

KARINA ROGÉRIO DE OLIVEIRA VIANA SOUZA

**POTENTIAL, SPATIAL DISTRIBUTION AND SUSTAINABILITY OF
SUGARCANE-ETHANOL IN BRAZIL: PROJECTIONS TO 2030**

Thesis submitted to the Universidade Federal de Viçosa, in partial fulfillment of the requirements of the Graduate Program in Food Science and Technology, for the degree of *Doctor Scientiae*.

VIÇOSA
MINAS GERAIS – BRASIL
2017

Ficha catalográfica preparada pela Biblioteca Central da Universidade
Federal de Viçosa - Câmpus Viçosa

T

S729p
2017

Souza, Karina Rogério de Oliveira Viana, 1984-
Potential, spatial distribution and sustainability of
sugarcane-ethanol in Brazil : projections to 2030 / Karina
Rogério de Oliveira Viana Souza. – Viçosa, MG, 2017.
xi, 74f. : il. (algumas color.) ; 29 cm.

Inclui apêndice.

Orientador: Ronaldo Perez.

Tese (doutorado) - Universidade Federal de Viçosa.

Inclui bibliografia.

1. Cana-de-açúcar. 2. Agrocombustíveis. 3. Cana-de-açúcar
- Produção - Economia - Sustentabilidade. I. Universidade
Federal de Viçosa. Departamento de Tecnologia de Alimentos.
Programa de Pós-graduação em Ciência e Tecnologia de
Alimentos. II. Título.

CDD 22 ed. 633.61

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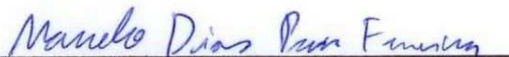
APPROVED: January 12, 2017.



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"... A man needs to travel. On his own, not through histories, images, books or tv. He needs to travel because of himself, with his eyes and feet, to understand what is his. For one day to plant his own trees and give them value. To know the cold to enjoy the heat. And the opposite. To feel the distance and the lack of shelter so as to feel good under his own roof. A man needs to travel to places he doesn't know to break this arrogance that makes us see the world as we imagine, and not just how it is or how it can be; that makes us professors and experts about things we haven't seen, while we should be students and just go seeing."

"Endless sea"- Amyr Klink

Acknowledgements

To God, for all blesses in my life and for giving me strength to support all difficulties.

To Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for funding my work in the Netherlands.

To Universidade Federal de Viçosa, for all support and the opportunity to accomplish this one more achievement.

To professors Marcelo Ferreira and Mateus Neves for accepting to make part of the final defense committee.

To professor Benício Chaves, for all suggestions given and for also accepting to make part of the final defense committee.

To professor Ronaldo Perez for all teaching in the past few years, for all advises and enriched discussions, that helped me to become a better professional. Thank you for all support since the beginning, for trusting me (sometimes more than I do), and for being a friend.

To professor Floor van der Hilst, for accepting me in her group and believing in me since beginning. Thank you for receiving me so well and making me feel part of the group. For all enriched discussions, for pushing hard and encouraging me to be better. Receive my heartfelt gratitude for all your time, support, patience and for coming to Brazil to the defense.

To professor Birka Wicke, for all valued suggestions given to the work, for all support and attention. Thank you for constantly being so kind, for your time and patience.

To Judith, for all support and for always being so solicitous. Thank you for presenting me a bit of the Dutch culture, for trusting me your friendship and becoming a friend for lifetime.

To be- basic team who received me so well in the group and always willed to help. Also, to Copernicus Institute – Utrecht University, for opening its door to me and for all support given.

To my friends and colleagues from Laboratório de Inovação e Tecnologia, for making the work environment nice to be in, and for all help when needed.

To Robson, my beloved husband, who has come all the way by my side,

for making me see the sun where I could only see clouds. Thank you for all support, patience, and for making me feel the most loved woman on earth. Love you!

Aos meus amados pais, Gilmar e Iranil, exemplo de força e trabalho duro, que me ensinaram desde pequena que um dos bens mais preciosos que temos é o conhecimento, e que por isso, devemos sempre buscá-lo. Obrigada por toda educação, incentivo, suporte e amor incondicionais.

To my sisters, Camila and Lara, for being example that with hard work and persistence we can achieve our goals and always go further. Thank you for all support, sisterhood and mainly, your friendship.

To Dani and Marcus, for always receiving me so well in their home and for being such good and special friends.

To all who direct or indirectly contributed with this work.

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LIST OF ABBREVIATIONS

BAU – Business as Usual

EJ – Exa joule, 1 EJ = 10^{18} Joule

EU – European Union

EtOH – Ethanol

FFV – Flex Fuel Vehicle

GDP – Gross Domestic Product

GHG – Green House Gas

GJ – Giga joule, 1 GJ = 10^9 Joule

GL – Giga liters

GIS – Geographic Information System

ha- hectare

IPCC – Intergovernmental Panel on Climate Change

PROG – Progressive

SI – Supplementary Information

TC – ton cane

US\$ - United States Dollars

yr - year

ABSTRACT

SOUZA, Karina Rogério de Oliveira Viana, D.Sc., Universidade Federal de Viçosa, January, 2017. **Potential, spatial distribution and sustainability of sugarcane-ethanol in Brazil: Projections to 2030.** Adviser: Ronaldo Perez. Co-adviser: Floor van der Hilst.

The sugarcane-ethanol sector is very important for the Brazilian economy, as it contributes to the country's GDP and generates a great number of jobs. In addition, it contributes to Greenhouse gas (GHG) mitigation by replacing fossil fuels. However, as this sector depends on a long term economic policy and is reason for socio-economic and environmental concerns, it has a future full of uncertainties. Therefore, the aim of this study is to identify, measure and assess these doubts to estimate ethanol demand and to assess the sustainable potential of sugarcane, of the current and future (2030) production, taking into account technical, economic and sustainability constraints. From a comparison of different projection models, the potential ethanol demand range for 2030 is defined. It is estimated that Brazil will demand 61.7 GL of EtOH in 2030, in the optimistic scenario, and 49 GL EtOH in the pessimistic scenario. Once demand is determined, the potentials of sugar cane ethanol production are calculated. A resource-focused assessment with a spatially explicit analysis is realized, using the geographic information system ArcGIS. The results for 2012 and 2030 scenarios, show that theoretically Brazil has a vast potential for sugarcane production, but when technical-economic constraints are taken into consideration, it significantly decreases. The same is true for the environmental and sustainable potential. Environmental criteria regarding the GHG emission reduction of and the protection of biomes are those that have the greatest impact on the reduction of the productive potential. For 2012 the highest sustainable potential for sugarcane is 0.76 EJ EtOH, but this can increase to 1.61 EJ EtOH towards 2030 if improvements happen in the fields and in industry. The results are lower than expected, but still represents sufficient production to meet the domestic demand. Concerning the increase in international market share, the results are not positive and suggest that Brazil

will hardly have surplus in sustainable production for export, following assumptions made in this study.

RESUMO

SOUZA, Karina Rogério de Oliveira Viana, D.Sc., Universidade Federal de Viçosa, janeiro de 2017. **Potencial, distribuição espacial e sustentabilidade da cana de açúcar-etanol no Brasil: projeções para 2030.** Orientador: Ronaldo Perez. Coorientadora: Floor van der Hilst.

O setor sucroenergético é muito importante para a economia do Brasil, pois tem participação importante no PIB nacional, e gera um grande número de empregos. Além disso, contribui para a mitigação de GEE por substituição de combustíveis fósseis. No entanto este setor por depender de uma política econômica de longo prazo, e estar no centro de muitas incertezas socioambientais e econômicas, o seu futuro possuem muitas divergências. Em função deste cenário, objetivo deste estudo identificar, medir e tratar estas incertezas de forma a permitir estimar a demanda de etanol e o potencial sustentável da cana-de-açúcar, da produção atual e futura (2030), levando em conta restrições técnicas, econômicas e de sustentabilidade. A partir de uma comparação de diferentes modelos de projeção de etanol identificou-se a possível faixa de demanda de etanol para 2030 no Brasil. A qual está estimada entre 61,7 GL de EtOH em 2030, no cenário otimista, e 49 GL EtOH no cenário pessimista. Uma vez determinada a demanda, os potenciais são calculados. Por outro lado, a partir de uma avaliação focada em recursos, com o uso de uma análise espacialmente explícita, e uso do sistema de informação geográfica ArcGIS, a partir do uso de restrições técnicas, econômicas e ambientais, projetou-se o potencial de produção de cana-de-açúcar no Brasil. Os resultados, para os cenários de 2012 e 2030, mostram que, teoricamente, o Brasil tem um grande potencial para a produção de cana-de-açúcar, mas quando restrições técnicas e econômicas são levadas em consideração, este potencial diminui significativamente. O mesmo é observado para o potencial ambiental e sustentável. Critérios ambientais quanto a redução das emissões de gases do efeito estufa e proteção de biomas, são os que possuem maior impacto na redução do potencial produtivo. Para 2012, o maior potencial sustentável da cana-de-açúcar é 0,72 EJ EtOH, e pode chegar a 1,61 EJ EtOH até 2030, se melhorias ocorrerem nos campos e na indústria. Este valor

projetado é muito inferior ao esperado, porém ainda representa produção suficiente para atender à demanda nacional. Quanto a participação no mercado internacional, os resultados não são positivos e sugerem que dificilmente o Brasil terá excedente de produção para exportação, seguindo as premissas do estudo.

1. Introduction

1.1 Context

Although the increasing estimates of global oil reserves, the percentage available for production is decreasing, and so the apprehension that global oil peak production has already been reached is also existent (MURRAY; KING, 2012). In contrast, the potential for renewable energy sources is certainly greater than the global energy demand (CHUM et al., 2011). Therefore, a substantial role for renewable energy in the energy mix is expected and makes it an important alternative to fossil fuels (GOLDEMBERG; COELHO; GUARDABASSI, 2008).

Bioenergy is currently perhaps the most promising of renewable energy sources (IRENA, 2014). It can be defined as the conversion of biomass resources such as agricultural and forest residues, or energy crops into useful energy carriers including heat, electricity and transport fuels (EC, 2015),

Sugarcane (*Saccharum* spp.) is an attractive feedstock for bioethanol production, considering both energy output: input ratio of approximately 9:1 and greenhouse gas (GHG) emission reductions close to 80% compared to fossil fuels (MACEDO; SEABRA; SILVA, 2008).

Brazil is currently the second largest bioethanol producer in the world and it is expected that sugar cane ethanol production will continue to increase rapidly towards 2030 (EPE, 2007; IEA, 2011; SCHUTZ; MASSUQUETTI; ALVES, 2013). Several studies have already indicated a large techno-economic potential of sugarcane-ethanol production in Brazil (EPE, 2007; WALTER et al., 2008a). This is because of potentially large land availability, favourable agro-ecological conditions, and long-term experience with sugarcane ethanol production (MARTINELLI; FILOSO, 2008; WALTER et al., 2011).

In Brazil, the harvest of 2016/2017 obtained 691 million ton of sugarcane (an increase of 3.8% compared to the harvest of 2015/2016), which produced 37 million ton of sugar and 30.3 GL of EtOH, in an area of around 9 million ha (CONAB, 2016). There are 370 sugarcane ethanol processing units in the country,

within more than a 1000 municipalities with activities linked to this sector (SIAMIG, 2016). The sector generated a PIB of R\$113 billion in 2015, presenting an increase of 5% compared to previous year (CEPEA, 2015). Inferences that sugarcane production has positive impact on GDP *per capita* of the cities the processing unit are installed, as well as in the cities around it, indicating positive socio-economic effects in the regions of production are presented by (MORAES; BACCHI; CALDARELLI, 2016).

Despite all favorable conditions hereby exposed, concerns about sugarcane sustainability has arisen and created uncertainties about its future (HISSA; FILHO, 2014; VIANA; PEREZ, 2013). Doubts have been raised about conversion of untouched areas into crops, resulting in a positive GHG emission balance and expansion to the Amazon biome, as well as questions about the disruption of food supply, risks of losing biodiversity and impacts on water quality and water availability (WALTER et al., 2011).

1.2 Problem and scientific relevance

As previously presented, the sugarcane-ethanol sector is very important to Brazil, because of many reasons, to quote its significant contribution to the country's GDP, a large number of jobs generated, and contributions to GHG emission savings (HERRERAS MARTÍNEZ et al., 2013; WALTER et al., 2008b). Together with the expectation of ethanol production rapidly increase towards 2030, there are the concerns about the way and to where this expansion can happen. Since 2012 the sector has gone through a techno-economic crisis and uncertainties about its future sustainable development have increased.

Within this context, having a prediction of the possible size of future sugarcane-ethanol market and knowing which regions are most favorable to a sustainable production is relevant to all stakeholders of this chain, to governments and policy makers. The better understanding of future possibilities of this sector can avoid negative impacts that an unexpected change in demand and production can bring.

Numerous studies (e.g: BUTT; HARTMANN; LENZ, 2013; FIELD; CAMPBELL; LOBELL, 2008; HISSA; FILHO, 2014; OKELLO et al., 2013; WATSON, 2011) have been conducted to better understand the potential of biomass energy sources, among this sources, sugarcane. The majority of papers found about this theme are resource-focused assessment, and varied in the method used, between statistical (BILGEN et al., 2015; BUTT; HARTMANN; LENZ, 2013; HABERL et al., 2010; JIANG et al., 2012; KUNG et al., 2014; SASAKI et al., 2009; SIMON; WIEGMANN, 2009; SMEETS et al., 2007) and spatial explicit analysis (BECCALI et al., 2009; DENG et al., 2015; DIOGO et al., 2014; ERB; HABERL; PLUTZAR, 2012; KEFFER et al., 2009; OKELLO et al., 2013; SCHUELER et al., 2013). The main difference between these two methods is that statistical methods are limited assessments, since only average values, such as land productivity, can be included.

To our knowledge, none of them have estimated spatially explicit the theoretical, technical, economic, environmental and sustainable potential of sugarcane-ethanol in Brazil. Because of the large spatial variation in attributes, like the potential yield of sugar cane and carbon stocks, calculating these potentials spatially explicitly will permit a more complete and accurate assessment compared to the previous estimations.

1.3. Aim and thesis outline

The aim of this study is to i) do a systematic review on ethanol demand, to identify the range of estimated demands up to 2030, and ii) develop a bottom-up approach to assess the theoretical, technical, economic, environmental and sustainable sugarcane potential spatially explicitly, demonstrating this for the current and future (2030) potential of sugarcane-ethanol.

The thesis is separated in two chapters. Chapter one presents a systematic review on ethanol demand projections for Brazil, the type of models used to do the projections, and the similarities and differences between them. Chapter two presents the spatially explicit assessment of sugarcane-ethanol production

potentials, of the current (2012) and future (2030) scenarios.

1.3.1. Research questions

The research questions to be addressed are:

- 1) What are the projections existent for ethanol demand in Brazil?
- 2) To what extent they are similar in methods and results?
- 3) How much ethanol will be demanded in Brazil up to 2030?
- 4) Will Brazil be able to meet the domestic demand and have a surplus to supply the international market, up to 2030?
- 5) What would be the most favourable spatial distribution of sugarcane expansion, in Brazil, taking into account sustainability constraints?
- 6) What are the most important parameters that influence the future ethanol demand and production potential?

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Chapter 2: Ethanol future demand in Brazil: a systematic review

2.1 Introduction

Estimating energy demand is important and essential to be done, although quite challenging for the energy planner, because decisions must be made in advance, due to the intrinsic characteristics of the energy sector, in a way that when needed, the right conditions are presented, ensuring that options are available to society (EPE, 2016).

Energy models are useful to explore future energy demand scenarios as they can guide decisions of policy regarding energy supply and transmission. By quantifying the consumption and estimating the impacts due to technological improvements, decisions can be made to support energy supply and technology incentives (KIALASHAKI; REISEL, 2014).

Forecasts on energy demand date back to the 60's. In this decade, (BALESTRA; NERLOVE, 1966) have estimated the demand for natural gas in the residential and commercial market of the USA, using time series. In the seventies, even more studies related to fossil and non-fossil energy sources were published (e.g. Brookes, 1973; Day, 1972; Gillies et al., 1973; Ray, 1973), and since then other numerous studies related to energy demand forecast have been developed, the majority of them appearing in the last 10 years (e.g. Anable et al., 2012; Bennouna and El Hebil, 2016; Ermis et al., 2007; Nekrasov and Sinyak, 2007; Schutz et al., 2013; Wang et al., 2011).

There are many types of methodologies and systems used to forecast the future demand of fossil and non-fossil energy sources. Long-range Energy Plan – LEAP, Market Allocation – MARKAL, World Energy Projection System – WEPS, All Modular Industry Growth – AMIGA, General Equilibrium Model, Panel Cointegration, Regression and Time series are some examples of models and methods used.

The estimation of future ethanol demand is of interest to Brazilian sugarcane and ethanol producers, for a number of reasons (SMITH, 2013). The sugarcane-

ethanol sector has a significant contribution to the country's GDP, generates a large number of jobs, and contributes to GHG emission savings (HERRERAS MARTÍNEZ et al., 2013; WALTER et al., 2008b). Having a prediction of the possible kind and size of future sugarcane-ethanol market is relevant to all stakeholders of the ethanol chain, because this can help planning energy policies, as well as implementation of new technologies, within time to avoid negative impacts that an unexpected change in demand can bring.

A number of studies (De Andrade Guerra et al., 2015; de Freitas and Kaneko, 2011; Empresa de Pesquisa Energética - EPE, 2007; Epe, 2015; Schutz et al., 2013; UNICA, 2010; van der Hilst et al, forthcoming) have assessed the sugarcane-ethanol demand in Brazil, up to 2030. Those forecasts have in common the type of energy, but they differ markedly among their outputs (e.g. total ethanol demand), and these divergences between models may be due to different assumptions concerning GDP growth, differences in the assumed growth of flex fuels vehicles fleet, and the energy-intensity of GDP, among others.

In this context, the objective of this review is to identify the projections existent for ethanol demand in Brazil, to what extent they are similar in methods and results, as well as why these similarities and differences happen, and what are the most important parameters influencing future ethanol demand. Two demands of the works assessed will be selected for discussion of possible scenarios of ethanol, on further work.

2.1.2 Paper structure

Section 2 presents a review and explanation of types of energy demand models used by several authors in the last 10 years. The objective of this section is first to assess methods for energy forecast in general, and then, in the next section (3), focus on ethanol demand forecast for Brazil. In section 3 a summary of projections for Brazil regarding future ethanol demand is presented. Section 3.1 focus on the outlook for ethanol until 2030. Several comparisons are done with the data available in each selected study, in order to investigate the differences and

similarities between the projections and to check the influence of the parameters used in those studies on future ethanol demand. Section 4 presents the concluding remarks regarding the differences and similarities of the ethanol demand models assessed and their estimated demands.

2.2 Energy demand projections

Energy demand modelling has shown to be an essential component for energy planning, formulating strategies and recommending energy policies. Since the early 1970s, when energy caught the attention of policymakers in the aftermath of the first oil crisis, research on energy demand analysis has vastly increased (BHATTACHARYYA; TIMILSINA, 2010).

The objective of an energy demand model is quantifying the energy requirements as a function of explanatory variables. Models may be used for various reasons. The most common goal of the energy models are the determination of regional and national energy supply requirements and the change in energy demand of a particular sector to know if an upgrade or addition of technology will be need (KIALASHAKI; REISEL, 2014).

Alternative methodologies for conducting energy surveys to estimate and project useful sectoral energy requirements have been developed (JEBARAJ; INIYAN, 2006). According to (SMITH, 2013), a projection is based on a set of assumptions. Over time, changed circumstances, updated information, policy shifts, etc. may undermine some or all of those assumptions, thus projections need to be uptaded.

There are many types of models that can be used in a demand projection study. They can be classified in several ways, such as static versus dynamic, univariate versus multivariate, and methods ranging from times series to hybrid models (SUGANTHI; SAMUEL, 2012).

In order to check what are the models that have been applied in energy forecast in the last 10 years, a systematic review was done. The criteria for selection is that the study perform an energy demand forecast, preferable up to

2030, and present the model/method used for the projection. The papers were collected at *Periódicos Capes* (collection of national and international publications), in order of relevance and number of citations. The other reports and works were obtained direct at the website of the authoring institutions.

Table 1 presents an overview of these types of models used in different studies related to energy future demand projections. The studies are organized in the table per type of methods applied.

Table 1: Summary of energy demand models found on literature, arranged per type of method applied.

	Method	Type of energy	Region of study	Period	References
Artificial Intelligence model	Artificial Neural Network - ANN	Non-fossil energy sources (solar, hydropower, wind, biomass, nuclear, hydrogen, etc.)	World	2007-2025	(Ermis et al., 2007)
		Transport energy	Turquia	2006-2020	(Murat and Ceylan, 2006)
		Natural gas, diesel, electricity	USA	2013-2030	(Kialashaki and Reisel, 2014)
Bottom – up	End-use Demand Modeling	Energy mix	Iran	2005-2030	(Moshiri et al., 2012)
		Electricity	Romania	2013-2050	(Malla and Timilsina, 2016)
	Integated Energy Planning Model - MIPE	Energy mix	Brazil	2005-2030	(Empresa de Pesquisa Energética - EPE, 2007)
		Natural gas		1995-2010	(Fernandes et al., 2005)
		Ethanol		2015-2030	(Schutz et al., 2013)
	LEAP	Energy mix	Republic of Korea	2006-2030	(Kim et al., 2011)
			China	2000-2030	(Wang et al.,

	Electricity	Taiwan	2008-2030	(Huang et al., 2011)	
		India	2012-2030	(Kale and Pohekar, 2014)	
		Panama	2012-2026	(McPherson and Karney, 2014)	
		Brazil	2007-2030	(De Andrade Guerra et al., 2015)	
	MARKAL	Biodiesel, diesel, gasoline	UK	2005-2050	(Anable et al., 2012)
		Electricity	World	2011-2030	(Panos et al., 2016)
Computable General Equilibrium – CGE	All Modular Industry Growth Assessment - AMIGA	Natural gas, renewable energy, nuclear and hydroelectric power, coal	USA	2000-2035	(Mintzer et al., 2003)
	CGE	Renewable energy	Morocco	2007-2020	(Landis and Timilsina, 2014)
	Input-output model	Energy	World	2005-2035	(Chen and Chen, 2011)
		Ethanol and bioelectricity	Brazil	2010-2020	(UNICA, 2010)
	Macroeconomic forecast	Ethanol and biodiesel	World	2009-2019	(FAPRI - Food and Agricultural Policy Research Institute, 2010)
	World Energy Model	Energy mix	World	2010-2035	(IEA, 2011)
	World energy projection system	Gasoline	US	2005-2040	(EIA, 2015)
Brazil			2005-2025	(Cerqueira Leite et al., 2009)	

Integrated model	Particle Swarm Optimization	Primary energy	China	2010-2020	(Yu et al., 2012)	
Partial equilibrium	Aglink-Cosimo Model	Biofuels	World	2012-2022	(OECD-FAO, 2013)	
Probability distribution	Hubbert curve	Oil and bioethanol	Brazil	2011-2070	(Moreira et al., 2014)	
		Petroleum		2012-2030	(Goldemberg et al., 2014)	
Time series	Auto regressive distributed lag - ARDL	Electricity	Cyprus	2008-2030	(Zachariadis, 2010)	
	Panel Cointegration	Ethanol	Brazil	2002-2006	(de Freitas and Kaneko, 2011)	
	Time series	Energy mix	Etanol and gasoline	Brazil	2006-2020	(Alencar, 2012)
					2014-2024	(FIESP, 2013)
			Ethanol		2015-2025	(Empresa de Pesquisa Energética - EPE, 2016)
			Gasoline and ethanol		US, EU-25, Japan, China, Brazil and the Rest of The World (ROW-BR)	2010-2015
Vector Error Correction - VEC	Energy mix	Morocco	2015-2030	(Bennouna and El Hebil, 2016)		

As can be seen in table 1, several papers have been published about energy forecast and, as expected, these assessments vary in type of energy, geographical region and level, and period forecasted. Most of the papers reviewed

discuss the future of energy in emerging countries, such as Brazil and China, which is understandable due the fact that those countries are expected to have higher demographic growth than developed countries, as well as higher GDP growth, thus they will have significant increase in demand for energy.

Various authors have carried out energy demand and supply forecast using bottom up models. From studies presented on table 1, the most used is LEAP (Long-range Energy Alternatives Planning), when was developed by the Stockholm Environment Institute (HEAPS, 2016). This model can be used to estimate energy utilization, generation and resources in all sectors of an economy (KALE; POHEKAR, 2014). LEAP is fast becoming the de facto standard for countries undertaking integrated resource planning, greenhouse gas (GHG) mitigation assessments, and Low Emission Development Strategies (LEDS) especially in the developing world (HEAPS, 2016).

The other bottom-up models, the Market Allocation model- (MARKAL) and the End-use model have also been used. MARKAL is an integrated energy system modelling platform used to analyse energy, economic, and environmental issues at the global, national, and municipal level over time (WRIGHT et al., 2010). The model employs demand for energy from the industrial, commercial, residential, and transportation sectors, as well as information on available energy technologies to determine from where the demanded energy would originate. The user define constraints such as, limits on technology, or caps on various emissions, and the model determines the least-cost mix of energy suppliers and technologies to please energy demand (ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAM, 2016).

The end-use model, also called techno-economic or engineering approach, uses energy billing data and detailed survey information on household, appliances, and capital characteristics to determine the end-use energy consumption by each type of appliance or capital and to simulate the total energy consumption for the sector, region, or economy (MOSHIRI et al., 2012).

The Integrated Energy Planning Model (*MIPE*), specific to Brazil, is also extensively used. It is a demand model developed by the Coordination of

Engineering Graduate Programs (*COPPE*) of Federal University of Rio de Janeiro, and has been used by the Energy Research Company of Brazil (EPE) for the elaboration of the most known and cited report of energy projections of Brazil: the National Energy Plan for 2030 (PNE 2030) (EPE, 2007). The demand module mixes the impact factors from the macroeconomic scenarios and technical issues from the different consumption sectors. Based on this module and the energy supply options in the supply module, the forecast is drawn up (FERNANDES; FONSECA; ALONSO, 2005).

The Artificial Neural Network (ANN) is an artificial intelligence based information-processing system that has certain performance characteristics in common with biological neural networks (KIALASHAKI; REISEL, 2014). ANNs are a class of flexible nonlinear models that can discover patterns adaptively from the data.

Another artificial intelligence model used is the Particle Swarm Optimization (PSO), that is a class of biologically inspired heuristics optimization algorithms, which includes Ant Colony Optimization (ACO). The basic idea of ACO is the imitation of the cooperative behaviour of ant colonies. Like other swarm-based techniques, the PSO consists of many individuals refining their knowledge of a given search space (YU; WEI; WANG, 2012).

Panel data models have both a cross-sectional and a time series dimension, where all cross section units are observed during the whole time period (KATCHOVA, 2015). Panel cointegration framework is used, allowing estimation of ethanol demand elasticities by region. The panel cointegration test is preceded by an examination of the data set starting with a test for the possible presence of a panel unit root (PUR) (DE FREITAS; KANEKO, 2011). Thus, the cointegration test examines whether a long-run equilibrium relationship exists among the variables when individual variables are non-stationary in nature. Once the cointegration relationship is established, the panel Vector Error Correction Model - VEC is used to investigate the direction of the causal relationship between variables, e.g. energy consumption and output growth (KUMAR MANDAL; MADHESWARAN, 2010).

Computable general equilibrium (CGE) models have garnered much attention recently for use in economic analysis, due in large part to their ability to simulate the impacts of prospective policies taking into account intersectoral and international interactions, capturing economy-wide impacts of a policy instrument, or a development activity (LANDIS; TIMILSINA, 2014). Despite this heavy usage—particularly in the analysis of broad-based policies relating to energy, climate and trade, CGE models are often criticized as being insufficiently validated. Key parameters are often not econometrically estimated, and the performance of the model as a whole is rarely checked against historical outcomes (BECKMAN; HERTEL; TYNER, 2011)

The AMIGA model, developed by the U.S. Department of Energy's Argonne National Laboratory, is a multi-sectoral simulation model of the U.S. economy. The model contains a detailed representation of the building, industry, transportation, and electricity sectors of the U.S. economy, including a database representing the investments in the transportation, electricity, and buildings sectors. Built around a series of behavioral equations concerning the acquisition, deployment, and retirement of energy-using capital stock in each sector, the model estimates the demand for energy services by sector and across the economy as a whole (MINTZER; LEONARD; SCHWARTZ, 2003).

The International Energy Agency – IEA annually publishes the World Energy Outlook – WEO, that demonstrate an overview of energy projections up to 2020, 2025, 2030, 2035 and 2040. To do the estimations they use the World Energy Model (WEM). The model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region (IEA, 2011).

The Energy Information Agency - EIA also publishes an annual report called International Energy Outlook – IEO and for the projections it uses a model called World Energy Projection System Plus (WEPS+), that consists of a Macroeconomic Model, Demand Models, Supply Models, a Main Model, Transformation Models and A Greenhouse Gases Model (CHANG; LEE; YOON, 2012).

These two approaches are the most famous and maybe complex models used to estimate energy future demand (AGENCY; GRUENSPECHT; ADMINISTRATOR, 2012). The main differences between these methods are that EIA base case assumes only current policies and regulations; there are significant differences on the United States - US energy production, demand, and prices across fuels; WEO forecasts a larger OPEC market share of global liquids production; WEO assumes GDP growth remains constant across wide-ranging side cases and WEO includes traditional, non-commercial biomass and waste in its renewables data which slows its growth rate compared to IEO resulting in an uneven comparison (AGENCY; GRUENSPECHT; ADMINISTRATOR, 2012). Concerning Brazil, the EIA addresses it only about petroleum consumption, and the IEA address the total energy demand of the country, not specifying it by sector or product.

An idealized Hubbert curve (IHC) is defined as having properties of production data resulting from a constant growth-rate under fixed resource limits (GALLAGHER, 2011). The Hubbert curve has been mainly used in studies about oil reserves. Hubbert's method is thought easy to implement since it only requires a least-square computation to estimate the parameters of a logistic or Gaussian curve. The area under the curve is exactly the amount of ultimate reserves. In a specific area, the ultimate reserves are the total oil that will be produced during the exploitation and, of course, this amount of oil can only be estimated. Thus, the Hubbert method is no more than the fitting of a bell-shaped curve on the production curve, with an area above the curve imposed by the estimate of ultimate reserves (MICHEL, 2011).

2.3 Ethanol demand for Brazil

When it comes to Brazil, few studies specific to ethanol demand projection, are found. From those reviewed and presented on section 2, seven are specific to ethanol in Brazil.

A total of eight projections were analysed in this section, being seven the ones specific to ethanol, and another one a study about electricity (DE ANDRADE GUERRA et al., 2015), which also discuss and present ethanol future projections for Brazil. The projections derive mainly from studies developed by the Energy research company - EPE (National Energy Plan 2030 and Ten-year Energy Plan 2024) and Industry Federation of Sao Paulo (Fiesp). Table 2 lists the studies from which projections and scenarios, that presented information concerning ethanol demand in Brazil, were extracted for analysis. Some of the studies analysed report ethanol demand data in terms of energy content, as millions of tonnes of oil equivalent (Mtoe), others in millions of barrels (bbl) per day or million or thousand liters (l) per year. In this way, all these values were converted into billion liters of ethanol per year, hereby presented as Giga (G). The values used for conversion were obtained from (AGÊNCIA NACIONAL DO PETRÓLEO GÁS NATURAL E BIOCOMBUSTÍVEIS, 2016).

Table 2: List of scenarios taken from the selected studies, considered for comparison in this paper.

Publication title, citation	Scenario examined ¹	Acronym in this work
Plano Nacional de Energia 2030 (Empresa de Pesquisa Energética - EPE, 2007)	B1	NEP B1
Perspectives on fuel ethanol consumption and trade (Walter et al., 2008b)	Scenario 1	Walter
Análise do balanço entre demanda por etanol e oferta de cana de açúcar no Brasil (Alencar, 2012)	Scenario Conab	Alencar
Demanda e oferta energética: uma perspectiva mundial e nacional para o etanol (Schutz et al., 2013)	Scenario B1	SZ B1
Outlook Fiesp 2023 - Projeções para o agronegócio brasileiro (FIESP, 2013)	Optimistic	Fiesp Op

Future scenarios and trends in energy generation in Base scenario AG BS
 brazil: supply and demand and mitigation forecasts

(De Andrade Guerra et al., 2015)

Demanda de Energia 2050 (Empresa de Pesquisa Reference EPE Ref
 Energética - EPE, 2016)

Etanol e bioeletricidade: a cana de açúcar no futuro Base scenario Unica
 da matriz energética (UNICA, 2010)

¹ the names of the scenarios follow the names presented in their original work. E.g. Scenario B1 is scenario B1 of *Plano Nacional de Energia* (which have 4 different scenarios).

Figure 1 shows the difference in estimated ethanol demand by the studies presented on table 2, and the historic consumption of ethanol in Brazil, from 1990 to 2015 (AGÊNCIA NACIONAL DO PETRÓLEO GÁS NATURAL E BIOCOMBUSTÍVEIS, 2016).

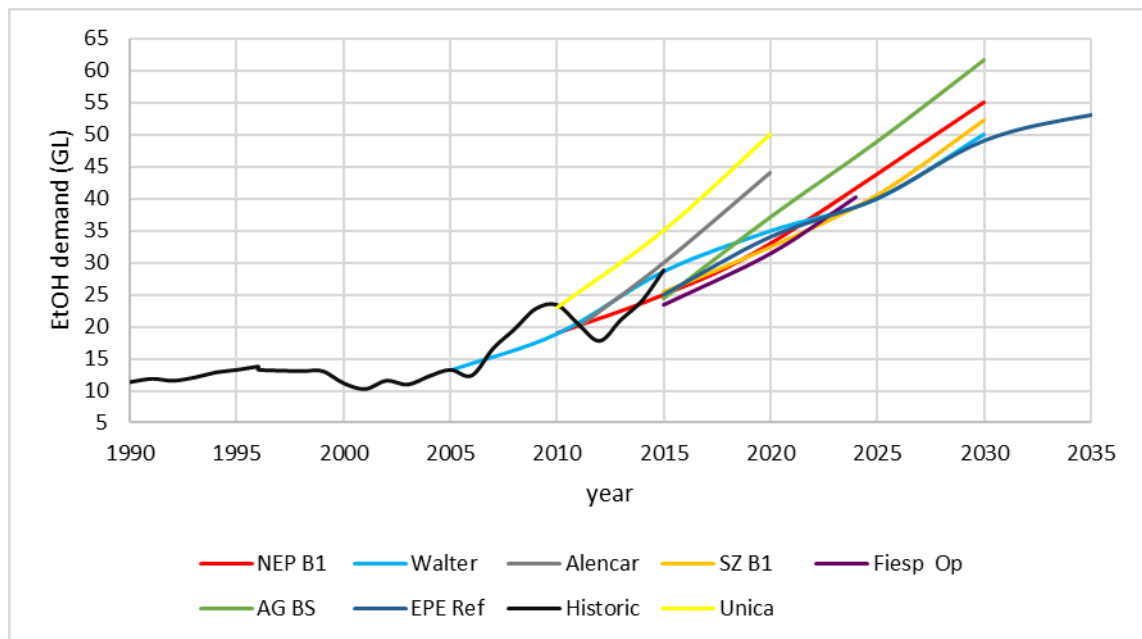


Figure 1: Different scenarios of projected ethanol demand for Brazil, per year.

All projections demonstrate that ethanol demand will significantly increase in the next 15 years, although they present a noteworthy range of predictions for a given year. The difference between the highest and the lowest projection for 2020

is 18.5 GI EtOH, and for 2030 it is to 12.7 GI, considering only the values that are presented in the studies and not extrapolating the curves (if extrapolating the difference would be expressively larger). These values are significant when compared to the actual consumption in 2015, which was 28.8 GI EtOH.

The year 2015 is included in all projections. As it can be seen, the projections for this year presented higher and lower results in comparison to the real consumption of 2015. In order to better demonstrate this proportion, figure 2 is built. On it is presented the fraction of 2015 EtOH demand projected for this same.

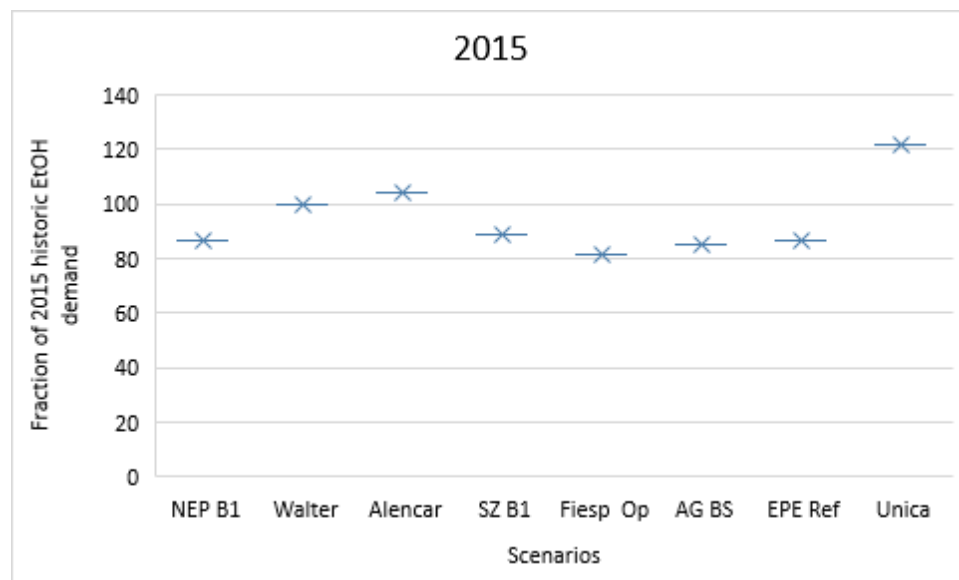


Figura 2: Range of EtOH demand projected, in selected scenarios, for 2015.

Most scenarios resulted in a projection lower than what actually happened in that year, and although Walter had a precise estimation, it cannot be affirmed that this is the best model to follow. The lower bound of NEP B1, SZ B1, Fiesp Op, AG BS and EPE Ref can be explained by the assumptions they've done concerning the sugarcane sub products growth rate, and GDP growth, which differ from EPE Ref (see table 4).

To check how accurate are the projections of the works assessed, the Mean Square Error (MSE) was calculated for those which projections could be compared to historic value, e.g., the works that presented estimations before 2015 could be

evaluate comparing to the real values of that period (See table 3). From the works selected, only SZ B1 couldn't be assessed because lack of data. The results show that the estimations of NEP B1 were the most accurate in the period assessed and Unica the worst.

Table 3: Mean square error of ethanol demand for the period 2013-2015.

	EPE						
	NEP B1	Walter	Ref	Alencar	Fiesp	AG BS	Única
MSE	2,96	5,86	7,42	10,34	10,97	41,21	61,02

2.3.1 Why do the projections differ

As could be seen on figure 1 and table 3, the demand estimated by the works markedly differ, although the studied sector be the same. The model used, the drivers considered and its values are some of the reasons to such difference exist.

In general, energy consumption exhibits a high, positive correlation with GDP (SMITH, 2013). Not all models here presented uses GDP as an input to build the scenarios analysed. This is consistent with the fact that ethanol market is not mainly driven by GDP, but also to the automobile market (flex fuel vehicles - FFV), population growth, oil price, technology improvement, electric cars fleet, etc, variables that are considered to have a strong relation with it. In this review the analysis are done only considering EtOH demand, GDP and flex fuel vehicles fleet. Even well knowing the importance of the other cited drivers, the variables detected are the only ones with accessible data in the respective papers/works. The other drivers are cited in some studies, but no detailed information is available.

Table 4 lists the principal economic assumptions available and associated with each of the scenarios hereby analysed, as well as the models used for each projection.

Table 4: Summary of key assumptions, per scenario.

Acronym	Annual growth GDP	Annual growth of vehicle fleet ¹	Assumptions	Model	Main drivers
NEP B1	2005-2030: 4.1	NI ²	Relevant reduction of income inequalities	MIPE	GDP growth, demographic evolution, world market growth
			Medium to high total economy productivity		
			World annual GDP: 2005-2025: 3.0%		
Walter	NU ³	NI	Based on the hypothesis that ethanol production from lignocellulosic materials will be feasible.	Time series	national and international ethanol consumption
			Ethanol consumption annually increase 2.6% in the period 2006-2011 and 3.5% in 2003-2030.		
Alencar	NU	2011-2014 : 6% 2015-2020: 4.6%		Time series	demographic evolution, consumption of fuels. Prices of gasoline and ethanol.
SZ B1	2005-2030: 4.1	NI	Used same assumptions of scenario B1 from NEP.	MIPE	GDP growth, demographic evolution, world market growth,
Fiesp Op	NU	NI	Demand will increase 74.6% from 2014 to 2024.	Time series	price of sugar, consumption of sugar and ethanol
AG BS	2005-2030: 4.1	2000-2007: 2.9%	Expansion scenario of rural activity	LEAP	Demographic evolution; GDP behavior; evolution of

					the vehicle fleet; new technologies
EPE Ref	2010-2020: 1.9% 2020-2030: 4.4% 2013-2050: 3.2%	2013-2050: 2.3%	Increase energy efficiency of vehicles in 1% a year	Time series	GDP, energy consumption, income-elasticity of energy, ethanol consumption
Unica, 2010	NI	NI	E Technology in 2020 Increase of FFV Energy efficiency Period forecasted: 2009-2019	Input-output model	gasoline and ethanol consumption, prices of ethanol and gasoline, GDP

¹ Motorcycles, cars and light commercial vehicles.

² Not informed (NI) the rate considered, but cite in the text that this variable is considered.

³ Not used (NU) in his model. The author considered only number of vehicles per social class and the vehicles fleet per state. Also, natural gas (NG), electric cars and oil were not considered.

From the studies/scenarios analysed (table 4), it can be observed that the difference in projected demand for ethanol, between scenarios, may be due mainly by the different assumptions concerning GDP growth and different assumptions concerning flex-fuel vehicles fleet growth. The period assessed in the studies also varied, with some of them being projections until 2020. Other drivers were also take into account, but this substantially varies between studies, and not all of them inform the data used, a fact that represent limitation to further conclusions and comparisons. Basically, three types of methods were used to project the demand: bottom up model, time series and general equilibrium model, being time series the most applied.

Except for Alencar, Fiesp OP and Walter's scenario that didn't use GDP in their forecast model, it is noted that the other GDP assumptions are by and large the same, derived from (EPE, 2007). When this is not true, they are broadly similar.

Comparing NEP B1, SZ B1, and AG BS with the world annual GDP growth of 3.0% (EPE, 2007), the expectation that the country grows more than the world average, up to 2030, is sustained. Even in the most pessimist scenario Brazil is assumed present higher growth than the average world rate. EPE Ref considers different rates for 2010 – 2020 and 2020-2030, and as can be seen, until 2020 Brazil's economy will grow less than the average world, changing this scenario only after 2020, when it will again present higher GDP growth rate as compared to the world. This assumption goes well with the actual economic scenario of Brazil, as published by the International Monetary Fund (IMF, 2016). According to it, in 2015 Brazil presented a negative GDP change of -3.8%, while the world presented a positive grow of 3.2% in the same year. In the period 2010-2020 it is projected for Brazil an annual GDP growth of 2%, and for the world 3.5% (IMF, 2016). According to (IEA, 2015), between 2020-2030 Brazil will again present higher GDP grow compared to the world. For the world, the average annual growth rate is expected to be 3.8% from 2020 to 2030, and for Brazil EPE Ref considers 4.4%, for the same period.

In order to observe the relation between GDP and ethanol demand, a combined graphic of historical ethanol consumption and GDP (both in percental variation) versus time is done (Figure 3).

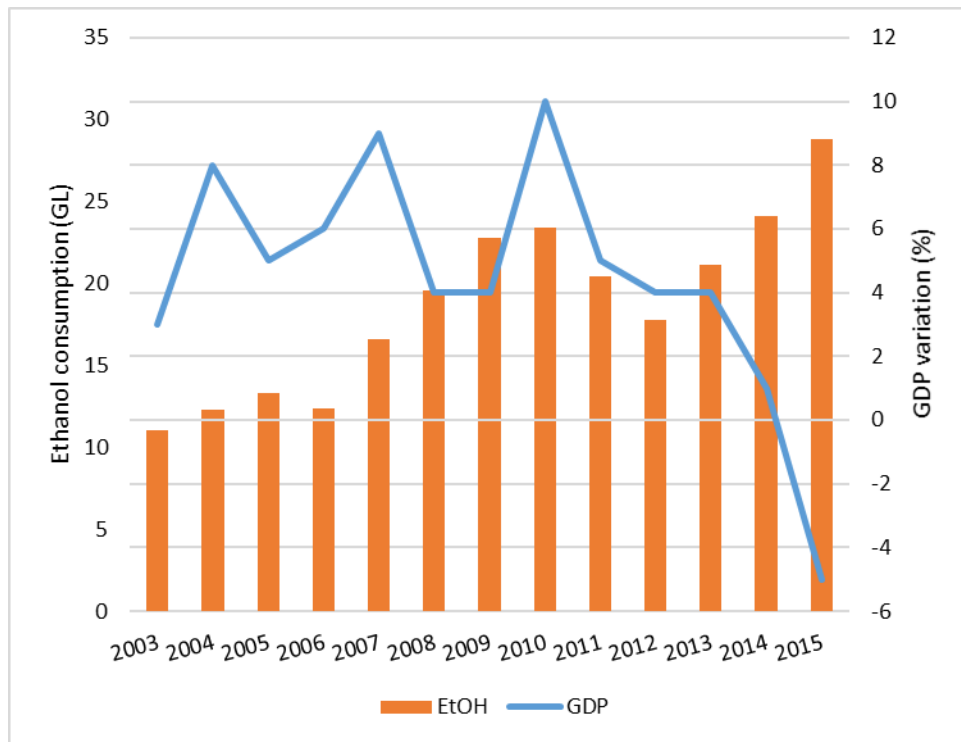


Figure 3: GDP variation (percental difference to base year -1995) (IBGE, 2016), and EtOH total consumption (ANP, 2016) versus time.

As can be seen on figure 3, between 2010 and 2012 there was a decrease in ethanol consumption. GDP presented the same behaviour of reduction, but after 2013, it continued decreasing, while EtOH presented an increase in consumption, indicating a change in their relation from positive to negative.

To better check the correlation existent between GDP and consumption of ethanol, and how strong is this correlation, the spearman coefficient was calculated. It is a non-parametric test to measure the degree of association between two variables, whether linear or not (HAUKE; KOSSOWSKI, 2011).

Figure 4 presents the graphic of ethanol consumption variation versus GDP variation and the spearman coefficient.

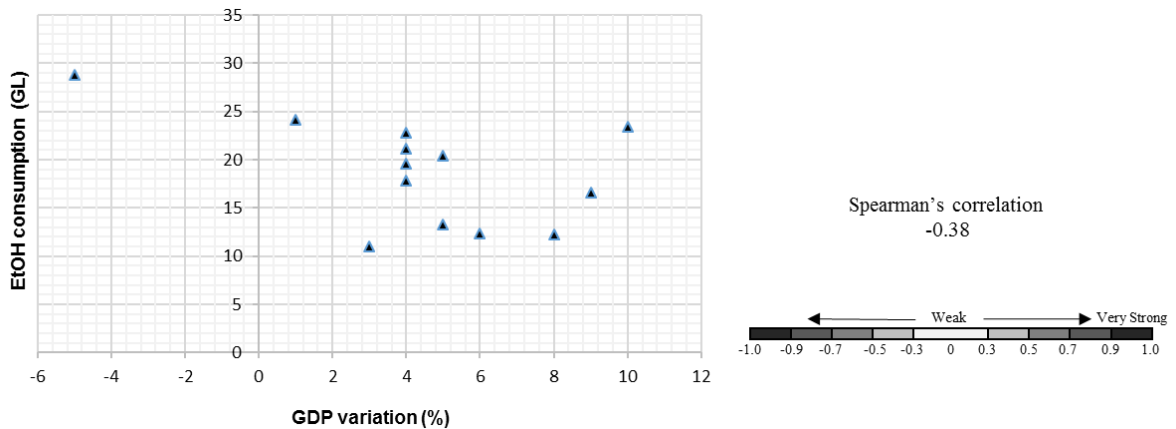


Figure 4: Correlation between ethanol consumption and GDP variation (percentual difference to base year - 1995) (IBGE, 2016), in Brazil, in the period of 2003 – 2015.

According to Spearman's coefficient, the correlation between GDP and the ethanol demand is in between moderate to weak, and as expected (from figure 3), they have a negative relation. Experts on ethanol market have already published notes informing that ethanol sector was growing more than GDP since 2013, changing their relation (Sindicape, 2015; CenarioAgro 2016). There are many factors that can explain this, as changes in consumer behaviour not due to increase on per capita income but because of public services deterioration (E.g. worsening of public transport system motivates people to acquire a new vehicle), increase of vehicle fleet due to the increase of credit lines, and competitive price of ethanol compared to gasoline, increasing its demand.

The projected evolution of GDP with time, up to 2030 is plotted on figure 5.

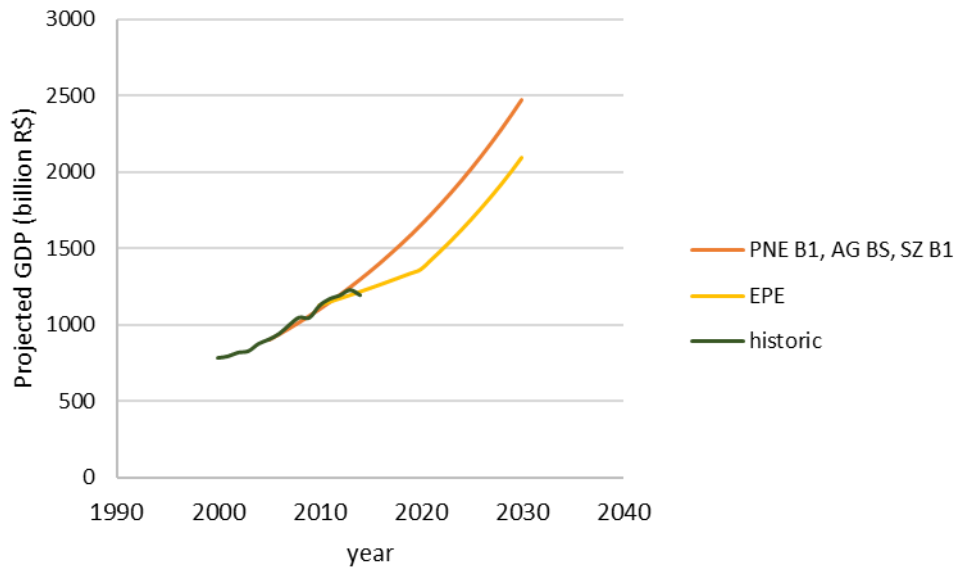


Figure 5: Projected future GDP (2015-2030) versus time, for scenarios selected.

Although GDP present moderate correlation with EtOH consumption, the projections of the works which used this variable were still compared, in order to better analyse them. In the graphic of project GDP versus time (Figure 5), note that only one scenario has different behaviour. This is due the fact that it is the only one that assumes different annual growth rates of GDP (see table 4). The difference between the highest and the lowest projection of GDP for 2020 is R\$294 million, and for 2030 it little increases to R\$380 million.

As presented before, the growth of FFV fleet is included in the majority of studies on ethanol demand projections. To observe the relation between ethanol consumption and FFV fleet, a combined graphic of historical ethanol consumption and FFV fleet is done (Figure 6).

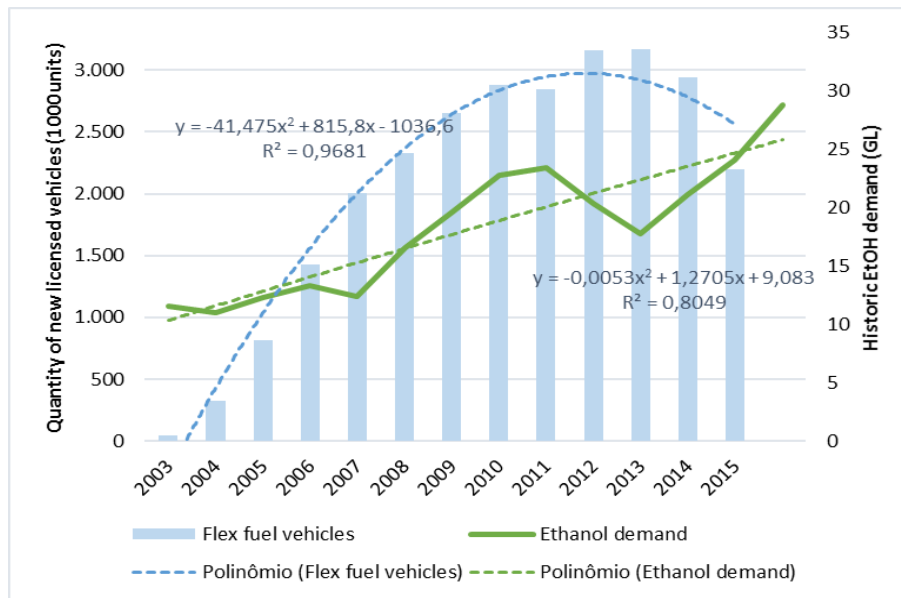


Figure 6: Quantity of licensed FFV (ANFAVEA, 2016), in Brazil, and historic total consumption of EtOH (ANP, 2016) versus time.

Checking figure 6, the market of FFV presented a retraction since 2013, and apparently, this didn't happen to the consumption of ethanol. Some of the scenarios, here analysed (table 4), considered on their models the influence of light vehicles fleet on the consumption of ethanol, and looking at figure 6 seems that this relation does not exist. To check the correlation between vehicles fleet and consumption of ethanol, the spearman coefficient was also calculated. Figure 7 presents the graphic of ethanol demand versus vehicle fleet and the spearman coefficient.

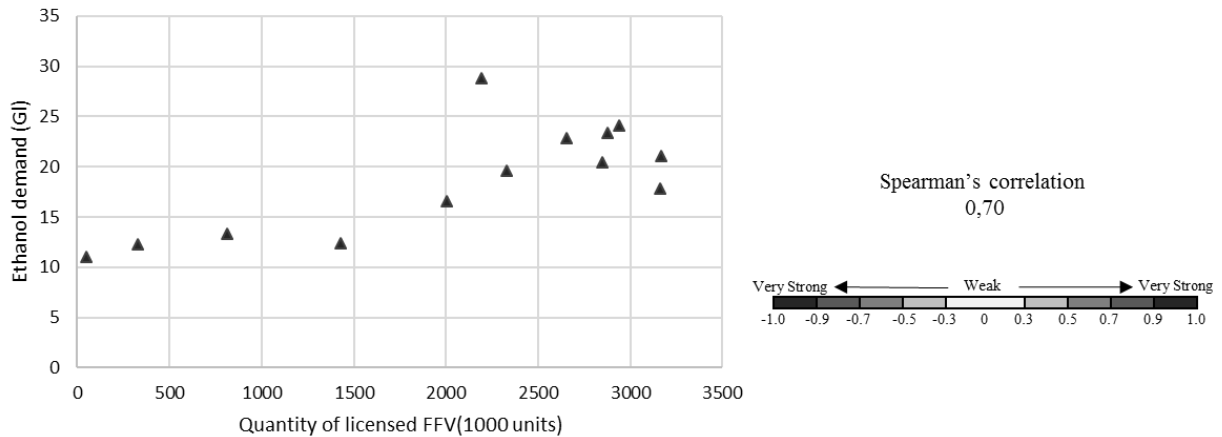


Figure 7: correlation between ethanol demand and the fleet of FFV in Brazil, in the period of 2003 – 2015.

The correlation between ethanol demand and fleet of vehicles is strong according Spearman's coefficient (Figure 7), thus this is an important variable to be considered in a model of future ethanol demand.

The projected evolution of flex fuel light vehicles fleet with time, and the correlation between projected fleet and projected demand of ethanol, for the scenarios that assumed this variable, are plotted in figure 8.

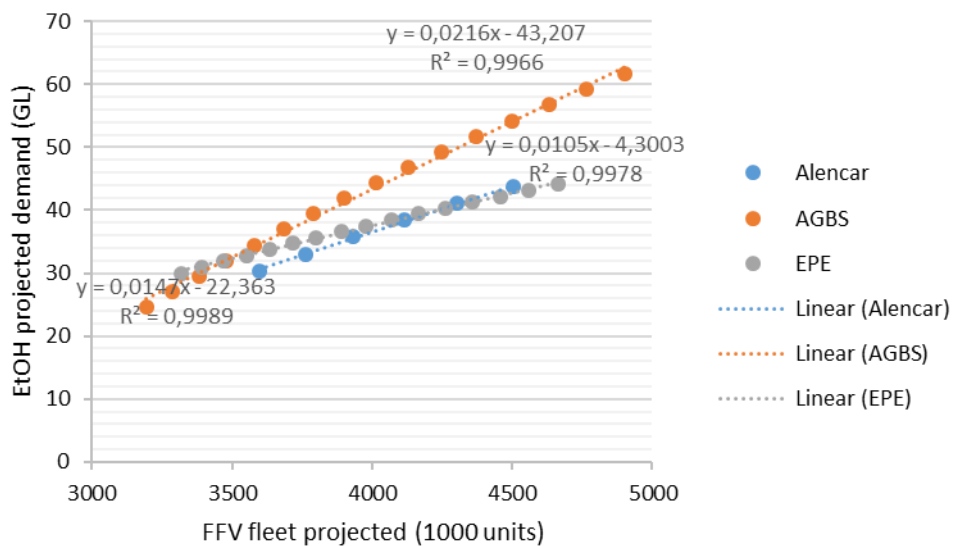
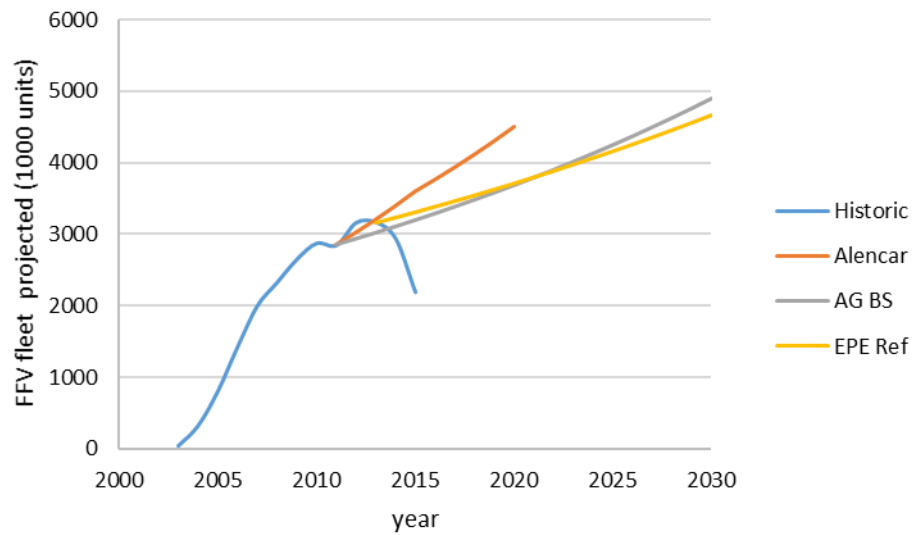


Figure 8: Projected future FFV fleet (2013-2030) versus time, for scenarios selected; and ethanol future demand versus FFV projected, for scenarios

In the graphic of project fleet versus time, note that the projections started before 2015, and except for Alencar, they have similar curve. Alencar considered in his model only the variance of car fleet, excluding the influence of GDP, which might explain the difference from others. Checking the difference between the highest and the lowest projection, for 2020 it is of 818 thousand vehicles, and for 2030, between AG BS and EPE Ref it decreases to 238 thousand, but could be

higher if extrapolate Alencar's projection. The correlation between FFV and ethanol consumption across scenarios is consistent with the Spearman's correlation estimated before, and is still evident on figure 8.

2.4 Concluding remarks

The adoption of a systematic review to identify the projections existents for ethanol future demand in Brazil was a useful approach to this study. Eight projections of ethanol demand have been selected and analysed. Divergences between projections are found to derive, mainly, from to differing assumptions concerning national GDP growth and FFV fleet. These two parameters present correlation to ethanol demand, therefore, it is concluded that they are important and must be included in an ethanol projection model.

Three types of methods were most used to project the ethanol demand: bottom up model, time series and general equilibrium model. The differences between the results of the scenarios assessed are mainly due to parameters considered, their values and how they are treated and linked in the models. Different models can use the same drivers and obtain different outputs, in the same way that different drivers in a same model, generates different results. Therefore, affirm what is the best model is a complicated task, since results are very dependent on the assumptions of the model designer, and in the transparency of data used.

From the studies analysed (table 4), five consider both GDP and FFV fleet: SZ B1, NEP B1, AG BS, Unica and EPE Ref, but three (SZ B1, NEP B1 and Unica) were not completely transparent and had limited use for the purpose of this review. Therefore, only , EPE Ref and AG BS, which provided the input and output data, were considered for final decision.

The results of the Mean Square Error (table 3), shows that, EPE Ref is more accurate than AG BS. Since EPE is estimated using time series model, that is more simple and is based on trend analysis, its resulting demand is chosen to construct a Business as Usual Scenario.

The demand obtained in AG BS is also selected and considered for further analysis. Although presenting the highest demand value, and the highest MSE, AG BS used a more complex model in comparison to EPE Ref, and not only considered the vehicles fleet and GDP, but also the expansion of rural activity. The model used is the LEAP, that is fast becoming a “de facto” standard for countries undertaking resource planning, which is the case of Brazil. The final demand of EtOH estimated with this model is 61.7 GI, in 2030, and can be used for a construction of an optimistic scenario, considering that ethanol will be more competitive and the growth rate of the last 3 years, that was higher than the usual, will be kept.

Therefore, concludes that the estimations for ethanol demand significantly vary according to the method and parameters considered, and through the analysis done, accomplishes that Brazil will have a projected demand ranging from 49 GL EtOH, in a Business as Usual Scenario, to almost 62 GL EtOH, in a optimistic scenario.

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Chapter 3: Spatially explicit assessment of the sustainable potential of sugarcane and ethanol in Brazil

3.1 Introduction

Biomass is expected to play an important role in meeting future demand for energy, materials and chemicals (IPCC, 2011; GEA 2012, Saygin et al 2014, IfBB 2015). However, the increasing deployment of biomass has fuelled the debate on its sustainability (Dornburg et al 2010). Many studies have assessed biomass potentials. However, estimates vary widely due to the type of potential assessed (e.g. theoretically, technically, economic, sustainable), the definitions applied, and the methods, assumptions and data used (Batidzirai 2012). Regarding the methods, numerous studies have conducted resourced-focussed¹ biomass potential assessments, using statistical methods to assess the bioenergy potential at a global (e.g. (FAAIJ; SMEETS, 2007; HABERL et al., 2011), regional (e.g. (SASAKI et al., 2009; SIMON; WIEGMANN, 2009) and local scale (e.g. (BILGEN et al., 2015; BUTT; HARTMANN; LENZ, 2013; JIANG et al., 2012; KUNG et al., 2014). However, as these statistical methods cannot account for geographically overlapping conditions for in- or excluding land available for bioenergy crop production (e.g. agro-ecological unsuitable land in conservation areas) and the spatial heterogeneity in productivity, they only provide first order estimations. Especially when it comes to sustainable biomass potentials, a spatially explicit assessment is required as the environmental and socio-economic impacts of biomass production depend on biophysical and socio-economic conditions which are spatially heterogeneous (VAN DER HILST et al., 2012).

¹Resource-focused assessments take into consideration the competition between different uses of the feedstock and environmental limitations of biomass production. Usually these types of studies focus on on assessing technical potentials (BATIDZIRAI et al, 2012).

Other studies have assessed bioenergy potentials spatially explicitly, also varying from global (DENG et al., 2015; ERB; HABERL; PLUTZAR, 2012; VAN VUUREN; VAN VLIET; STEHFEST, 2009), to regional (BECCALI et al., 2009; KEFFER et al., 2009; SCHUELER et al., 2013), and local (DIOGO et al., 2014; HISSA; FILHO, 2014; OKELLO et al., 2013; SMEETS; FAAIJ, 2010) scale, differentiating between theoretical, technical and economic potentials. However, it is often not transparent what criteria are applied and how different types of potentials relate to each other. In addition, no study has assessed the sustainable biomass potential spatially explicitly taking environmental and socio-economic criteria into account.

Based on these shortcomings identified in the existing literature, the objective of this study is to i) develop a systematic approach to assess the theoretical, technical, economic, and sustainable biomass potential spatially explicitly, and ii) demonstrate this for the current and future (2030) potential of sugar cane ethanol production in Brazil.

We focus on Brazil because it is currently the second largest bioethanol producer in the world and it is expected that sugar cane ethanol production will continue to increase rapidly towards 2030 (EPE, 2007; IEA, 2011; SCHUTZ; MASSUQUETTI; ALVES, 2013). Several studies have already indicated a large techno-economic potential of sugarcane-ethanol production in Brazil (EPE, 2007; WALTER et al., 2008a). This is because of potentially large land availability, favourable agro-ecological conditions, and long-term experience with sugar cane ethanol production (MARTINELLI; FILOSO, 2008; WALTER et al., 2011). Despite these advantages, the sugar cane ethanol sector in Brazil has gone through a crisis since 2012. This is due to an increase in production costs, sugarcane crop failure, lack of competitiveness of ethanol compared to fossil gasoline, and the late investment in mechanisation and the recovery of sugarcane plantations (CNA, 2014). In addition, concerns about its sustainability (e.g. losses of carbon stocks and biodiversity related to the conversion of native vegetation to sugar cane production) have created uncertainties about the future of the sugar cane sector in Brazil (HISSA; FILHO, 2014; VIANA; PEREZ, 2013). In this context, there is a

need for a better understanding of the potential for sustainable expansion of the sugar cane ethanol sector. A few studies (ALKIMIM; SPAROVEK; CLARKE, 2015; HISSA; FILHO, 2014; MONTEIRO; SENTELHAS, 2014) have spatially explicitly assessed the sugarcane-ethanol potential in Brazil. These studies mainly focus on the biophysical potential but also apply some economic and / or environmental constraints, e.g. forest and protected areas are excluded from the potential. However, a systematic assessment of the sugar cane potential in Brazil and how this potential is affected by sustainability constraints is lacking so far. Our analysis allows quantifying the different types of potentials for the current and projected sugar cane ethanol potential and to identify the most promising regions for sustainable sugar cane expansion in Brazil.

3.2 Methodology

The overall approach of this study is to spatially explicitly assess the theoretical, technical, economic and sustainable of potential of sugar cane ethanol production in Brazil for the reference situation (2012), and project how these potentials might change in the future (2030). All potentials are analysed spatially-explicitly by using the geographic information system ArcGIS and calculated at a cell size of 25 km² (2500 ha). The potentials are calculated in GJ ethanol production per year.

3.2.1 Definition of different types of potentials

In this study, the theoretical, technical, economic and sustainable potential are assessed. It is assumed that the sustainable potential meets both the economic and environmental criteria. Therefore, also the environmental potential is assessed separately. Table 5 provides an overview of the definitions and constraints per type of potential. The supplementary information presents a more detailed description.

Table 5: Overview of the definitions and related constraints of the different types of potentials as applied in this study; based on (BATIDZIRAI; SMEETS; FAAIJ, 2012).

Potential	Definition	Constraints applied in this study
Theoretical	Maximum amount of biomass production potential, which can be considered theoretically available for bioenergy production under optimal agricultural and forestry management	Excluded areas: urban areas, surface water, steep slopes (30%) and areas of solid rock and bare soil.
Technical	Fraction of the theoretical potential, which is available under current technological possibilities, not needed for food production or legally excluded	Excluded areas: <ul style="list-style-type: none"> - Areas in use for food, feed and fibre crops, pastures, rangeland and planted forests. - Legally excluded areas: legal reserves, permanent preservation, military areas, indigenous land, terrain with slopes higher than 12%.
Economic	Share of the technical potential, which meets economic criteria	economic criterion: Sugar cane ethanol production costs < ethanol prices.
Environmental	Share of the technical potential, which meets environmental criteria	Environmental criteria: <ul style="list-style-type: none"> - GHG emission - Organic soils - Water availability - Biodiversity- high and low preservation requirements - Possibility of mechanical harvesting (100%) - Natural forest, Amazon and Pantanal biome
Sustainable	Fraction of the economic	Economic and environmental as

	and environmental potential, where the two potentials intersect and thus account for economic and environmental criteria (social criteria are accounted for in terms of ensuring food security and economic viability of the production ¹)	defined above
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¹Many of the social criteria included in sustainability criteria, such as labour conditions or gender issues are not possible to assess ex-ante, as they are specific for an implemented project. However, the socio-economic criterion ‘food security’ is addressed as the assessment excludes current and future food demand in the technical potential. In addition, the economic viability threshold ensures that there are potential benefits for farmers and the local economy.

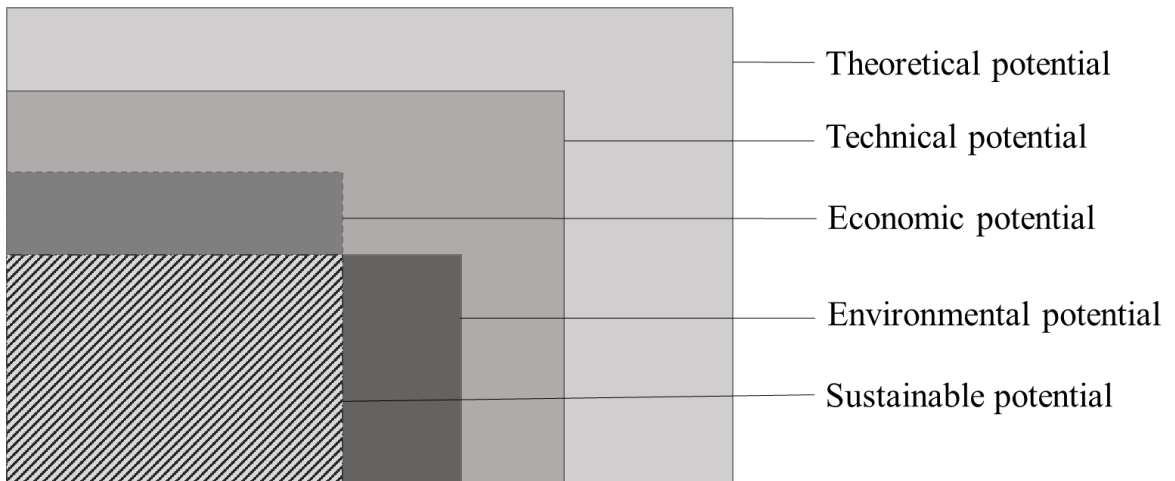


Figure 9: Relation between theoretical, technical, economic, environmental and sustainable potential. Adapted from BATIDZIRAI et al., 2012.

3.2.2. Calculation of potentials

The sugar cane ethanol potentials depend on the land availability, the potential sugar cane yield on the available land, and the conversion efficiency of sugar cane to ethanol (Equation 1).

$$P_{x,y} = \eta_y \cdot \sum_{i=1}^n (Y_{i,y} \cdot a_{i,x,y} \cdot c) \quad (1)$$

$P_{x,y}$	Total ethanol production for potential x (theoretical, technical, economic,	GJ EtOH /y
η_y	Conversion efficiency in year y	GJ EtOH/TC
$Y_{i,y}$	Sugarcane yield in cell i in year y	TC/ha/yr
$a_{i,x,y}$	Availability of cell i for sugarcane cultivation	1=available;0=unavailable
c	Area of grid cell	ha

The total area available for sugarcane cultivation $A_x = (\sum_{i=1}^n (a_{i,x,y} \cdot c))$ depends on the constraints applied for each type of potential (as explained in the following subsections). All types of potentials change over time due to developments in these constraints as well as sugarcane yield and conversion efficiency.

The sugar cane yield in cell i in year y ($Y_{i,y}$) is determined by the spatial variation in agro-ecological suitability for sugar cane S_i (taking into account soil, climate, water and terrain conditions) and its maximum attainable yield (M_y) according to management practices in year y (equation 2).

$$Y_{i,y} = (S_i \cdot M_y) \quad (2)$$

S_i	Agro-ecological suitability for	Fraction of maximum
M_y	Maximum attainable sugar cane yield	TC/ha/yr

The maximum attainable yield (M) for the reference year 2012 is calculated based on the national average sugarcane yield in 2012 and the average agro-ecological suitability of all cells in use for sugarcane in 2012. In line with long term

historical trends, it is assumed sugar cane yields will increase towards 2030 due to improved agricultural practices. The annual growth rate assumed is based on Jonker et al (2015) and van der Hilst et al (forthcoming).

As presented in Table 5, the theoretical potential assumes the maximum amount of sugarcane under optimal agricultural management. As the optimal management, cannot be further improved, the maximum yield value for 2012 and 2030 is considered to be the same in the theoretical potential.

The first-generation ethanol processing technology is applied with incremental improvements over time, based on the study of Jonker et al (2015).

Area Available for Theoretical Potential

The total area theoretically available (A_{th}) is calculated according to Equation 3, which indicates the constraints that are considered for the theoretical potential.

$$A_{th} = A_{tot} - A_w - A_c - A_u - A_r - A_{bs} - A_{ss} \quad (3)$$

A_{th}	Area available for the theoretical	ha
A_{tot}	Total area of Brazil	ha
A_w	Water surface area (rivers, lakes and	ha
A_c	Coastal area	ha
A_u	Urban areas	ha
A_r	Area of solid rock	ha
A_{bs}	Area of bare soil	ha
A_{ss}	Area of steep slopes (higher than 30%)	ha

By applying Equation 3 spatially explicitly, we are able to determine which grid cell is available for the theoretical potential. This allows us to calculate the theoretical potential using Equation 1. Although the extent of some areas excluded in the theoretical potential could change over time (e.g. urban areas), the impact of these changes on the land availability is considered to be marginal. Therefore, the

land theoretically available for sugar cane ethanol production in Brazil is assumed to be constant over time.

Area available for Technical Potential

The area technically available ($A_{t,y}$) for sugarcane production is obtained by excluding areas already used for crop, livestock and forest production (all change over time), as well as areas in use for conservation, military purposes and indigenous people (all assumed to remain constant over time) as defined in Equation 4.

$$A_{t,y} = A_{th,y} - A_{f,y} - A_{pf,y} - A_{pp,y} - A_{rg,y} - A_p - A_{ir} - A_m - A_{ind} - A_{sl} \quad (4)$$

$A_{t,y}$	Area technically available for sugarcane production	ha
$A_{f,y}$	Cropland area in year y	ha
$A_{pf,y}$	Areas of planted forest in year y	ha
$A_{pp,y}$	Areas of planted pasture in year y	ha
$A_{rg,y}$	Areas of rangeland in year y	ha
A_p	Areas of permanent preservation	ha
A_{ir}	Areas of legal reserves	ha
A_m	Military areas	ha
A_{ind}	Indigenous areas	ha
A_{sl}	Areas with slopes higher than 12%	ha

The land use for other functions is based on the land use change projections of Brazil from 2012 to 2030 of van der Hilst et al (in prep). Two scenarios are included in these projections. In the Business as Usual (BAU) scenario, the developments in agricultural productivity are based on historical trends (FAO, 2013; IBGE2013a) and multiple outlooks on agricultural production in Brazil (e.g. FIESP and ICONNE 2012; OECD and FAO 2014). In the progressive (PROG) scenario, it is assumed that the annual productivity increase is twice as high as the

BAU scenario, resulting in lower land requirements for the agricultural sector in 2030.

Area available for Economic Potential

The area available for the economic potential ($A_{e,y}$) is obtained by excluding areas that are economically not viable for sugarcane ethanol production (Equation 5):

$$A_{e,y} = A_{t,y} - A_{v,y} \quad (5)$$

$A_{e,y}$	Area economically available for sugar cane ethanol production	ha
$A_{v,y}$	Areas where sugar cane production for ethanol is not profitable	ha

The economic criterion applied to define economic viability is that ethanol production costs are lower than ethanol prices. The ethanol costs are calculated at plant-gate and include all costs related to sugarcane production, transport from field to the ethanol plant, and ethanol processing costs including investment cost (equipment, building and engineering) and operational expenses (maintenance costs, labour and administration expenses), see equation 9.

$$C_{Etotal,i,y} = \frac{C_{sc,i,y} + C_{t,y}}{\eta_y} + C_{ep} \quad (6)$$

$C_{Etotal,i,y}$	Total cost of ethanol production in cell i year y	US\$/m ³ EtOH
$C_{sc,y}$	Cost of sugar cane production in cell i year y	US\$/ tonne cane
$C_{t,y}$	Cost of sugar cane transport in year y	US\$/ tonne cane
η_y	Efficiency of ethanol production form sugar cane	m ³ EtOH/ tonne cane
C_{ep}	Cost of ethanol processing	US\$/m ³ EtOH

Not only the costs of ethanol production are spatially heterogeneous, also the prices of ethanol vary over geographical areas. In this study, five price regions are distinguished based on the price levels in the states of *São Paulo*, *Alagoas*,

Pernambuco, Mato Grosso and Goiás. The spatial variation in ethanol production costs is compared to the spatial variation in prices, only the areas where the ethanol production costs are below ethanol prices are assumed to be economically viable. As there is large variation in the economic performance of ethanol production and ethanol prices, the economic viability is highly uncertain. Therefore, for this approach ranges are considered by combining highest ethanol production costs and lowest ethanol prices (low profitability) and lowest production costs and highest ethanol prices (high profitability). An outlook on the profitability of ethanol production is estimated based on the cost developments of first generation ethanol production (Jonker et al, 2015) and estimation in ethanol price developments (van der Hilst et al., in prep.).

Areas Available for Environmental Potential

The area available for the environmental potential ($A_{e,y}$) is defined as the technically available area ($A_{t,y}$) that meets all the environmental criteria presented in Table 6, calculated with Equation 10.

$$A_{e,y} = A_{t,y} - A_{ghg,y} - A_b - A_s - A_w \quad (7)$$

$A_{e,y}$	Area available for sugar cane ethanol production in year y in	ha
$A_{ghg,y}$	Area with supply chain GHG emission reductions above the	ha
A_b	Area with high biodiversity	ha
A_s	Area with organic soils	ha
A_w	Area with water shortages	ha

These environmental criteria are defined based the many sustainability certification schemes, criteria and codes of conducts for biofuel production that have been developed in recent years. Although there is a wide variety in the specific sets of criteria and indicators, there is a general consensus on the key areas of concerns. Some of these sustainability criteria can be assessed ex-ante and spatially explicitly, while others are directly related to the implementation of

specific projects. Based on the identified key points of concerns and the ability to assess indicators spatially explicitly, a selection of key environmental constraints is included in this study (see Table 6). For each of these environmental indicators, a threshold value is determined based on literature review, see Table 6.

Table 6: Constraints considered in the environmental potential.

Indicator	Issue	Requirements
Environmental	GHG emissions	60% GHG emission savings compared to fossil fuel comparator (EU RED 2009/28/EC), taking into account all life cycle emissions, incl. direct LUC.
	Biodiversity	Areas with 4 or more layers of biodiversity priority areas for the non-strict level and 3 or more layers for the strict level (IUCN, 2015)
	Soil	Organic soils are excluded
	Water	Areas with water stress are excluded (Luck et al, 2015).
	Biomes	Amazon, Pantanal and Upper Paraguay River Basin are excluded (MANZATTO et al., 2009)

GHG emissions are calculated according to the Intergovernmental Panel on Climate Change (IPCC) methodology on GHG emission accounting (IPCC, 2006). The total emissions (tonne CO₂-eq/ m³ EtOH) account for land use change and all emissions from the life cycle of the ethanol production chain. The total emissions are then compared to the fossil fuel comparator and all areas that allow ethanol to reduce emissions by 60% compared to fossil fuels are included in the area available for the environmental potential.

Since the definition of areas of high biodiversity varies across studies and sustainability schemes, we chose two levels of strictness to show the effect of this choice on the results. The levels are defined by the number of priority areas for biodiversity that overlap in any given cell: the less strict option (called non-strict) follows the existing literature, where the areas with at least four or more priority areas for high biodiversity must overlap in order to be excluded (KAPOS et al., 2008). The other option (called strict) comprises cells in which at least three or more priority areas overlap (JENKINS; PIMM; JOPPA, 2013). The following priority areas for high biodiversity are used based on spatial datasets from different organizations comprising: i) mammals, amphibians and reptiles classified as near threatened (NT), vulnerable (VU), endangered (EN), or critically endangered (CR) species (IUCN, 2015); ii) the Global 200 ecoregions, selected by World Wildlife Fund –WWF because of their exceptional levels of biodiversity (OLSON; DINERSTEIN, 2002); iii) the Endemic Bird Areas (EBAs) of Brazil (SAVE Brasil, 2015); and iv) protected areas (IBGE,2015). For the non-strict level, we consider the VU, EN and CR threatened species. For the strict level, we consider also NT.

The organic soils are determined following the (IPCC, 2006) and excluded for both 2012 and 2030 scenarios.

Areas presenting water stress were obtained from Luck et al (2015). They made projections for both scenarios, and the include the indicators of change in water supply, water demand, water stress and seasonal variability, assessed also under scenarios of climate and economic growth.

Areas Available for Sustainable Potential

The sustainable potential is defined in this study as the technical potential that meets both the economic and environmental criteria defined above, see Equation 8. The key social aspects (i.e. economic viability and food security) are already accounted for in the economic and technical potential, respectively (Table 5): Food security concerns are considered by excluding all the land that is required for food, feed and fibre production. Economic viability is considered by excluding

the areas where sugar cane production for ethanol is not profitable so that a reasonable income for the farmer and a contribution to the rural economy is ensured. Therefore, the sustainable potential also includes the key socio-economic conditions. However, other socio-economic indicators cannot be modelled spatially specifically because of the lack of available and suitable data, and because many socio-economic issues are often related to the design of a specific project (e.g. labour conditions).

$$A_{s,y} = A_{t,y} - A_{v,y} - A_{ec,y} \quad (8)$$

$A_{s,y}$ Area sustainably available for sugar cane ethanol production in ha year y
 $A_{ec,y}$ Area where environmental criteria are not met ha

Data input

The data and assumptions made to calculate the potentials are presented on table 7.

Table 7: Input data

	Unit	2012	BAU	Prog	Reference
Productivity annual growth rate	%		0.7	1.5	van der Hilst et al., in prep.
Sugarcane maximum yield	Tonne cane/ha	156 ¹	172 ²	198 ²	¹ Anuário da Agricultura Brasileira, 2015 ² Estimated by authors, see text.
Capacity ethanol plant	Tonne cane/hour	500	500	500	
Conversion	m ³ /tonne	0.082	0.096	0.096	Jonker et

efficiency (<i>Cf</i>)	cane				al.,2015
EtOH cost	R\$/m ³	483,40	450,42	450,42	Jonker et al., 2015.
Energy content of sugarcane ethanol (<i>f</i>)	EJ/ m ³ EtOH	2.1325 x 10 ⁻⁸	2.1325 x 10 ⁻⁸	2.1325 x 10 ⁻⁸	ANP, 2015
Ethanol price growth rate			1.096	1.087	van der Hilst et al., in prep.
Discount rate	%	0.12	0.12	0.12	Jonker et al., 2015

3.3 Results

Sugarcane production potential in Brazil can be very high to very low, depending on the constraints and criteria taken into account. From the analysis done, is possible to affirm that sugarcane-ethanol sector is very sensible not only to technical constraints, but mainly to sustainability criteria.

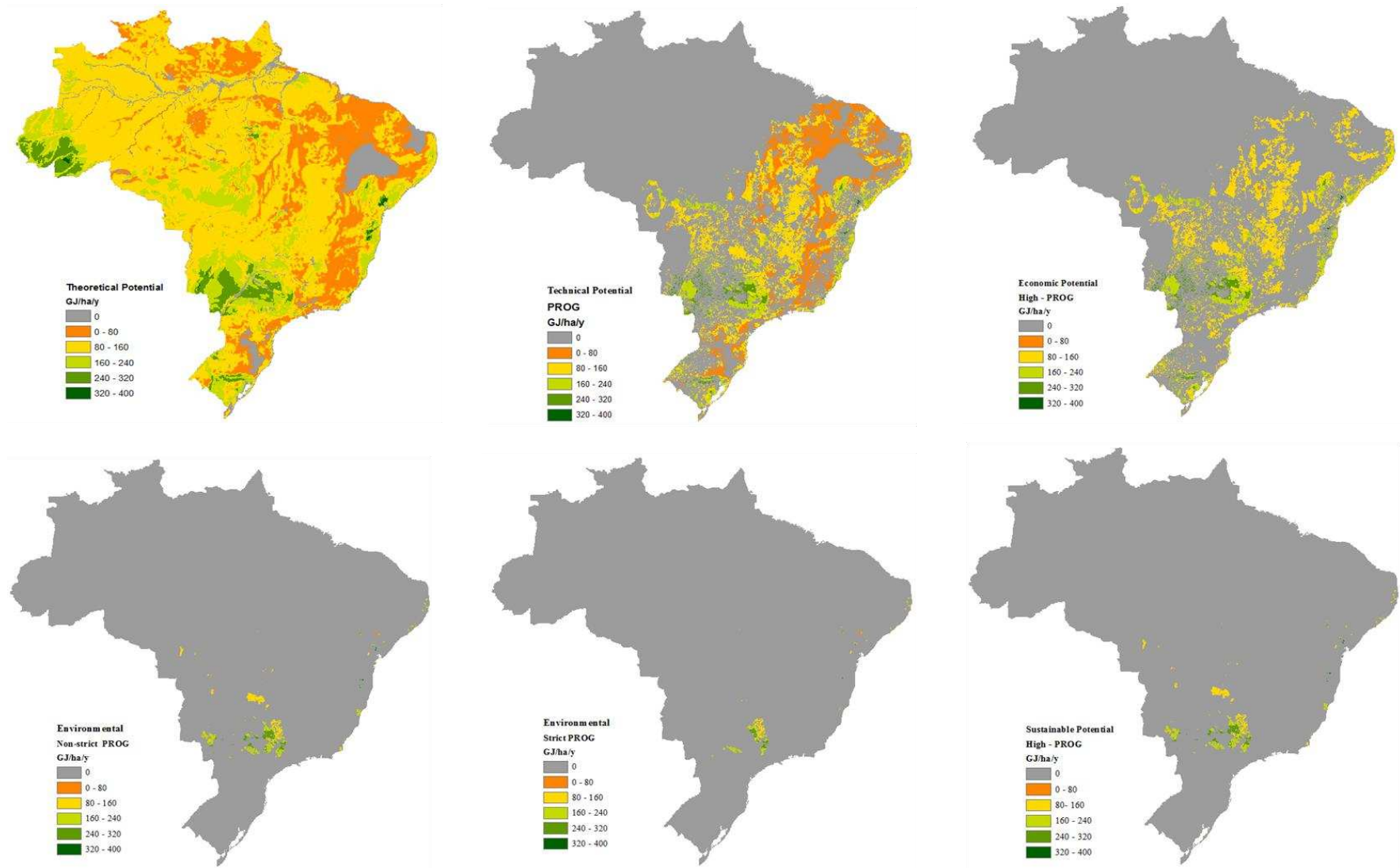
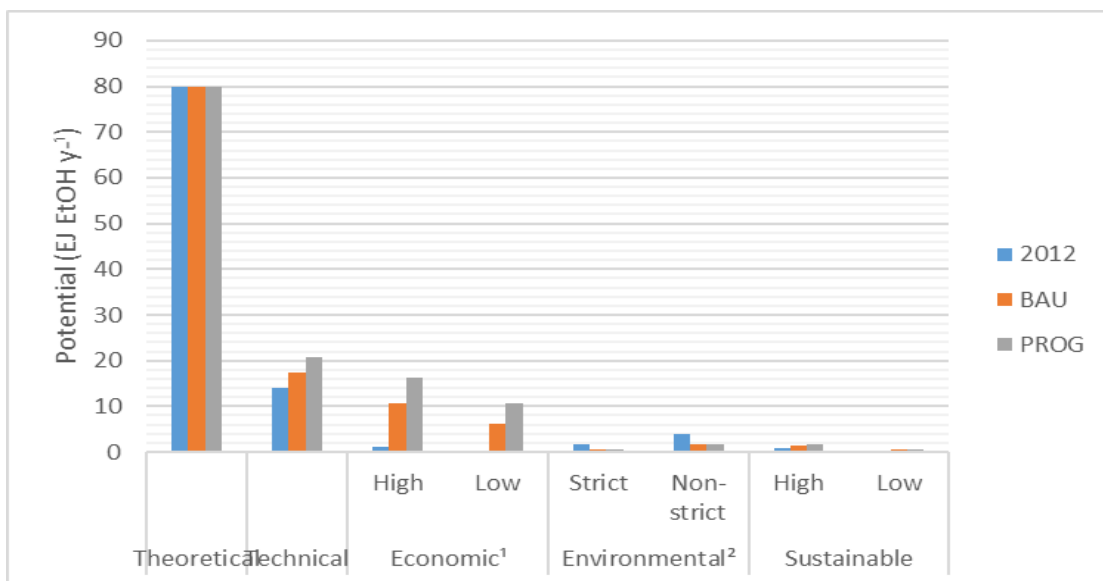


Figure 10: Overview of maps of all potentials, in GJ EtOH per ha, for 2030 Progressive scenario.

As can be seen on figure 10, the state of Sao Paulo (SP), which is currently the biggest producer of sugarcane-ethanol, will continue being the biggest producer since it presents more sustainable areas to sugarcane production, in 2030. In 2012, Brazil had 8.48 million ha of planted sugarcane, being almost 50% planted in SP (CONAB, 2016). For 2030, is estimated the same area for BAU scenario, and 8.86 million ha to the PROG scenario. The other states in the map with considerable amount of sustainable area are Mato Grosso do Sul (MS), Goias (GO) and Minas Gerais (MG). From these 3 states, between 2012 and 2016 (current harvest) GO is the state that has grew more in area, around 28%, but presented the lowest yield development, increasing in 4% sugarcane productivity. On the other hand, MS, which for 2030 scenarios demonstrate better potential (figure 10) than GO and MG, after SP, has grown less in area between 2012 and 2016, around 10%, and increased in 15% the sugarcane yield, indicating that this state has advanced on sugarcane production technology, and is a good option for future investments.

Figure 11 displays all five potentials estimated in this work. As can be seen, the main reductions happen from theoretical to technical, and technical to environmental and sustainable. From the highest potential (theoretical) to the lowest (low sustainable), there is a decrease of 99%. Since the theoretical is quite unrealistic, comparing the highest technical to the lowest sustainable, the percental decrease is still high, around 98%. These results can impress, but is important to remember that they present a range of potential Brazil has to produce sugarcane, and as constraints are measured, the lower the potential obtained. Next, the results are better presented following the order of analysis.



¹ It comprises the areas that are feasible to sugarcane and ethanol production due to their economic viability.

² This potential uses the technical potential and takes into consideration the environmental criteria. It is calculated to obtain the sustainable potential, when it is combined with the economic potential (non-strict x highest economic potential and strict x lowest potential).

Figure 11: Ethanol production potential, in EJ yr⁻¹, in Brazil.

Theoretical potential

The theoretical potential is the biggest potential (80 EJ EtOH) and it elucidates the huge potential Brazil could have if only the biophysical limits to sugarcane production were the constraints to its production. Between 2012 and 2030 scenarios there is no difference of potential due the fact that the theoretical potential considers the maximum attainable yield of sugarcane, and this must be the same for both years. Therefore, the theoretical map on figure 10 elucidates the same for 2012 and BAU scenario.

The regions with high potential (between 320-400 GJ EtOH per ha) of sugarcane-ethanol production are concentrated in the center-south region of Brazil, mainly Sao Paulo, Mato Grosso do Sul and Goias states; and in the north, at Acre state; and few areas in the north-east region (which is historically producer of sugarcane). The total potential of sugarcane production, in 2012, was $3,66 \times 10^{10}$ ton of cane, which is 54 times the real production in that year, $6,71 \times 10^8$ ton of cane.

Technical potential

Excluding areas that are no longer available to sugarcane production due to technical and non-technical constraints, such as areas of food production (crop and pasture areas), permanent preservation and legal reserves, the potential decreases from theoretical to technical by more than 75% (see figures 10 and 11), for 2012, 2030 – BAU and 2030-PROG.. But still the technical potential is high, comparing to the current harvest (2016/2017), of 1.18 EJ EtOH (Conab, 2016/2017). The technical potential in 2012 was 14 EJ EtOH and in 2030 is estimated to be between 17 to 21 EJ EtOH. There is a difference of 7 EJ of EtOH between the lowest (in 2012) and the highest (PROG scenario) technical potential, demonstrating the possibility of the sector expand in 47%, in energy terms.

Although the 2030 BAU and PROG scenarios presented higher potential than 2012, less area is available to sugarcane production in 2030 (see figure 11). The area technically available to sugarcane production, in 2012 was 215 million ha available, and for 2030, the PROG scenario is estimated to have 204 million ha, and 197 million ha the BAU Scenario, around 8% lower than 2012. These differences between 2012 and 2030 BAU and PROG, apparently are not too big, but comparing it to the actual sugarcane planted area in Brazil, that is around 9 million ha (Conab, 2016), that is a significant difference.

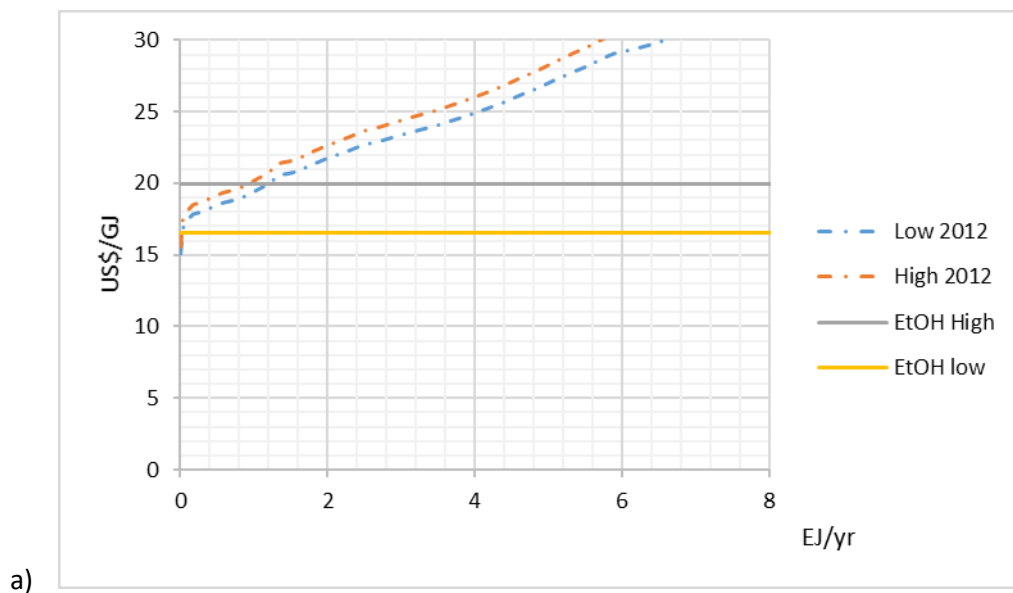
Economic potential

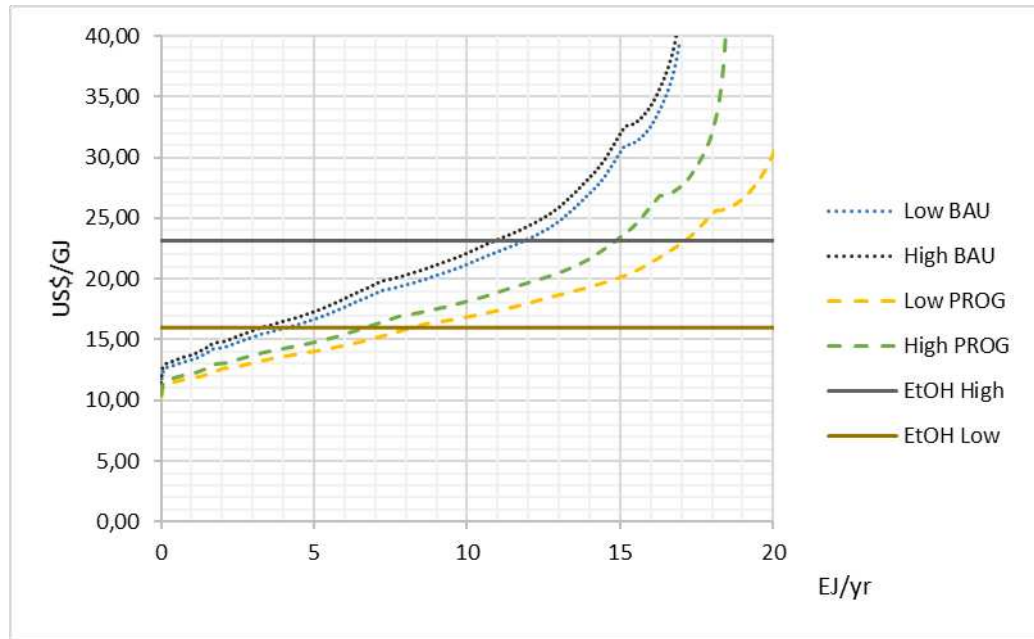
As presented on figure 10, there is a decrease from technical to economic potential for all scenarios, being it more significant for 2012, which agrees with Viana and Perez (2013) that the sector was in a crisis in that year. Although presenting a reduction on potential, the scenarios for 2030 still show high potential for sugarcane production. Comparing the lowest economic potential in 2030 (BAU low) with the highest in the same year (PROG high), thus englobing the whole range of possible potential, the results show a possibility of sugarcane-ethanol production differ in 10.1 EJ EtOH, being substantial. This big variance is mainly consequence of the yield difference

between scenarios. As presented before, PROG scenario is considered to grow, on yield, twice the considered for BAU scenario, thus the revenue in PROG scenario is much higher than in BAU scenario. Also, because technological improvements assumed to happen, less area will be need in the PROG scenario, generating lower feedstock production cost (the majority of costs are per area - ha), resulting in higher profit.

To both 2012 and 2030 scenarios, Piauí state, great part of Maranhão, Ceará, Recife and some areas of Minas Gerais and Bahia states do not present any economic potential to sugarcane production, and the states that concentrate the highest potentials are Sao Paulo, Mato Grosso do Sul and Acre.

Cost supply curves (Figure 12) are constructed in order to make clear the difference between cost and potential of ethanol production, for the reference year 2012 and the scenarios for 2030. These curves rank the potential supply according to the total cost to produce 1 GJ of ethanol (includes feedstock production, primary transport and industrial processing cost) in each year studied.





b)

Figure 12: Cost-supply curves of ethanol, for (a) the reference year 2012 and (b) other 2030 scenarios.

As presented in figure 12 (a and b), the cost of production (represented by the dashed lines) decreases with time for both scenarios. The lines EtOH high and EtOH low represent the prices paid in Brazil, for the GJ Ethanol, in each year and scenario investigated. Combining the highest price with the low-cost curve, obtain the total potential when ethanol has high profitability. Taking the highest price for EtOH, the result for the progressive scenario is 16.2 EJ EtOH and for the business as usual 10.6 EJ EtOH, in accordance to previous presented on figure 10.

Also, interesting to note from both graphs is that the costs between low and high don't vary much, but the differences between BAU and PROG scenarios, and between low and high EtOH prices are quite significant. Observing the prices of ethanol is possible to see another reason for the big range of economic potential, the difference between the highest and lowest price, in 2030, is around 30%, and in 2012, was around 20%. Each state in Brazil has its own tax rate applied to ethanol, which explain this significant difference between prices.

Environmental Potential

The environmental potential is calculated in order to check the influence of environmental constraints in the total potential of sugarcane – ethanol production. The results show that, the potential varies in more than 50%, depending on the level of strictness applied. For the non-strict level, in 2012 the potential of sugarcane-ethanol production is 3.79 EJ EtOH, for 2030 scenarios this potential decreases in almost 40%, achieving 1.57 EJ EtOH for BAU and 1.62 EJ for PROG. When we take a stricter view concerning the requirements, the potentials drastically decrease (1,71 EJ EtOH for 2012, 0.61 EJ for 2030 BAU and 0.65 EJ EtOH for 2030 PROG). The first point that calls attention in this potential is that in 2012 it was higher than the 2030 scenarios. The explanation for this results is the fact that in 2030 the area available to sugarcane production is smaller, and other areas (crop and pasture areas), excluded in this potential are bigger.

Other point to note is that the difference between scenarios is quite low, as can be checked on figure 11. This is also explained by the area and yields considered. The area available for this potential on PROG scenario is 10.5% smaller than BAU scenario, but the sugarcane yield considered for 2030 PROG is 15.3% higher than 2030 BAU, thus the area is compensated by the yield and a higher potential is generated.

GHG emission is the constraint that has bigger impact on the results of the environmental potential, reducing it on more than 85% (figure 11). As can be seen on table 8, the resulting environmental potential is more affected by restrictions on stricted areas of high biodiversity, biomes Amazon, Pantanal and Upper Paraguay River Basin and areas with increase on GHG emissions due to land use change, has the greatest impact.

Table 8: Environmental criteria breakdown for 2012 and 2030 scenarios, when only one constraint is considered in the assessment.

	2012	BAU	PROG
Organic soils	0%	0%	0%
Water	0%	1%	0%
Biodiversity NS¹	1%	17%	1%
Biodiversity S²	27%	27%	27%
Biome	52%	52%	52%
GHG emission	84%	95%	96%

¹ NS – non strict assumption concerning areas of high biodiversity

² S- Strict assumption concerning areas of high biodiversity

Sustainable Potential

The final potential obtained presents the lowest potentials, which makes sense due the fact that it is calculated with the remaining area from the previous potentials. As presented in figure 11, the sustainable ethanol potential estimated for 2012 is very low (ranging from 0.02 EJ EtOH to 0,76 EJ EtOH) when comparing to the results of the other potentials (see maps for 2012 and 2030 BAU in SI). From the environmental to sustainable potential, there is a reduction of 80% for 2012, which is explained by economic crisis that the ethanol sector faced in that year.

2030 BAU and PROG scenarios did not vary much from the previous potential to this one. Observing the maps, e.g. figure 10, the areas sustainably available to sugarcane-ethanol production are basically the same in the environmental potential. In this case, what drove this potential is the environmental and not the economic potential, like in 2012. The potential ranged from 0.44 EJ EtOH to 1.61 EJ EtOH, and although is quite low, it is still

enough to attend the projected demand for this year, estimated to be 1.31 EJ EtOH, according to (DE ANDRADE GUERRA et al., 2015).

The result for 2012, spatially explicit, does not present the reality in Brazil. Regions that also have large production of sugarcane in Brazil, as Minas Gerais and Goiás, do not appear in the map as sustainable. This possibly happened because these areas were not economically feasible in that year. However, from an environmental point of view, there is still plenty of area to produce sugarcane-ethanol. For 2030, the results demonstrate that the area available to sugarcane production will be lower than the current planted area. In 2016/17, Brazil had 8.9 million hectares of sugarcane planted (CONAB, 2016) and for 2030 PROG the results show availability of 8.5 million hectares. Concerning the possibility of attending the demand projected for that year, although less area will be available, the efficiency on plantation and increase on yield can guarantee this, but few ethanol will be available to export.

Sugarcane-ethanol production is most favourable to SP (southeast region), and MS states (northeast region), because they present sustainable potential in all scenarios assessed. SP is already the biggest producer in the country, and MS, has presented better improvements concerning sugarcane productivity.

The centre-south of Brazil concentrate the production of sugarcane. According to (CONAB, 2016), in the harvest of 2016/2017, 62.2% of the planted area are in the south east region, and 19,9% are in the center-west, where the sector has already expanded its production, mainly to GO and MS states.

In the south the production is smaller and concentrate in Parana state, as presented in the map of 2012. For 2030, the production is not promising to this region, and mainly a concern to Rio Grande do Sul, where in 2012, existed one ethanol plant (UDOP, 2016).

3.4 Discussion

In this study, was performed a bottom up assessment of sugarcane-ethanol production potential, presenting systematically and spatially explicit, five types of potential: theoretical, technical, economic, environmental and

sustainable. It was shown that, up to 2030, Brazil will be able to sustainably produce sugarcane, and to attend the estimated national demand (DE ANDRADE GUERRA et al., 2015; EPE, 2016). It was observed that the potentials are mainly correlated to the maximum attainable yield of sugarcane, and the amount of area available. Higher the yield achieved, higher the potential and lower the area needed. And also, it was demonstrated how the constrains, mainly concerning land use and environmental criteria, have great impact on the estimated potential.

Many studies (EPE, 2007; WALTER et al., 2008a) proposes that Brazil has a large techno-economic potential of sugarcane production, but there is a lack of information concerning the sustainable potential. As shown on results section (figures 10 and 11), Brazil presents high techno-economic potential up to 2030, but when environmental constraints are take into account, the scenarios completely change, and support the concerns about the sustainable expansion of sugarcane, thus the future of the sector in Brazil (Hissa and Filho, 2014; Viana and Perez, 2013).

Several works discuss the expansion of sugarcane in Brazil, into areas of other uses, mainly pasturelands (ALKIMIM; SPAROVEK; CLARKE, 2015; HISSA; FILHO, 2014; LAPOLA; PRIESS; BONDEAU, 2009; WALTER et al., 2015), but in this study, these areas are also excluded in the technical potential. Different from e.g. Alkimim et al., 2015, that discuss the possibility of a sustainable production of sugarcane using pasturelands (considering that productivity in these areas will increase), in our study is understood that pastures and crop production will need more area to attend the demand of food, and sugarcane must increase productivity to diminish the necessity of more area, and to not compete with land for this use, in accordance to van der Hilst et al (in prep.).

Also in the technical potential, the Biomes Amazon, Pantanal and Alto Paraguay were excluded following the decree-law (DEC 6.961/2009) of the Brazilian government, but this can change due to a proposal of law (PLS 626/2011) that is in process at Brazilian National Congress. This proposal deals with the sustainable cultivation of sugarcane in altered areas in Cerrado and Campos Gerais biomes, located at the legal Amazon, and establishes

guidelines for agroecological zoning of the region. If PLS 626/2011 be approved and becomes a decree-law, the scenarios accessed will be completely different (probably higher), although the scenario adopted in this study be more appropriate.

The economic criterion applied to assess the economic feasibility was that ethanol production costs are lower than ethanol prices. The subsidy of ethanol production sometimes granted by Brazilian government to ethanol producers was not considered in this analysis, due to its unpredictability, but this is one factor that would positively impact the potential.

Still on economic potential, alternative approach exists to assess the economic viability of sugar cane ethanol. A key example is the analysis of the profitability of sugarcane compared to other agricultural activities in terms of net present value (in line with the approach of e.g. van der Hilst et al, 2010). But, this approach has a major drawback in that prices fluctuate inter and intra-annually so that results are not robust. In addition, forecasting costs and prices of all alternative crops and livestock systems towards 2030 becomes even more uncertain. Therefore, production costs and prices of ethanol were compared. However, given that a farmer or sugar cane producer decides based largely on the profits per hectare we also assessed the economic viability based on sugar cane production profitability compared to other agricultural activities for 2012 (see SI for a description of the approach, assumptions and data). The results obtained for the economic potential were 0.1EJ EtOH for the highest profitability, 0.00057 EJ for the average and 0 for the lowest, noticeably lower than the ones (see figure 11 results section) obtained with the other approach, showing the impact the sector can have, once other agricultural activities become more attractive than sugarcane.

The suitability maps of sugarcane and the other food crops, that we used in this study, were basically the same. The regions that presented higher suitability to sugarcane production, also presented higher suitability to other food crops, as well as regions that are known to have high production of a specific crop, apparently wouldn't be feasible following the suitability maps, indicating lack of accuracy concerning them. This presents one of the limitations to do this work that was to obtain reliable spatial data for Brazil. All

suitability maps were obtained from international data base, as well as the majority of others, demonstrating a gap existent in this field of work, in Brazil.

Future analysis on socio-economic potential, spatially explicit, are necessary to a more accurate conclusion concerning sustainable potential of sugarcane. Also, more knowledge is required concerning the economic competition between sugarcane and other agricultural activities (including pasturelands), as well as the dynamics of the entire agricultural sector. In this study a first step was done by assessing the sustainable potential of sugarcane of the entire Brazil, spatially explicit, taking into account technical, economic and environmental constraints.

Therefore, while many studies have tried to explain techno, economic or environmental potential, separately, this work gives a comprehensive overview on the sugarcane-ethanol potential in Brazil. Showing that spatial heterogeneity in productivity affect the potential, and sustainability constraints can have great impact in the future of this sector. This results will not only impact positively researches, but also give directions to policy makers and investors in the sector, showing which areas should be invested and which needs a profounder investigation and analyses.

3.5 Conclusion

The application of spatial explicit analysis to the estimation of the theoretical, technical, economic, environmental and sustainable potentials, generated satisfactory results and confirmed to be indicated to this kind of assessment.

It is concluded that Brazil has capacity to attend the national projected demand of ethanol, but its sustainable potential is not as high as expected, and the participation in the international market with the surplus of production will be small, and more possible to occur if improvements on yield happen. In the progressive scenario, an area of 8.48 million ha will be available to sugarcane production by 2030, generating 1.61 EJ EtOH (75.5 GL of EtOH).

The centre-west region (Mato Grosso do Sul and Goias states) and part of south east (Sao Paulo state) region will be the most attractive and important area to sustainable ethanol production.

The potential of sugarcane production is significantly affected by sustainability constraints. Most of the sustainability criteria are established and required by organizations from developed countries, which bases on country-origin issues, suggesting that the impact would be different if most constraints were based on local socio-economic and environmental characteristics; with threshold values specific by region. It is also concluded that sustainability criteria are in majority subjective, from which different interpretations and assumptions can be taken.

The ex-ante analysis of land availability, economic feasibility and compliance of sustainability criteria to sugar cane production, gives insights to which areas should or should not be invested with sugar cane ethanol production. This allows a more consistent and wise planning for bioenergy production, helping to reduce the risk of projects and investments.

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Supplementary Information

SI 1. Determination of maximum yield:

To determine the maximum yield, we used the LU map and the suitability map, to obtain first an average yield and then the maximum yield using this value. With the LU, it was separated first the areas where have food production. Within this area, it was checked in the suitability map, for each crop, the average of suitability represented in the selected area. The value obtained, it was combined with the average of productivity found at Conab database. A calculation was done in order to obtain what would be the maximum yield in 100% of suitability (table S1).

Table S1: Crops and pasture maximum yield, in 2012.

Crop	Season	Average area	Average Yield (kg/ha)	Mx Yield 2012 (kg/ha)
Beans	1st /wet	0,3172	1046	3297,60
	2nd/dry	0,3172	746	2351,83
Corn	1st	0,2694	4314	16013,36
	2nd	0,2694	4209	15623,61
Soy		0,3203	2665	8320,32
Wheat		0,215	2557	11893,02
Rice	wet	0,3052	4776	15648,75
	dry	0,4171	4776	11450,49
Sugarcane t/ha		0,451	68,3	151,44
Coffee		0,364	1269	3486,26
Pasture	extensive (UA/ha)	0,3814	1,82	4,77
	intensive (UA/ha)	0,3814	3,4	8,91

SI 2. Sugarcane profitability compared to the profitability of other agricultural activities (crop and livestock production)

The NPV of seven selected crops, corresponding to 88% of the total harvested area in Brazil (IBGE, 2015), in 2012, and of livestock (extensive and intensive management) are calculated. Land costs, field operation costs

(contractor, machinery, labour and diesel costs), input costs (seeds, fertilizers and pesticides) and fixed costs (insurance, soil sample assessment, etc.) (Hilst et al., 2010; Batidzirai et al., 2012) are some of the expenses taken into consideration to calculate the cost associated to crop production.

The spatially explicit NPV of each crop is calculated using as input the suitability map of each crop (S_c), and their respective prices (V), in order to obtain the revenue (R), per location a (See Eq. S1). There is a separated model for each crop and type of livestock management.

$$R = S_c \times M_{fy} \times V - C_{cy} \quad (\text{Eq. S1})$$

M_{fy} represents the maximum yield of each crop, in year y , obtained using the same method as for sugarcane; and C_{cy} represents the total cultivation cost of each crop, in the year y .

Coffee and sugarcane are not annual crops, in this way, must first calculate the cash flow of each, to obtain the NPV of each crop (Hilst et al., 2010), in R\$/ha, and then the annual NPV ($aNPV$) (Embrapa, 2015), following equation S2. Using the Excel, a dispersion graphic of $aNPV$ versus yields is done, in order to obtain a curve and the equations that provides the relation between yield and economic feasibility. These equations are used in the ArcGIS, for the models of these two crops.

$$aNPV = \sum_{t=1}^{t=x} \frac{\sum_{n=1}^N (B_n) - \sum_{m=1}^M (C_m)}{(1+a)^t} \times \frac{a(1+a)^t}{(1+a)^t - 1} \quad (\text{Eq. S2})$$

Where B_n represents the revenues of monetary flow n per ha; C_m the costs of monetary flow n per ha; a the discount rate and t the annuity period, in years.

To assess the profit of pastures for livestock, the costs (C_p) (R\$/ha) and revenues (R\$/ha) were calculated as following equations (eq. S3 e S4).

$$C_p = f_u \times C_l \times CS \quad (\text{Eq. S3})$$

Where f_u (@/UA) is the mass, in @, per unit of animal; C_i is the cost of each @, in R\$/@; CS (UA/ha) is the support capacity of pastures; and @ is a mass unit used by the cattle market in Brazil, and corresponds to 15kg; and UA is unit of animal.

$$\text{Revenue} = f_u \times CS \times V_l \quad (\text{Eq. S4})$$

Where V_l is the price, in R\$/@, of live animal.

The results of equations 9 and 10 are used as input in the ArcGIS. These values are related with the suitability map of pastures, in order to obtain the yield profitability per location a.

The values obtained from Anualpec, to assess each type of management, were:
Extensive:

For production (@/UA/year) was calculated the average of the values in the Anualpec, and the result was 5.5.

Maximum supporting capacity (CS) was 0.9

Intensive:

For production (@/UA/year): 7.72@/UA

Maximum supporting capacity (CS) was 1.7 UA/ha

The resulting maps from all these models (crops NPV, sugarcane and coffee aNPV, livestock) are overlaid and a new map is generated. In this one, per grid cell, is selected the product with higher profitability for each range low, average and high profitability. The areas where sugarcane does not appear are considered the areas economically unfavourable for sugar cane production, following the condition of approach 1.

Table S2, presents the prices and costs considered for this approach.

Crop	Season	Price (R\$)			Cost (R\$/ha)		
		Low	Average	High	Low	Average	High
Beans	1st /wet and 2nd/dry	1,1/kg	1,55/kg	1,82/kg	2659,8	2659,76	2659,8

Corn	1st	0,34/kg	0,39/kg	0,44/kg	1573,6	2014,1	2673,2
	2nd	0,34/kg	0,39/kg	0,44/kg	1190,7	1253,32	1363,8
Soy		0,61/kg	0,69/kg	0,80/kg	1050,2	1200,78	1304,9
Wheat		0,37/kg	0,42/kg	0,45/kg	1182,1	1473,6	2211,2
Rice	wet	0,39/kg	0,48/kg	0,64/kg	1736,5	1736,53	1736,5
	dry	0,39/kg	0,48/kg	0,64/kg	4136	4396,5	4657
Pasture	extensive (UA/ha)	81,3/@	91,18/@	109,9/@	22,44	169,41	283,18
	intensive (UA/ha)	81,3/@	91,18/@	109,9/@	78,03	602,86	1240,4
Sugar cane		45,57/t	52,89/t	55,81/t	4398,4	4660,4	4685,5
Coffee		5,05/kg	5,89/kg	6,31/kg	7728,2	7728,2	7728,2

SI 3. GHG emissions

Table S4. Yield assumed for calculation of carbon stock change.

		Average area	Average Yield (kg/ha)	Mx Yield 2012	Mx yield 2030
Natural forest	Warm moist	0,59	220	372,9	316,9
	tropical dry	0,33	210	636,4	540,9
	tropical moist	0,53	220	415,1	352,8
	tropical wet	0,58	300	517,2	439,7
	tropical montane	0,53	145	273,6	232,5
Rangeland				29,6	14,1
Grass, shrubs and abandoned	Warm moist	0,681851038	21,2	31,1	102,9
	tropical dry	0,309539009	21,2	68,5	226,7
	tropical moist	0,492091664	21,2	43,1	142,6
	tropical wet	0,492869741	21,2	43,0	142,4
	tropical montane	0,532818605	21,2	39,8	131,7
Planted forest	Warm moist	0,681851038	171,2	251,1	352
	tropical dry	0,309539009	94,8	306,3	430
	tropical moist	0,492091664	133,2	270,7	380
	tropical wet	0,492869741	224	454,5	638
	tropical montane	0,532818605	37,2	69,8	98
Pasture				18,6	23,5

SI 4. Maps sustainable potential for 2012 and 2030 BAU.

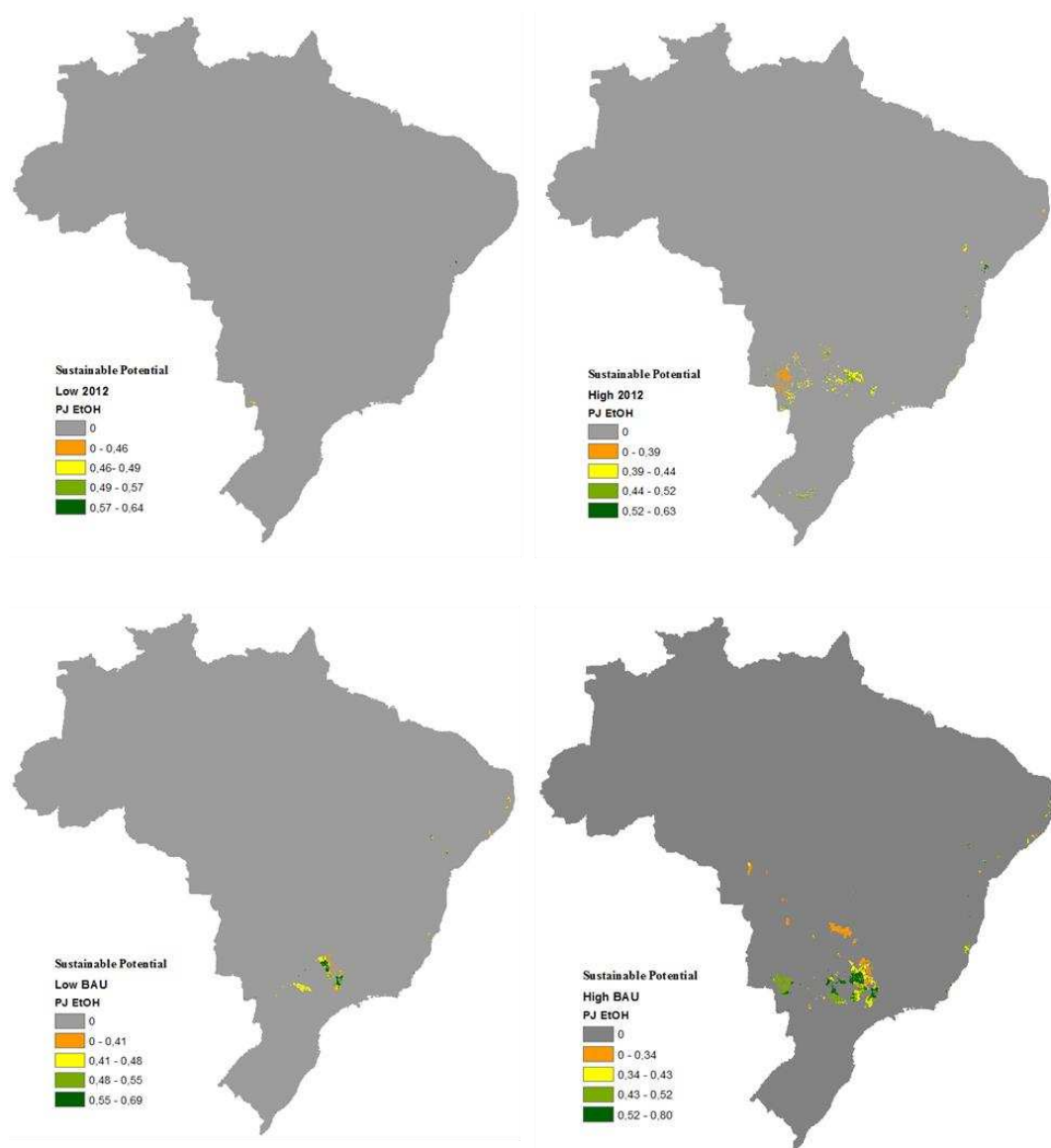


Figure SI 1. Sustainable potential for 2012 and 2030 BAU, in PJ EtOH per grid.

4. General conclusions

In this study, was performed a systematic review and a bottom up assessment of sugar cane, to identify and estimate the current and future (2030) demand and sustainable production potential of it, taking in account technical, economic and environmental constraints.

Chapter 2 presents the systematic review concerning types of methodologies used to estimate future demand, and shows what that have been published addressing ethanol future consumption in Brazil, up to 2030. In review of more than 35 works, 8 were selected. Those papers and reports selected differed in type of methodology used, in drivers considered for assessments, in growth rates applied for e.g. GDP and flex fuel fleet, in period assessed, and in demand estimated.

To say what is the best model, which generates the best estimation is complicated, since every model has its particular characteristic, and results are very dependent on the assumptions of the model designer, and in the transparency of data used. Although being complicated, a competition of model through some statistical analysis, gives directions to which models/scenarios and results use. It was concluded that the scenarios of EPE, which adopted time series to estimations, and from Andrade Guerra, which used a bottom up model (LEAP), were the most accurate and accomplished the drivers considered important to ethanol demand models.

Therefore, concludes that the estimations for ethanol demand significantly vary according to the method and parameters considered, and for Brazil the projected demand, up to 2030, ranges from 49 GL EtOH, considered for a Business as Usual Scenario, to almost 62 GL EtOH, adopted in an optimistic scenario.

Accomplishing the goal to know if Brazil will be able to attend the national demand, studied on chapter 2, and to supply the international market with possible surplus of production, the sustainable production potential of sugarcane ethanol is estimated.

Thereby, on chapter 3, was performed a bottom-up assessment of sugarcane-ethanol production potential, presenting systematically and spatially

explicit, five types of potential: theoretical, technical, economic, environmental and sustainable. Was showed that, up to 2030, Brazil will be able to sustainably produce sugarcane, and to attend the estimated national demand, in a best scenario, it can be concluded that Brazil will have enough to supply the national market and to attend the international market with 26.5GL of EtOH, being a great contribution (around 35% of the production). But, in a worst scenario, Brazil will have to import 41.1 GL of EtOH to attend the national demand.

The most favourable location to invest on sugar cane ethanol production, in 2030, will continue be the center-south of Brazil being the states of Mato Grosso do Sul, Goias and Sao Paulo the most attractive and feasible, considering sustainability constraints.

One of the goals of this thesis was also to check how sustainability constraints impact on the sugar cane ethanol potential. And as shown on chapter 3, they have great effect on the techno-economic potential. Thus, we conclude these constraints couldn't be treated in a general form, and threshold values should be specific by region, taking into account spatial heterogeneity. Most criteria considered in this study, to quote areas of high biodiversity, are subjective, and different interpretations can be done.

It can be settled that in the progressive scenarios, less land will be needed to sugarcane production, so smaller the conflict with other land uses, bringing as benefits high GHG emissions savings and no competition to food production. Though, to this scenario happen technological developments on sugarcane production must happen, stressing the necessity of more investments in this sector.

An ex-ante analysis of the estimated demand of ethanol, and availability of land to sugar cane production, as well as economic feasibility and areas of environmental importance gives insights of the possible future of the sector, helping to identify which areas should or not be invested to ethanol production, allowing to investors and energy planners a more consistent and wise planning of a sustainable ethanol production, thus diminishing investments risk and failure of new projects.