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An agent-based modeling approach

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Exploring policy options to spur the expansion of ethanol production and consumption in Brazil: An agent-based modeling approach

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ABSTRACT

The Brazilian government aims to increase the share of biofuels in the energy mix to around 18% by 2030, which implies an increase of ethanol production from currently 27 bln liters to over 50 bln liters per year. Biofuel policies play an important role in ethanol production, consumption, and investment in processing capacity. Nevertheless, a clear understanding of how current policies affect the evolution of the market is lacking. We developed a spatially-explicit agent-based model to analyze the impact of different blend mandates and taxes levied on gasoline, hydrous, and anhydrous ethanol on investment in processing capacity and on production and consumption of ethanol. The model uses land use projections by the PCRaster Land Use Change model and incorporates the institutions governing the actors' strategic decision making with regard to production and consumption of ethanol, and the institutions governing the interaction among actors. From the investigated mix of policy measures, we find that an increase of the gasoline tax leads to the highest increased investments in sugarcane processing capacity. We also find that a gasoline tax above 1.23 R$/l and a tax exemption for hydrous ethanol may lead to doubling the production of ethanol by 2030 (relative to 2016).

1. Introduction

During the 2015 United Nations climate conference in Paris, Brazil indicated that bioenergy will significantly contribute towards their realization of climate objectives. The Brazilian government aims to increase the share of biofuels in the energy mix to around 18% by 2030 (Federative Republic of Brazil, 2015), which implies that ethanol demand will increase from 27 bln liters per year in 2016 to more than 50 bln liters in 2030 (IEA, 2017). If this projected demand for ethanol is to be met by domestic supply, it would be necessary to double the production of ethanol in the next years. It is expected that over 70% of the increase in ethanol supply is to be met by hydrous ethanol because of the technical blend constraints of anhydrous ethanol in the fuel market (Tolmasquim et al., 2016). Nevertheless, the feasibility of achieving this increase in ethanol supply with the current set of policies is unclear. The effect of existing Brazilian policies on the evolution of the ethanol market is not well understood (De Gorter et al., 2013).

The Brazilian experience with biofuels dates back to the early part of the last century. Nevertheless, it was not until the global crisis in 1970 that the Brazilian government initiated the large scale implementation of ethanol in Brazil with the ProAlcool program (Rosillo-Calle and Cortez, 1998). Since then, Brazil has become the world's top producer of sugar and, until 2005, the top producer of ethanol. Nowadays, Brazil has the second largest production of ethanol after the U.S. de Carvalho et al. (2016). Key success factors of the Brazilian ethanol market are the favorable environmental conditions, technological innovations, and the governmental policy (Stattman et al., 2013).

On the technical side, technological innovations such as flex plants and flex vehicles are at the core of the ethanol market structure. Flex plants can produce flexible ratios of sugar and ethanol from sugarcane (McKay et al., 2015). Based on the water content, ethanol can be classified as: hydrous ethanol (up to 4.9% v/v of water) and anhydrous ethanol (up to 0.4% v/v of water). Users of flex vehicles can switch back and forth from E100 (hydrous ethanol) to gasohol (a blend of gasoline and anhydrous ethanol, of which the max share of anhydrous ethanol is 27.5% v/v due to technical limitations) (Pacini and Silveira, 2011). Indeed, this flexibility at both the supply and the demand side of the market is one of the factors responsible for the success of ethanol in

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Brazil (Alonso-Pippo et al., 2013).

On the policy side, the governmental ethanol policy has undergone many changes (Stattman et al., 2013). The ProAlcool program had different phases (creation, consolidation, expansion, and political uncertainty) with different characteristics (Rosillo-Calle and Cortez, 1998). The period 1979–1985 was marked by strong state intervention, whereas the sugar and ethanol industry were deregulated in the 1990s. In this period subsidies and regulation were gradually removed (Hira and de Oliveira, 2009). The revitalization of the ethanol market was triggered by the introduction of the flex vehicle in 2003 (de Freitas and Kaneko, 2011).

The behavior of the Brazilian ethanol market is shaped by both governance structures and policy instruments. The interaction between farmers and mill/distillery owners is governed by the Conselho de Produtores de Cana-de-Açúcar, Açúcar e Etanol do Estado de São Paulo (CONSECANA-SP) mechanism. In this governance structure, the sugarcane price is determined by two factors: the amount of total recoverable sugar (TRS) in the sugarcane and the prices of sugar and ethanol on the domestic and foreign markets (Ferraz Dias de Moraes and Zilberman, 2014). Policy instruments such as blend mandates, and taxes levied on gasoline, hydrous, and anhydrous ethanol influence patterns of demand and production of ethanol. For instance, when the government increased the CIDE (**C**ontribution for **I**ntervention in the **E**conomic **D**omain) tax for gasoline in 2015, ethanol demand and production increased (Barros and Berk, 2015). These instruments and their interaction produce distortions in the ethanol market that might shape both the development of the ethanol industry (Demczuk and Padula, 2017; Khanna et al., 2016), and the share of biofuels in energy consumption.

The understanding of the effect of policies on the ethanol market is still limited. Analyses have been carried out to shed light on the effects of U.S. policies on Brazilian markets (Archer and Szklo, 2016; Debnath et al., 2017), on the ethanol-sugar-oil nexus (Bentivoglio et al., 2016), on the effects of blending targets around the world on sugarcane demand in Brazil (Banse et al., 2008; Lapola et al., 2009) and on the effects of Brazilian policies on ethanol markets (De Gorter et al., 2013; Demczuk and Padula, 2017; Drabik et al., 2015; Cavalcanti et al., 2012).

Studies using a structural economic model of the Brazilian ethanol market include Drabik et al. (2015) and Demczuk and Padula (2017). The mathematical model of Dabrik et al. indicated that a low gasoline tax and a high tax exemption for anhydrous ethanol lead to a reduction in both ethanol and sugar prices. Nevertheless, this model neglected the effect of institutions at two levels. First, at the level of decision making, the profit maximizing behavior by the flex plants that determines the production of ethanol and sugar was not included. Although the authors did take into account the shift in demand curves from E100 to gasohol, this mechanism was imposed on the model. In reality, consumption patterns for both fuels emerge as a result of the strategic behavior of the flex vehicle users (Pacini and Silveira, 2011). Second, at the level of governance structures, the model neglected the CONSECANA-SP mechanism that determines the sugarcane price.

Demczuk and Padula (2017) developed a system dynamic model to analyze the effect of Brazilian policies on the development of the ethanol industry. The authors argued that the liberalization of the gasoline prices and the homogenization of sales taxes on ethanol among the Brazilian states could reduce uncertainty in the ethanol sector, and thus encourage investments in technology and production capacity. This modeling study incorporated the CONSECANA-SP mechanism, but it neglected the profit maximizing behavior by the flex plants and the arbitrage in the consumption of gasohol and hydrous ethanol by the flex vehicle users, as well as the diversity among flex plants (e.g. they do not produce the same sugar to ethanol ratio under the same market prices) and among the flex vehicle users (e.g. they do not all consume the same fuel given the same fuel prices).

In this study, we developed a spatially-explicit agent-based model of the Brazilian ethanol/sugar market to explore the effect of biofuel policies on the market behavior. The model accounts for the institutions governing the actors' strategic decision making with regard to production of ethanol by including the profit maximization behavior of the flex plants; the consumption of ethanol by including the arbitrage behavior of the users of the flex vehicles; and the investment in processing capacity of sugarcane. The model is spatially explicit to account for the influence of the location of the sugarcane fields and their availability on the decision of investment in sugarcane processing capacity. The agent-based model uses land use projections provided by the PCRaster Land Use Change (PLUC) model (Verstegen et al., 2016) to explicitly account for expansion of land for sugarcane production in specific locations. The agent-based model also accounts for the interaction among actors by incorporating the CONSECANA-SP and supply and demand mechanisms; for the diversity among actors by including differences in the preferences in the consumption of ethanol of flex vehicles users, and differences in the production ratio of sugar and ethanol of flex plants. In particular, the model is used to shed light on the following research question:

- What is the combined effect of different options for blend mandate and tax levied on gasoline, hydrous, and anhydrous ethanol on the development of the sugarcane-ethanol market in Brazil?

We focus only on sugarcane-ethanol (1st generation ethanol[1]) as it is projected that the highest share in the production of ethanol in the period 2017–2030 will come from sugarcane-ethanol. According to Tolmasquim et al. (2016), 2nd generation ethanol[2] will emerge in considerable volumes as of 2023, reaching 2.5 billion liters in 2030.

The paper is organized as follows: Section 2 provides a description of the concepts underpinning the model structure, an explanation of the developed agent-based model, and the data used. The results are presented in Section 3, followed by a discussion in Section 4. Finally, conclusions are drawn in Section 5.

2. Theory and method

This section describes the methodological improvements performed and considered crucial for modeling the ethanol market in Brazil.

2.1. System diagram and conceptual framework

Fig. 1 shows a system diagram of the Brazilian ethanol/sugar market. The system is analyzed from the perspective of the Brazilian government. It is assumed that the Brazilian government aims to increase the share of ethanol in the energy matrix as well as encourage expansion in sugarcane processing capacity of flex plants. While the government has used policy instruments to spur the production and consumption of ethanol such as investments in RD&D in universities and research centers, subsidies to metallurgic industries and farmers, fiscal policies (tax levied on gasoline, hydrous, and anhydrous ethanol), and blend mandates, we focus on fiscal policies and blend mandates. It is assumed that the behavior of the system is driven by a number of external factors as depicted in Fig. 1.

The Brazilian ethanol market is a complex adaptive system. It consists of heterogeneous actors (farmers, ethanol/sugar producers, distributors, and end-users) interacting in a dynamic environment and regulatory regime. Actors constantly adapt their behavior to changing market prices and available supply of ethanol and sugar. Producers

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[1] 1st generation ethanol refers to the ethanol that has been derived from edible sources such as corn, starch, and sugarcane.

[2] 2nd generation ethanol refers to the ethanol that has been derived from non-food biomass such as lignocellulosic biomass, agricultural residues or waste, and non-food energy crops.

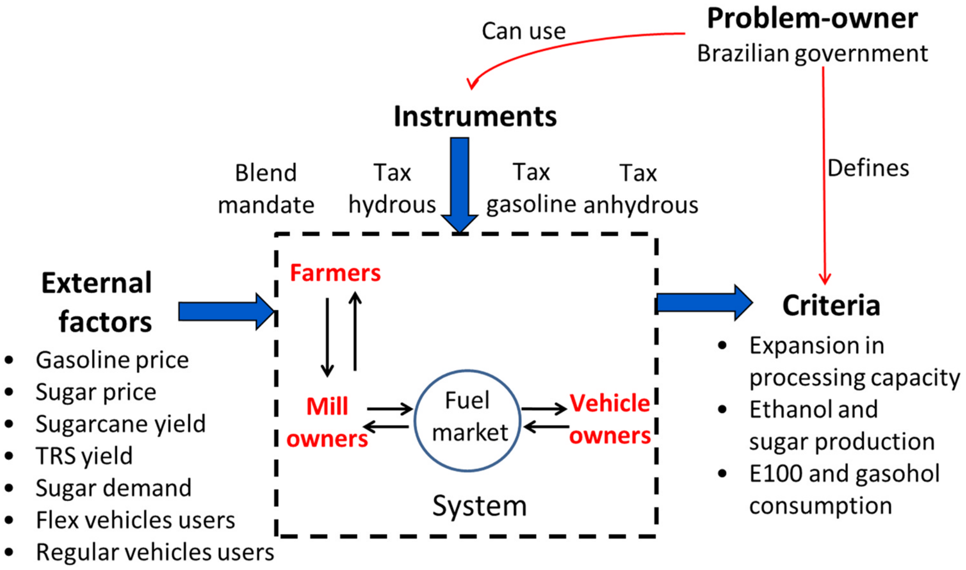

Fig. 1. System diagram with interacting actors of the Brazilian ethanol market.

adjust their production ratio between ethanol and sugar in accordance to their own specific market expectation. Flex vehicle users switch from E100 to gasohol if a significant increase in ethanol prices occurs, and switch back in case of a decrease.

The system was conceptualized based on the tenet that an adequate representation of a complex system stems from the integration of knowledge of various domains and disciplines (van Dam et al., 2013). The conceptual framework proposed by Moncada et al. (2017a) was chosen as a starting point for analysis as it has been successfully used in the analysis of how institutions affect the evolution of biofuel supply chains in Germany (Moncada et al., 2017b). The basic principle of the framework assumes that the behavior of the complex socio-technical system is the result of the interaction of three elements: the physical system, the network of actors, and institutions (see Fig. 2).

The physical system refers to the physical objects such as: farms, mills/distilleries, and vehicles. The actors are the entities that make decisions such as: farmers, mills/distillery owners, and end-users (car owners). Finally, institutions are the rules that shape actors' behavior. Examples of institutions are: norms, regulations, technical and operational standards, legislation, policies, governance structures, and traditions (North, 1990).

Institutions interact with the network of actors at different levels. At the level of one single actor, institutions (i.e. games) refer to the rules, norms and shared strategies of individuals within an organization. In the Brazilian ethanol market, the selection of a production ratio for sugar/ethanol by refineries accounts for the interaction between

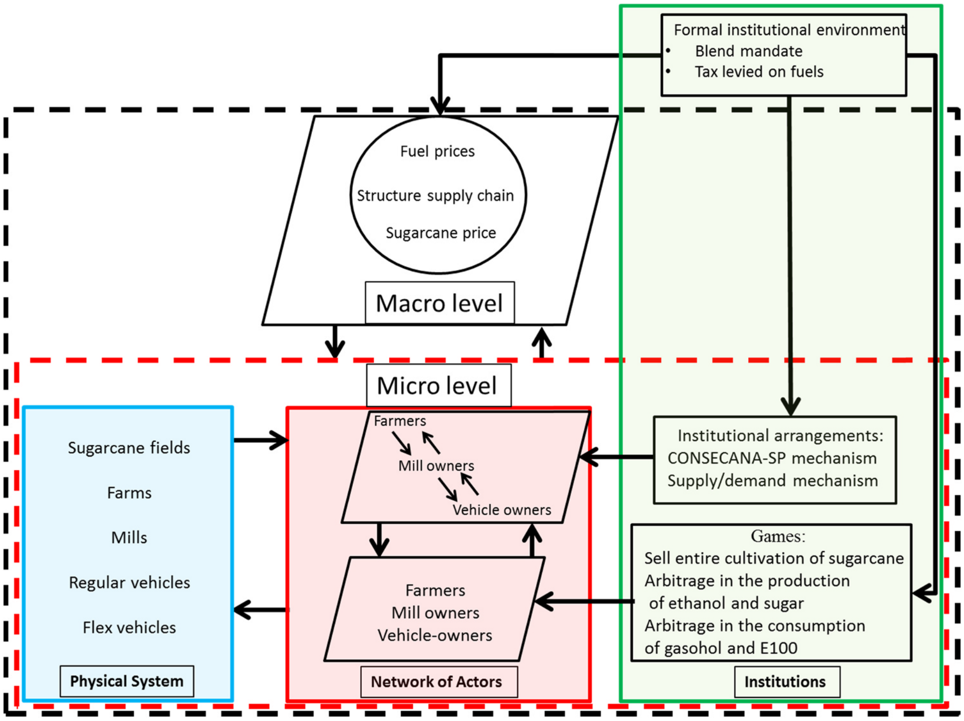

Fig. 2. Conceptual framework adapted from Moncada et al. (2017a). The dashed black box line represents the system boundaries. The dashed red box line separates the micro level from the macro level. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

institutions and actor at this level. At one level of analysis higher (i.e. institutional arrangements), institutions describe how different actors interact. Usually, this interaction is carried through by three mechanisms: spot market, bilateral contracts, and vertical integration. In this study, the interaction between farmers and mills/distillery owners is governed by the CONSECANA-SP mechanism. At the same level of analysis, it was assumed that the interaction between mills and car drivers is governed by a supply-demand mechanism. That is, the price and quantity of the fuels to be traded are determined by the intersection of the supply and demand curves. In reality, however, distribution companies and gas stations owners are responsible for a significant share of the final prices because of cartel practices. At the highest level of analysis (i.e. formal institutional environment), institutions refer to the rules of the game. The blending mandate, tax exemptions, and the promotion of flex vehicles are examples of institutions in the Brazilian ethanol market. At this level, institutions are assumed to be exogenous. We focus our analysis on the effect of the blend mandate and taxes levied on gasoline, hydrous and anhydrous ethanol on the development of the sugarcane-ethanol market.

The theories used to describe the interaction among different building blocks are: complex adaptive systems (CAS), and rational choice theory. CAS is used to describe how the macro behavior of the system emerges as a result of the interactions among different system components and how, in turn, these components adapt to the macro behavior they created (Holland and Miller, 1991). Rational choice theory is used to describe the decision making of mill owners and flex vehicle owners with regard to the production and consumption of ethanol, respectively (Browning et al., 2000).

Supported by these theories, the conceptual framework is formalized into an agent-based model to analyze the influence of formal institutions on the evolution of the Brazilian sugarcane ethanol market. Agent-based modeling (ABM) was chosen as a modeling paradigm for its explicit bottom-up approach, easiness of including the effect of preferences on actors' decision making, the actors' diversity, and actors' adaptive behavior. These are necessary elements to describe a complex adaptive system such as the Brazilian ethanol market. These elements have been neglected by previous studies (De Gorter et al., 2013; Demczuk and Padula, 2017; Drabik et al., 2015). Applications of ABM in the analysis of socio-technical systems vary from economics (Padgett et al., 2003; Boero et al., 2004; Robinson and Rai, 2015; Farmer and Foley, 2009) to energy systems (Connolly et al., 2010; Bale et al., 2015; Kuznetsova et al., 2014; Li and Shi, 2012; Rai and Henry, 2016) and supply chains (van Dam et al., 2009; Behdani et al., 2010).

2.2. Modeling framework

The modeling framework consists of two building blocks: the PLUC model and the agent-based model of the Brazilian sugar-ethanol market. PLUC is a spatial explicit land use change model that stochastically projects annual land use maps (Verstegen et al., 2012). In a previous study, it has been applied to Brazil, for which it projects the expansion and contraction of 11 different land use types between 2012 and 2030 at a 5 × 5 km resolution (Verstegen et al., 2016). As sugarcane is one of the 11 land use types, this study provides us with annual probability maps of the occurrence of sugarcane fields from 2012 to 2030. This information is supplied to the agent-based model of the Brazilian market to model the expansion in the production of sugarcane. It is assumed that this process of expansion is driven by an increase in the demand for sugar or ethanol.

The structure of the agent-based model was designed using the pattern-oriented-modeling approach (Grimm et al., 2005). Three patterns guided the design: flexibility in the production of ethanol and sugar, flexibility in the consumption of ethanol, and the location of sugarcane availability. The model is spatially-explicit as the sugar market is local, decentralized, and land for expansion is limited. The following description of the agent-based model is based on the ODD (Overview, Design concepts, and Details) protocol proposed by Grimm et al., (2006). The model was implemented in NetLogo (Wilensky, 1999) along with the R extension of NetLogo (Thiele and Grimm, 2010).

2.2.1. Purpose

the aim of the model is to study the influence of various policy instruments on the expansion of the Brazilian sugarcane ethanol market. Unlike previous thinking about the Brazilian ethanol market (De Gorter, 2013; Demczuk and Padula, 2017; Drabik, 2015), this model takes a bottom-up approach. The impact of policies on both actors' preferences for production and consumption of ethanol, and actors' interactions is explicitly modeled.

A hallmark of the Brazilian ethanol market is its flexibility in both production and consumption of ethanol. The mapping between policies and actor behavior leads to a better description of the flexibility of the ethanol market, which is the result of the aggregation of actors' decision making on production and consumption of ethanol.

2.2.2. Entities, state variables and scales

The entities in the model are the actors in the supply chain. Actors, contrary to traditional economic analysis, behave based on their own local information (i.e. actors have bounded rationality). Farmers, mills/distillery owners, and drivers are the actors considered in our analysis of the ethanol-market. Farmers perform the role of sugarcane producers and suppliers; the main farmers' state variables are: farm area, sugarcane yield, and TRS yield. Mills/distillery owners perform the role of sugar and ethanol producers and suppliers; the main mills/distillery owners' state variables are: type (flex plant, sugar plant, and ethanol plant), sugarcane processing capacity, production costs, and production ratio of sugar and ethanol. Vehicle owners perform the role of fuel consumers; main vehicle owners' state variables are: vehicle type (flex vehicle,[3] regular vehicle[4]), energy demand, and preferences in the consumption of fuels. Farmers and mills are modeled spatially explicitly, whereas drivers are not. This is because we assumed that E100 and gasohol prices are uniform over space. The global environment consists of the policy instruments (blend mandate, taxes on gasoline, hydrous, and anhydrous ethanol), and the exogenous factors (annual world market prices of sugar and gasoline, number of flex and gasohol vehicles, sugar demand, and sugarcane and TSR content yield). The temporal extent of the model is 18 years (2013–2030) and the time step is one year. The model is spatially explicit, covering the whole of Brazil. The PLUC input has a resolution of 5 × 5 km.

2.2.3. Process overview and scheduling

the scheduling is formed by a set of events that take place sequentially in discrete periods within a year. During harvest season, farmers *harvest sugarcane*, *negotiate* with the mills agents about price and quantity to be traded and *deliver the sugarcane* to the mill as it was agreed. These transactions are decentralized and take place at different locations. The interaction between farmers and mills agents is bound to their spatial location. Mills only interact with farmers within a radius of up to 50 km (Sant'Anna et al., 2016).

Mills/distillery owners *store* the sugarcane and maximize profits *by deciding on volumes of sugar, hydrous and anhydrous ethanol to be produced*. In each time period, Mills/distillery owners *produce* sugar and ethanol and *ask prices and quantities to the sugar and fuel markets*. Drivers *choose* between E100 and gasohol based on relative prices. According to the market outlook, mills agents *decide about the expansion of the sugarcane processing capacity*. The new sugarcane processing capacity starts operation at the third year of construction.

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[3] Flex vehicles can run in any combination of E100 (hydrous ethanol) with gasohol (blend of gasoline and anhydrous ethanol).

[4] Regular vehicles can only run with gasohol.

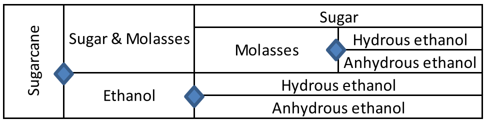

Fig. 3. Levels of decision as to production of sugar, hydrous, and anhydrous ethanol. Each rhomboid represents a level of decision making in the model.

2.2.4. *Design concepts*

The concepts underpinning the design of the agent-based model are presented below.

Basic principle: The basic principle applied in the model is the rational choice theory. This theory is used to describe the decision making on production of sugar and ethanol, and consumption of gasohol and E100. Nevertheless, unlike previous studies (De Gorter et al., 2013; Demczuk and Padula, 2017; Drabik et al., 2015), this model incorporates the influence of diversity in preferences in the decision making process.

2.2.4.1. Emergence. Emergent system dynamics includes gasohol and E100 prices, total production of sugar and ethanol, total demand for gasohol and E100, and the expansion of the processing capacity of sugarcane.

2.2.4.2. Adaptation. Flex mill owners and the drivers of flex vehicles are the entities that exhibit adaptive behavior in the model. Owners of flex mills adapt their production ratios of ethanol/sugar based on market signals (see Fig. 3). This behavior is driven by a profit maximization strategy. Thus, high prices of sugar (ethanol) lead to an increase in the production of sugar (ethanol).

The decision of the flex mills about the volumes of sugar and ethanol to be produced is modeled as an optimization problem as presented below:

$$\max_{x_s,\, x_h,\, x_{hm}} f = \sum_{i=1}^{3} \pi_i \tag{1}$$

subject to:

$$x_{s_{\min}} \le x_s \le 0.65 \tag{2}$$

$$0.2 \le x_h \le x_{h_{\max}} \tag{3}$$

$$0.2 \le x_{hm} \le x_{h_{\max}} \tag{4}$$

where π_i is the profit derived from product i(sugar, hydrous, and anhydrous), x_s is the ratio of sugar production to sugarcane processed (the rest is used for ethanol production),x_h is the ratio of hydrous production to total ethanol production from sugarcane (the rest is anhydrous),x_{hm} is the ratio of hydrous production to total ethanol production from molasses. $x_{s_{\min}}$ is the minimum in the ratio of sugar production to sugarcane processed, $x_{h_{\max}}$ is the maximum in the ratio of hydrous production to total ethanol production. Values for $x_{s_{\min}}$ and $x_{h_{\max}}$ differ among mills. These values were obtained from a uniform distribution $x_{s_{\min}} \in U(a, b)$ and $x_{h_{\max}} \in U(c, d)$ for sugar and hydrous ethanol, respectively. The intervals of the uniform distribution are determined in the calibration of the model (see Appendix A).

To account for the influence of policy instruments (i.e. gasoline tax) on the decision making about the volumes of hydrous and anhydrous ethanol to be produced, it was assumed that the values in Eqs. (3) and (4) are estimated based on the variation of the gasoline tax with respect to the value of the gasoline tax used in the model calibration.[5]

$$\Delta t_G = t_G - t_{G_{baseline}} \tag{5}$$

$$\Delta x = \frac{\left(\frac{\Delta t_G}{0.22} \cdot 10\right)}{100} \tag{6}$$

$$x_{h_{\max}} = x_{h_{\max}} + \Delta x \tag{7}$$

where:

Δt_G: difference in the gasoline tax with respect to the baseline.
t_G: gasoline tax.
$t_{G_{baseline}}$: gasoline tax in the baseline.
Δx: difference in the maximum production ratio of hydrous with respect to the baseline.

Drivers of flex vehicles react to price signals and change from one fuel to the other on a daily basis, for this type of vehicles can use either ethanol or gasoline. The criterion for choosing ethanol (E100) as opposed to gasoline is:

$$\frac{P_{ethanol}}{P_{gasoline}} \le T_c \tag{8}$$

where T_c is the drivers' preference of the relative price between E100 and gasoline. $P_{ethanol}$ and $P_{gasoline}$ are the prices for ethanol and gasoline, respectively. On average, E100 is considered to deliver 70% of the mileage of gasoline for the same volume of fuel. Thus, according to classical economic theory, $T_c = 0.7$, whereas in our model $T_c = N(m,\ 0.1)$ to account for the fact that some drivers have a preference for the consumption of ethanol even when this is not the optimal choice (Pacini and Silveira, 2011). The mean of the normal distribution (m) is calibrated (see Appendix A). Strategic behavior of drivers as to buying gasohol/flex vehicles was neglected. The scope of the model as to drivers' decision making was limited to the choice of the consumption of fuels.

2.2.4.3. Objectives. Flex mill owners are profit maximizing agents. They aim to maximize their profits by shifting the production ratio of sugar to ethanol. The production ratio is a measure of the sugarcane used to produce sugar and ethanol. A technical constraint is that this ratio has to be between 35% and 65% (De Gorter et al., 2015). Drivers of flex vehicles aim to meet their energy demand by choosing between gasohol and E100. Farmers aim to sell their entire sugarcane cultivation to the owners of flex/distillery plants.

2.2.4.4. Learning/prediction. Mills forecast prices and demand for sugar and ethanol (hydrous and anhydrous). The method used for forecasting is the double exponential smoothing[6] (Holton Wilson et al., 2002). The forecasting is used to inform the decision making as to whether to invest in a new flex plant or not. Agents lack any learning mechanisms.

2.2.4.5. Sensing. Farmers, owners of mills/distilleries and drivers are assumed to know, without uncertainty, the global variables (i.e., market prices).

2.2.4.6. Interaction. Farmers directly interact with owners of mills/distilleries in their neighborhood through the negotiation about a contract for the supply of sugarcane. The main issue in the contract is the sugarcane price. This interaction is modeled through the CONSECANA-SP mechanism. Mills interact indirectly with neighboring mills by competing for contracts with farmers in their common sourcing region in the sugarcane market.

In the CONSECANA-SP mechanism the pricing of sugarcane is based on two variables: the amount of total recoverable sugar (TRS), which

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[5] This equation was derived based on the assumption that owners of flex plants will only produce hydrous ethanol when the gasoline tax increases to 2.46 R$/l.

[6] The double exponential smoothing is a forecasting method. The forecast value at any time is a function of all the available previous values. Nevertheless, recent observations are given relatively more weight in forecasting than the older observations. Unlike the simple exponential smoothing, the double exponential smoothing adds a growth factor to the equation to account for changes in the trend.

expresses the sugar content that is used for sugar and ethanol production, and the price of TRS. Values of TRS per ton of sugarcane are given to the farmer agents.

The TRS price is linked to the average market selling prices of three different products (sugar, hydrous and anhydrous ethanol), over the period of one harvest season. The CONSECANA-SP model then assumes that sugarcane accounts for 59.5% of the production costs of sugar, and accounts for 62.1% of ethanol production (Ferraz Dias de Moraes and Zilberman, 2014). Thus, remuneration to suppliers is done according to these percentages.

$$P_s^{TRS} = P_s^{ave}\cdot 0.595\cdot\left(\frac{1}{sc_s}\right) \tag{9}$$

$$P_h^{TRS} = P_h^{ave}\cdot 0.621\cdot\left(\frac{1}{sc_h}\right) \tag{10}$$

$$P_a^{TRS} = P_a^{ave}\cdot 0.621\cdot\left(\frac{1}{sc_a}\right) \tag{11}$$

where:

P_s^{TRS}, P_h^{TRS}, P_a^{TRS} are the TRS prices for sugar, hydrous ethanol, and anhydrous ethanol, respectively, in Reais per kilogram of TRS. P_s^{ave},P_h^{ave}, P_a^{ave} are the average market selling prices for sugar, hydrous ethanol, and anhydrous ethanol in Reais per kilogram of sugar and Reais per litre of ethanol, respectively. sc_s, sc_h, sc_a are the stoichiometric coefficient for sugar, hydrous ethanol, and anhydrous ethanol, respectively.

Nevertheless, the TRS price is unique for each processing plant as sugar sales and ethanol sales volumes differ depending on the production ratios of each processing facility. The TRS price for a processing plant *i* is based on weighing the product TRS price with the volumes of each product:

$$P_i^{TRS} = P_s^{TRS}\cdot\left(\frac{\mathrm{Pr}_s}{\mathrm{Pr}_t}\right) + P_h^{TRS}\cdot\left(\frac{\mathrm{Pr}_h}{\mathrm{Pr}_t}\right) + P_a^{TRS}\cdot\left(\frac{\mathrm{Pr}_a}{\mathrm{Pr}_t}\right) \tag{12}$$

$$Pr_t = Pr_s + Pr_h + Pr_a \tag{13}$$

where:

P_i^{TRS} is the TRS price of the plant *i* in Reais per kg of TRS.Pr_s,Pr_h, and Pr_a are the total production of sugar, hydrous ethanol, and anhydrous ethanol of the plant *i*, respectively in kilograms of TRS.

The interaction between mills and drivers is mediated via the fuel market. The concept of preference of the relative price between E100 and gasoline is at the core of the modeling of the fuel market. Let $Q^0{}_g$, and $Q^0{}_e$, be the initial demand (measured in GEELS[7]) of gasohol and E100, respectively. Let $P^0{}_g$, and $P^0{}_e$ be the initial market prices calculated at values of demand of gasohol and E100, respectively. When the price gap between gasohol and E100 narrows, some flex car owners who previously preferred hydrous ethanol will find it attractive to switch to the blended fuel. In this case, the demand for gasohol increases to $Q^1{}_g$ whereas the demand for E100 decreases to $Q^1{}_e$. This change in demand for fuels affects the relative price as new values for the market prices are determined ($P^1{}_g$,$P^1{}_e$). This iterative process continues until the relative price remains constant (i.e. the equilibrium is reached). This mechanism is shown in Fig. 4. The equilibrium is described by the pairs ($Q^*{}_g$,$P^*{}_g$),($Q^*{}_e$,$P^*{}_e$).

2.2.4.7. Stochasticity. The model is initialized stochastically. Properties such as farmers' yields, mills' production capacities and drivers' preferences of the relative fuel prices are randomly assigned among the agents. The decision making of farmers agents about expansion of sugarcane fields and the locations of new mills is modeled stochastically based on the probabilities calculated by the PLUC model (Verstegen et al., 2016).

2.2.4.8. Collectives. The model neglects the formation of aggregations among individuals.

2.2.4.9. Observation. Expansion of the ethanol/sugar production capacity, production of sugar and ethanol, demand of ethanol, and ethanol prices are the main key performance indicators.

Initialization: 418 mill agents, 3715 farmer agents, and 2500 driver agents are initialized for the year 2013. The location of mills and their type (sugar plant, ethanol plant, and flex plant) are based on real spatial data for the year 2013 (Picoli, 2013). The location of the farmers is based on the stochastic projections of the PLUC model for 2013. Table 1 presents the parameters that describe the state of the agents at the start of the simulation.

2.2.5. Input data

The behavior of the model is driven by 7 exogenous parameters: gasoline and sugar prices, number of flex and regular vehicles, productivity of both sugarcane and the TRS content, and sugar demand. The productivity of both sugarcane and the TRS content is assumed to be constant during the period 2013–2030. The values for sugarcane yield and TRS content yield are 75 t/ha and 140 kg TRS/t, respectively. These values were set out based on historical developments (UNICA, 2017). Projections for the other parameters up to 2030 were retrieved from the literature (see Table 2). The number of vehicles is assumed to be exogenous ought to that they are driven by macro-economic variables such as level of urbanization, population density, and the growth of the Gross Domestic Product (GDP). Prices can be either current (nominal) prices or constant (real) prices as we assumed an inflation of zero.

2.2.6. Submodels

The algorithm that describes the investment in new processing capacity consists of four steps. This algorithm is followed by every single mill owner. The first step is to assess the financial status. It is assumed that mill owners are willing to invest in new processing capacity if they are making profits. The second step is to forecast the demand of sugar and ethanol. If this demand is increasing, then mill owners determine the profitability of building a new processing capacity by calculating the net present value (NPV) of the project. Finally, if the project is profitable (i.e. NPV $>$ 0), then mill owners invest in new processing capacity. The values of the parameters used in the net present value calculation are reported in Table 3–5. It is assumed that mill owners have a different perception of risk in the investment. This difference in the perception of the risk was captured by using different values for the discount rate.

Critical assumptions that underpin the model structure are:

- Brazilian policies are constant during the modeled timeframe.
- Brazil is an open system. That is, Brazil can either import or export ethanol if required.
- There are neither import tariffs nor export tariffs for ethanol.
- The international price of ethanol is endogenous and it is calculated based on the domestic price. The ratio of domestic price of ethanol (both hydrous and anhydrous) to the international price of ethanol is 1:1.3 (Crago et al., 2010).
- The exchange rate of Brazilian Reais to US dollars is constant during the timeframe.
- The international demand for hydrous and anhydrous ethanol is a sink. This demand is considered only when the domestic demand for ethanol is already satisfied. Imports of ethanol are only considered if there is a shortage in the domestic production.
- The fuel preferences of drivers remain constant during the timeframe of the simulation.
- The share of electric vehicles in the road transport sector is negligible during the timeframe of the simulation.
- Economic resources are available for new investments in processing

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[7] Gasoline energy equivalent liters.

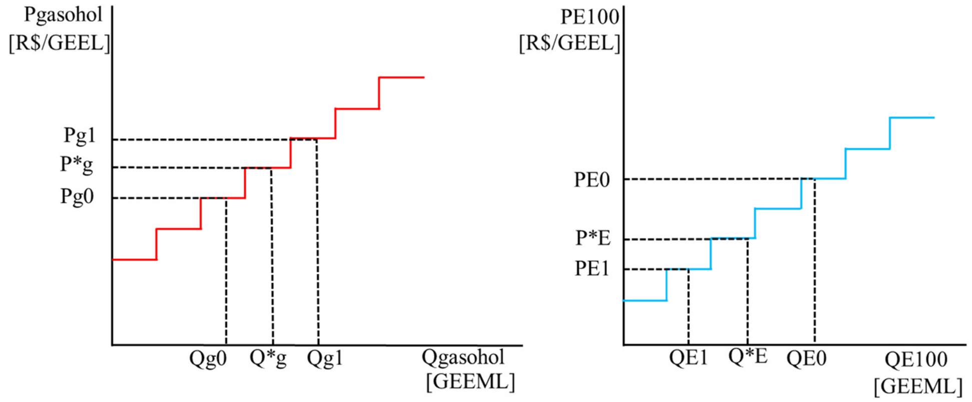

Fig. 4. Shifts in demand for gasohol and E100.[8]

Table 1
Parameters used in the initialization of the simulation (representing the year 2013).

Parameter	Value	Brief description	Units
Farmers			
initial-number-farmers	3715	initial number of farmers	–
farm-a	2500	farm area	ha
yield-SC	75	yield of sugarcane per hectare	t/ha
yield-TRS	140	yield of total recoverable sugar per ton of sugarcane	kg/t
Mills			
number-sugar-mill-plants	10	number the sugar plants	–
number-ethanol mill plants	83	number of ethanol plants	–
initial-number-flex-mill-plants	325	number the mills plants	–
proc-capacity[a]	(Brazil, 2015; Rosillo-Calle and Cortez, 1998)	processing capacity of sugarcane	Mt SC
yield-sugar-SC[b]	U(119, 146)	yield of sugar per ton of sugarcane	kg/t
yield-hydrous-SC[b]	U(83, 92)	yield of hydrous ethanol per ton of sugarcane	l/t
yield-anhydrous-SC[b]	U(79, 88)	yield of anhydrous ethanol per ton of sugarcane	l/t
yield-ethanol-molasses	U(8, 10)	yield of ethanol from molasses per ton of sugarcane	l/t
sugar-proc-cost	U(41, 51)	processing cost of sugar per ton of sugarcane	R$/t
hydrous-proc-cost	U(14, 17)	processing cost of hydrous ethanol per ton of sugarcane	R$/t
anhydrous-proc-cost	U(25, 31)	processing cost of anhydrous ethanol per ton of sugarcane	R$/t
prod-ratio-sugar[c]	U(**0.5**, 0.6)	proportion of sugarcane that is used to produce sugar	–
prod-ratio-hydrous[c]	U(0.2,**0.5**)	proportion of sugarcane that is used to produce hydrous ethanol	–
prod-ratio-hydrous-molasses	U(0.2, 0.5)	proportion of ethanol produced from molasses that is used to produce hydrous ethanol	–
Drivers			
Type		gasohol; flex	–
Demand	47244	energy demand per vehicle	MJ/y
preference-relative-price[c]	N(**0.9**, 0.1)	value in the relative price that determines the consumption pattern of the driver *i*. Values of the relative price higher than the individual relative price lead to consumption of gasohol by the driver	–
Global variables			
blend-mandate	23	blend mandate	%
tax-gasoline	1.23	tax levied on gasoline	R$/l
tax-hydrous	0.30	tax levied on hydrous ethanol	R$/l
tax-anhydrous	0.05	tax levied on anhydrous ethanol	R$/l

[a] The distribution of the production capacity was based on Valdes (Valdes, 2011).
[b] It is assumed that the differences in the yields are due to differences in industrial efficiencies between mills/distilleries.
[c] The values in **bold** were obtained from the model calibration (see Appendix A).

capacity of sugarcane.

2.3. Modeling the biofuel policies

The blend mandate and the taxes levied on gasoline and ethanol shape the behavior of the ethanol market by influencing the ethanol prices and the mandate for anhydrous ethanol. Ethanol prices along with gasoline and sugar prices influence actors' decision making on production, consumption, and investment. The price of gasohol hinges on the gasoline price, anhydrous ethanol price, gasoline tax, anhydrous tax, and blend mandate. Similarly, the price of E100 hinges on the hydrous ethanol price and the tax levied on hydrous ethanol. The total supply of gasohol in the market is based on the total production of anhydrous and the blend mandate. The total supply of E100 into the market is equivalent to the total production of hydrous ethanol. Taxes and blend mandates are assumed to be constant during the time frame of the simulation. The mapping between biofuel policies and prices and demand is presented below (De Gorter et al., 2013; Drabik et al., 2015):

$$P_F = \alpha \cdot (P_A + t_A) + (1 - \alpha) \cdot (P_G + t_G) \tag{14}$$

$$P_{E100} = P_H + t_H \tag{15}$$

$$\alpha = \frac{V_A}{V_F} \tag{16}$$

where P_F, P_A, P_G, P_{E100}, and P_H are the price of gasohol, anhydrous

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[8] GEEML: gasoline energy equivalent million liters.

Table 2
Definition of the exogenous parameters.

Year	Sugar demand[a] [Mt]	Nominal sugar price[b] [US$/kg]	Nominal crude oil price[c] [US$/bbl]	Number Flex Vehicles[d] [millions]	Number Regular Vehicles[d,e] [millions]
2013	34.85	0.39	104.08	23	15
2014	35.92	0.37	96.20	26	14
2015	36.94	0.30	50.80	28	13
2016	37.88	0.40	42.80	30	13
2017	38.76	0.40	55.00	32	13
2018	39.58	0.40	60.00	35	13
2019	40.33	0.40	61.50	37	13
2020	41.01	0.40	62.90	40	13
2021	41.63	0.39	64.50	43	13
2022	42.19	0.39	66.00	46	13
2023	42.67	0.39	67.60	49	14
2024	43.09	0.39	69.30	53	14
2025	43.45	0.39	71.00	56	14
2026	43.74	0.39	72.80	59	14
2027	43.97	0.39	74.60	62	15
2028	44.13	0.38	76.40	66	16
2029	44.22	0.38	78.20	69	17
2030	44.25	0.38	80.00	73	17

[a] The demand of sugar was calculated based on results reported by the MAGNET model (Jonker et al., 2016).

[b] Retrieved from (WorldBank, 2017). The ratio of domestic price of sugar to the international price is 1:1.2 (Haley, 2013).

[c] The ratio of crude oil price to gasoline price is 1:1.2 (Zana, 2013).

[d] Retrieved from (Baran and Legey, 2013; Belincanta et al., 2016).

[e] Regular vehicles only can use gasohol (blend of gasoline and anhydrous ethanol. The maximum blend of anhydrous ethanol in gasohol is 27.5% v/v).

Table 3
Estimates of fixed capital investment costs and processing costs[a].

Capacity [Mt/y]	Sugar		Ethanol	
	Fixed Capital Investment[b] [MUS$]	Processing cost[c] [MUS $/yr]	Fixed Capital Investment[b] [MUS$]	Processing cost[d] [MUS $/yr]
1	32.05	8.84	32.13	8.88
3	69.16	26.52	101.83	26.64
5	98.89	44.19	173.02	44.44

[a] Include all the processing costs other than the feedstock cost.

[b] Based on the data reported in ((PECEGE, 2015)).

[c] Based on the data reported in (Jonker et al., 2015).

[d] Based on the data reported in (Santos et al., 2017).

Table 4
Financing and production assumptions.

Parameter	Value	Unit
plant lifetime	20	yr
installation time	3	yr
Income tax rate[a]	37	%
depreciation period	10	yr
discount rate[b]	U(10,20)	%

[a] Reference value for Brazil.

[b] Flex owners of flex plants differ in their perception of risk in the investment decision. Here, we use the discount rate as proxy for risk perception. The difference in risk perception among owners of flex plants was modeled by using a uniform distribution.

ethanol, gasoline, E100, and hydrous ethanol, respectively in Reais per liter. t_A, t_G, and t_H are the taxes levied on anhydrous ethanol, gasoline, and hydrous ethanol, respectively in Reais per liter. α denotes a blend mandate for anhydrous ethanol. V_A and V_F are the volumes of anhydrous ethanol and gasohol, respectively in liters.

Table 5
Plant start-up schedule.

Year	TCI schedule	Plant availability (% of capacity)
− 2	33,33% Fixed Capital	0
− 1	33,33% Fixed Capital	0
0	33,33% Fixed Capital	0
1		30
2		70
3		100

The structure of the fuel taxes in Brazil is complex. Taxes vary by state and they may be changed at any point in time. To cope with this complexity, we assumed that taxes remain constant during the timeframe of the simulation. We also assumed homogeneity in the distribution of fuel taxes in Brazil. That is, fuel taxes are equally enacted in the different states of Brazil. In this study, we use as a baseline the values reported by De Gorter et al. (2013) for the period 2011/2012 in the state of Sao Paulo. Based on this baseline scenario, we defined extreme scenarios for the fuel taxes. One extreme consists of fuel taxes equivalent to the double of those reported in the baseline. The other extreme consists of tax free fuels. The blend mandate scenarios were defined based on the baseline, the minimum requirement of blending, and the blending wall. Table 6 presents the values used in the baseline and extreme scenarios.

3. Results

In this section, we describe the results of the influence of three different levels of blend mandate and tax levied on hydrous ethanol and gasoline on the development of the sugarcane-ethanol market. We focus on four relevant aspects: the expansion of sugarcane processing capacity, the location of new processing facilities, consumption patterns of flex vehicle owners, and production of sugar, hydrous and anhydrous ethanol.

The results are presented in a matrix of 9 panels defined by the blend mandate and the gasoline tax variables. The effect of the hydrous tax is presented by different colors in each panel. For a given tax levied on anhydrous ethanol, the 9 panels describe all of the possible permutations among blend mandate and taxes levied on gasoline and hydrous ethanol (see Table 6). The results presented below correspond to a tax levied on anhydrous of 0.05 R$/l as the effect of the anhydrous tax on investment in processing capacity, production and consumption of ethanol is negligible (see Appendix B).

3.1. Spatial pattern and evolution of sugarcane processing capacity

Fig. 5 and Fig. 6 show the evolution of the processing capacity for different combinations of gasoline tax, blend mandates, and tax levied on hydrous ethanol. As expected, the investment in new processing capacity of sugarcane increased as the gasoline tax increase. In the period 2020–2030, with a hydrous tax of 0.3 R$/l, the investment in new processing capacity grows at the average rate of 0.38% (see Fig. 5**a**) and 6.61% (see Fig. 5**c**) per year. The investment in new

Table 6
Values used for the policy instruments in the baseline and extreme scenarios.

Policy instrument	Scenario			
	Low	Baseline	High	Units
Gasoline tax	0	1.23	2.46	R$/l
Hydrous ethanol tax	0	0.3	0.6	R$/l
Anhydrous ethanol tax	0	0.05	0.1	R$/l
Blend mandate	20	23	26	%

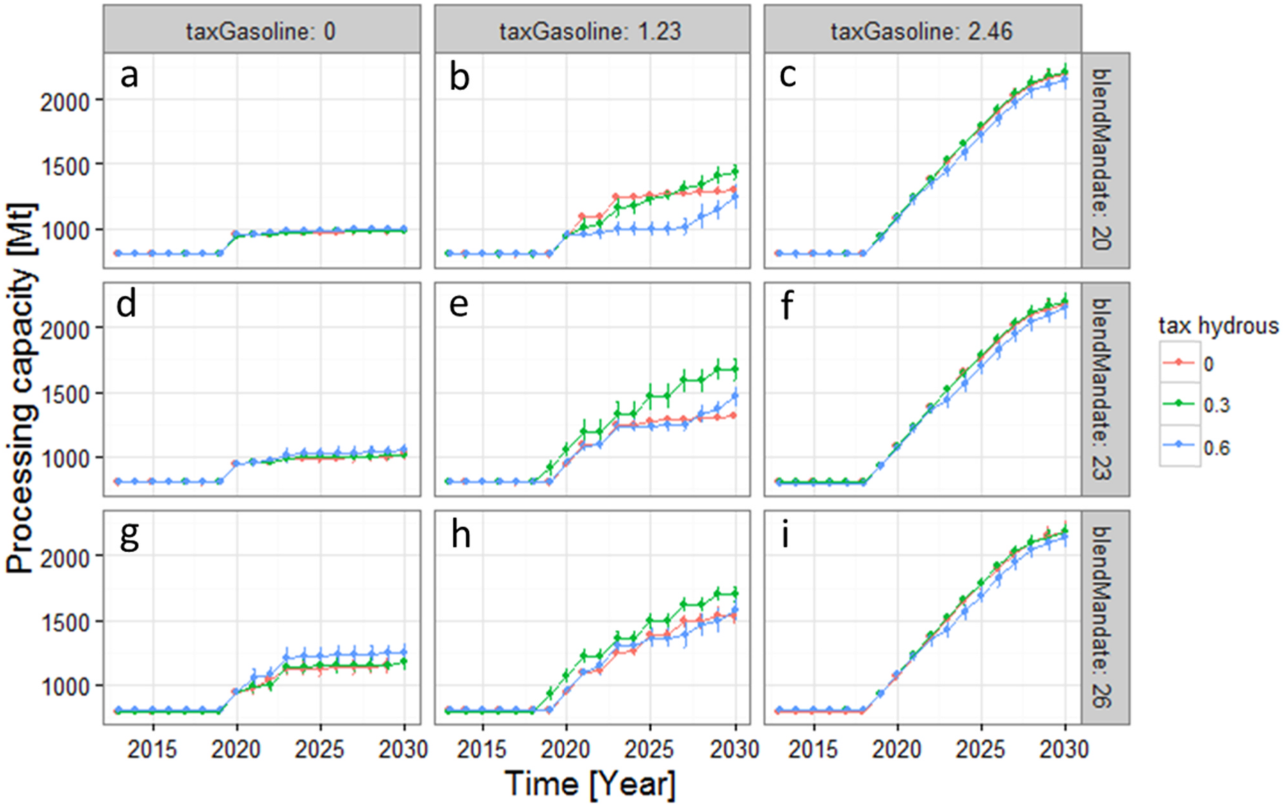

Fig. 5. Sugarcane processing capacity as a function of time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.05 R$/l. Forty repetitions were carried out in the simulations for each combination of policy instruments. Dots and the err bars represent the mean and the standard deviation over these forty repetitions, respectively.

processing capacity increased as the blend mandate increased only when the tax levied on gasoline was 0 R$/l and 1.23 R$/l, respectively. In the period 2020–2030, with a tax levied on hydrous ethanol of 0.6 R$/l, the investment in new processing capacity grows at the average rate of 0.45% (see Fig. 5**a**) and 2.53% (see Fig. 5**g**) per year. With a gasoline tax of 2.46 R$/l, the effect of the blend mandate on the investment of processing capacity of sugarcane was negligible.

The hydrous tax only caused difference between scenarios in the investment of new processing capacity of sugarcane when the gasoline tax was 1.23 R$/l. The investment in new processing capacity was higher when the hydrous tax was 0.3 R$/l. In the period 2020–2030, when the taxes levied on hydrous ethanol are 0 R$/l, 0.3 R$/l, and 0.6 R$/l, the investment in new processing capacity grows at the average rate of 2.94%, 3.89%, and 2.43% per year, respectively (see Fig. 5**b**). This behavior is because in this regime both prices of hydrous and anhydrous ethanol influence the decision making on investment in new processing capacity. When there is a tax exemption for hydrous ethanol, the demand for hydrous ethanol increases, which leads to an increase in the price of hydrous ethanol and to a decrease in the price of anhydrous ethanol. Nevertheless, the increase in hydrous price is insufficient to offset the effect of low anhydrous price on the investment decision. A similar mechanism is activated when the tax levied on hydrous ethanol is 0.6 R$/l. In this case, the increase in anhydrous ethanol price is insufficient to offset the effect of low hydrous price on the investment decision. Therefore, the investment in total sugarcane processing capacity when the hydrous tax is 0 R$/l and 0.6 R$/l is less than that invested when the hydrous tax is 0.3 R$/l. The effect of the tax levied on anhydrous ethanol on the expansion of the processing capacity was negligible (see Appendix B).

The spatial pattern (Fig. 6) shows that the expansion started in the center of Sao Paulo state, moved to Goiás and a small part of Mato Grosso, and finalized in the west side of Mato Grosso do Sul state. The majority of processing capacity of these plants was approximately 5 Mt. An increase in the gasoline tax led to a continuous deployment of new plants across the timeframe, resulting in a more pronounced east-west expansion pattern.

3.2. Consumption patterns of flex vehicles

The percentage of owners of vehicles (flex and gasohol) demanding E100 (hydrous ethanol) was influenced by the interaction between the gasoline tax and hydrous tax (Fig. 7). In 2030, the mean percentage of consumers of E100 increases 20% when the gasoline tax increases from 1.23 R$/l to 2.46 R$/l and there is a tax exemption on hydrous ethanol. For hydrous taxes of 0, 0.3, and 0.6 R$/l, the mean percentage of consumers of E100 in 2020 is 60%, 41%, and 29%, respectively (see Fig. 7**f**). In general, an increase in the gasoline tax and a reduction in the hydrous tax led to an increase in the consumption of hydrous ethanol. As expected, a tax exemption on gasoline led to very low consumption of ethanol.

At values of gasoline tax of 1.23 and 2.46 R$/l, the development of crude oil prices influenced the behavior of the consumption patterns of flex vehicles users (see Table 2, column 4). This pattern is characterized by a dip in the consumption of E100 in 2017. The consumption patterns of owner of flex vehicle were independent of the level of blend mandate. The effect of the tax levied on anhydrous on the share of flex vehicle users consuming E100 was also negligible (see Appendix B).

3.3. Production of sugar, hydrous and anhydrous ethanol

Patterns in the production of sugar are connected to patterns in the expansion of processing capacity (see Fig. 5 and Fig. 8). This connection hinges on the gasoline tax. A tax free gasoline regime favors the production of sugar compared to ethanol. The production of sugar,

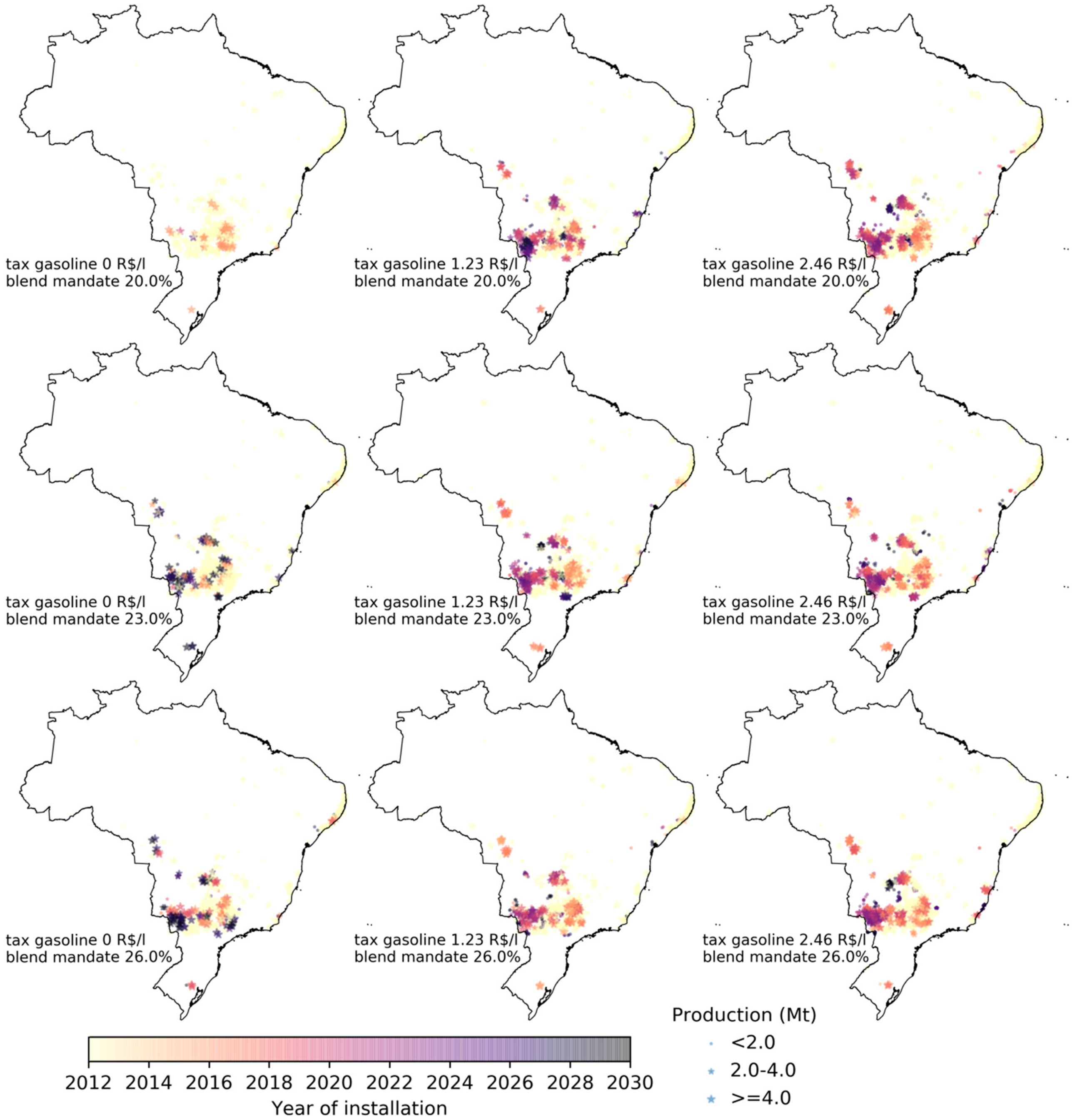

Fig. 6. Location, year of installation, and processing capacity of sugarcane plants as a function of different combinations of blend mandate and gasoline tax. Tax on gasoline in R$/l. Blend mandate in %v/v. Hydrous tax = 0.3 R$/l. Anhydrous tax = 0.05 R$/l. This figure shows the results for a single simulation run. To show that the patterns shown here are representative across runs with the same policy instrument values, results for another simulation run out of the forty repetitions are presented in Appendix B.

however, is limited by the rate of expansion of processing capacity. On the contrary, in a regime characterized by a high gasoline tax, the production of sugar is driven by the rate of expansion of processing capacity as this regime favors the production of ethanol. The effect of the blend mandate, tax levied on hydrous ethanol and anhydrous ethanol (see Appendix B) on sugar production is negligible.

As shown in Fig. 9, an increase in the gasoline tax led to an increase in the production of hydrous ethanol and to a decrease in the production of anhydrous ethanol. Furthermore, an increase in the tax levied on hydrous ethanol led to a decrease in the production of hydrous ethanol and to an increase in the production of anhydrous ethanol. When there was a tax exemption for gasoline, the effect of the hydrous tax on the production of both hydrous and anhydrous ethanol was negligible.

For values in the blend mandate of 23% and 26%, a gasoline tax of 1.23 R$/l, hydrous tax of 0.3 R$/l, and anhydrous tax of 0.05 R$/l, an oscillating behavior was observed in the production of hydrous and anhydrous ethanol. This behavior is due to the interplay of two factors. First, the fuel choice of owners of flex vehicles shifts between two states when the tax levied on hydrous ethanol is 0.3 R$/l. The second factor is the myopic behavior of the owners of the mills plants as to production of ethanol. In economic theory, this oscillating behavior in the production of ethanol is described by the Cobweb theory (Ezekiel, 1938).

The dip in the production of hydrous ethanol in 2014, when the gasoline tax was 2.46 R$/l, is due to two factors: the myopic behavior of

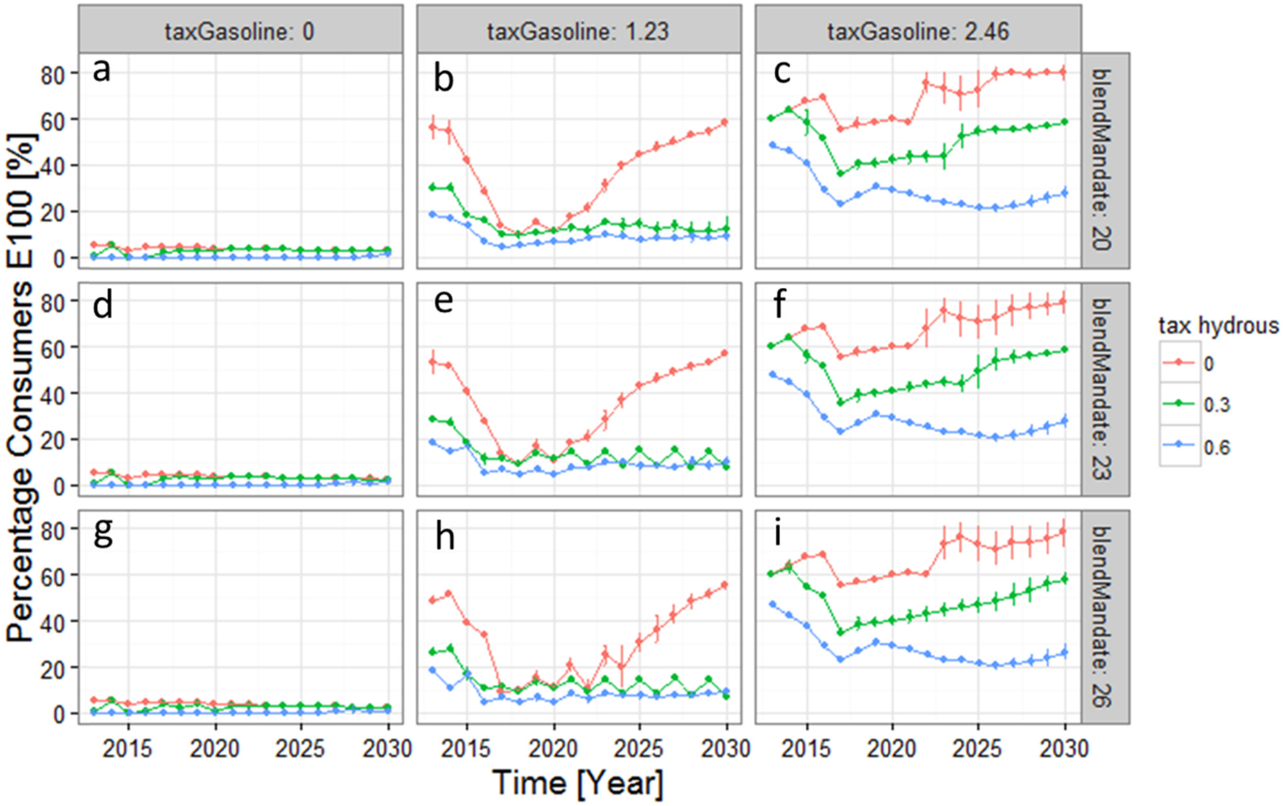

Fig. 7. Percentage of flex vehicle owners that consume E100 over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.05 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

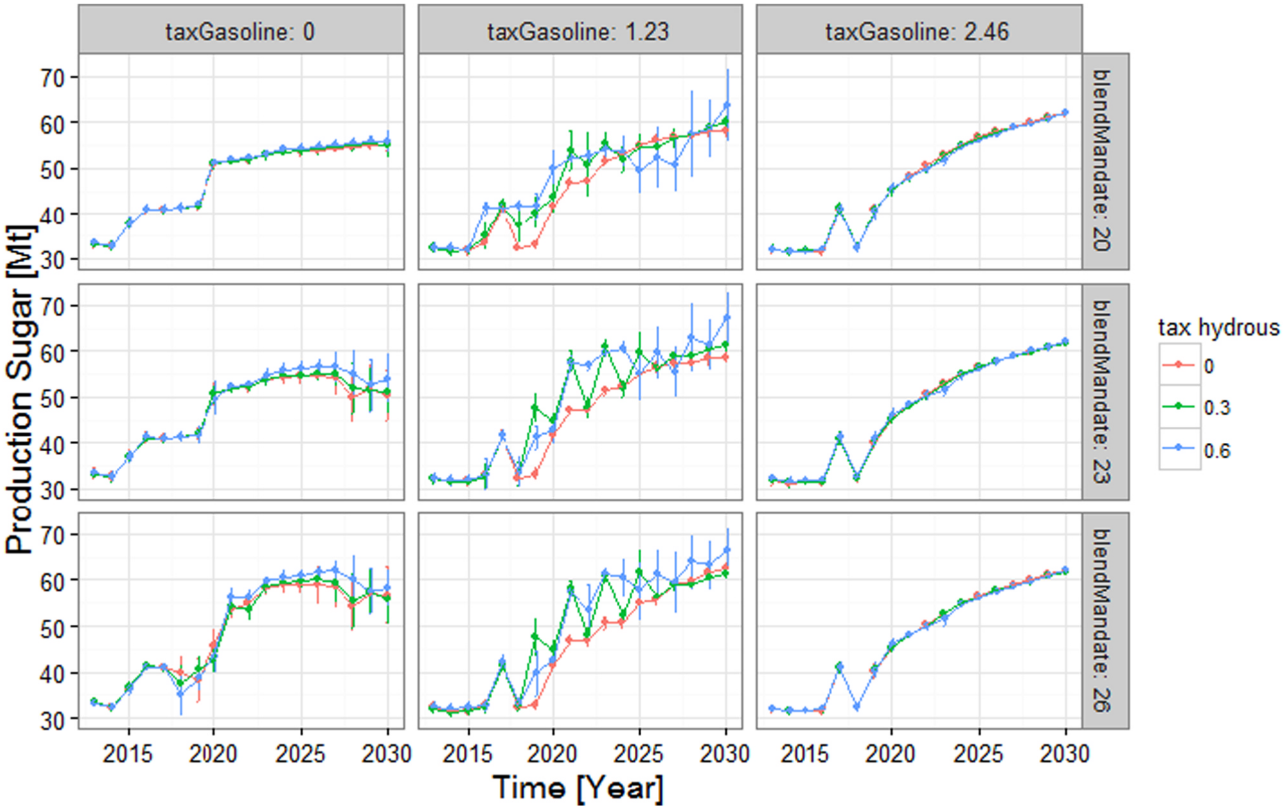

Fig. 8. Total production of sugar in Brazil over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.05 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

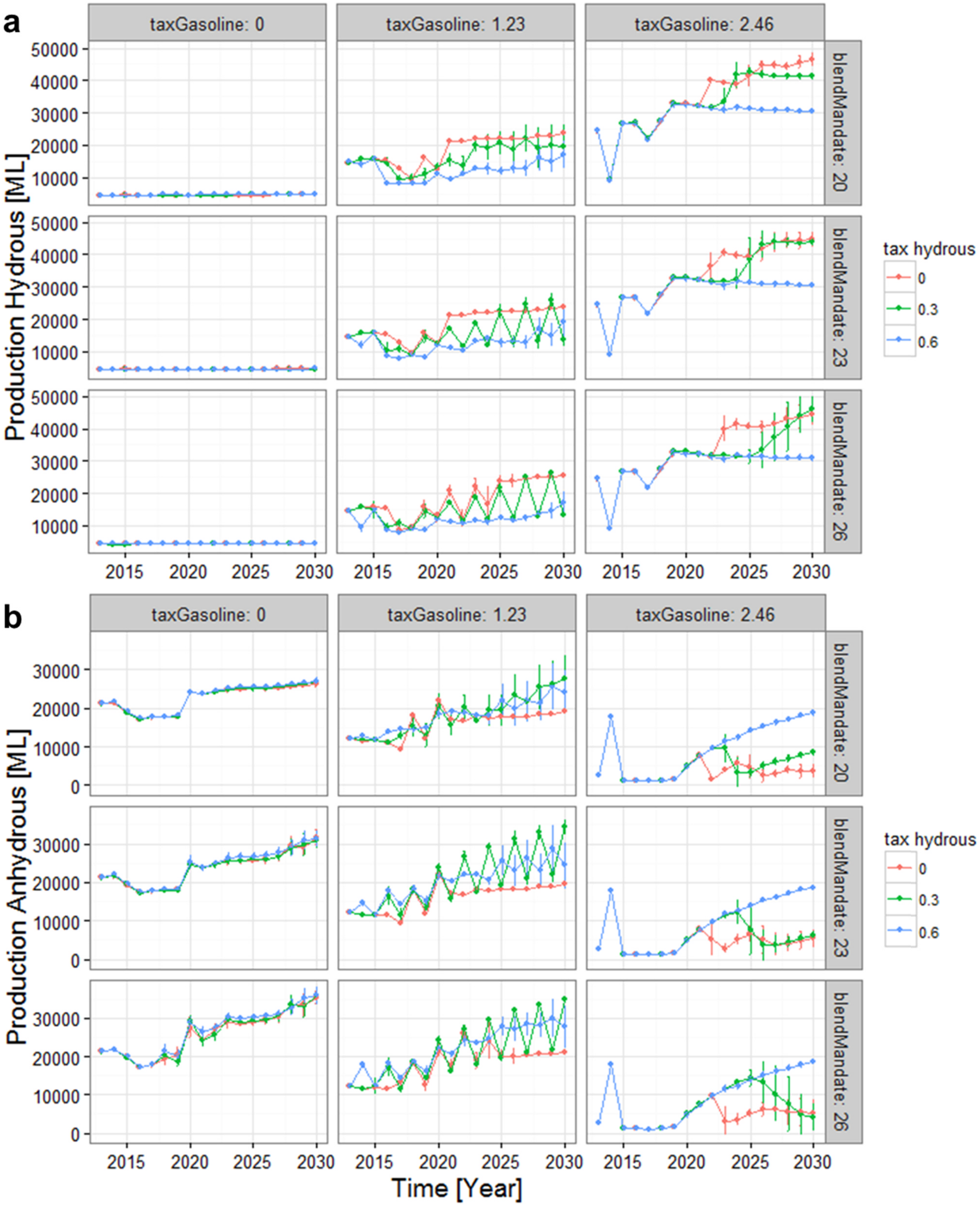

Fig. 9. Total production of hydrous (a) and anhydrous ethanol (b) in Brazil over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.05 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

owners of flex plants and the extreme options as to the production of hydrous and anhydrous ethanol. At this level of the gasoline tax, flex plants are incentivized to produce only hydrous ethanol unless the price of anhydrous ethanol is high enough, in that case, flex plants drastically reduce the production of hydrous ethanol. This situation happened in 2013, when the crude oil price was high, which led mill owners to reduce the production of hydrous ethanol in 2014 because of their myopic behavior.

For a gasoline tax of 1.23 R$/l and a hydrous tax of 0.3 R$/l, an increase in the blend mandate magnified the oscillating behavior in the production of both hydrous and anhydrous ethanol. For the rest of permutations between gasoline tax and hydrous tax, the effect of the blend mandate on the production of hydrous and anhydrous was negligible. As shown in Appendix B, the effect of the anhydrous ethanol tax on the production of hydrous and anhydrous ethanol was also negligible.

4. Discussion

We found that under the set of chosen policy measures, the expansion of the sugarcane processing capacity in Brazil is driven most by a high gasoline tax (see Fig. 5), provided that the policy landscape remains stable, that the effect of import and export tariffs on the market is negligible, and that the share of electric vehicles in the road transport sector remains small up to 2030. This insight is in line with that reported by Demczuk and Padula (2017).

An increase of the gasoline tax leads to a continuous deployment of new plants between 2015 and 2030. The pattern of expansion shows an east to west pattern, from Sao Paulo state to Goiás, Mato Grosso, and Mato Grosso do Sul (see Fig. 6). These patterns are in line with those reported by Lapola et al., (2009), for it is expected that the deployment of new processing capacity will take place predominantly on productive lands. Also, a general trend was found in the deployment of new processing capacity. This trend is characterized by the deployment of large scale sugarcane processing capacity plants. This finding is in line with the results reported by Jonker et al. (2016).

We found that the consumption pattern of the owners of flex vehicles hinges on the interaction among gasoline prices and taxes levied on gasoline (see Fig. 7). Namely, the gasoline tax exhibits a correlated effect on E100 demand. This finding is in line with those of de Freitas and Kaneko (2011). Finally, we found that the production patterns of sugar, hydrous and anhydrous ethanol are influenced by the gasoline tax (see Fig. 8 and Fig. 9). A tax-free regime favors the production of sugar compared to ethanol but limits the increase in its production over time. An increase in the gasoline tax leads to an increase in the production of hydrous ethanol and to a decrease in the production of anhydrous ethanol.

For the Brazilian government that strives for enhanced consumption of renewable fuels in the energy mix, our findings suggest that an increase in the gasoline tax (above 1.23 R$/l) and a reduction in the hydrous tax (less than 0.3 R$/l) may lead to doubling the production of ethanol by 2030 (relative to 2016). Nevertheless, the government needs to be cautious when implementing this policy as it can have negative impacts on the productivity level of ethanol producers or in the ethanol prices. The gasoline tax may disincentive ethanol producers in striving for technological improvements as this protection mechanism guarantee that ethanol is competitive with gasoline. One subject that remains to be explored is to what extent the gasoline tax should be increased to incentivize the investment in processing capacity.

5. Summary and conclusions

This study was conducted to answer the following research question: what is the combined effect of a blend mandate and a tax levied on gasoline, hydrous, and anhydrous ethanol on the development of the ethanol market in Brazil? To answer this question, we developed an agent-based model of the Brazilian ethanol market.

We found that the evolution of the Brazilian ethanol market is driven mostly by a gasoline tax. A high gasoline tax leads to increased investment in sugarcane processing capacity, to an increase in the consumption of E100, and to an increase in the production of hydrous ethanol. Given that the Brazilian government aims to increase the consumption of hydrous ethanol in the energy mix in 2030, and thus needs to double the supply of ethanol, our findings suggest that this goal is achievable if the gasoline tax is increased above 1.23 R$/l and the hydrous ethanol is tax-free.

Our study applies a number of key enhancements to prior studies. First, it models the expansion of the sugarcane processing capacity in Brazil spatially-explicit, as the investment decision making in new sugarcane processing capacity is bound to the land availability and location (van der Hilst, 2018). Second, it incorporates the CONSECANA-SP mechanism to model the interaction between farmers and producers. Finally, it includes preferences in and variation between the decision making of consumers. Overall, these characteristics have been neglected in previous analyses to ensure mathematical tractability and rigor. As we show here, agent-based modeling allows a richer description of the system without sacrificing the desirable rigor of formal analysis.

This approach, however, does have some limitations. First, the current instability of the policy landscape in Brazil is neglected. The policy instruments are subject to change in shorter time frames. For instance, in reality, the blend mandate is adjusted depending on the industry capacity to deliver ethanol, oil prices, and size of the fleet. This instability might increase the perceived risk level in decisions on whether or not to invest in processing capacity. Second, technological innovations in the road transport sector have been neglected. The introduction of e.g., electric vehicles, can drastically change fuel consumption patterns. Third, the effect of import and export tariffs on the Brazilian ethanol market is neglected. Fourth, we neglected the role of distribution companies and gas stations owners on the final prices of ethanol.

Moreover, the heuristics used to model the decision making as to the production of hydrous and anhydrous ethanol under extreme values of the gasoline tax (0 R$/l and 2.46 R$/l) need to be improved. Further research should map the relationship between gasoline tax and decision making as to ethanol production. Given the important role that distribution companies and gas station owners play on the determination of ethanol prices, we also recommend to investigate the effect of the market power of distribution companies and gas stations owners on the evolution of the Brazilian sugarcane-ethanol supply chain, and what factors play an important role in the emergence of these cartels. We also recommend assessing the impacts of the variation of taxes and mandates by state on the evolution of the system, as favorable tax regimes may incentivize the production of ethanol in expansion areas. Finally, inasmuch as the Brazilian policy landscape is leaning to spur the production of advanced biofuels (2nd generation biofuels), we recommend researching the emergence of 2nd generation ethanol supply chains and their co-evolution with sugarcane-ethanol supply chains in the Brazilian context.

Yet, this study provides new insights into the workings of the Brazilian ethanol market under different policy landscapes. A further step would be the institutional design of the Brazilian ethanol market. The approach proposed in this study could be used to guide the institutional design process. Namely, the agent-based model could be used to assess the impact of different, potentially new, policy instruments on the ethanol market. Specifically, policy instruments aimed to increase both investments in sugarcane processing capacity and hydrous ethanol production.

All in all, as biomass/biofuel markets are complex and context-dependent, we argue that we should strive for developing models that incorporate the necessary mechanisms for a reliable description of the problem at hand, instead of using only one modeling paradigm (i.e.

Computational General/Partial Equilibrium Models) to analyze different problems in different geographies. This study is a step forward in the development of an ecology of models that provides a richer description of biomass/biofuels markets. The agent-based model developed in this study illustrates how to incorporate the effect of preferences into the actors' decision making, how to include governance structures, and how to map biofuel policies onto actor behavior. As we show here, these elements and their interaction are necessary to produce system behavior. Notwithstanding their importance, these elements are neglected by mainstream approaches.

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Appendix A. Model calibration

This appendix describes the method used to estimate the parameters with high uncertainty in the model. It also presents the results obtained from the model calibration, and discusses the fit between historical data and model outcomes.

Some of the sources of high uncertainty in the model are the preferences in production of sugar and ethanol as well as preferences in the consumption of fuel. We incorporate the preferences in production of sugar and ethanol into the model by using the parameters: *minimum production ratio of sugar to ethanol* and *maximum production ratio of hydrous ethanol to anhydrous ethanol*. The minimum production ratio of sugar establishes the lower limit in the production of sugar compared to ethanol. This limit cannot be lower than the technical constraint (i.e 35%). The maximum production of hydrous ethanol establishes the maximum production of hydrous ethanol compared to anhydrous ethanol. Similarly, we incorporate preferences in consumption of E100 (hydrous ethanol) compared to gasohol (blend of gasoline with anhydrous ethanol) into the model by using the parameter *preference in the relative price of ethanol to gasohol.*

These preferences in production of ethanol and sugar as well as in consumption of ethanol vary among individual actors. To account for this heterogeneity in the preferences, we distributed these preferences among actors by assuming either a uniform or normal distribution. The parameters used to model these distributions were estimated based on historical data.

The approach used for the model calibration was *best-fit* calibration.[9] The model was calibrated for the period 2013–2016. The mean squared error was used as a measure of model fit to the time series. The calibration criteria are presented in Table A.1.

The objective function to be minimized is:

$$f = \sum_{i=1}^{3} MSE_i \tag{A.1}$$

$$MSE_i = \frac{1}{n}\sum_{j=1}^{n} (\hat{Y}_i - Y_i)^2 \tag{A.2}$$

where f is the objective function to be minimized, and MSE_i is the mean squared error of them calibration criterion i. $\hat{Y}$ is the vector of n predictions, and Y is the vector of observed values. It was assumed that the policy landscape remains stable during the period 2013–2016. The values of the policy instruments used in the minimization of the objective function are reported in Table A.2.

The results of the minimization of the objective function are presented in Fig. A.1. It was found that the effect of the *minimum production ratio of sugar to ethanol* on the objective function was negligible. When the values in the relative price of ethanol to gasohol were greater than 0.6, the objective function displayed a clearer pattern. This pattern was characterized for both exhibiting a minimum value for the objective function and for being robust. Table A.3 reports the values that yield a minimum in the objective function.

Table A.1
Calibration criteria.

Year	Production ratio [%]		Production ratio [%]		Consumption ratio [%]	
	Sugar	Ethanol	Hydrous	Anhydrous	Hydrous	Anhydrous
2013	45.20	54.80	55.64	44.36	54.79	45.21
2014	43.20	57.00	57.59	42.41	53.95	46.05
2015	40.60	59.40	61.43	38.57	62.03	37.97
2016	46.30	53.70	57.48	42.52	55.67	44.33

Table A.2
Policy instruments.

Policy instrument	Value	Units
Blend mandate	23	%
Tax levied on gasoline	1.23	R$/l
Tax levied on hydrous ethanol	0.3	R$/l
Tax levied on anhydrous ethanol	0.05	R$/l

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[9] Railsback, S. and V. Grimm, *Agent-based and individual-based modeling: A practical introduction.* 2011: Princeton University Press.

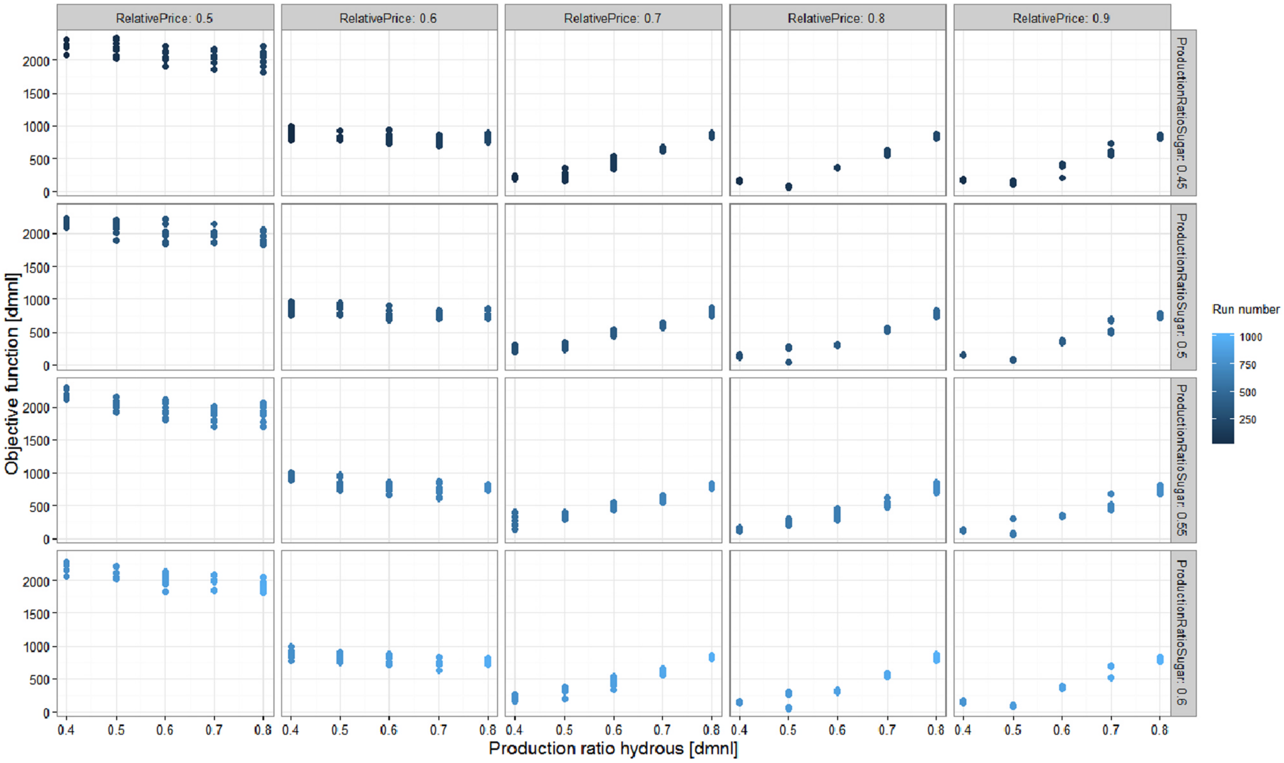

Fig. A.1. Minimization of the objective function as a function of the mean of production ratio of hydrous, the mean of production ratio of sugar, and the mean in the drivers relative preference for relative price.

Table A.3
Results of the calibration.

Parameter	Value
min production ratio sugar to ethanol[a]	0.5
max production ratio hydrous to anhydrous (in ethanol)[a]	0.5
preference in the relative price of ethanol to gasohol[b]	0.9

a. the parameter calibrated is used to calculate the interval [a, b] of a uniform distribution.
a = parameter − (parameter * percentage-deviation).
b = parameter + (parameter * percentage-deviation).
The percentage of deviation is assumed to have a value of 10%.
b. the parameter calibrated corresponds to the mean of a normal distribution. The standard deviation was assumed to have a value of 0.1. We use this value in the standard deviation to ensure that the distribution of the parameters lies on the specific interval in which the parameters have realistic values. From economic theory, these values lie around 0.7 (see Pacini and Silveira (2011))[11].

A comparison between the model outcomes and historical data is presented in Figs. A.2–A.4. These figures show the median and the 90% envelope of the results obtained from the agent-based model developed in this study. Model outcomes were distilled from simulations that used the values reported in Table A.2 and Table A.3. The simulations consisted of 1000 repetitions. The historical data used for the model calibration (reported by UNICA[10]) is also presented in the figures.

Model results for consumption ratio of hydrous to anhydrous ethanol were the calibration criterion that exhibited higher deviations with historical data (see Fig. A.2). These deviations are because of the assumption of a stable policy landscape. Patterns in consumption ratio of hydrous to anhydrous ethanol are sensitive to the policy landscape, for the policies analyzed in this study aim to directly steer the drivers' consumption patterns.

The higher difference between model outcomes and historical data for production ratio of hydrous ethanol to anhydrous ethanol occurred in the year 2015 (see Fig. A.3). This discrepancy might be explained by the increase of the contribution for intervention in economic domain (CIDE) for gasoline in 2015.[12] This increase in the gasoline price led to higher demand for hydrous ethanol as consumers decisions are driven by the ratio

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[10] UNICA. unicadata. 2017; Available from: http://www.unicadata.com.br/index.php?idioma=2.

[11] Pacini, H. and S. Silveira. Consumer choice between ethanol and gasoline: lessons from Brazil and Sweden. Energy Policy, 2011. 39(11): p. 6936-6942.

[12] Barros, S., C. Berk, Brazil. Biofuels Anual. Biofuels - Ethanol and Biodiesel, in: GAIN report. 2015, USDA Foreign Agriculture Service.

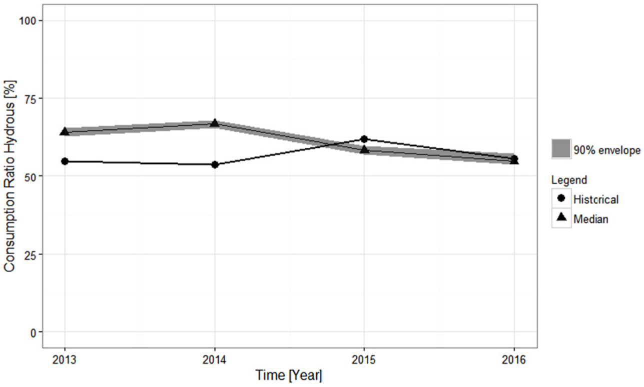

Fig. A.2. Consumption ratio of hydrous to anhydrous ethanol over time: model results and historical developments. The confidence interval was calculated over 500 runs for the calibrated parameter values. Confidence interval: 90%.

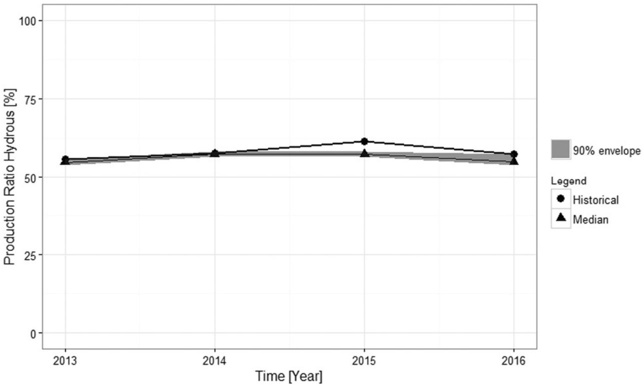

Fig. A.3. Production ratio of hydrous to anhydrous ethanol over time: model results and historical developments. The confidence interval was calculated over 500 runs for the calibrated parameter values. Confidence interval: 90%.

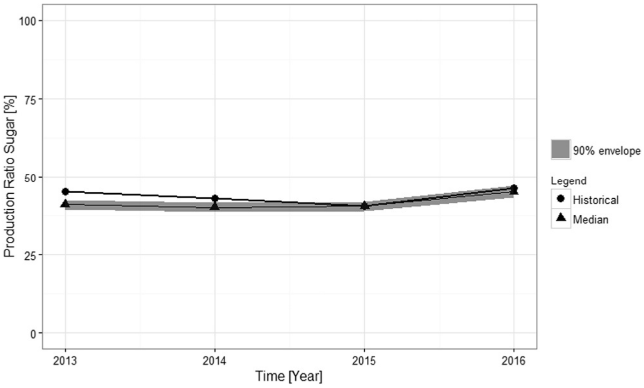

Fig. A.4. Production ratio of sugar to ethanol over time: model results and historical developments. The confidence interval was calculated over 500 runs for the calibrated parameter values. Confidence interval: 90%.

between ethanol and gasoline prices in the pump. Major demand for hydrous ethanol led to an increase in the price of hydrous ethanol, and thus to a decrease in the production of anhydrous. This behavior was neglected by the model because of the assumption that policy instruments remain constant during the timeframe of the simulation. The agreement between the historical data and model outcomes for the production ratio of sugar to ethanol is high (see Fig. A.4). With exception of the results related with the consumption ratio of hydrous to anhydrous ethanol, the model results exhibited a similar dynamic reported to that reported in the historical data.

Appendix B. Model results

This appendix presents the results of the effect of fuel taxes and blend mandate on investment in production capacity, sugar and ethanol production, and ethanol demand. The results are presented in a matrix of 9 panels defined by the blend mandate and the gasoline tax variables. The effect of the hydrous tax is presented in each panel. For a given scenario of the tax levied on anhydrous ethanol, the 9 panels describe all of the

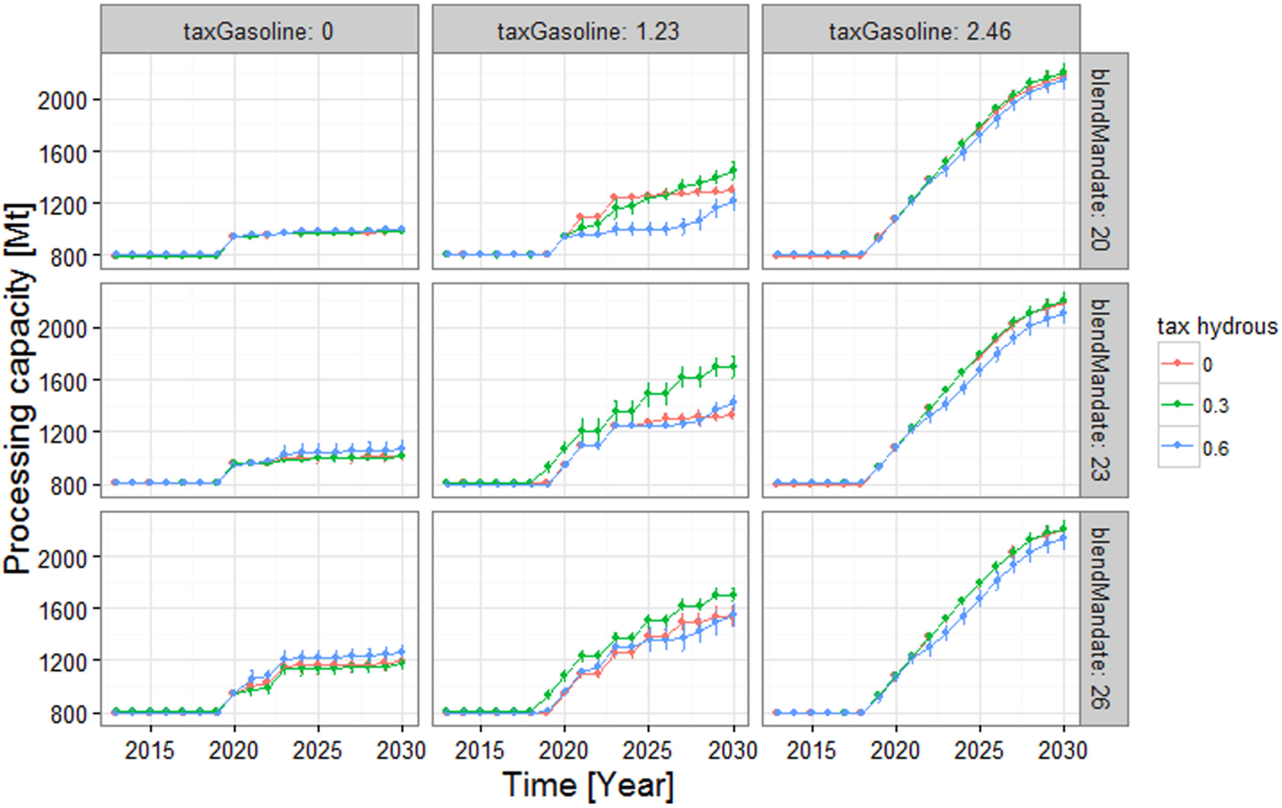

Fig. B.1. Processing capacity of sugarcane as a function of time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0. R$/l. Dots and the err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

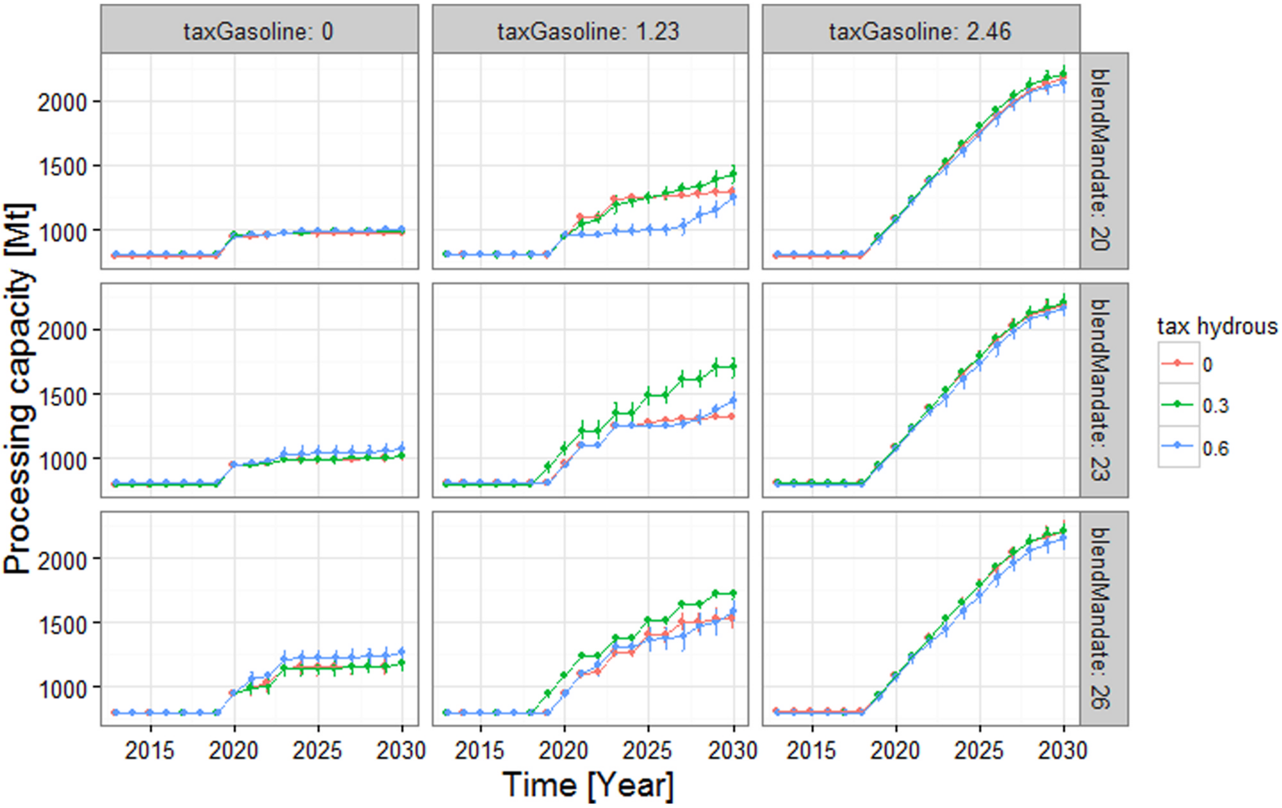

Fig. B.2. Processing capacity of sugarcane as a function of time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.1 R$/l. Dots and the err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

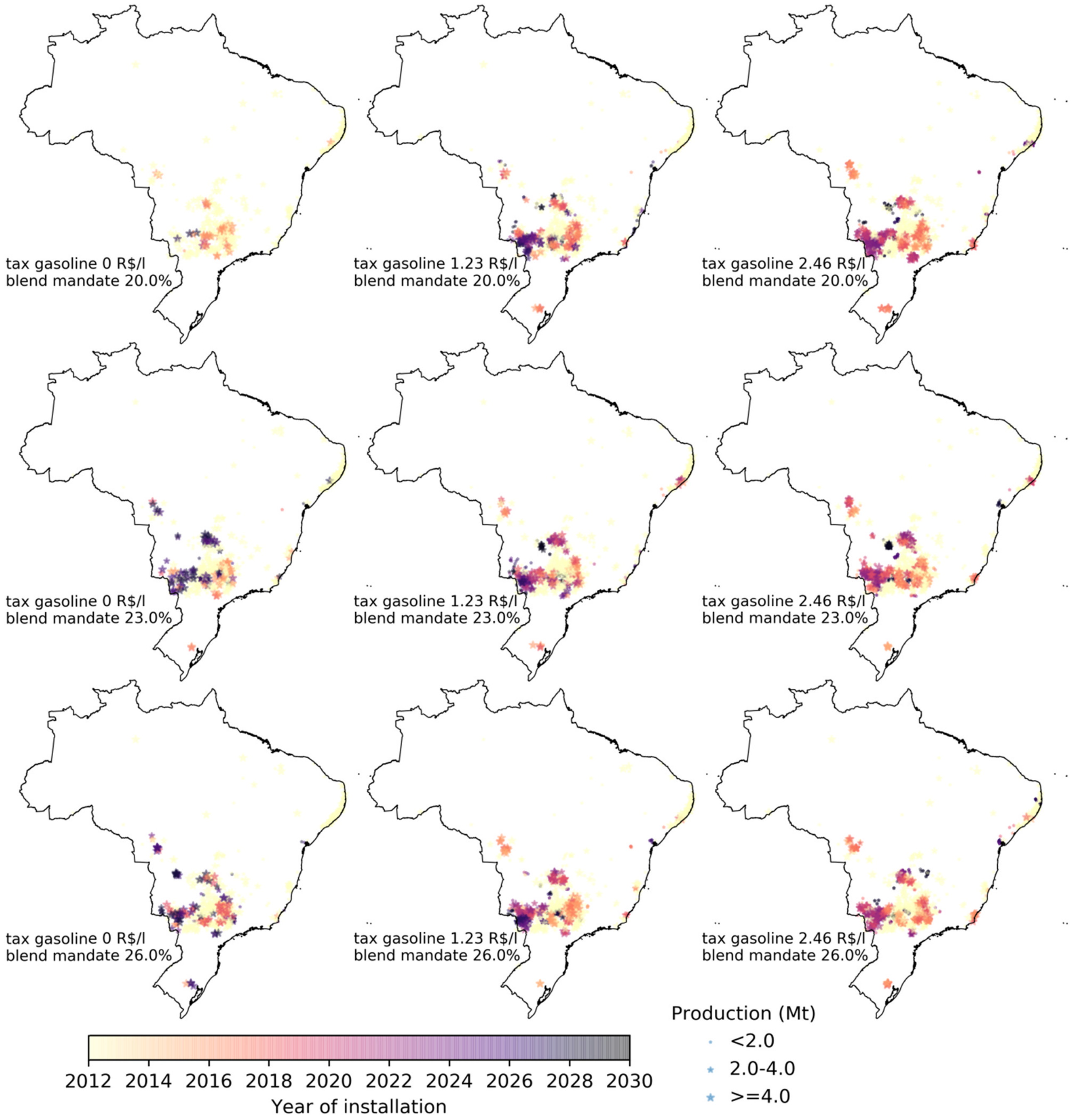

Fig. B.3. Location, year of installation, and processing capacity of sugarcane plants as a function of different combinations of blend mandate and gasoline tax. Tax on gasoline in R$/l. Blend mandate in %v/v. Hydrous tax = 0.3 R$/l. Anhydrous tax = 0.05 R$/l. This figure shows the results for a simulation run different to that used in Fig. 6.

possible permutations among blend mandate and taxes levied on gasoline and hydrous ethanol.

Figures below present the effect of anhydrous tax (i.e. 0 and 0.1 R$/l, respectively) on the processing capacity (Figs. B.1 and B.2), on consumption patterns of the owners of flex vehicles (Figs. B.4 and B.5), and on the production of sugar (Figs. B.6 and B.7) and ethanol (Figs. B.8 and B.9). Fig. B.3 presents spatial patterns in the deployment of new processing facilities for a simulation run other than one used in Fig. 6.

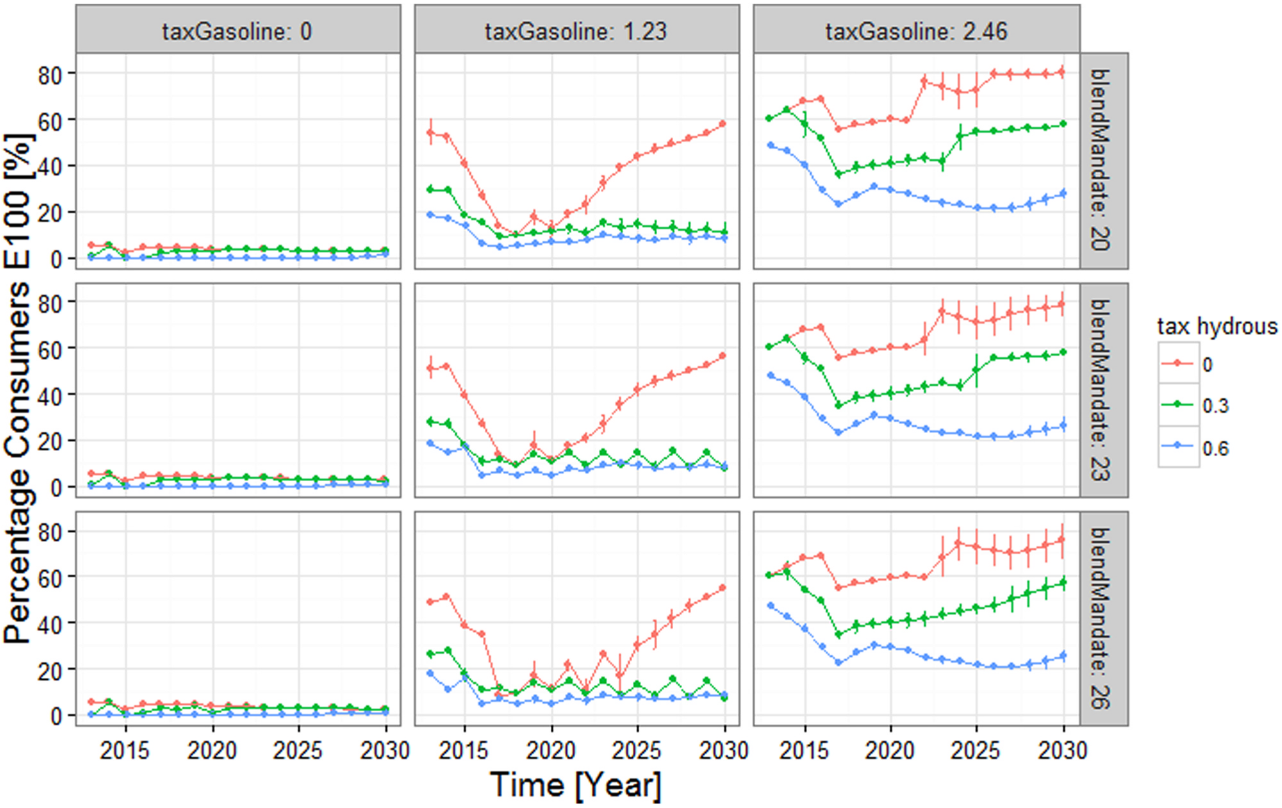

Fig. B.4. Percentage of drivers that consume E100 over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

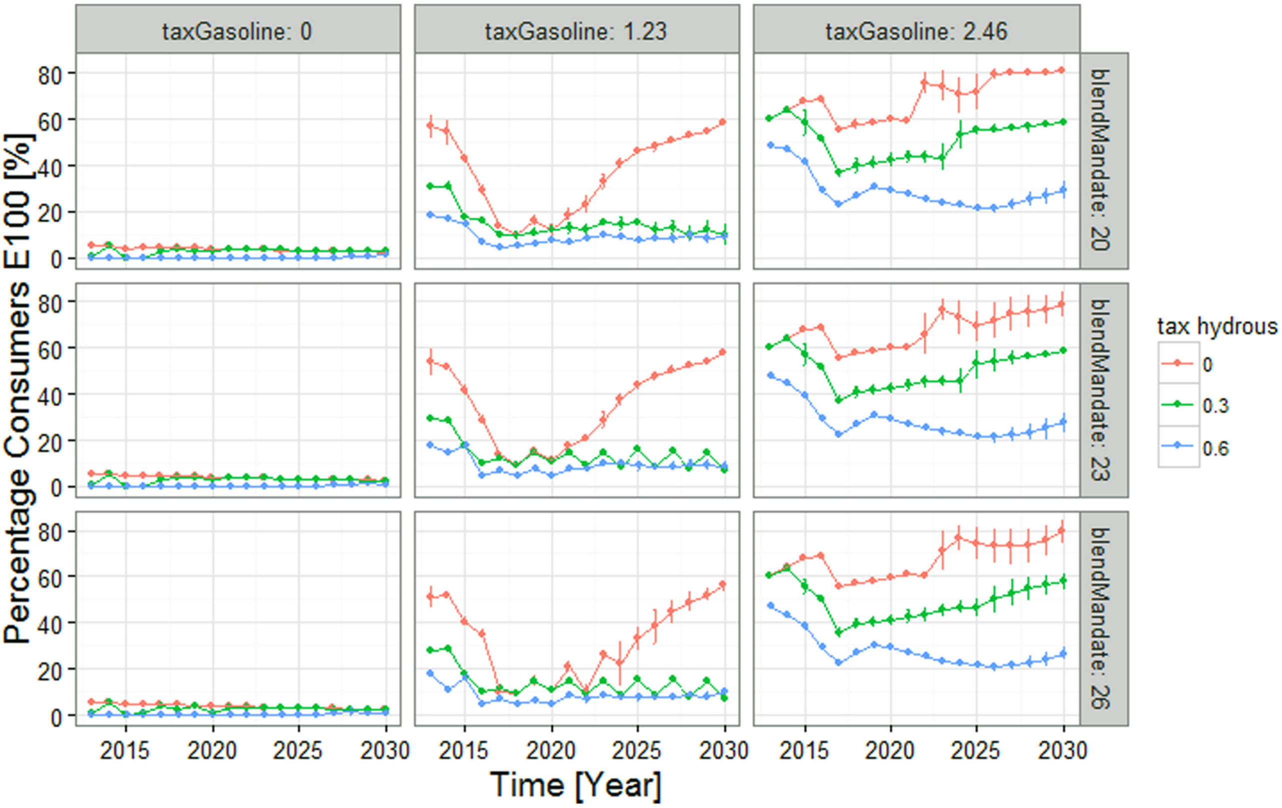

Fig. B.5. Percentage of drivers that consume E100 over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.1 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

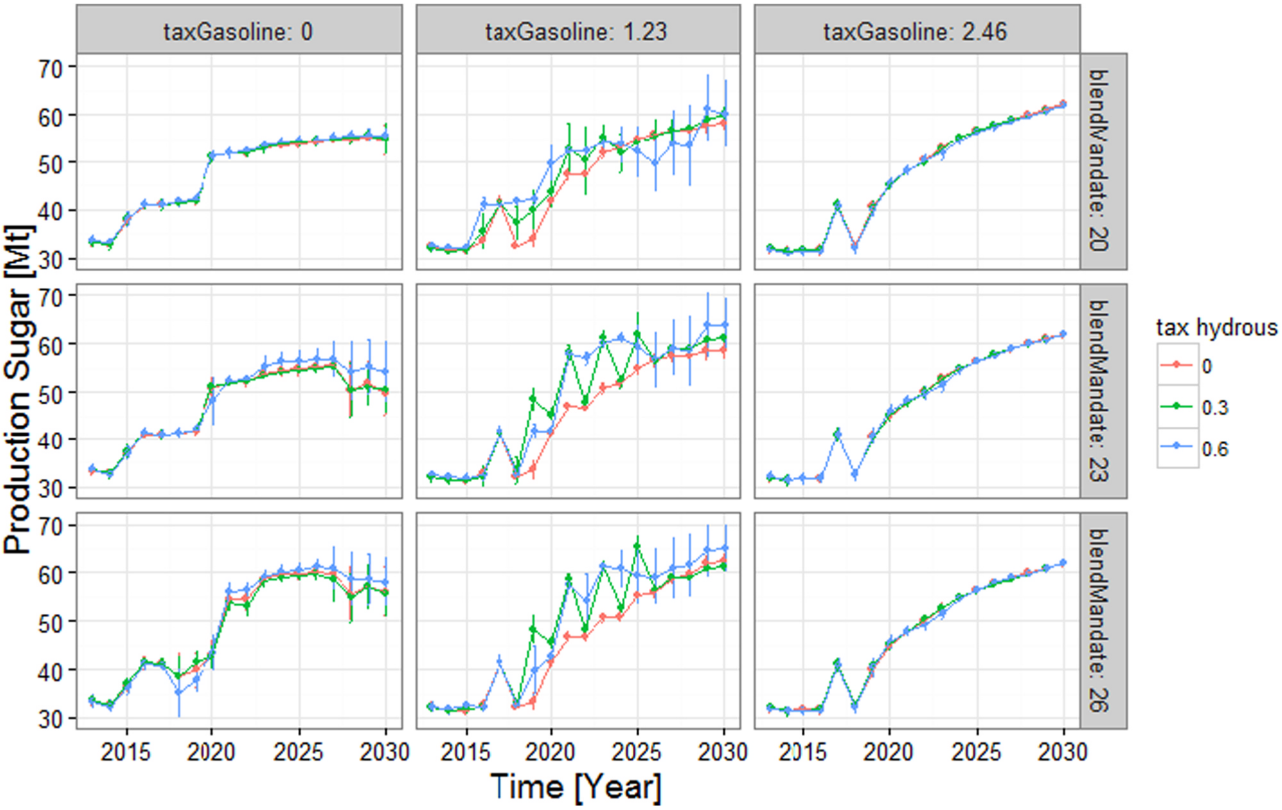

Fig. B.6. Total production of sugar in Brazil over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

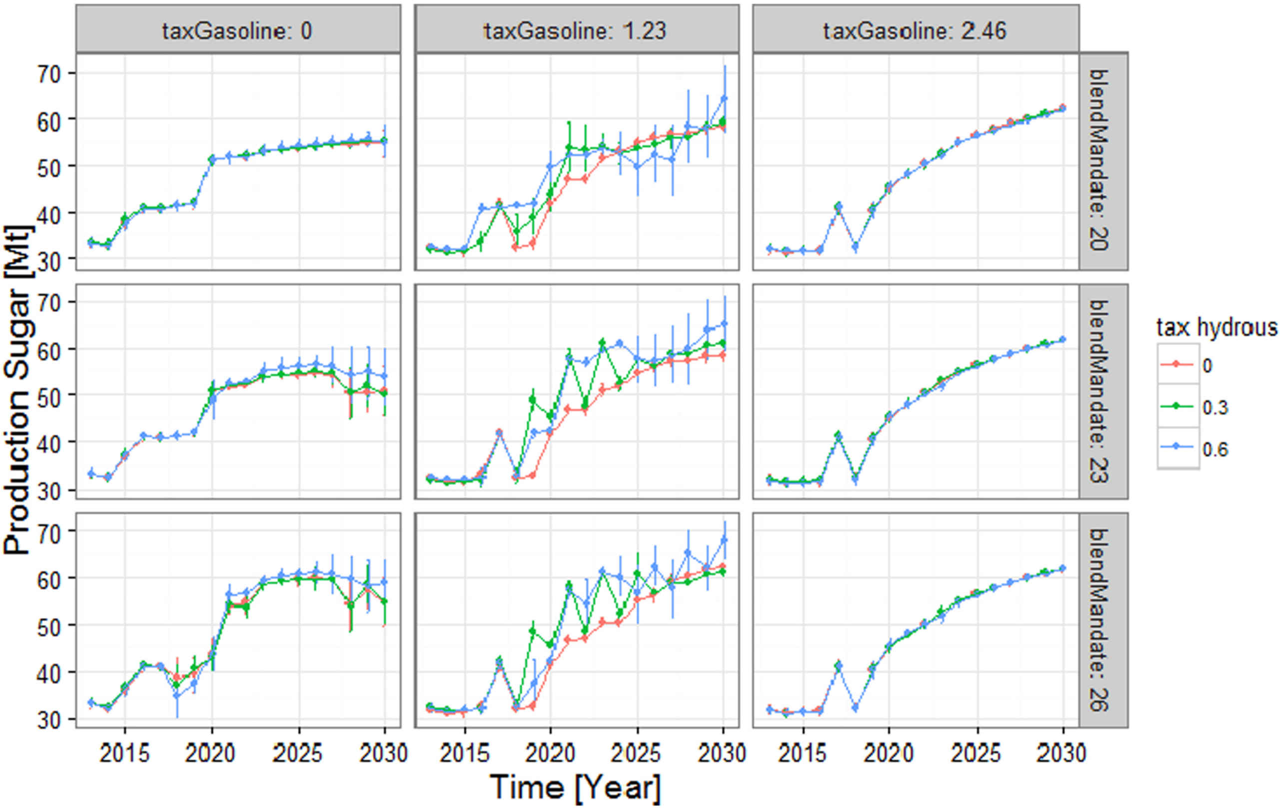

Fig. B.7. Total production of sugar in Brazil over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.1 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

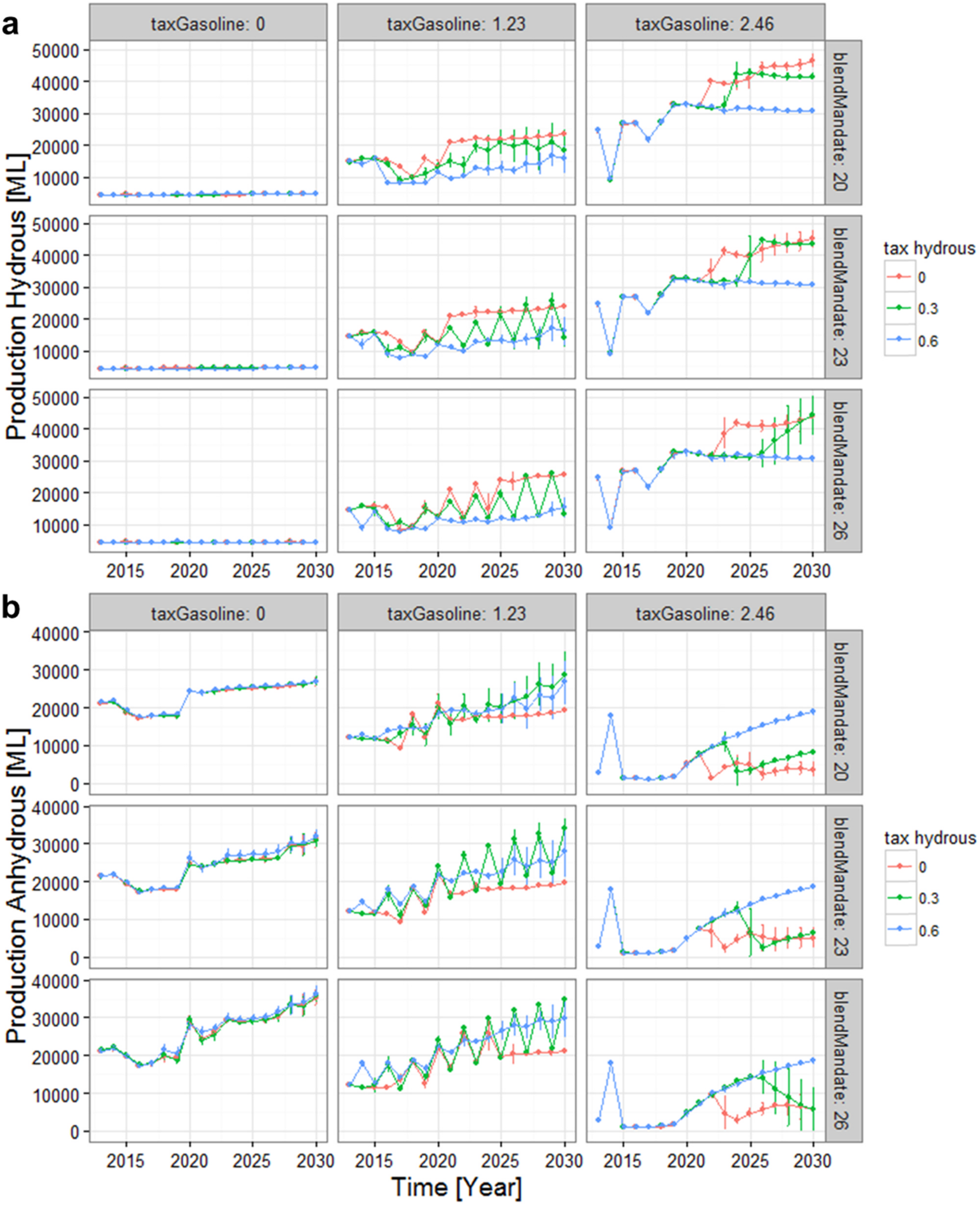

Fig. B.8. Production of hydrous (a) and anhydrous ethanol (b) over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

Fig. B.9. Production of hydrous (a) and anhydrous ethanol (b) over time for different combinations of blend mandate and tax levied on gasoline and hydrous ethanol. Tax on gasoline and hydrous ethanol in R$/l. Blend mandate in %v/v. Anhydrous tax = 0.1 R$/l. Dots and err bars represent the mean and the standard deviation, respectively. Forty repetitions were carried out in the simulations for each combination of policy instruments.

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