reference to the Conference of the Parties to the Convention, states that emissions reduction allows an increase in temperature of no more than 2°C (over an unspecified period of time), the long-term goal being to hold that increase to a maximum of 1.5°C. These

*Corresponding author. E-mail: jose.caixeta@usp.br. Tel: + 55 19 3429 4580. Fax: + 55 19 3429 4441.

values are important because the reduction targets for the second commitment period have yet to be defined.

In 2015, the Brazilian government released what was called Intended Nationally Determined Contribution (INDC) towards achieving the objective of the UNFCCC. Brazil intends to reduce greenhouse gas emissions by 37% below 2005 levels until 2025 and by 43% until 2030. The scope under these objectives will be implemented without prejudicing the use of the financial mechanism of the Convention or of other modalities of international cooperation and support, with a view to enhance effectiveness or even to anticipate such an implementation (INDC, 2015).

Furthermore, Brazil will concentrate efforts in increasing cooperation initiatives with other countries, particularly in areas such as biofuels and low carbon, resilient agriculture, renovation and reforestation activities and management of protected areas.

In Brazil, the National Energy Balance Sheet, published by the Ministry of Mining and Energy in 2011 revealed that, in 2010, the industrial sector was responsible for 35.6% of the energy consumption in the country, followed by the transportation sector, with 28.8%, and the energy production sector, with 10.5%. Within the transportation sector, the main contributor to this high consumption is the railroads. In 2008, 58% of the cargo moved in the country was transported by rail. On many of the shipping routes, especially those that lead to ports, intermodal transportation could be used.

In the specific case of the sugarcane supply chain, the main products, sugar and ethanol, must often be transported more than 2000 km to reach their consumer market. Therefore, there is obvious dependence on the use of trucks in order to distribute the products.

In 2010, the sugarcane industry in Brazil generated revenues of R$50 billion and a foreign exchange of R$24.3 billion. Approximately 90% of the milling of sugarcane, the first step in the production of sugar and ethanol, occurs in the south-central region, which ultimately supplies most of the domestic and foreign markets (UNICA, 2011). Approximately 70% of all sugar production in Brazil is destined for the international market. Sugar from Brazil accounts for 53% of the global market. Although it would be possible to use the railways, the primary mode of transportation to the port is by road, because, among other factors, the ports do not have enough storage capacity or adequate infrastructure to receive large loads of sugar. In addition, the offloading time from trains is less than optimal and there is little availability of freight for return trips, as well as a shortage of cars and locomotives. Furthermore, there are right-of-way issues among railway companies and there is a need for improvements in the rail networks.

Ethanol sales are concentrated on the internal market. In 2003, flex-fuel vehicles were introduced. With the expansion of the national flex-fuel fleet, an increasing number of consumers became able to choose between ethanol (that is, hydrous ethanol) and gasoline (which is blended with anhydrous ethanol, in accordance with the current legislation). In 2010, flex-fuel vehicles came to account for 48.1% of the total national fleet.

Ethanol destined to supply the domestic market is transported from the refineries to the distribution centers, from which it is allocated to filling stations. On both legs of this route, the product is moved almost entirely by road, despite the possibility of using railways and waterways.

If the entire carbon cycle is taken into consideration, ethanol produces up to 90% fewer greenhouse gas emissions than gasoline. Prioritizing the use of less polluting modes of transport could increase the appeal of ethanol as an alternative energy source and ensure its sustainability. International programs are increasingly aware of these environmental issues and have recognized ethanol as a product that counters global warming. Mitigation of transport-related emissions could further expand the market for ethanol through its labeling as a sustainable product, the payment of rewards for its use or even the use of methods of certification.

Estimates for 2020, from the Brazilian Sugarcane Industry Association (UNICA), are promising, especially in terms of the potential demand for products of the Brazilian sugarcane industry. For sugar, the UNICA estimates that exports will reach approximately 8.9 million tons and that approximately 2.4 million tons will be sold on the domestic market. As for ethanol, the UNICA estimates that flex-fuel vehicles will come to account for 81% of the national fleet and that external programs for the use of ethanol from sugarcane will have expanded, the demand reaching 13.2 million m3 in the United States alone. The expansion of this capacity would require the expansion of the routes to market, principally the intermodal routes, involving railways, waterways and pipelines, not only for economic reasons but also for environmental considerations. Such an increase in the amount of cargo transported by road would solidify the country's dependence on this mode of transport and increase the share of the transportation sector in the total emissions in the country.

These reductions will help the country to fulfill its stated reduction targets in INDC 2015, corresponding to an estimated reduction of 66% in terms of greenhouse gas emissions per unit of GDP in 2025 and of 75% in terms of emissions intensity in 2030, both in relation to 2005.

The use of renewable energy and a clean energy matrix are important facts to meet less reduction the temperature (Brazil already has one of the largest and most successful biofuel programs to date).

The text published at the end of COP 21 entitled “Transforming our world: the 2030 agenda for sustainable development” for United Nations describes, among other economic and social aspects, the commitment of 190 countries in minimizing the impacts of climate changes on the planet until 2030.

The goal 13 of the text presents the measures to be adopted to combat climate changes and its impacts. Besides measures based on political strategies and awareness of the importance of mitigation, the document suggests a joint target of US$ 100 billion per year until 2020 for the mitigation to be undertaken through UFCCC (United Nations, 2015).

Given its importance, the global climate change requires broad international cooperation to accelerate the reduction of global emissions of greenhouse gases and to deal with the adaptation of its negative impacts. Thus, the document reiterates the commitment to keep global temperature increase below 2 or 1.5°C.

Therefore, the mitigation actions to be taken by Brazil may contribute to the goal of reducing the impacts of climate changes in the world.

The importance of the impact of transport on the environment has prompted various studies in recent years several studies on the topic. Bartholomeu (2006) proposed quantifying the environmental and economic impact of the conservation of Brazilian highways. The author proposed that theme because roads play a major role in the Brazilian transport network, as well as because road transportation makes a significant contribution to greenhouse gas emissions. From an economic perspective, the author assessed issues such as fuel consumption, vehicle maintenance and travel time. The same author also assessed the reduction in the environmental externalities arising from greenhouse gas emissions. The data collected showed that well-maintained roads provide economic gains (less fuel consumed) and environmental benefits (fewer greenhouse gas emissions).

In a study conducted in Liao et al. (2009) compared road transportation and intermodal transportation, in terms of CO_2 emissions, for the transport of containers. The authors employed emissions modeling based on variables such as the intensity of activity and CO_2 emission factors. The results showed that it is possible to significantly reduce emissions of CO_2 by shifting from road transportation to transportation via coastal waterways.

Bauer et al. (2009) conducted a study whose objective was to minimize emissions through the use of intermodal cargo transport. In a departure from the traditional approach, in which the focus is on minimizing the variable cost of transportation, the authors proposed using emissions as an objective function variable, so that the focus would be environmental. The cost minimization was obtained by rerouting the trips to be made between Poland, Austria and the Czech Republic. The new, proposed map reduced cargo transport distances, and the use of intermodal transportation provided a reduction in greenhouse gas emissions. Following that same line of reasoning by Suzuky (2011) posited that greenhouse gas emissions can be reduced by changing the routes of delivery trucks, which reduces fuel consumption.

According to the author, the route must be planned in a way that the heaviest items are unloaded first. The model suggests the minimization of fuel depending on the distance traveled. The results show that it is possible to save fuel only by such planning, based on the approximate distances to be traveled.

Pan et al. (2013) studied the reduction in cargo transport-related greenhouse gas emissions that could be achieved by aggregating the supply chain, using as a study case the flow of goods from a large distribution network, consisting of two retail supply chains. Through a network of streams, the authors attempted to integrate the supply chain by optimizing the load factor for each truck. The authors also evaluated the effects of the environmental and economic costs, using two objective functions in parallel. To estimate the environmental cost, they inserted the function of minimizing CO2 emissions from the transport of goods, whereas they inserted the function of minimizing shipping costs in order to estimate the economic cost. The results indicate the possibility of a 14% reduction in emissions when road transportation alone is used, compared with a 52% reduction when road and rail transportation are used in conjunction. Within the economic context, there was a convergence between the results obtained with minimizing the cost of transport and minimizing emissions when using road transportation alone, meaning that it is possible to reduce emissions and costs when road transportation is used more efficiently. However, when the model assumed the use of more than one transport mode, the results pointed to a trade-off between cost and emissions, because the former cannot be reduced without increasing the latter. Therefore, there is a dilemma between the environment and the economy. In the model employed, cost minimization did not necessarily prioritize the minimization of emissions, and vice versa.

Given the significant contribution of the transportation sector to greenhouse gas emissions and the possibility that changing the mode of transportation will reduce its impact on the environment, this study aims to estimate the benefits, in terms of the reduction in greenhouse gas emissions, to be gained from modifying the national transport network, as it pertains to the sugarcane industry, in order to make it more economically efficient and to use energy sources that are more sustainable. We tested the hypothesis that reorganization of the network through the use of intermodal transportation would provide environmental gains by reducing greenhouse gas emissions. Specifically, we attempted to estimate the economic and environmental impact if the changes projected for the 2020-2021 period in Brazil - including the expansion in transportation infrastructure provided for in the two phases of the Accelerated Growth Program

Table 1. Estimated production of sugar and ethanol in the 2020-2021 during the harvesting season, used in calculating the origin-destination flows in the model.

Product	Market		Total
	Domestic	Foreign	
Ethanol (millions of m^3)	59.5	15.0	74.5
Sugar (millions of tons)	13.0	36.4	49.4

Private and public investment in logistical infrastructure: AGP 1 and 2.

(AGP 1 and AGP 2) developed by the federal government, as well as the reorganization of the sector proposed by private business - are implemented

METHODOLOGY

Origin-destination network

In general, modeling techniques that are used for simulating traffic flows involve the spatial division of the study region into cargo zones in which specific locations are designated centroids of loading and unloading (the points of origin and destination of the cargo) by ESALQ-LOG (2009). In Brazil, the loading centroids in the origin-destination network for the sugarcane industry are sugar and ethanol mills.

As previously mentioned, approximately 70% of the sugar manufactured in Brazil is intended for export, and many of the unloading centroids are therefore seaports. The remaining 30% is divided between consumer use (40%) and industrial use (60%). For the domestic (consumer) sugar market, we selected the municipality with the largest population parameter within each of the micro-regions in Brazil. For each centroid, we used the industrial gross domestic product for the corresponding micro-region as a proxy for the demand for the product, whereas the total population of the micro-region was used as a proxy for domestic consumption.

For ethanol, the unloading centroids are the distribution centers, which imply that all ethanol sold on the domestic market passes through one of those centers and that the ports are used only for ethanol destined for foreign markets. For the purposes of this study, we considered only transportation between plants and distribution centers, because shipping from distribution centers to filling stations involves distances that are relatively short and are primarily covered by road.

Given that the goal of this study was to estimate the origin-destination flow of sugar and ethanol for the 2020-2021 harvest season and evaluate the impact of the planned AGP 1 and AGP 2 infrastructure projects, we attempted to determine whether the increased availability of modes of transport other than road transportation potentiates more intensive use of those alternative modes, thereby reducing economic costs and, more importantly, the environmental impact of cargo transport in Brazil.

To collect the necessary data for the 2020-2021 harvest season, the UNICA estimates of sugar and ethanol production were used, which are presented in Table 1, according to the specific type of market (domestic and foreign).

On January 22, 2007, Federal Decree No. 6025 established the AGP, the objective of which is to stimulate private investment and to expand public investment in infrastructure (Brazil Decreto, 2007). The AGP envisages the construction of railroad lines, including the New Trans-northeastern, Northern and North-South lines, as well as the East-West Integration line. In addition, the AGP proposes waterway recovery and improvement projects along eight corridors, including dredging, boulder removal, installing additional signaling, expanding terminals, updating inland ports and the deployment of lock-and-dam systems. For the specific case of ethanol, the logistics system operated by the company Logum Logistics aims to integrate the waterway system with the pipeline operated by the energy company Petrobras (Brazilian Petroleum). Thus, these projects were included in the modeling designed to estimate the origin-destination flows of sugar and ethanol in the 2020-2021 harvest season.

Proposed mathematical model

The origin-destination flow via a transportation network was estimated with a linear optimization model aimed at minimizing CO2 emissions and, in parallel, minimizing the cost of transportation. Traditionally, the cost function variable is shipping cost. However, in this case, we used environmental cost, defined as the CO2 emissions for the various modes of transportation, as a competing objective function.

The simulation of the origin-destination flows for sugar and ethanol, with the objective of minimizing CO2 emissions, was based on the Minimum Cost Flow Problem model devised by Ahuja[1], as adapted by the

[1] AHUJA, R.K.; MAGNANTI, T.L.: ORLIN, J.B. **Network flows.** New Jersey: Prentice Hall, 1993. 846 p.

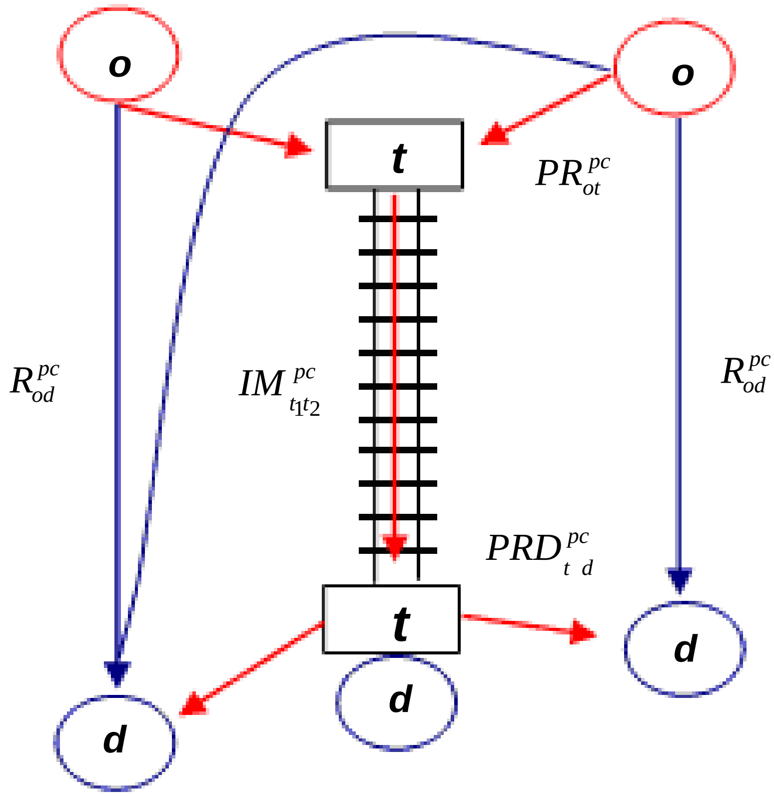

Figure 1. Schematic Diagram of the Minimum Cost Flow Problem model.
Source: Research and Extension in Agribusiness Logistics Group, Luiz de Queiroz Graduate School of Agriculture, University of São Paulo (ESALQ-LOG, 2010).

Research and Extension in Agribusiness Logistics Group of the University of São Paulo Luiz de Queiroz Graduate School of Agriculture (ESALQ-LOG, 2009). The objective function of minimizing shipping costs and the constraints presented by this work were grounded in the adapted model. The objective function of minimizing CO2 emissions presented by the Minimum Cost Flow Problem model has been adjusted by the author on the basis of the equation provided in the adapted model. In brief, an objective function that addressed the minimization of CO2 emissions was developed by referencing the original function (which minimizes the shipping costs).

Figure 1 provides a schematic diagram for the optimization of the network flows, in which each node of the network can be a source region, a region of demand or even a transshipment terminal. The arcs represent the transportation modes available for the flow of cargo (ESALQ-LOG, 2009).

In the estimation of the flow of products of the sugarcane industry, the nodes are the municipalities that have sugar and ethanol mills; the fuel distribution centers; ports; and the centroid municipalities for sugar demand within the micro-regions.

In this model, the arcs represent the road, rail, waterway and pipeline modalities available in 2010, as well as those provided for by the public and private infrastructure projects. Each parameter shown in Figure 1 refers to a node of the network, the flows being defined as follows: *o*: origin (loading centroid); *d*: destination (unloading centroid); and *t*: transshipment terminal (terminal for cargo transfer between modes of transport).

For the mathematical structure of the model, we defined the transfer terminals, by type, as follows: t_1 and t_2 - transshipment terminals for loading and unloading, respectively corresponding to the origin and destination of the cargo flow on a given stretch of railway, pipeline or waterway; and *b* - base for (ethanol) distribution (ethanol distribution center). The proposed mathematical model has the following variables:

- R^{pc}_{od}: Road flow of the product *p* from *o* to *d*, linked to the marketing channel (c, domestic or export market)
- PR^{pc}_{ot}: The flow product *p*, drayage between the center load generator *o*, and terminal load transfer *t*, linked by market channel *c*
- $IM^{pc}_{t_1t_2}$: Intermodal flow of *p* (by rail, water or

pipeline) between t_1 and t_2, linked to *c*

- PRD_{td}^{pc}: The flow product *p,* drayage between cargo transfer terminal *t* bound to the load center of attraction *d*, linked to the market channel *c*

The main objective of the model proposed in this study is to break with the traditional approach of estimating the minimization of transportation costs, by taking environmental issues into consideration. Therefore, in addition to estimating economic costs (that is, shipping costs), we estimated environmental costs (CO_2 emissions). Thus, the model seeks to minimize CO_2 emissions, measured in kilograms per kilometer, in the movement of cargo from *o* to *d*. The sum of flows (corresponds to the volume of cargo procurable by intermodal transportation alternatives. The objective function of minimization of CO_2 emissions, expressed in full, is as follows:

$$ET = \sum_p \sum_{t_2} \sum_d \sum_c (R_{td}^{pc}\, x\, E_{od}^{p}) + \sum_p \sum_o \sum_{t_1} \sum_c PR_{ot}^{pc}\, x\, E_{ot}^{p} + \sum_p \sum_{t_1} \sum_{t_2} \sum_c (IM_{t_1t_2}^{pc}\, x\, E_{t_1t_2}^{p}) + \sum_p \sum_{t_2} \sum_d \sum_c (PRD_{td}^{pc}\, x\, E_{td}^{p}) \quad (1)$$

where*ET* is the total CO_2 emissions, and *E* is the amount of CO_2 emissions for each section of the route.

The minimization of CO_2 emissions, through the minimization of *ET*, is a criterion of the model. For another proposed scenario, the model will be solved by adopting an objective function equation in which the criterion is the minimization of the total cost of transportation (*CT*). Thus, we will be able to determine the impact that minimizing CO_2 emissions has on the *CT* and, subsequently, the impact that minimizing the *CT* has on CO_2 emissions. We intend to evaluate those effects for the 2020-2021 harvest season, considering two scenarios in relation to the AGP 1 and AGP 2 infrastructure projects to be undertaken: one in which those changes have not been implemented; and one in which they have been implemented and the additional modes/new routes of transport are in use.

We will draw comparisons between the two scenarios and thus determine the economic and environmental benefits to be gained from the insertion of these new cargo routes.

The model is expected to allocate flows in such a way that intermodal transportation will be used more intensively and bring not only economic benefits but also environmental gains, with a greater focus on the latter. The minimization of logistical costs (*CT*) is given by the following equation:

$$CT = \sum_p \sum_o \sum_d \sum_c R_{od}^{pc}\, x\, F_{od}^{p} + \sum_p \sum_o \sum_{t_1} \sum_c PR_{ot}^{pc}\, x\, F_{ot}^{p} + \sum_p \sum_{t_1} \sum_{t_2} \sum_c (IM_{t_1t_2}^{pc}\, x\, F_{t_1t_2}^{p}) + \sum_p \sum_{t_2} \sum_d \sum_c (PRD_{td}^{pc}\, x\, F_{td}^{p}) \quad (2)$$

where*F* corresponds to the freight value for each section of the route.

The minimization of costs model and the minimization of CO_2 emissions model are both restricted by the mathematical expressions (equations or inequalities) that follow:

$$\sum_d \sum_c R_{od}^{pc} + \sum_t \sum_c PR_{ot}^{pc} = SUP_o^{pc} \quad (3)$$

$$\sum_o \sum_c R_{od}^{pc} + \sum_t \sum_c PRD_{td}^{pc} = DEM_d^{p} + EXP_d^{p} \begin{cases} \forall d \\ \forall p \end{cases} \quad (4)$$

$$\sum_{o \in o_{uf}} \sum_{d \in d_{ports}} R_{od}^{pc} + \sum_{o \in o_{uf}} \sum_t PR_{ot}^{pc} \le EXP_{uf}^{p} \begin{cases} \forall p \\ \forall uf \\ c \equiv c_{export} \end{cases} \quad (5)$$

$$\textstyle\sum_o R_{od}^{pc} + \sum_t PRD_{td}^{pc} \ge EXP_d^{p} \begin{cases} \forall p \\ \forall d \in d_{ports} \\ c \equiv c_{export} \end{cases} \quad (6)$$

$$\sum_o PR_{ot_1}^{pc} + \sum_{t_2} IM_{t_2t_1}^{pc} = \sum_{t_2} IM_{t_2t_1}^{pc} + \sum_o PRD_{t_2d}^{pc} \begin{cases} \forall p \\ \forall\, c \\ \forall\, t \end{cases} (7)$$

where*SUP* is the supply of sugar and ethanol, *DEM* is the demand for sugar and ethanol, *EXP* is the export of sugar and ethanol, and *UF* is the *Unidade da Federação* (Federal Unit, Brazilian state or district).

In the specific case of ethanol, the model requires that every flow in which the unloading centroids are in the domestic consumer market has a transshipment terminal (distribution center) as its origin. Thus, the model does not allow ethanol to reach the filling stations at retail without first passing through a distribution center. For the export routes, flows can be directly from the loading centroids (ethanol plants) to the unloading centroids (ports).

Due to this particularity, the model was adapted and equations (8) through (10) present specific restrictions for ethanol:

$$\sum_{t_2 \in b} PRD_{t_2d}^{pc} = DEM_d^{p} \begin{cases} \forall d \\ p \equiv ethanol \\ c \equiv c_{domestic} \end{cases} \quad (8)$$

$$\sum_o R_{od}^{pc} \sum_{t_2} PRD_{t_2}^{pc} = EXP_d^{p} \begin{cases} \forall d \in d\_ports \\ p \equiv ethanol \\ c \equiv c_{export} \end{cases} \quad (9)$$

Table 2. Emissions of CO_2 for each mode of transportation.

Mode of transportation	Road	Rail	Water	Pipeline
CO_2 emissions (kg/km)	1.64	0.481	0.334	0

Table 3. Comparison between the two scenarios and the two objective functions, based on estimates of sugar production from the 2020-2021 sugarcane harvest in Brazil.

Objective function	Costs	Emissions
Minimizing emissions		
Scenario 1	R$61.87/tst	0.042 tCO_2/tst
Scenario 2	R$54.42/tst	0.034 tCO_2/tst
Minimizing costs		
Scenario 1	R$59.06/tst	0.046 tCO_2/tst
Scenario 2	R$51.81/tst	0.038 tCO_2/tst

Scenario 1, infrastructure projects not completed; Scenario 2, all infrastructure projects completed and new modes/routes in use; R$, Brazilian reals; tst, ton of sugar transported; tCO_2, tons of CO_2 emissions.

$$\sum_{d \in d\_ports} \sum_{o \in uf} R_{od}^{pc} \sum_{d \in d\_ports} \sum_{t_2} PRD_{t_2 d}^{pc} = EXP_{uf}^{p} \begin{cases} \forall uf \\ p \equiv etanol \\ c \equiv c_{export} \end{cases} \tag{10}$$

This proposed mathematical model of optimization was processed with the use of the linear programming solver CPLEX (IBM Corporation, Armonk, NY, USA) via General Algebraic Modeling System software (http://www.gams.com/download/). The compilation time was 94.29s, the generation time was 20.75s, and the run time was 68.16s.

Data

The data relating to CO_2 emissions for water, rail and road routes were obtained from a document published by the Brazilian National Agency for Waterway Transportation (Oliva, 2010). Data relating to CO_2 emissions for pipelines were provided by Transpetro (a division of Petrobras)[2]. Table 2 shows the emission values considered for each transportation mode.

The road freight values were obtained from the data base of the Freight Information System by ESALQ-LOG (2010). However, that database does not include all available routes needed to estimate the model.

[2]TRANSPETRO. **Emissões de CO_2 no escoamento por dutovia** [CO_2 emissions from transport via pipeline]. In-house communication. Contact: faletranspetro@petrobras.com.br. Dated: Jan 27, 2011.

Therefore, an estimate was made using a linear regression model within the ordinary least squares method. In the estimation, the units of measure of the freight values, in Brazilian reals (R$), were R$/ton of sugar transported and R$/$m^3$ of ethanol transported, in relation to the distance covered.

To estimate rail freight values, we used the rates obtained with the shipping simulator devised by the Brazilian National Agency for Overland Transport (ESALQ-LOG, 2010). Pipeline freight values were based on the rates charged by Transpetro for the transportation of fuels via its pipeline network. The waterway freight *t* values were estimated from the rates currently charged on the Tietê-Paraná and Madeira routes.

RESULTS AND DISCUSSION

Sugar

Table 3 shows a comparison between the two scenarios (infrastructure projects not completed versus all infrastructure projects completed and new modes/routes in use) for the transport of sugar. When the focus was minimizing costs, the greater use of intermodal transportation was estimated to reduce emissions (in tons of CO_2 per ton of sugar transported) by 0.008tons per ton and costs (in R$ per ton of sugar transported) by R$7.25per ton, compared with 0.008tons per ton andR$7.45per ton, respectively, when the focus was minimizing emissions. The AGP 1, AGP 2 and privately funded infrastructure projects will generate economic and environmental benefits to sugar producers, who will be

Table 4. Comparison between the two scenarios and the two objective functions, based on estimates of ethanol production from the 2020-2021 sugarcane harvest in Brazil.

Objective function	Costs	Emissions
Minimizing emissions		
Scenario 1	R$60.31/m^{3}et	0.064 tCO_2/m^{3}et
Scenario 2	R$51.10/m^{3}et	0.038 tCO_2/m^{3}et
Minimizing costs		
Scenario 1	R$51.10/m^{3}et	0.074 tCO_2/m^{3}et
Scenario 2	R$45.04/m^{3}et	0.040 tCO_2/m^{3}et

Scenario 1, infrastructure projects not completed; Scenario 2, all infrastructure projects completed and new modes/routes in use; R$, Brazilian reals; m^{3}et, cubic meters of ethanol transported; tCO_2, tons of CO_2 emissions.

able to earn and trade carbon credits. In addition, the producers will be able to access new consumer markets, because the product will have a sustainable brand and contribute to Brazil meeting its voluntary targets for reducing greenhouse gas emissions.

Over a period of less than three years, the savings generated from the expansion of the rail and waterway networks could be approximately 1.1 million tons of CO_2 emissions and R$1.1 billion, for the transport of sugar alone, given the estimated 49.4 million tons to be transported. If the new routes are not ready for use and there are no restrictions on the use of intermodal transportation, regardless of which objective function is applied, there would be approximately 2.2 million tons of CO_2 emissions/year and the costs would be R$2.9 billion/year.

In contrast, if all of the new modes and routes of transportation are fully able for use, the model allocates routes so that, on average, CO_2 emissions would be approximately 1.7 million tons/year and transportation costs would R$2.5 billion/year. We emphasize that these results were obtained assuming that the relative freight values and the degree of competitiveness among the various modes of transport would remain constant over time.

This assumption was made because predicting alterations in the relative freight values was not within the scope of this study and would have no scientific basis for consideration.

As previously mentioned, approximately 70% of the sugar manufactured in Brazil is for export. Railways, by their design, enable cargo to be more concentrated. Therefore, rail transport could be used more intensively without the need to also use the road network for distribution among the final destinations within the various micro-regions.

Improving the transportation infrastructure in the country is important in that it can reduce the costs incurred in the marketing of sugar, as well as providing environmental benefits.

Ethanol

Because the sugarcane industry incurs economic costs and emits CO_2 in the transport of ethanol, the insertion of new transport routes is expected to have a significant impact and intensify the debate on the importance of the transportation sector and environment. Table 4 shows a comparison between the two scenarios (infrastructure projects not completed versus all infrastructure projects completed and new modes/routes in use) for the transport of ethanol. When the focus was minimizing costs, the greater use of intermodal transportation was estimated to reduce emissions by 0.034 tons of CO_2 per cubic meter of ethanol transported and costs by R$10.32 per cubic meter of ethanol transported, compared with 0.026 tons of CO_2 per cubic meter and R$9.21 per cubic meter, respectively, when the focus was minimizing emissions. Therefore, the environmental benefit of minimizing costs is evident.

As in the case of sugar, it is noteworthy that there lative freight values among transport modes were assumed to remain constant, which might have precluded an even greater shift toward the use of intermodal transportation, especially when the objective was to minimize costs. The possible gains in competitiveness arising from improvements in infrastructure could result in even greater benefits.

In addition to the possibility of earning and selling carbon credits, ethanol producers, like sugar producers, might be able to access new consumer markets, because the derivatives of sugar cane could be transported in a sustainable manner, producers always seeking to maintain a balance between supplying the market and protecting the environment.

If the entire carbon cycle is taken into consideration, the use of ethanol produces up to 90% fewer CO_2 emissions than does the use of gasoline. Ethanol has gained worldwide recognition as an advanced fuel. In the United States, there is a market in biofuel credits for ethanol from sugarcane, because it has a mitigation capacity greater than that of ethanol from corn. The possibility to further reduce emissions from the production cycle of ethanol from sugarcane could increase the value of the biofuel credits and open new consumer markets for the product.

Another point in favor of the adoption of sustainable practices and the more widespread use of less polluting modes of transport is the ability to contribute to Brazil meeting its voluntary targets for reducing greenhouse gas emissions.

Over a period of less than three years, the savings generated from the expansion of the rail, waterway and pipeline networks used in the transport of ethanol could be approximately 5.5 million tons of CO_2 emissions and R$2.2 billion, with an estimated 74.5 million cubic meters to be transported. When we aggregate the values obtained for sugar with those obtained for ethanol, those estimates increase to 6.6 million tons of CO_2 emissions and R$3.3 billion. In monetary terms, this would be a savings in logistics that would directly increase the competitiveness of the products, regardless of the benefits that transportation that is more sustainable would provide to society and the extent to which it would improve the image of the sector. In addition, the sugarcane industry is expected to achieve a reduction in CO_2 emissions of 112 million tons by 2020, and the mitigation of 2.2 million tons of CO_2 obtained by altering the transportation modalities for the origin-destination flows of sugar and ethanol would amount to nearly 2% of that goal.

Our findings related to the products of the sugarcane industry indicate that improving the transportation infrastructure is an important means of reducing the costs incurred in the marketing of sugar and ethanol, as well as providing environmental benefits. However, it should be evident that such improvements must be accompanied by incentives for the shipper to use modes of transportation other than the roadways. In addition, it is essential that measures be taken to provide shippers with the sense of security needed in order for them to opt for this type of transport. Furthermore, structural problems, such as differences in rail gauge, the lack of railcars for loading and the lack of right-of-way must be resolved among the companies operating the railway lines.

Conclusion

The trade-off between minimizing transport costs and minimizing transport-related CO_2 emissions was evident in both scenarios and for both products. The estimated reduction in CO_2 emissions occurred at the expense of transport costs. When the model was focused on reducing CO_2 emissions, the flow of cargo was concentrated in the less polluting modes of transportation and was then distributed to the consumer markets over short distances, compared with intermodal transshipment unloading. Although generating less pollution, transportation over these short stretches is associated with higher freight values due to the fixed costs involved. In addition, more intensive use of intermodal transportation could increase the distance traveled, also resulting in an increase in transportation costs. The fact that we assumed fixed relative freight values among the various modes of transportation might have impeded the distribution of the use of intermodal transportation by the model.

Our findings underscore the importance of using a transportation network that is less polluting and more well-balanced. We have shown how the sugarcane industry can make a greater contribution to that goal, especially considering that, in the case of ethanol, clean and sustainable initiatives are among the main principles highlighted by the industry.

The mitigation of 2.2 million tons of CO_2 obtained in 2020 by altering the transportation modalities for the origin-destination flows of sugar and ethanol represents about 0.3% the target the Brazilian's reductions in 2030 [0.8 GtCO2e (this impact is generated only by changing a transportation mode)].

The improvement in transport infrastructure in the country is an important reduction of costs incurred in the marketing of sugar and ethanol, and the benefits generated by environmental issues. However the infrastructure available for use of is only one aspect of the logistics system in Brazil. In selecting a mode of transport, the shipper considers timely issues such as transit time, guarantees of safe transfer, losses, fulfillment of contracts, transportation availability and competitiveness of pricing, as well as structural aspects such differences in rail gauge, the availability of railcars for loading and right-of-way between railway line operators. Pending the resolution of these questions there can be no expansion of infrastructure that makes the national transportation network more sustainable. It is up to governments, transportation concerns and industry officials to advise shippers and facilitate their decisions regarding the various modes of transportation. The fact that the use of intermodal transportation brings only benefits is obvious and has been proven. What is needed is to make it a viable alternative in a way that its use becomes commonplace and habitual.

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