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Mapping environmental and techno-economic bioenergy potentials of Brazil

Techno-economische en ecologische bio-energie potentiëlen van Brazilië in kaart
(met een samenvatting in het Nederlands)

Proefschrift

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CONTENTS

ABBREVIATIONS

ASTM	American Society for Testing and Materials
ATJ	Alcohol To Jet
BAU	Business As Usual
BJF	BioJet Fuel
CAPEX	Capital Expenditure
COP	Conference Of Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DSHC	Direct Sugar to HydroCarbons
EHR	Eucalytpus Harvest Residues
EPE	Empresa de Pesquisa Energetica
FCI	Fixed Capital Investment
FSC	Forest Stewardship Council
FT	Fischer-Tropsch
GAEZ	Global Agro-Ecological Zones
GHG	GreenHouse Gases
GIS	Geographic Information System
HEFA	Hydroprocessed Esters and Fatty Acids
HTL	HydroThermal Liquefaction
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IGP-DI	Indice Geral de Preços - Disponibilidade Interna
IIASA	International Institute for Applied Systems Analysis
INDC	Intended Nationally Determined Contributions
ISCC	International Sustainability and Carbon Certification
LCOE	Levelized Cost Of Energy
LHV	Lower Heating Value
NDVI	Normalized Difference Vegetation Index
NPV	Net Present Value
OPEX	Operational Expenditure
PEFC	Programme for the Endorsement of Forest Certification
RUSLE	Revised Universal Soil Loss Equation
SCS	SugarCane Straw
SOC	Soil Organic Carbon
SSR	Straw to Sugarcane Ratio
TRL	Technology Readiness Level

Introduction

1

1.1. THE NEED FOR BIOENERGY SYSTEMS IN BRAZIL

A key challenge throughout the 21st century is to reduce climate change, while promoting socio-economic development [1]. Developing transition pathways from fossil to renewable energy sources is of paramount importance to mitigate greenhouse gas (GHG) emissions [2]. Of modern renewable energy resources, biomass for bioenergy is one of the most flexible options to reduce fossil energy dependency as it provides a diversified portfolio for different uses, e.g. transport biofuels, heat, electricity, chemicals [3], and it can be stored and readily dispatched when needed [4]. Many bioenergy technologies can be still further developed in terms of their efficiency, production costs and end products [5,6]. Bioenergy can have positive socio-economic impacts, such as rural development and energy security [7,8]. However, at the same time, there are also many concerns about the sustainability of bioenergy because of the potential environmental and socio-economic impacts mainly related to biomass feedstock production (e.g. deforestation, loss of biodiversity, increase in land-related GHG emissions, impacts on food security). Therefore, promoting bioenergy production requires sustainable use of natural resources.

Globally, Brazil is one of the largest producers of renewable energy [9] due to the abundance of natural resources. Currently, a significant share (~45%) of its primary energy consumption is supplied by renewable sources, of which 1.6 EJ is supplied by hydropower and 3.6 EJ by biomass [10]. The bioenergy sector in Brazil is traditionally represented by the sugarcane ethanol industry since the 1970s, and currently has the second world largest ethanol production with more than 30 billion liters [11]. To a lesser extent, the Brazilian bioenergy sector is represented by the biodiesel industry, mostly sourced from soybean oil. In the coming years, the contribution from biofuels in the transportation sector is expected to increase considerably, due to adoption of new biofuel mandates (e.g. 15% biodiesel blend) and the increasing sugarcane ethanol as well as corn-ethanol production [12,13]. The recently approved national biofuel policy (Renovabio) will be a crucial driver for this by remunerating certified biofuel producers with carbon credits [14].

The ethanol industry also supplies bioelectricity surplus sourced from sugarcane residues. Between 2007 and 2018, bioelectricity surpluses from the sugarcane industry increased from 3.2 TWh to 21.5 TWh, contributing approximately 7% to the national electricity mix in 2018 [10,15,16]. Currently, almost 15% of the national electricity generation mix still depends on fossil resources. Energy outlooks for Brazil project biomass and other renewables to substitute part of the fossil resources in the coming decade, as well as to supply part of the growing electricity demand [17] (figure 1.1). The increase in the contribution from biomass to the energy mix is needed to meet the Brazilian Intended Nationally Determined Contribution (INDC) agreed at COP 21 [18].

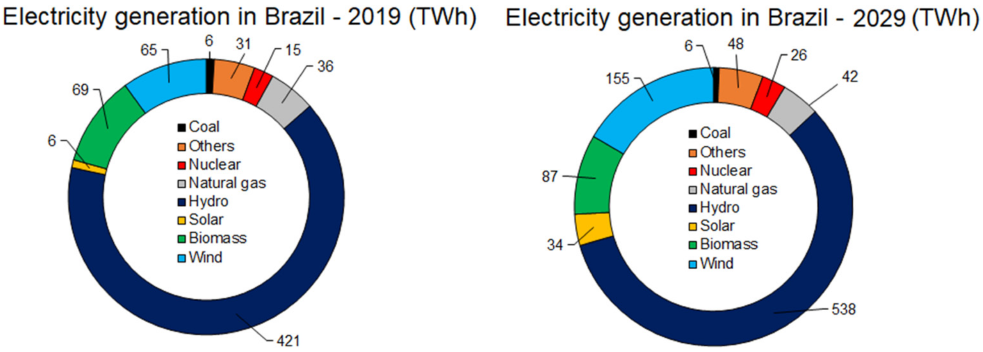

Figure 1.1: Current and projected electricity generation mix in Brazil (2019: 649 TWh, 2029: 936 TWh). Note that "Others" refers to other non-renewable sources (e.g. oil). Adapted from EPE (Brazilian Energy Research Office) [17].

In parallel, there is also a growing interest to transform the current ethanol-centered production model into a model focusing on a variety of bio-based products (including new fuels and chemicals), e.g. by using biorefineries [19]. In these emerging systems, aviation biofuels[1] (also called biojet fuels) are raising the attention of bioenergy stakeholders worldwide [3]. The International Air Transport Association (IATA) has set significant targets to reduce GHG emissions from the aviation sector towards 2050 [20]. Biojet fuels (BJF) are expected to play an important role to meet these targets in the coming years (figure 1.2), as few other technological options are currently available. For example, the large scale commercial adoption of electric aircrafts for civil aviation is unlikely in the first half of 21st century [21].

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[1] It can be also found as renewable jet fuel (RJF) or sustainable aviation fuel (SAF), and refers to the full substitute of Jet A/A-1. Therefore, it should comply with several quality criteria, such as freezing point, energy density, thermal stability, [297].

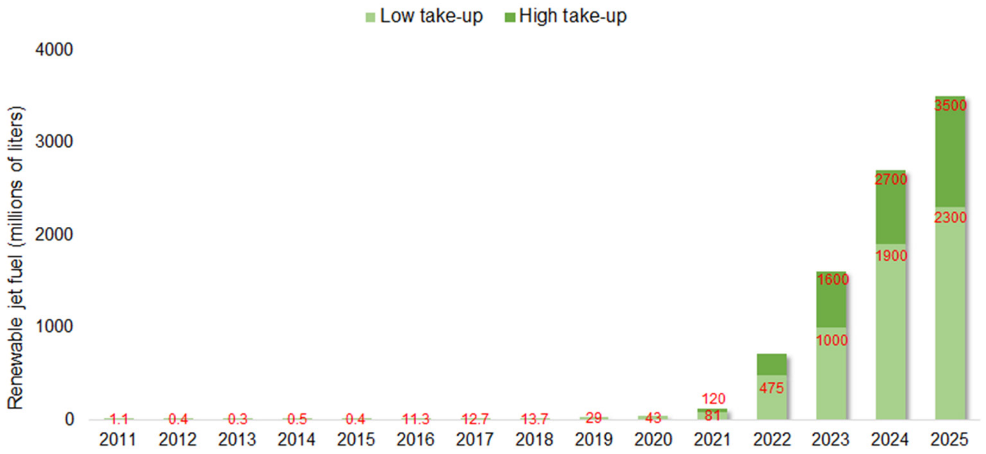

Figure 1.2: Past, current and future developments of renewable jet fuels (BJF) production in the world, adapted from International Civil Aviation Organization - ICAO [22]. Low take-up refers to a moderate increase in BJF production due to a low number of production facilities. High take-up refers to the full output of current and future dedicated BJF facilities, driven by policies and airline decision-making.

BJF production could possibly require large amounts of biomass resources depending on the market development. In Brazil, it could be mostly sourced from both biomass residues and energy crops given the large existing agricultural production and further expanding land use. If so, this should be aligned with the most recent international standards of sustainable bioenergy production, e.g. GHG emission reduction, ecological preservation and social welfare [23,24]. Considering that current bioenergy production is already projected to grow in the coming years (i.e. increase of 5%/year for sugarcane ethanol [25] and 12.6%/year for biodiesel [26]), and emerging BJF use may further increase the demand for biomass resources, it is pivotal to monitor and quantify the biomass resources and bioenergy potentials.

1.2. BIOENERGY POTENTIAL ASSESSMENTS

Various types of bioenergy potentials can be distinguished (figure 1.3). Based on extensive literature review, Batidzirai et al. [27] provide definitions of different levels of bioenergy potentials. For energy crops and forests, the theoretical potential is the maximum amount of bioenergy that can be produced within fundamental biophysical limits, considering theoretically optimal management of biomass resources. For biomass residues, the theoretical potential is assumed to be equal to the total amount of residue production. The technical potential of bioenergy represents the share of the theoretical potential that can be produced under a given technological condition, and taking into account the competitive uses of land and biomass resources.

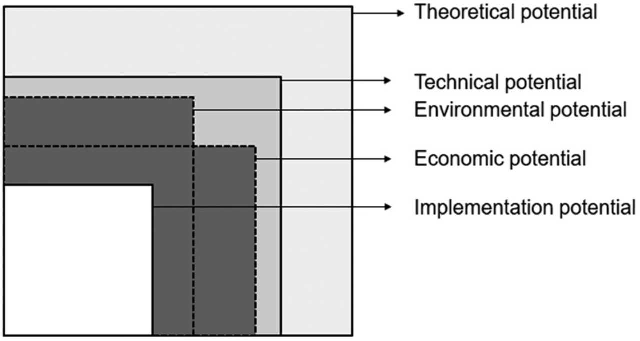

Figure 1.3: Schematic representation of various levels of bioenergy potentials. Adapted from Batidzirai et al. [27].

The environmental or ecologically sustainable potential is the fraction of the technical potential that can be obtained considering environmental restrictions, such as soil, water and biodiversity preservation [27]. The environmental potential of different bioenergy systems around the world is a major research topic [28–30]. Many of the environmental impacts of bioenergy are related to land use change resulting from biomass production. For that reason, most of the environmental concerns focus on impacts related to the use of dedicated energy crops, such as carbon and water footprint, soil conservation, biodiversity, among others [31–33]. In addition, with increasing demand for biomass residues for current or future bioenergy applications, there is also an increasing ecological concern on its use. More specifically, the removal of post-harvest biomass residues available in the field (e.g. sugarcane straw, corn-stover) for bioenergy production leads potentially to important environmental implications, such as soil losses, GHG emissions, and loss of biodiversity [34–36].

The economic potential (also called market or techno-economic potential) represents the share of the technical potential which meets economic criteria, such as competitiveness with fossil fuel [27]. The techno-economic potential depends on a series of techno-economic factors, such as biomass availability, scale of production, technology progress and infrastructure availability [37]. While the majority of the environmental potential studies are dedicated to the biomass production system, the studies on the techno-economic potentials are mainly focused on the biomass supply chains [38–40]. The fraction of the techno-economic potential that meets environmental criteria as well as economic criteria and that can be implemented within a certain timeframe under current socio-political conditions, is referred to as the implementation potential [27]. For example, Mai-Moulin et al. [41] have recently attempted to quantify such implementation potentials for six regional case studies, although with limited attention to the socio-political conditions.

Estimations of the various bioenergy potentials vary significantly across studies due to the heterogeneity of geographical scales, time horizons, methodologies, assumptions and datasets employed. Important aspects determining the environmental and techno-economic potentials of bioenergy have large spatial and/or temporal variability, such as land availability, biomass yields, technological and infrastructure development [42–44]. To address the heterogeneity of these factors, bioenergy potentials should be assessed spatially explicitly and for different points in time [42,45–47]. As it is expected that the role of bioenergy in Brazil is consolidated in the coming years, it is important to assess the environmental and techno-economic potentials of bioenergy to assure current and future sustainable bioenergy production. Hence, a key research challenge on bioenergy potential quantification is to address environmental impacts and techno-economic factors in a spatially and temporally explicit manner.

1.3. KNOWLEDGE GAPS ON SPATIAL ASSESSMENTS OF BIOENERGY POTENTIALS

Bioenergy potentials can be evaluated spatially explicitly at different geographical scales. A number of studies assessed global biomass potentials, which often require complex integrated assessment models, coupling multiple datasets [33,48,49]. Other spatial assessments of bioenergy potentials are carried out at continental (or national) and regional levels, e.g. to assess the contribution of bioenergy to meet specific GHG emission reduction targets, to energy diversification and to rural development (see examples for Europe [50,51], Africa [52], USA [53] and China [54,55]). In Brazil, the most investigated bioenergy system is sugarcane ethanol production, but due to size of the country and the limited data availability, spatially explicit assessments of ethanol production are often only deployed on a regional level, such as for a state or a prominent production region [45,56]. Most of the spatially explicit studies on the environmental impacts of sugarcane ethanol cover solely the agricultural stage by quantifying the (expansion of) sugarcane areas, yields, and GHG emissions from LUC and cultivation [57–62]. To a lesser extent, some studies combine the spatial distribution of sugarcane production, the location of sugarcane mills, and the demand hubs to quantify environmental impacts and techno-economic factors of ethanol production [45,56,63]. The combination of these spatial components is important to model bioenergy supply chains, and therefore, to better estimate the overall impacts and costs of bioenergy production.

In modern sugarcane ethanol production systems, bioelectricity surpluses are frequently produced as a by-product, based on bagasse availability [64]. For this bioenergy system, the number of spatially explicit assessments is limited, and largely based on estimations using agricultural production data aggregated at regional or municipality level [65–67]. With the switch to mechanized sugarcane harvesting in the past two decades and the increasing competition for bagasse, the abundant availability of sugarcane straw on the field has also raised the need for spatial assessments of straw availability. This is due to straw location specific environmental and techno-economic factors, such as yield levels, straw recovery logistics, and agricultural management [68,69]. Outside Brazil, a considerable number of studies have carried out spatially explicit assessments to quantify bioelectricity potentials based on biomass residues [30,46,70–72]. In Brazil, apart from aggregated studies [65,67], recent studies started to include field specific data to quantify technical and techno-economic potential of sugarcane straw and bioelectricity [73–75]. However, the impact of the spatial distribution of supply chain components (i.e. sugarcane straw availability, and the location of bioelectricity conversion plant and distribution hubs) on the techno-economic potential of bioelectricity has not been covered. Moreover, these studies are often deployed at a single geographical scale (either local or regional). However, as the potentials are affected by the interplay of local and regional factors, it is important to assess both scales simultaneously. Such an approach provides relevant information for a broad range of stakeholders.

The potentials of emerging advanced biofuels, such as BJF, have been estimated in different regional studies worldwide [37,38,52,76]. BJF potentials in different regions may vary substantially due to heterogeneity of biomass availability. In Brazil, several studies have analyzed several drivers and constraints for sustainable BJF production [77–83]. Martini et al. [80] focused on mapping and quantifying the land availability that could be used for BJF production. In addition, other studies have focused on the use of biomass residues as the most promising resource for BJF [84–86]. However, the spatial variation of land availability and biomass yields are often not assessed. These factors should not be overlooked, as they typically have a large impact on the biomass production costs, GHG emissions, and on the overall environmental and techno-economic potential of bioenergy supply chains [42,45].

To date, very few studies make use of spatial datasets to assess the performance of emerging BJF supply chains. De Jong et al. [87] have carried out a spatially explicit study on the techno-economic performance of BJF supply chains from wood residues in Sweden. Cavalett and Cherubini [88] provide a detailed bottom-up spatial assessment on the sustainability of BJF production routes (supply chains) in Norway. However, these studies are not focused on the spatial distribution of BJF potentials; instead, the spatially explicit data of biomass availability is used as a mean to address specific techno-economic and sustainability research questions on BJF production. On the other hand, Staples et al. [89] show the geographical distribution of environmental impacts of potential BJF supply chains in US, by spatially explicitly modeling the water footprint and land availability. However, none of the aforementioned studies have quantified the spatio-temporal variability of biojet potential. To the best of our knowledge, the study of Carvalho et al. [76] is the most complete spatial assessment on the current BJF potential in Brazil, as it considers spatial infrastructure data to estimate techno-economic and environmental aspects. As a downside, the study does not consider the spatially explicit and temporal variation of land availability and biomass yield levels. Moreover, it also does not include the temporal developments in BJF technologies and infrastructure availability in Brazil. These attributes may have a large effect on the techno-economic and environmental performance of BJF supply chains [87,90,91], especially as many BJF technologies are expected to be further improved in the coming years. In summary, there is an important knowledge gap as current studies do not account for spatial and temporal variation of land availability, agro-ecological conditions, biomass production costs and the developments in technology and infrastructure to address the techno-economic and environmental potential of BJF production.

1.4. AIM AND THESIS OUTLINE

The objective of the thesis is to spatially explicitly assess the current and future environmental and techno-economic potentials of bioenergy supply in Brazil at different geographical scales. To reach this goal, the following research questions are addressed.

- I - How to spatially explicitly quantify the environmental and techno-economic potential from biomass residues and energy crops over time?
- II – How to spatially explicitly quantify the environmental and techno-economic potential of bioenergy supply chains given the development of conversion technologies and infrastructure?
- III - What is the current and future environmental and techno-economic potential of bioelectricity and BJF supply chains in Brazil from energy crops and biomass residues, and what is the spatial distribution?

Research questions I, II and III are addressed in chapters 2 - 5 (Table 1.1), at various geographical scales, timeframes and levels of complexity. In chapters 2 and 3, the bioelectricity potentials from sugarcane straw are assessed spatially explicitly in the state of São Paulo (Brazil) considering the 2012 crop-year. In chapters 4 and 5, various BJF supply chains from energy crops and biomass residues are assessed to map and quantify the environmental and techno-economic bioenergy potentials in Brazil in 2015 and 2030. Table 1.1 provides an overview of the chapters and the research questions they address.

Table 1.1: Overview of the research questions addressed in each chapter of the thesis. Light green indicates that the chapter partially addresses the research question. Dark green indicates that the chapter fully addresses the research question.

Chapter	Title	Research questions		
		I	II	III
2	Bioelectricity potential from ecologically available sugarcane straw in Brazil: A spatially explicit assessment	▨	▨	▨
3	Spatial assessment of the techno-economic potential of bioelectricity from sugarcane straw	▨	■	▨
4	Spatial modeling of techno-economic potential of biojet fuel production in Brazil	▨	▨	▨
5	Mapping the environmental and techno-economic potential of biojet fuel production from biomass residues in Brazil	▨	■	▨

In chapter 2, the environmental potential of bioelectricity production from sugarcane straw in Sao Paulo state is assessed. To quantify the bioelectricity from the environmental potential of sugarcane straw in São Paulo for the 2012 crop-year, the spatial variability of sugarcane is assessed by combining spatial datasets of sugarcane fields and remote sensing time-series data on sugarcane yield. Based on the straw-to-sugarcane ratio and scenarios on the amount of straw that needs to remain on the field for environmental reasons, the environmental potential of sugarcane straw for bioelectricity purposes is calculated. Then, a potential collection radius for each of the 174 mills in the state of São Paulo is determined and a typical power plant to operate with sugarcane straw is assumed to estimate the bioelectricity potential from sugarcane straw.

In chapter 3, the techno-economic potential of bioelectricity production from sugarcane straw is quantified and mapped. The techno-economic potential of bioelectricity from sugarcane straw is assessed by carrying out a cost analysis for both the straw recovery and bioelectricity production. The spatial distribution of the environmental potential of straw availability for bioelectricity determined in chapter 2 is used as input data. Then, the effects of the spatial distribution of sugarcane straw availability on the straw recovery costs are calculated. Thereafter, the composition of the bioelectricity production costs is assessed based on the selected system configuration of a typical high-pressure power plant adjacent to the mill to produce exportable bioelectricity. By setting a bioelectricity cut-off price, the techno-economic potential of bioelectricity from sugarcane straw is estimated for each of the 174 sugarcane mills as well as for the entire state of São Paulo in the 2012 crop-year.

In chapter 4, the recent (2015) and future (2030) techno-economic potential of BJF production routes in Brazil is assessed taking into account the spatio-temporal developments in biomass potential and technical developments in the BJF production routes. The techno-economic assessment analyzes the development in potential land availability for biomass for BJF production, given the development in other land use functions, the spatial variation in agro-ecological suitability for the cultivation of different energy crops, and expected temporal development in energy crop yields. The resulting spatial distribution of biomass potential is used to calculate the biomass production costs (i.e. farm-gate plus transportation costs). The BJF production costs are calculated considering an integrated greenfield feedstock production plant with a BJF biorefinery which converts the raw biomass to BJF. The BJF transportation costs are calculated assuming the shortest route from the BJF plant to the nearest airport in Brazil. Finally, the techno-economic potential is determined by selecting the location specific minimum BJF total costs (BJF production cost plus the BJF transportation cost) across the production routes and compare this to the location specific fossil jet fuel price range.

Chapter 5: In this chapter, the spatio-temporal variation of the environmental and techno-economic potential of BJF from biomass residues is assessed. Different production routes sourced from sugarcane straw and eucalyptus harvest residues are considered. Different than in chapter 1, two environmental criteria are applied for the assessment of the environmental potential of biomass residues: erosion risk and SOC balance. The techno-economic potential is based on the approach developed in chapter 4, where the BJF production costs are calculated considering the technological development in BJF conversion technologies over time. The techno-economic potential is quantified according to the airport specific fossil jet fuel price range.

2

Bioelectricity potential from ecologically available sugarcane straw in Brazil: a spatially explicit assessment

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Abstract. The electricity mix of Brazil is for 80% composed by renewable sources, of which the majority is supplied by hydropower. However, as the domestic energy demand is expected to increase and the abilities to expand hydropower capacity in Brazil are constrained, it is important to increase the contribution of other renewable energy resources. Considering the high theoretical potential and mature conversion technologies, bioelectricity from sugarcane straw could be a promising option. Our study aims to assess the bioelectricity potential from ecologically available sugarcane straw in the state of Sao Paulo (Brazil) at multiple scales for the 2012 crop-year. We use a spatially explicit approach taking into account the spatial distribution of sugarcane fields, the spatial variation of sugarcane yield, the location and the milling data of each mill. We define a business as usual, a moderate and a high scenario on the amount of straw that can be removed given environmental constraints. The bioelectricity potential from ecologically available sugarcane straw is estimated between 18.7 - 45.8 TWh in Sao Paulo, equal to 22-37% of the electricity demand. The results show large geographical differences, with generally higher potentials and shorter collection radiuses for the mills in the traditional sugarcane areas compared to the mills in the expansion areas. We conclude that bioelectricity from sugarcane straw could have a significant contribution to the electricity supply in Brazil. The identification of regions with high potentials for bioelectricity production could support local and regional decision making on bioenergy planning.

2.1 INTRODUCTION

International energy policies have established ambitious targets regarding the use of renewable energy sources for electricity production, e.g. the Renewable Energy Directive (EU-RED) from the European Commission [1] and the Clean Power Plan from the Environmental Protection Agency of United States [2]. Unlike many other countries, Brazil has more than 80% of its electricity mix composed by renewable sources, of which the majority is supplied by hydropower [94]. However, the seasonality of hydropower, as well as the increasing periods of unexpected droughts incurs the insecurity of supply of hydroelectricity [95]. In addition, as the domestic energy demand is expected to increase and the abilities to expand hydropower capacity in Brazil are constrained by socio-environmental concerns [96], it is important to increase the contribution of other renewable energy resources.

In Brazil, the use of sugarcane residues to produce bioelectricity has steadily grown since in the last decade [16]. Currently, bioelectricity from sugarcane bagasse represents 6-8% of the electricity produced in Brazil [97]. However, considering the large sugarcane production, the current bioelectricity produced from sugarcane residues is rather limited [98]. To increase the bioelectricity production, the use of sugarcane straw has been occasionally employed as a supplementary source [99]. The sugarcane straw comprises the leaf part of the sugarcane plant (also composed by stalks and belowground biomass), divided in typically green tops and dry leaves on the side of the plant with moisture levels ranging between 11-68% [69,100]. Due to the high nutrient and moisture content, the tops and green leaves are recommended to be left on the field [101]. This could have many agronomic and environmental advantages: nutrient recycling, plant growth, soil carbon accumulation, soil biodiversity, and more water availability due to less soil evapotranspiration [36,69,100–103]. However, there is also a great potential of sugarcane straw for bioenergy purposes due to the high energy content, efficient conversion technologies and the large theoretical availability [100,104,105]. Therefore, it is important to understand how much sugarcane straw could be available for bioelectricity purposes given that part of the straw is needed to meet the agronomic and environmental requirements [69,106].

The main studies quantifying the potential of sugarcane residues (bagasse and straw) for bioelectricity purposes in Brazil, generally rely on aggregated data sources at different geographical coverages. The Decadal Energy Plan (PDE) [105] has projected scenarios for the development in bioelectricity production from sugarcane residues in Brazil. For a business-as-usual scenario considering a conservative conversion efficiency, a technical potential of 63 TWh is projected for 2026. In 2009, UNICA (Brazilian Sugarcane Industry Association) and COGEN (Cogeneration Industry Association) using 20% *w/w* of straw to sugarcane ratio (SSR) and a straw removal rate of 70%, estimated the potential of bioelectricity from sugarcane straw at 33.2 TWh for the state of São Paulo in 10 years' time [107]. For the 2014 crop-year, Trombeta et al. [65] quantified the bioelectricity potential for a diversified group of sugarcane mills across the country. The results were aggregated at sub-state level and showed an overall bioelectricity potential of 47 TWh for the Brazilian central-south region.

Although these studies provide information on the potentials of bioelectricity from sugarcane straw, they lack field reality as the information on the biomass availability is derived from macroeconomic projections or aggregated data sources. Therefore, the spatial variability of sugarcane straw variability at field level is neglected. This hampers local decision-making, as it remains unclear where and how much sugarcane straw are available and for which mills it would be promising to increase their bioelectricity production. To minimize the uncertainties in estimating the bioelectricity potentials from sugarcane straw, a spatially explicit assessment on straw availability for bioenergy production is required [27,50]. Such bottom-up assessment is relevant for policy makers to comprehend and explore the bioenergy potential in a given region.

The objective of our study is to assess the bioelectricity potential from ecologically available sugarcane straw in Brazil at field, mill and state level, taking into account the spatial variation in sugarcane yield and the milling information of each mill. We select the state of São Paulo as case study because of the large representation of the state in the sugarcane market (i.e. more than 50% of the national sugarcane production in 2012, i.e. 329 x 10^6 Mg) [108] and the advanced technological stage of the main mill groups [109]. In addition, since the 2002 state law on phasing out the burning of sugarcane fields before harvest, São Paulo has been leading the research on the applications on sugarcane straw [68]. Among the Brazilian states, São Paulo is by far the largest electricity consumer, using about 30% of the electricity produced in Brazil [110]. Also, São Paulo is an electricity importer from other Brazilian regions, such as state of Paraná and North Region, where important hydroelectricity plants are located [110]. For these reasons, both the need and opportunity to develop other renewable energy sources (such as bioelectricity from straw combustion) are very prominent in the state of São Paulo. We assess the potential for the 2012 crop-year (sugarcane planted in 2011 and harvested in 2012) for two reasons. First, the high-quality was freely available for the 2012 crop-year [58,111]. Secondly, the sugarcane industry faced multiple crises [112] in the following 2013 and 2014 crop-years, which have led to a massive shutdown of the mills in that period. Consequently, the data for these crop-years are assumed not to be representative. The spatial modeling method employed in this study can be replicated in other case studies both in Brazil and other bioenergy-producing countries.

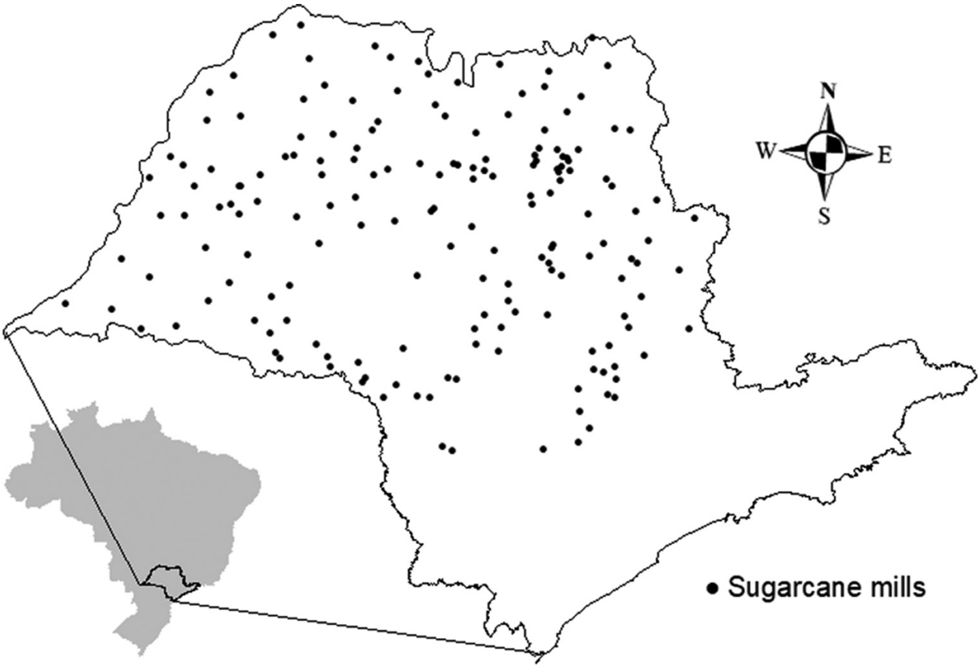

Figure 2.1: Location of the 174 operating sugarcane mills in São Paulo (Brazil) in the 2012 crop-year.

2.2. METHODS

To quantify the bioelectricity potential from ecologically available sugarcane straw in São Paulo for the 2012 crop-year, we first assess the spatial variability of sugarcane by combining spatial datasets of sugarcane fields and remote sensing time-series data on sugarcane yield. Based on the SSR and scenarios on the amount of straw that needs to remain on the field for environmental reasons, the ecological availability of sugarcane straw for bioelectricity purposes is calculated. Then, the potential collection radius for each of the 174 mills in the state of São Paulo is determined (see figure 2.1) and a typical power plant to operate with sugarcane straw is assumed to estimate the bioelectricity potential from sugarcane straw for each mill in São Paulo state.

2.2.1. Spatial variation in sugarcane yield

To assess the spatial variation in sugarcane yield in the state of São Paulo, we use the 2012 crop-year state level sugarcane mask from the Canasat project [58]. The Canasat project annually monitored the cultivation of sugarcane in the central-south region of Brazil. The spatial data of Canasat has been widely employed for assessments of the sugarcane sector in Brazil because of its high spatial accuracy [113,114]. However, it provides only information on where sugarcane is cultivated and not on the spatial variation in sugarcane yield. To cover this issue, we use the vegetation index - a spectral ratio from remote sensing data used for vegetation assessment - from Normalized Difference Vegetation Index (i.e. NDVI from MOD13Q1 product) [111,115].

The NDVI is often used in studies for crop yield estimations by virtue of the high correlation with the greenness phase of crops [116]. For our study, we generate the spatially explicit annual mean NDVI value for the 2012 crop-year (i.e. calculated based on 23 images from September 2011 to September 2012, at 16 days interval and a pixel size of 250 meters) (figure 2.2). The mean NDVI data is clipped with the CANASAT sugarcane mask, with mean NDVI values ranging from 0.2 to 0.86 in the 959,891 pixels (figure 2.2). These mean NDVI values are rescaled to sugarcane yield levels based on the average sugarcane yield annually reported by IBGE (i.e. Min.: 20.8 Mg.ha^{-1}; Max.: 112.1 Mg.ha^{-1} [117].

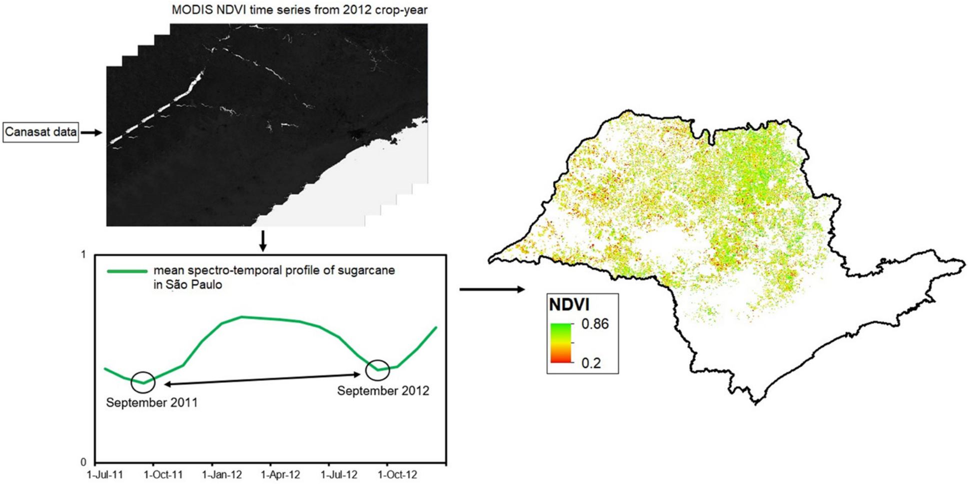

Figure 2.2: Extraction of the NDVI time series (i.e. 2012 crop-year composite bands) from September 2011 to September 2012 clipped with CANASAT sugarcane mask.

2.2.2. Ecological availability of sugarcane straw

Ecological potential assessments of bioenergy considers the ecological availability of a given resource under the current technology capability while preserving the local ecosystems [27,46]. To calculate the ecological availability of sugarcane straw for bioelectricity purposes, the SSR and the straw removal constraints are considered. The first is defined as the total amount of straw on the standing plant, consisting of tops, green and dry leaves [69]. In this study, the state average of 14% *w/w* is used to quantify the maximum amount of sugarcane straw available (i.e. the theoretical potential) [68].

Regarding the straw removal constraints, there are many uncertainties about the amount of straw that needs to be left on the field for environmental and agronomic purposes [102,118]. Thus far, no quantitative assessment for sugarcane straw mulching levels at a regional level was carried out. Ideally, from the bioenergy producer perspective, the sugarcane straw supplier seeks to recover the maximum amount of straw available in a given area instead of moving to another location because of high costs of switching sites. On the other hand, with higher amount of straw recovered, higher nutrient (i.e. fertilizers) application is required in the forthcoming sugarcane cycle to compensate the organic and mineral compounds removed with the straw [119]. Additionally, sugarcane straw needs to be left on the field to maintain soil organic matter levels, protect the soil from erosion, preserve micro and macro-fauna and improve the soil structure and soil moisture content [68,69,101]. Therefore, it is highly recommended that a given minimum amount of sugarcane straw has to be maintained on the field depending on the local agro-ecological conditions (e.g. meteorological, soil properties and crop features and management) in order to continuously provide the local ecosystem services [102].

According to Hassuani et al. [68], 7.5 Mg.ha^{-1} of straw (dry basis) should be left on the field for controlling weed and pests. Similarly, Nunes et al. [102] suggested that 7 Mg.ha^{-1} of straw is the minimum required for assuring environmental and agronomic benefits. Based on these reference values, we define a Business as Usual (BAU) scenario of 7.5 Mg.ha^{-1} of straw that has to be maintained on the field. Progressively, we also define the Moderate and High scenarios with straw mulching levels of 5.4 Mg.ha^{-1} and 3.2 Mg.ha^{-1}, respectively. These average numbers are retrieved from Cardoso [106] for a typical sugarcane yield level (i.e. 82.1 Mg.ha^{-1}) and were established assuming technical and environmental/agronomic constraints for straw removal. Then, the ecological availability of sugarcane straw for the three scenarios is calculated for every pixel using equation 2.1.

Equation 2.1

$$SA_p = Y_p \times SSR - SM$$

SA_p	Straw availability in pixel *p*	Mg.ha^{-1}
Y_p	Sugarcane yield in pixel *p*	Mg.ha^{-1}
SSR	Straw to sugarcane ratio	%
SM	Straw mulching levels on dry basis	Mg.ha^{-1}

2.2.3. Bioelectricity potential from sugarcane straw at mill level

To assess the bioelectricity potential at the mill level, we assume that the mills only collect the sugarcane straw from the fields in their sugarcane collection area. The collection radius of each mill is set in accordance to the milling data of the 174 mills for the 2012 crop-year. The milling data is acquired through the Brazilian Sugar and Ethanol Guide [120], which covers the milling data of most of the 174 operating mills in the 2012 crop-year. The missing milling values are filled by approaching the remaining mills directly. Based on the crushing capacity of each mill in 2012, the radius for each mill is defined by combining the spatial distribution of the sugarcane mills (figure 2.1) containing the respective milling data, and the spatial distribution of sugarcane. The radius is defined by the circular area of which the cumulative sum of the sugarcane yield equals the amount of sugarcane crushed in 2012 crop-year (figure 2.3). In this calculation, no losses during the harvesting and transportation operations are accounted for. We assume that the straw available in the collection area of the sugarcane mill (i.e. ecologically available) is used in the mill to produce bioelectricity (i.e. electricity generating capacity).

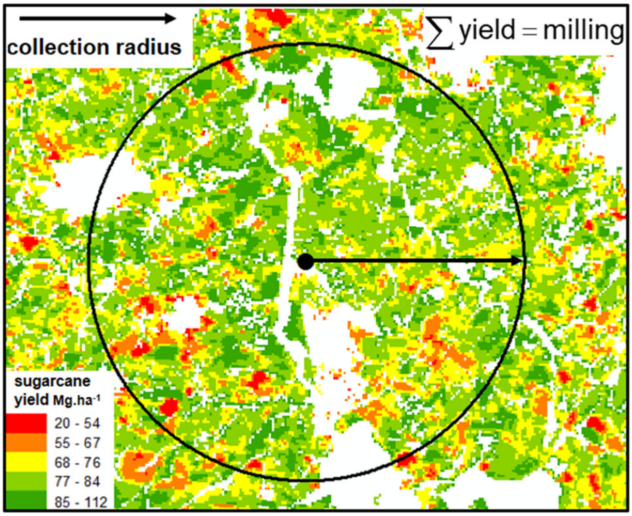

Figure 2.3: Schematic representation of the biomass collection radius calculation: from the mill location, a circular selection is employed where the cumulative sum of the pixels containing sugarcane yield values should match the milling data.

To convert the amount of sugarcane straw available into bioelectricity (equation 2.2), we assume a Lower Heating Value (LHV) of straw of 13.3 MJ kg^{-1} on wet basis (i.e. 15% moisture content), based on Seabra et al. [121]. The 15% moisture content can be reached naturally when the straw remains on the field for a drying period of 10 to 15 days after sugarcane harvest [122]. The baling system recovery route is usually deployed to recover the straw available on the field. This route is rated as a promising option for straw recovery due to the high energetic quality of the straw delivered at the mill [123]. Moreover, no straw losses in both on-farm and transportation operations is assumed (i.e. the amount of straw recovered on the field is the same as that feeds the boiler).

Equation 2.2

$$El = \sum \frac{SA_{pm} \times 13.3 \times Eff_m}{3.6}$$

El	Bioelectricity potential	kWh
SA	Straw availability in pixel *p* in mil *m*	kg
13.3	Lower Heating Value (15% moisture content)	MJ kg^{-1}
Eff_m	Conversion efficiency in mill *m*	%
3.6	Megajoule to kilowatt conversion	MJ kWh^{-1}

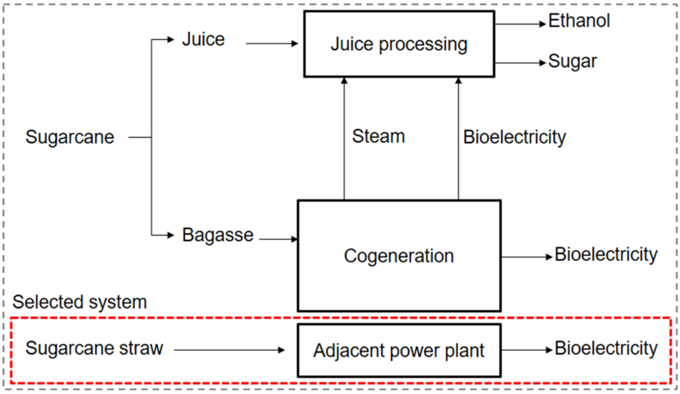

Figure 2.4: Conceptual framework of the sugarcane mill. The selected system, i.e. adjacent power plant (red dashed line box) has its process design and technical parameters described in Seabra et al. [4,121].

For the bioelectricity system, we consider a power plant adjacent to the sugarcane mill exclusively to produce exportable bioelectricity from sugarcane straw (figure 2.4). This additional power plant comprises Rankine system with high pressure and temperature boilers (65 bar/480ºC), Condensing Extraction Steam Turbines (CEST) [4], and does not supply the internal energy demands of the sugarcane mill. This is typical power plant found in modern sugarcane mills designed to produce large bioelectricity surpluses [65,124]. The bioelectricity surpluses sourced from bagasse in the cogeneration system of the sugarcane mill are not estimated for not being the target of our study.

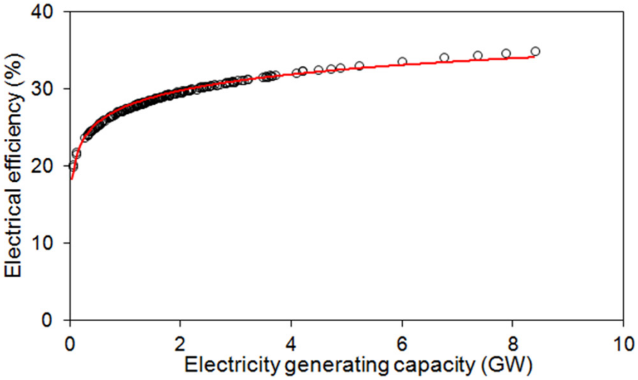

Figure 2.5: Assumed relationship between the electrical efficiency and electricity generating capacity of the power plant adjacent to the sugarcane mills. Based on Cutz et al. [125].

To calculate the variation of electrical conversion efficiency in the adjacent plants, we adapt a realistic range of electrical efficiency varying from 20% to 35% as function of the electricity generating capacity of the power plant (see figure 2.5). This is based on the empirical relationship between electrical conversion efficiency and electricity generating capacity of biomass CHP plants determined by Cutz et al. [125], and a review of studies concerning bioelectricity systems in Brazilian sugarcane mills [126–128].

2.2.3.1. Sensitivity analysis

To assess the impact of uncertainties in key input variables on the bioelectricity potential from ecologically available sugarcane straw, a sensitivity analysis is performed. The three key parameters selected are: moisture content of sugarcane straw, the SSR and the electrical conversion efficiency. Apart from the straw removal rate, these parameters are expected to have a large effect on the bioelectricity production. The straw moisture content is varied between 40% moisture (i.e. 9.3 MJ kg) and dry basis (i.e. 15.6 MJ kg) [68,106]. The SSR is varied from 11 to 17%, based on Hassuani et al. [68]. To the electrical conversion efficiency range of 20-35%, a small absolute variation of ±5% (i.e. 15-30% and 25-40%) is primarily applied in accordance to the reality of the sugarcane power plants [127]. In this parameter, we also assess the sensitivity of the bioelectricity potential for fixed efficiencies values of 20% and 35% applied in all the adjacent power plants.

2.3. RESULTS

The bioelectricity potential from the ecologically available sugarcane straw are based on the spatial explicitly assessment of ecological availability of sugarcane straw and the capacity of the 174 operating sugarcane mills in 2012 crop-year.

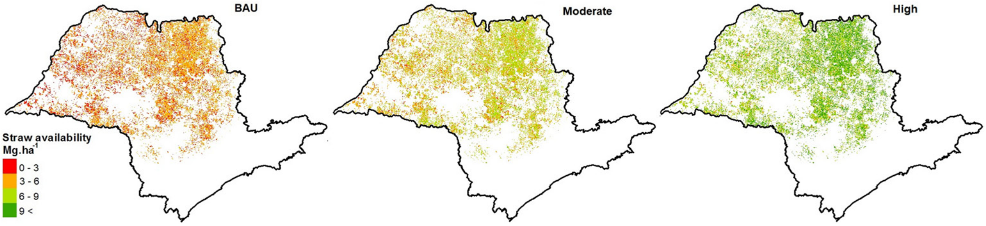

Figure 2.6: The spatial distribution of sugarcane straw availability per hectare in the BAU, Moderate and High scenarios.

Based on sugarcane yield levels and 14% of SSR, the theoretical potential of sugarcane straw in the state of São Paulo is estimated at 58.9 × 10^6 Mg (i.e. the total amount of sugarcane straw production on the fields). Considering the 3 scenarios on straw mulching levels, the ecological availability of sugarcane straw is 16.7 × 10^6 Mg (BAU), 28.3 × 10^6 Mg (Moderate) and 40 × 10^6 Mg (High) (figure 2.6). Accounting all the fields (i.e. pixels of the spatial data), the straw removal rate ranges from 0 to 82%, with averages of 31% (BAU), 51% (Moderate) and 72% (High) (figure 2.7).

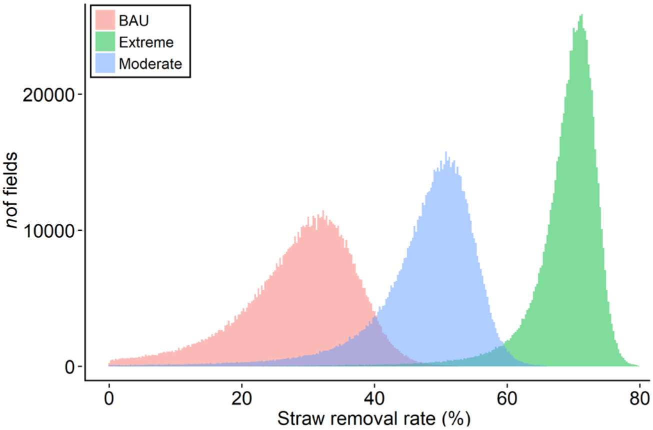

Figure 2.7: The straw removal rate (in % of sugarcane straw theoretically available on the field) for approximately 900,000 sugarcane fields (5.6 Mha) in São Paulo for the BAU, Moderate and High scenarios.

At mill level, the collection radius ranges from 2.3 to 30.4 km and the ecological availability of sugarcane straw in the Moderate scenario at mill level ranges from 5.7 to 632.5 × 10^3 Mg (see figure 2.8). The distance-supply plot on the right-hand graph of figure 2.8 shows that the collection radius is not necessarily a function of the amount of sugarcane processed. Due to the spatial distribution of sugarcane fields and their respective yield levels, some mills need to go for long distances to meet their ecological potential of sugarcane straw. The mills that require long collection areas are mostly located in sugarcane expansion areas in the West of São Paulo, where the sugarcane fields are more sparsely distributed. Moreover, the ongoing sugarcane expansion in that area mainly occurs on less fertile sandy soils. Consequently, the yield levels tend to be lower compared to traditional optimal agronomic areas (e.g. fertile clayey soils) in the Northeast of São Paulo [129,130]. Conversely, sugarcane mills with large ecological availability of sugarcane straw (e.g. > 200 × 10^3 Mg) essentially occur in the north eastern part of the state due to the high density of sugarcane fields and the high agro-ecological suitability.

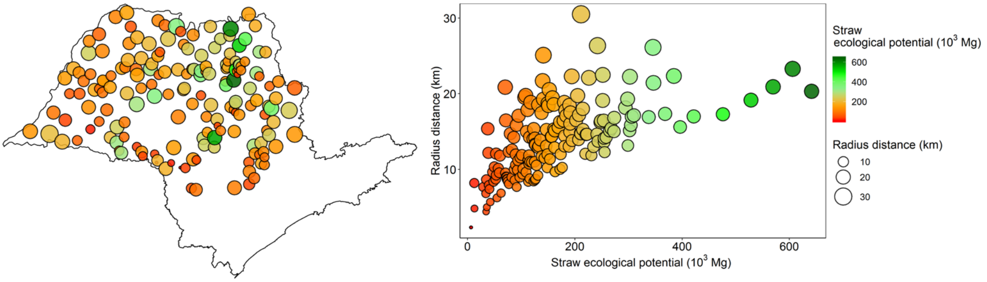

Figure 2.8: Ecologically available sugarcane straw in the Moderate scenario aggregated at mill level in relation to the straw collection radius.

To highlight the differences in the ecological availability of sugarcane straw and the collection radius of the mills, we select the mill with the highest sugarcane straw availability (mill A) and the one that has the longest radius (mill B) (figure 2.8). Mills A and B are typical mills from different regions (approx. 430 km from each other) and we compare them based on the Moderate scenario (i.e. 5.4 Mg.ha^{-1} straw mulching) (figure 2.9). Only 13% of the area within the straw collection area of Mill B is represented by sugarcane fields, whereas the collection area of mill A has a much higher sugarcane density of 75%. The density of sugarcane fields has large effect on agricultural operations and consequently in straw recovery logistics. Each field from mill A could provide on average 6.5 Mg.ha^{-1} of sugarcane straw (straw removal rate: 50%), whereas mill B 5.2 Mg.ha^{-1} (straw removal rate: 44%). For 273 hectares of sugarcane fields within the collection radius of mill A, no straw can be recovered, while in the collection area of mill B this applies to 402 hectares (black areas in figure 2.9). Given that vast amount of land operated by the sugarcane mills, the number unavailable fields presented in the Moderate scenario are negligible, accounting for less than 1% in both mills. The absence of sugarcane straw is due to sugarcane reforming areas or last ratooning cycles (i.e. lowest yield levels throughout the 6 years of sugarcane cycle).

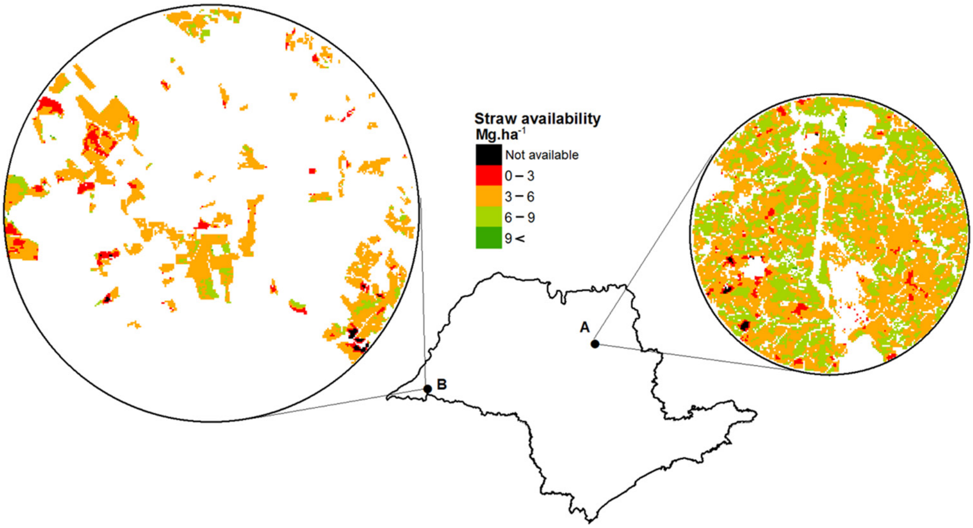

Figure 2.9: Spatial distribution of the ecological availability sugarcane straw of mill A (Ribeirão Preto region) and B (Presidente Prudente region) within their collection radius. This comparison elucidates the differences between sugarcane systems of typical mills in the northeast (traditional areas) and West (expansion areas) of São Paulo.

The bioelectricity production per mill ranges between 2.5 - 508.2 GWh in the BAU scenario, 4.2 - 817 GWh in the Moderate scenario, and 5.9 - 1144 GWh in the High scenario. In figure 2.10, the histograms indicate the distribution of the sugarcane mills according to their bioelectricity potential from ecologically available sugarcane straw in each scenario. For BAU and Moderate scenarios, the majority of sugarcane mills have a production of bioelectricity up to 200 GWh (light green bars), which represents 89% (BAU) and 66% (Moderate) of the total number of mills. Differently, the majority of mills (53%) in the High scenario have the potential to supply more than 200 GWh. Beyond that, there are sugarcane mills in the Moderate and High scenarios could potentially supply more than 500 GWh of bioelectricity (light blue bars), which is currently comparable to a medium size fossil-based power plants in Brazil [131]. The total bioelectricity potential from ecologically available sugarcane straw of the 174 mills in São Paulo is estimated at nearly 45.8 TWh in the High scenario, which is approximately six times higher than the bagasse-based bioelectricity surplus produced in 2012 (7.2 TWh) in the state of São Paulo and more than the double of the current surpluses (21.4 TWh) in Brazil [15,109]. In the Moderate and BAU scenarios, the bioelectricity potential from ecologically available sugarcane straw respectively reduces to 31.8 TWh and 18.7 TWh.

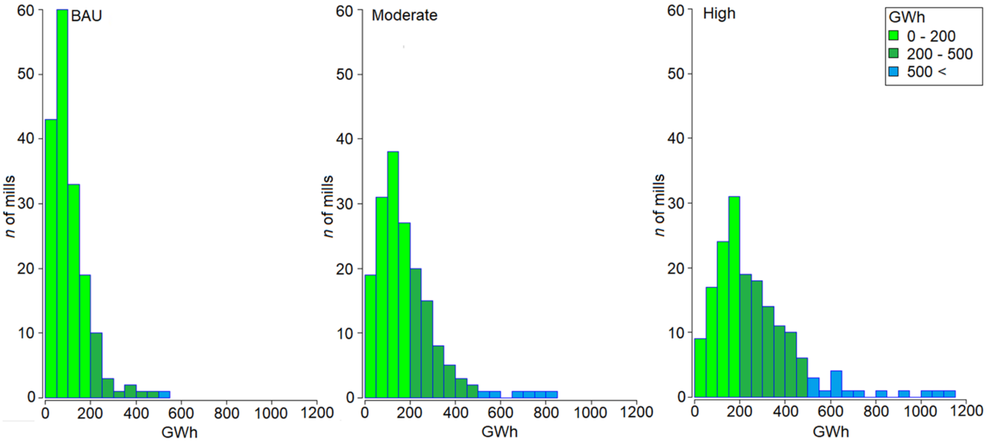

Figure 2.10: Bioelectricity production of the sugarcane mills of 2012 crop-year for BAU, Moderate and High scenario on ecological availability of straw.

In the sensitivity analysis, no significant change is verified as all the parameters present a similar linear behavior for the variation applied (figure 2.11). The most prominent difference is the steeper decrease of the bioelectricity potential as the moisture content increase in the Moderate and High scenarios, whereas in the BAU scenario the variation is minor. This happens because most of the bioelectricity in the BAU scenario is sourced from mills with homogeneous high-yield fields. The parameter that presents the highest variation (5.6 TWh - 59.9 TWh) in the bioelectricity production among the scenarios is the SSR (straw-sugarcane ratio). The other parameters, straw moisture content and the electrical conversion efficiency are characterized by similar impact on the bioelectricity variation (13.1 TWh - 53.7 TWh and 15.6 TWh - 53.3 TWh, respectively). The latter is also assessed by using the maximum (35%) and minimum (20%) electrical efficiencies fixed for all the mills, showing similar bioelectricity potential range between 12.3 TWh and 52.7 TWh among the scenarios.

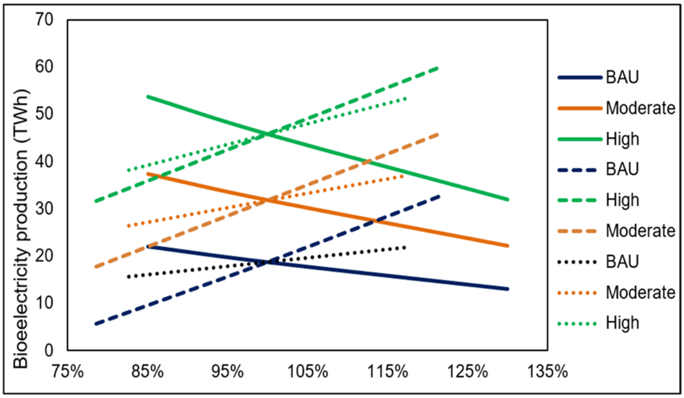

Figure 2.11: Sensitivity analysis of the bioelectricity potential from ecologically available sugarcane straw in the BAU, Moderate and High scenario. In the vertical axis, the sensitivity of bioelectricity potential can be analyzed. In the horizontal axis, the relative variation of the key parameters is shown: straw moisture content (85% - 130%); straw-sugarcane ratio (79% - 121%); electrical conversion efficiency (83% - 117%).

2.4. DISCUSSION

2.4.1. Results

The ecological availability of sugarcane straw in 2012 crop-year ranges from 16.7 × 10^6 Mg in the BAU scenario to 40 × 10^6 Mg in the High scenario. At field level, we show that the amount of straw recovered varies from 0 to 14.8 Mg.ha^{-1}, representing a removal rate of 0-82%. Low amounts of straw per hectare may not be economically advantageous as it compromises the straw recovery costs of sugarcane straw depending on the recovery route employed [119].

Currently, the average of exportable bioelectricity per Mg of sugarcane (i.e. electricity yield) in Brazil is 32.1 kWh.Mg^{-1} [15]. In our scenarios, the range of electricity yield (i.e. kWh per Mg of sugarcane) is estimated between 46 kWh.Mg^{-1} and 120 kWh.Mg^{-1}. Moreover, our results present that in 2012 crop-year, the mills could have produced 45.8 TWh of bioelectricity from sugarcane straw in the High scenario. This is between 40% and 60% of the fossil-based (e.g. coal, natural gas) electricity currently produced in Brazil [132], while the energy demand required for mobilizing the sugarcane straw [133] is below 5% of the bioelectricity production for all scenarios. Compared to the High scenario, the potentials in the BAU (18.7 TWh) and the Moderate (31.8 TWh) scenarios are considerably lower. These numbers, however, would still meaningfully contribute to the annual electricity supply at state level (i.e. ranging from 22% to 37% of the current electricity supplied in São Paulo) [134]. As shown in the sensitivity analysis, the bioelectricity potential from ecologically available sugarcane straw has a larger variation (5.6 TWh - 59.9 TWh) due to uncertainties in the SSR, which highly depends on the sugarcane cultivar, ratooning cycle and meteorological effects [68]. Other parameters, such as straw moisture content and conversion efficiency are also assessed, presenting lower variations between 13 TWh and 53 TWh. Nonetheless, the impact of the uncertainty of these parameters should be constantly considered in alternative bioenergy systems and in different potential assessments (e.g. techno-economic).

The results also show regional differences of mills located in traditional and expansion areas of sugarcane production. Unlike the mills in the traditional sugarcane areas (e.g. Northeast of São Paulo), which have a high agro-ecological suitability for sugarcane cultivation, the typical mills located in expansion regions are hindered by a lower level of straw availability per hectare and a lower density of sugarcane fields. With new sugarcane mills, it is expected that the sugarcane density and thereby sugarcane straw availability will increase in the expansion areas in the coming years [56]. The expansion areas in the state of São Paulo are also characterized by the high presence of sandy soils, which is a constraint for straw removal as it is likely to have high water infiltration inducing agronomic and environmental issues [129]. Alternatively, the presence of other land uses (e.g. eucalyptus plantation and annual crops) could serve as a supplementary source of agricultural residues, which could alleviate the seasonal availability of sugarcane straw. The use of alternatives sources for bioelectricity production is already a reality in Brazil

Apart from these underlying geographical differences, the real production of bioelectricity surpluses in 2012 in typical mills from these regions does not fully represents the results of the ecological availability of sugarcane straw for bioelectricity production. Based on the 2012 cogeneration ranking [120], the top ten bioelectricity producer mills from traditional areas have presented similar bioelectricity surpluses as the best cases from the expansion areas. Despite the similar contribution, the mills with the highest capacities of the state, normally located in traditional areas, have a significant internal demand for bagasse to thermal energy for producing sugar and 1G ethanol. As verified by Trombeta [65], typical mills from traditional areas still have cogeneration systems only designed to operate with bagasse at lower efficiency rates, reducing the bioelectricity surpluses. Differently, the prominent mills located in expansion areas are normally brownfields and greenfields built in the last decade [135]. As a downside, the amount of less suitable areas available in expansion areas hampers the production of sugar-based core-products. Consequently, the internal demand for bagasse tends to be lower, contributing to envision a business model focused on bioelectricity surpluses (e.g. new boilers, straw usage). This strategy has recently resulted in higher revenues compared to mills in traditional areas [136].

2.4.2. Methods and recommendations for future studies

In the spatial modeling, we consider that each mill was supplied by the nearest sugarcane fields within the established collection radius. This approach can be very realistic for isolated mills in regions with low competition for sugarcane areas, whereas it can be much less realistic for clusters of mills in traditional sugarcane regions of the state. In fact, the clusters of mills are competing for the same sugarcane areas, and therefore may have to source from more distant sugarcane fields, which may have underestimated the collection radius. Specifically, a spatial optimization exercise matching the sugarcane supply pixels with the mills' capacity seeking to minimize the collection distances should be addressed as a continuation of this study to provide a more realistic spatial distribution of the fields to each mill [45,137]. Broadly, future studies on bioenergy potentials should prospect and incorporate spatially explicit information to precisely assess the characteristics of local contextual factors and their potential impact on plant capacity. More than understanding the geographical differences, spatially explicit assessments ultimately contribute for a more precise estimation of the bioenergy potentials.

To assess the ecological availability of sugarcane straw for bioelectricity production, we assume only straw mulching levels as environmental criterion to maintain local environmental services. This is a decisive indicator as it largely affects the bioenergy system from the agronomic (e.g. fertilizer application, weed control) [68] and environmental perspective (e.g. organic carbon maintenance and erosion control) [36,138,139]. To improve our study, agro-ecological variables (e.g. soil, meteorological and topographic data) should be considered to modeling the straw mulching required at field level, rather than the assumed fixed mandatory mulching levels as used in our study. It should be also noted that other environmental constraints can play an important role in limiting the potential and have to be considered in further studies. As example, the assessment of carbon [140] and water [141] footprint throughout the bioelectricity from sugarcane straw supply chain. From the market perspective, there may be a strong increase in non-agronomic competitive uses for sugarcane straw in the future, namely 2nd generation ethanol [142]. Thus, the supply of low cost alternative residues either available within (e.g. bagasse, lignin) or outside (e.g. wood chips) the mill is of great importance to maintain bioelectricity surpluses [143,144].

To the extent of our knowledge, no sugarcane mill power plant is currently operating exclusively with sugarcane straw. The sugarcane straw is normally mixed with bagasse at similar sizes to reduce the damages in the boiler caused by chemical compounds available in the straw (e.g. potassium and chlorine) [69,100]. Other key assumption taken refer to the baling system recovery route, which is seen as an efficient recovery route for bioenergy purposes due to low moisture content of the straw delivered at the plant [123]. However, the straw baled could contain high content of mineral impurities depending on the fraction of straw recovered (i.e. chances are higher as the baler machine gets close to the soil).

Therefore, if great quantity of undesirable mineral compounds is burn along with the straw in the boilers, this could also lead to damages in the boiler [100].

The bioelectricity from sugarcane straw requires efficient power plants to minimize the technical challenges. These power plants have been gradually introduced in the main sugarcane mills in the last years to generate great bioelectricity surpluses and also to receive sugarcane straw. In this study, we assume a relationship between the capacity of the plant and the electrical efficiency [125]. This is not necessarily true when comes to bioelectricity business in Brazilian sugarcane mills. In general, the adoption of high efficient boilers has been triggered by recent built modern sugarcane mills with medium capacity that conceive bioelectricity as a core business model such as ethanol and sugar. Based on that, it is highly recommended that future studies explore the transition of sugarcane mills to the bioelectricity venture taking into account historical, geographical and local contextual factors. This could better describe the electrical efficiency of the plants in sugarcane mills and consequently the bioelectricity potential at mill level.

2.5. CONCLUSION

Using spatially explicit data on 2012 crop-year, we assess that the sugarcane mills from state of São Paulo (Brazil) have a large ecological availability of sugarcane straw for bioelectricity production. Based on the scenarios analyzed (BAU, Moderate and High), the sugarcane mills have an ecological availability of sugarcane straw ranging from 16.7×10^6 Mg to 40×10^6 Mg. The areas with large potential of sugarcane straw are located in the Northeast region of São Paulo with the presence of very suitable fields for straw recovery. With an electric conversion efficiency ranging from 20% - 35% across the mills, the total bioelectricity potential from ecologically available sugarcane straw in São Paulo ranges between 18.7 TWh and 45.8 TWh, and at mill level the potential varies from 4 GWh to 1140 GWh in the scenarios.

The comprehension of the spatially explicit ecological availability of sugarcane straw for bioelectricity production at mill level may support policy makers in decentralizing energy policies at local scale. In parallel, we assess that yield levels and distances for straw supply have high spatial variability over the sugarcane mills of the state. Therefore, our study could be used as platform to assess the location effect on the sustainability of bioelectricity from sugarcane straw supply chain. This could provide reliable results on bioelectricity potentials at local and regional levels supporting different bioenergy stakeholders.

3

Spatial assessment of the techno-economic potential of bioelectricity production from sugarcane straw

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Abstract. The techno-economic potential of bioelectricity from sugarcane straw is highly affected by the availability and distribution of straw, the scale of the sugarcane mill and its proximity to the grid connection. All these parameters present high spatial variation. This study aims to spatially assess the techno-economic potential of bioelectricity from straw of the mills from São Paulo state (Brazil). It is assumed that all 174 mills are equipped with an adjacent power plant, and that all straw within the collection radius of the mill can potentially be used in the adjacent power plant. The straw costs are assessed making use of the spatial information on straw availability and the collection radius of the mills. The bioelectricity costs are calculated taking into account the scale efficiency, investments and operational costs, and cost of connecting to the nearest transmission infrastructure. The bioelectricity costs range between 68–266 US$.MWh^{-1} across mills. The mills with high bioelectricity potential and low costs are generally large mills located in traditional sugarcane areas characterized by suitable agro-ecological conditions. Assuming a cut-off price of 80 US$.MWh^{-1}, the techno-economic potential of bioelectricity of straw in Sao Paulo is 14.2 TWh, which equals 10% of total electricity consumption of the state.

Keywords. sugarcane, biomass, electricity, costs, spatial distribution, mills

3.1. INTRODUCTION

Contrasting with the expected decrease of large scale hydroelectricity production, the contributions of other renewable technologies to electricity production are expected to increase in Brazil [98]. These contributions are predominantly represented by wind, solar, small hydropower stations and biomass [98]. The latter, despite having lower expected cost reductions compared to solar and wind energy, is projected to maintain its 10% share in the renewable electricity mix up to 2025 [98]. Sugarcane residues currently contribute for more than 80% to the national bioelectricity supply [145]. In 2015, the sugarcane sector in Brazil produced approximately 20.2 TWh of bioelectricity surpluses, which represented 4.3% of the total national electricity consumption [16,105].

The advantages of producing bioelectricity from sugarcane residues are the high number of mills that cogenerates bioelectricity in the same unit along with their core products, e.g. sugar and ethanol, and their proximity to big electricity consumers in the Brazilian Center-South (e.g. state of Sao Paulo) [104,146]. Currently, the main feedstock to produce bioelectricity in Brazil is the sugarcane bagasse, which is a residue from the sugarcane stalks crushed at the mill [124]. Due to high bagasse availability at low cost, most of the mills became fully energy self-sufficient, and some of them export large surpluses to the grid [146,147]. However, the increasing competition for bagasse could harm bioelectricity supply in the long run, as the mills may draw the attention to high added-value products, such as advanced cellulosic ethanol and biomaterials [104,142]. Hence, alternative high potential residues should be assessed to cover the increasing electricity demand [148].

In the 2000's, agricultural improvements and environmental laws have led to important changes in the agricultural phase of sugarcane production [68]. Particularly, the consolidation of sugarcane mechanical harvesting instead of manual harvesting through sugarcane straw burning has stimulated the use of straw as a source for bioelectricity. Previous studies indicated that straw have the current largest technical potential available (range of 42 - 105 Mt) for bioenergy in Brazil [84,98,149], which makes it the largest (and almost untapped) biomass residue source. But unlike bagasse, straw is an on-field residue that usually requires a separate costly and time consuming operation to be recovered [119].

Seabra and Macedo [4], Cardoso et al. [119] and Michelazzo [122] all show the straw recovery costs as a key parameter impacting the profitability of bioelectricity production, which is mainly explained by straw availability per hectare and transportation distance to the mill. Both parameters present high spatial heterogeneity over the sugarcane fields due to variability of agro-ecological and accessibility conditions [119,123,150,151]. Moreover, other techno-economic issues also affect the viability of producing exportable bioelectricity from straw [65,74,124,126,152]. Trombeta found a high regional variability in the mills' boilers and cogeneration systems, strongly related to the scale of the sugarcane mills. Additionally, Cavalcante [152] raised the importance of proximity of the mill to the electricity grid to enable low bioelectricity costs.

All the aforementioned studies highlight the effect of spatial dependent parameters at field (straw availability and transportation distances), mill and regional levels (power plant scale and availability of regional transmission infrastructure) on the bioelectricity production costs. However, there is no comprehensive assessment of how the spatial variation of each of these aspects jointly affects bioelectricity production costs. Similar studies have partially covered this knowledge gap either in a different scope [74] or in different bioenergy systems [45]. Even so, no study has reconciled spatially explicit data available at different geographical levels to provide multi-scale techno-economic information of bioelectricity production from crop field residues. Such information is crucial for investors and policy makers to comprehend and explore the techno-economic potential of bioelectricity in a given region.

The objective of our study is to spatially explicitly assess the techno-economic potential of bioelectricity production from sugarcane straw in sugarcane mills at field, mill and regional levels. We thereby also assess how the spatial variation of the key parameters affect the cost structure of bioelectricity and identify how the techno-economic potential could be improved. To provide comprehensive assessment on the techno-economic potential, we select the state of Sao Paulo in 2012 sugarcane crop-year as a case study because of the high quantity sugarcane mills (174) in this region and due to the high spatial resolution data availability for 2012 crop-year. The spatial modeling method employed in this study can be replicated in other study areas both in Brazil and other sugarcane- producing countries. The assessment is built upon the environmental potential assessment of bioelectricity from sugarcane straw of *Cervi et al* [153].

3.2. METHODS

The techno-economic potential of bioelectricity from sugarcane straw is assessed by carrying out a cost analysis for both the straw recovery and bioelectricity production. First, we assess the straw availability for bioelectricity production by accounting for the spatial distribution of sugarcane fields, the spatial heterogeneity of sugarcane yield and the straw removal rates. Then, we calculate the effects of the spatial distribution of sugarcane straw on the straw recovery costs, expressed in US dollars per tonne of straw (US\$.t^{-1}). Thereafter, we assess the composition of the bioelectricity production costs based on the selected system configuration of a typical high-pressure power plant adjacent to the mill to produce exportable bioelectricity expressed in US dollars per megawatt-hour (US\$.MWh^{-1}). By setting a bioelectricity cut-off price, we assess the techno-economic potential of bioelectricity from sugarcane straw for each of the 174 sugarcane mills as well as for the entire state of São

Paulo in 2012 crop-year. All cost input data are adjusted to real values of 2015 using IGP-DI price index [154] and all the cost data available in Brazilian Reais (R$) are converted to US dollars applying exchange rate of 1 R$ = 0.4 US$ (from January of 2015).

3.2.1. Straw availability

The data on the spatial distribution of sugarcane straw availability is based on the assessment of the environmental potential of bioelectricity from sugarcane straw for each sugarcane mill in São Paulo for the 2012 crop-year developed in *Cervi et al.* [153]. The study combined the spatial distribution of sugarcane and its yield levels in São Paulo at 250m "pixel" resolution with the location of the 174 operating mills in 2012 crop-year (figure 3.1 - left). Each mill was fed by its respective milling (crushed) data in 2012 crop-year. Based on that, the collection radius was defined by the circular area of which the cumulative sum of the sugarcane yield matches the amount of sugarcane crushed in 2012 crop-year (figure 3.1 - right).

In the study of *Cervi et al*. [153], different scenarios of straw recovery were assessed based on the amount of straw that is assumed to be left on the field for agronomic and environmental purposes. In the scenarios, fixed rates of straw mulching of 3.2 $t.ha^{-1}$, 5.4 $t.ha^{-1}$ and 7.5 $t.ha^{-1}$ on dry basis were assumed based on literature [68,102,106]. In this study, we use the moderate scenario of 5.4 $t.ha^{-1}$ of straw mulching on dry basis, which on average represents approximately 50% of the total straw available on the field. In total, this scenario account for an environmental potential of 28.3 Mt of sugarcane straw for bioelectricity production comprising all the sugarcane mills in São Paulo.

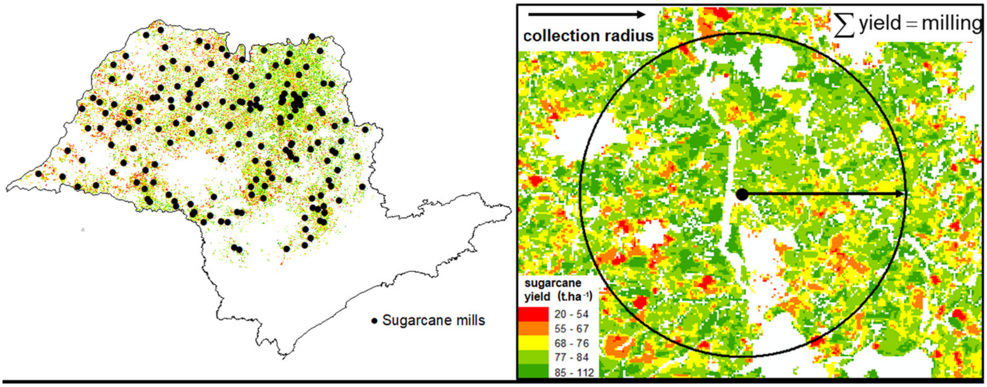

Figure 3.1: Left: Sugarcane yield map and the 174 mills in operation (black dots) in the state of São Paulo in 2012 crop-year. Right: Calculation of the collection radius around the mills matching the summation of the sugarcane yield in the collection radius with milling data of the mill [153].

3.2.1.1. Straw recovery costs

Sugarcane straw can be collected by many recovery routes [155], which should be selected based on the trade-off between the quality required by the end-product and the recovery costs [122]. For our analysis, we select the baling system, which is currently one of the most common straw recovery routes used in Brazil for bioelectricity and cellulosic ethanol production (Raízen/Shell mill, *pers. comm.* [156]). In the conventional mechanized harvesting of sugarcane, the harvester releases the straw back to the field. The straw remains on the field for approximately 15 days for natural drying. Then, with the appropriate machinery, the straw is windrowed, baled, loaded into the truck (representing the on-farm straw operation costs) and transported to the mill (representing the transportation costs) (figure 3.2). For further details of these operations, see the studies of Cardoso et al. [106,119,123].

Figure 3.2: The sugarcane straw baling system, including straw operations (in green) and transportation (in blue).

To calculate the total straw recovery costs, we consider both the farm-gate and transportation costs. See equation 3.1:

Equation 3.1

$$C_s = C_f + C_t \times d$$

Item	Description	Unit
C_s	Total straw recovery cost	US$.t^{-1}
C_f	Straw farm-gate cost	US$.t^{-1}
C_t	Straw transportation costs	US$.t^{-1} km^{-1}
d	Transportation distance	km

In this study, the farm-gate cost of straw (C_f) is composed by the cost of agricultural input required for the following crop-year to compensate the nutrient losses related to the straw removal from the field, plus the straw operational costs (e.g. machinery costs, depreciation, diesel and labor for windrowing and baling) [119]. The farm-gate costs of sugarcane straw decrease with increasing yield levels [42], in a nonlinear way due to economies of scale. We based our calculation of the farm-gate cost of sugarcane straw on the study of Cardoso et al. [123]. Using their data, we fitted a power trend line to estimate the relation between straw availability and the farm-gate cost. We only include the fields with more than 1 t.ha^{-1} of sugarcane straw available to ignore negligible amounts of straw recovery and avoid outlier straw recovery costs. See equation 3.2 and the supplementary material – SM 3.1.

Equation 3.2 $$C_f = 65.35 \times Y^{-0.631}$$

Item	Description	Unit
C_f	Straw farm-gate cost	US\$.t^{-1}
Y	Straw availability	t.ha^{-1}

Michelazzo [122] has assessed the transportation cost of the baling system of sugarcane straw, and showed the relation between distance and cost. Accordingly, we estimate the average transportation cost of sugarcane straw (C_t) at 0.19 US\$.t^{-1} km^{-1}. In our study, the distance (*d*) from straw field to the mill is calculated spatial explicitly using a Geographic Information System (GIS). Due to the lack of data on non-paved roads at which the sugarcane is mainly transported, we assume a tortuosity factor of 1.4, as suggested by Monforti et al. [50].

3.2.2. Bioelectricity production costs

Currently, most of the mills only use sugarcane bagasse as feedstock for bioelectricity production and have low efficient cogeneration systems to fulfill their own energy demand [65]. To scale-up the bioelectricity production using all recovered sugarcane straw, a retrofit to large boilers would be needed. As no information on the current status of the boilers in sugarcane mills is available, our selected system comprises a new power plant adjacent to the main sugarcane mill, which is fully dedicated to generate bioelectricity to be exported to the grid (figure 3.3). To standardize the assessment, the adjacent power plant comprises a Condensing Extraction Steam Turbines (CEST) system with medium/high pressure and temperature [4,157], which is implemented in all 174 mills assessed in São Paulo. According to Dantas et al. [124], this technology will remain a competitive bioelectricity production option in the medium to long term.

To calculate the bioelectricity production costs, we assume that all adjacent power plants operate with full scale, i.e. all the sugarcane straw available within the collection radius of the mill is used for bioelectricity production. With the scale determined by the amount of straw available, we adapt a realistic range of electrical conversion efficiency in sugarcane mills [126,127] that varies from 20% to 35% as function of the electricity generating capacity of the adjacent power plants (supplementary material – SM 3.2).

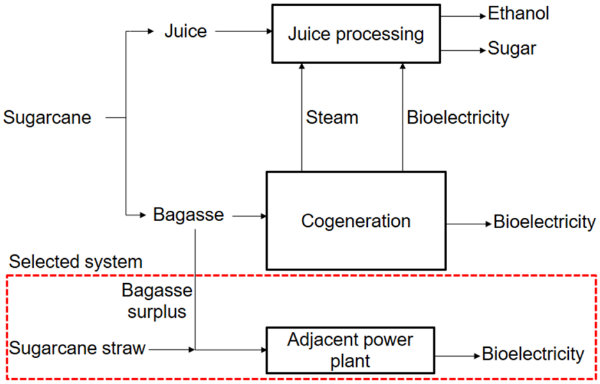

Figure 3.3: System configuration of sugarcane mill with an adjacent plant to produce exportable bioelectricity (red dashed outline).

As highlighted by Leal et al. [69] and Menandro et al. [100], there are technical limitations (e.g. size of particles, chemical compounds) in operating a power plant exclusively fed by sugarcane straw. Therefore, we assume that part of the bagasse that are not used in the cogeneration system in the main mill (i.e. 35% of bagasse surplus for external use, based on [4,121]) is used to feed the adjacent power plant jointly with the sugarcane straw (i.e. mixed composition) (figure 3.3). The bagasse normally has moisture content of 50% [68] and it is available at no additional cost [4]. Moreover, the bagasse is mostly used in the adjacent power plant during the off-season (i.e. December to March) to avoid technical risks of storing sugarcane straw (e.g. accidental fire). The assumptions on the biomass availability are described in table 3.1.

Table 3.1: Sugarcane bagasse and sugarcane straw used in the mill and in the adjacent power plant:

Parameters	Biomass	
	Bagasse [c]	Straw
Residue to sugarcane ratio (kg.t^{-1})[a]	260	140
Use in the main mill power plant (%)	65	0
Use in the adjacent power plant (%)	35	100[d]
Moisture content (%)[b]	50	15

[a] Bagasse: available at the mill [121]. Straw: available at the field [68].

[b] Lower Heating Value (LHV): 13.3 MJ.kg^{-1} for straw (at 15% moisture content) and 7.2 MJ.kg^{-1} for bagasse (at 50% moisture content) [121]. The potential reduction in moisture content of the bagasse stored for off-season is not considered.

[c] Bagasse storage costs are neglected in the cost analysis as it represents less than 5% of the straw recovery costs [158].

[d] Total amount of straw recovered from the field (i.e. the environmental potential).

The bioelectricity production costs are calculated using the Levelized Cost of Energy – LCOE, which comprises all the costs throughout the supply chain of bioelectricity production from sugarcane straw. The discounted feedstock (straw recovery) costs and capital and operational expenditures (CAPEX and OPEX) over the lifetime of the plant are divided by the total discounted bioelectricity production output. The LCOE is commonly employed in economic assessments of renewable electricity systems [159], and it allows for the comparison of the costs structures of bioelectricity production of different sugarcane mills. The LCOE is calculated at field (pixel) level, taking into account the field specific straw recovery costs and the mill specific CAPEX and OPEX, as shown in equation 3.3.

Equation 3.3

$$\mathrm{LCOE}^{pm} = \frac{\sum_{t=1}^{n}\left(I_t^m + M_t^m + \left(Cs \times LHV \times \frac{eff}{3.6}\right)_t^{pm}\right) \times (1+r)^{-t}}{\sum_{t=1}^{n} E_t^m \times (1+r)^{-t}}$$

Item	Description	Unit
LCOE^{pm}	Bioelectricity production costs at field p of mill m	$US\$.MWh^{-1}$
I_t^m	CAPEX in year t at mill m	$US\$.MW^{-1}$
M_t^m	OPEX in year t at mill m	$US\$.MW^{-1}$
Cs_t^{pm}	Straw recovery costs in year t at field p of mill m	$US\$.t^{-1}$
LHV	Lower Heating Value	$MJ.kg^{-1}$
eff	Conversion efficiency	%
3.6	Conversion MJ to kWh	MJ/kWh
E_t^m	Electricity generated in year t at mill m	MWh
n	annuity period	years
r	discount rate	%

The CAPEX and OPEX vary across the mills by virtue of their plant scale and the grid connection distance from the mill to the nearest distributor substation. To standardize the assessment, we assume that all the mills still have to connect to the grid, while in reality some of the mills are already (partly) connected to the grid. To calculate the Fixed Capital Investment (FCI) of each mill, we assume a reference capacity of 50 MW [4] and typical scale factor for power plants of 0.7 [154] (table 3.2).

Embedded in the CAPEX, the grid connection investments are not considered scale dependent, which means that the all mills need to invest equally in a substation facility and general connection equipment in order to export the bioelectricity from sugarcane straw (i.e. the fixed investments). In addition, there are also the variable connection investments related to the length (distance) of the transmission lines (table 3.2), which are calculated spatially explicitly from the mill point to nearest distributor substation. A tortuosity factor of 1.2 was applied to the Euclidian Distance to account for geographical constraints, such as terrain slope, conservation and built-up areas [160]. Table 3.2 summarizes the techno-economic parameters of the adjacent power plant.

Table 3.2: Techno-economic parameters of the adjacent power plant.

Parameter	Units	Value
Reference scale [a]	MW	50
Operating time [b]	hours	8406
Scale factor [c]	-	0.7
Electrical conversion efficiency [d]	%	20-35
CAPEX [e, f]	MUS$$_{2015}$	77.4
Transmission line [g]	MUS$$_{2015}$.km^{-1}	0.33
OPEX [h]	MUS$.MW.y^{-1}$_{2015}$	0.21
Discount rate [i]	%	12
Project lifetime [j]	years	25

[a] As simulated by Seabra et al. [121].

[b] In this configuration, the adjacent power plant operates during both harvest season and off-season for approximately 11 months in total. In the power plant of the main mill (cogeneration), the bioelectricity is exclusively produced from bagasse, only operating during the season (6 months). Based on Seabra and Macedo [4].

[c] Typical scale factor used in techno-economic assessments of sugarcane biorefineries [74,154].

[d] The variation of efficiency in the adjacent plant is available in Cervi et al. [153].

[e] The majority of CAPEX is composed of the FCI for a 50 MW reference power plant estimated at 77.4 MUS$$_{2015}$, including working capital (4 MUS$$_{2015}$) [4].The project finance was assumed as 100% Equity.

[f] The additional part of CAPEX stems from the fixed transmission investments of 9.3 MUS$$_{2015}$ for grid connection (e.g. substation, converters), which is not scale dependent [152].

[g] Variable investment in grid connection per kilometer of transmission line [152].

[h] Operational costs: include consumables, labor, overhead, maintenance and insurance [4].

[i] Commonly applied for private investments in bioelectricity projects in Brazil. Adapted from Dantas et al. [124].

[j] Plus 3 more years to build the power plant before the first year of production, which refers to the years -2, -1 and 0.

3.2.3. Techno-economic potential of bioelectricity

The techno-economic potential is assessed by assuming a bioelectricity cut-off price of 80 US$.MWh^{-1}, which represents a typical value in the regular Brazilian bioelectricity market and is also used as reference in some studies [143,158]. The techno-economic potential is estimated at mill level and field level. In the first, all sugarcane straw fields available within the collection radius of each mill is used in the adjacent plant, accounting for the average straw recovery costs and the bioelectricity conversion costs given the related scale of the adjacent plant result in the average bioelectricity costs at mill level. The mills with an average bioelectricity production costs below 80 US\$.MWh^{-1} are considered to be part of the techno-economic potential.

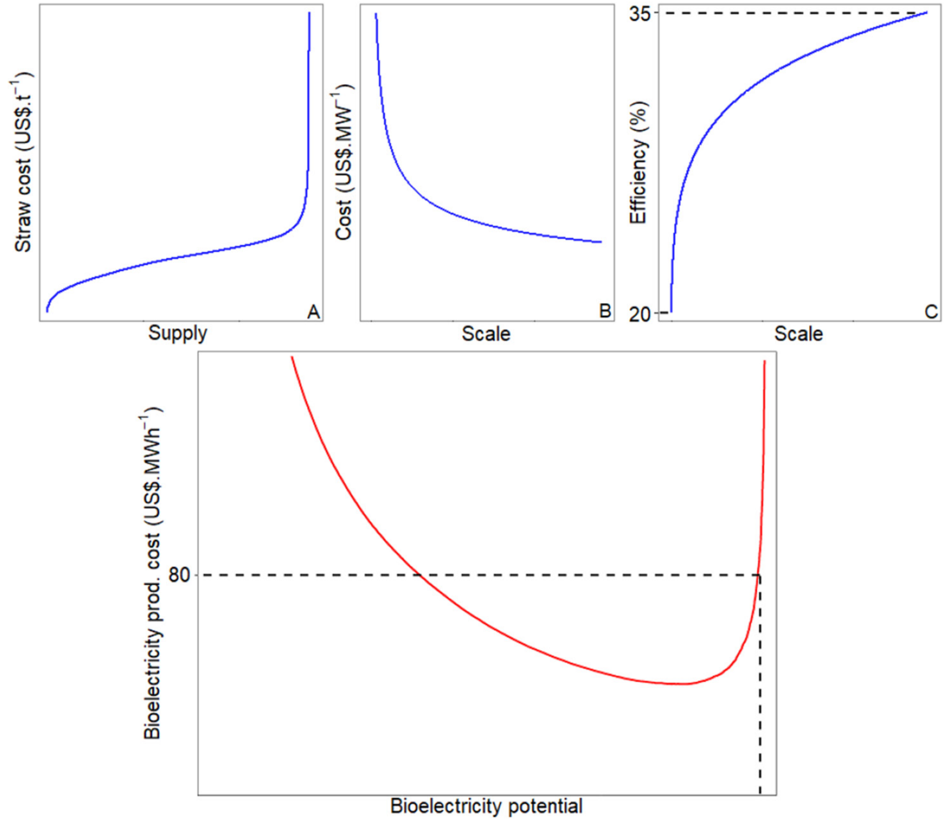

Figure 3.4: Schematic representation on how the techno-economic potential is estimated at field level through the optimization of the adjacent power plant scale. Blue curves: graphical representation of cumulative straw cost-supply (A) cost-scale (B) efficiency-scale (C) of bioelectricity production from sugarcane straw. Red curve: optimal bioelectricity potential.

The drawback of mill level assessment is that all the fields in the collection radius of the mill are included in calculating the average straw recovery costs, including the ones with very high straw recovery costs. This could result in excluding some mills from the techno-economic potential because of a few costly outliers' straw fields. If it is assumed that only the fields with low straw recovery costs are included, the average straw recovery costs at the mill level go down. However, when only part of the straw available in the collection area of the mill is used in the adjacent power plant, the scale and the conversion efficiency need to be adjusted to match the lower straw supply, which results in higher bioelectricity conversion costs. Therefore, we determine the techno-economic potential at field level by making use of the cumulative straw cost-supply curve (A - figure 3.4), the cost-scale (B - figure 3.4) and the efficiency-scale curve (C - figure 3.4) of each mill. The optimal scale and related efficiency is assessed for which the techno-economic potential is maximized for each mill. This optimization calculates the maximum amount of bioelectricity that could be produced with costs < 80 US\$.MWh^{-1} (red curve - figure 3.4).

To assess the sensitivity in the techno-economic potential of bioelectricity from sugarcane straw, we consider the uncertainty of the following parameters: straw mulching levels, bioelectricity cut-off price; discount rate; straw moisture content; conversion efficiency; bagasse availability and cost; FCI and OPEX. The high volatility of bioelectricity prices in Brazil is a key concern regarding the economic viability of power plants in sugarcane mills [146]. In addition, fluctuations in the FCI, OPEX and discount rate due to influencing economic factors (e.g. exchange ratio of imported equipment, annual inflation, political issues, financing options) could have strong effect on the bioelectricity costs [4,121,124,161]. In regards of straw, the mulching levels are dependent on agronomic features [123], which results in high uncertainty of the amount of straw that can be recovered and therefore, in the cost-supply of straw and the techno-economic potential of bioelectricity [119]. Similarly, the moisture content of sugarcane straw has a great variability over the fields, because of agronomic and operational reasons that highly affects the electricity generating capacity and efficiency [4]. There is a high variation in the reported conversion efficiency of bioelectricity from straw, which is only partly explained by the variation in scale. The conversion efficiency strongly affects the amount and the cost of bioelectricity produced [162]. At last, we consider variation in the assumption of 35% bagasse surplus supplied to the adjacent plant at no additional cost, influencing the feedstock costs and the adjacent plant capacity. The variation rate for each parameter is based on similar ranges found in literature, see table 3.3.

Table 3.3: Considered variations in the key techno-economic parameters in the sensitivity analysis

Parameter	Unit	Original values	Variation	Variation rate (% of original value)
Straw mulching levels [a]	$t.ha^{-1}$	5.4	3.2-7.5	59-138
Bioelectricity cut-off price [b]	$US\$.MWh^{-1}$	80	56-104	70-130
Discount rate [c]	%	12	8.4-15.6	70-130
Straw moisture content [d]	%	15	0-40	70-115
Conversion efficiency [e]	%	20 - 35	15 – 30; 25 – 40	82-117
Bagasse availability rate [f]	%	35	20–50	57-143
Bagasse cost [g]	$US\$.t^{-1}$	0	0 - 6	-
FCI [h]	M.US$	77.4	61.9 – 92.8	80-120
OPEX [i]	$M.US\$.MW.y^{-1}$	0.21	0.17 – 0.25	80-120

[a] Straw mulching levels: Amounts of sugarcane straw that should be left on the field to comply with environmental and agronomic requirements of sugarcane fields. Based on Cervi et al. [153].

[b] Bioelectricity cut-off price: bioelectricity selling prices threshold between 2008 and 2009 in the regular market reported by Grisi et al. [147]. Prices in the spot market are not accounted due to high variation in short periods.

[c] Discount rate: ±30% variation agree with debt financing options of bioelectricity projects in Brazil and with the Brazilian macro-economic conjunctures [124]. Differently from high value-added bioproducts, bioelectricity from sugarcane residues does not have the innovative appeal leading to extremely low discount rates [163].

[d] Straw moisture content: although it is unrealistic to supply sugarcane straw on a dry basis due to variability of environmental conditions on the field, many studies have been used dry basis as reference [104,142]. Therefore, we vary the straw moisture content from 40% (9.3 $MJ.kg_{straw}$) to dry basis (15.6 $MJ.kg_{straw}$).

[e] As the variation of 20-35% represents the reality of power plants in Brazilian sugarcane mills, we applied a small variation of ±5% based on reported values from literature [127].

[f] The bagasse availability rate is related to the thermal energy required by the mill to produce sugar and ethanol. We vary ±15% around the assumed fixed rate of 35% to address annual variation in sugarcane supply. A scenario with no bagasse available is possible, but not assessed due to technical constraints of operating boilers using only straw as fuel [100].

[g] The opportunity cost of sugarcane bagasse could increase according to the demand of competitive uses (e.g. animal feed, 2G ethanol). According to Carpio and Souza [146], current bagasse opportunity cost can be set at 6 $US\$.t^{-1}$.

[h] A similar variation rate of ±20% for both FCI and OPEX are applied in the sensitivity analysis carried out by Seabra et al. [4].

3.3. RESULTS

The results are based on the individual techno-economic assessment of all 174 operating mills in São Paulo in 2012 crop-year. In section 3.3.1, we firstly present the spatial variation of straw recovery costs at mill level. In section 3.3.2, we show the variation in bioelectricity production costs and the different cost structures across the mills. Based on the bioelectricity production costs and the selected cut-off price, the techno-economic potential of bioelectricity from sugarcane straw is presented in section 3.3.3. The sensitivity of the bioelectricity potential for variations in key parameters is presented in section 3.3.4.

3.3.1. Straw recovery costs

Figure 3.5 (left) shows the spatial distribution of the 174 mills coupling their average straw recovery costs and straw environmental potential of the 2012 crop-year in São Paulo. Based on that, a sugarcane straw cost-supply curve ranging from 21 to 35 US\$.t^{-1} is drawn by combining the 174 operating mills of the state of São Paulo (figure 3.5 - right). The size of the circles in figure 3.5 represents the sugarcane straw available at each mill, ranging from 5.7 to 632.4 kt of straw. In general, mills with a significant straw supply (i.e. > 200 kt) present average straw recovery costs between 26 - 30 US\$.t^{-1}. Although these mills profit from economies of scale due to a large straw supply, they also face higher transportation costs due to longer a collection radius. Differently, most of the mills with a low sugarcane straw supply (i.e. < 100 kt) are either concentrated in the higher (> 30 US\$.t^{-1}) or lower (< 26 US\$.t^{-1}) range of average straw recovery cost. Therefore, the straw cost supply curve hints no apparent relationship between the amount of sugarcane straw supply in each sugarcane mill and their respective average straw recovery costs. On the other hand, the map of figure 3.5 shows a geographic pattern due to high presence of mills with high straw recovery costs in the West of São Paulo and the occurrence of mills with low straw supply costs in the East of São Paulo.

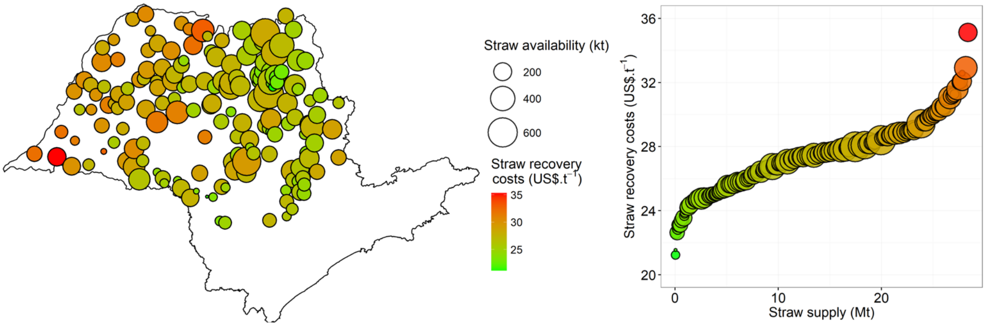

Figure 3.5: Left: Spatial distribution of the sugarcane mills with their respective technical potential of sugarcane straw (size of the circles) and average straw recovery costs (color of the circles). Sharing the same legend, in the right, the regional cost-supply curve of sugarcane straw given the average straw recovery costs per mill in 2012 crop-year in São Paulo.

To highlight the difference among the regions in the state of São Paulo, we divide the mills into four classes based on the straw recovery costs and potential of sugarcane straw per mill. Using the threshold of average costs at 27.1 US\$.t^{-1} and the average straw supply at 163.1 kt, we establish the following classes: HCHS – high costs and high supply; HCLS - high costs and low supply; LCHS – low costs and high supply; LCLS – low costs and low supply. Figure 3.6 presents the geographical distribution of the four classes of mills and their respective cost-supply curves.

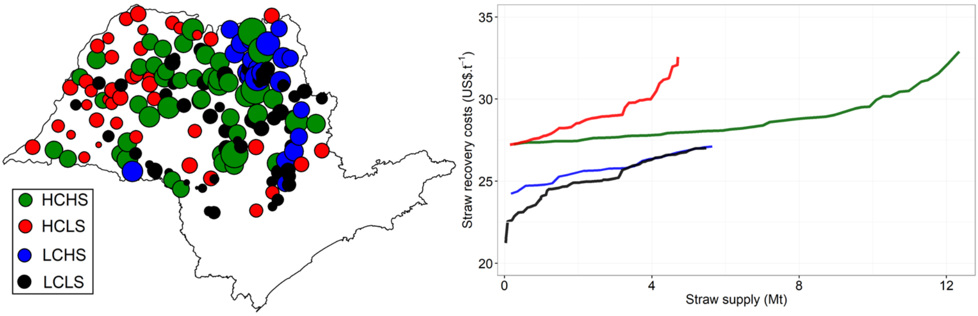

Figure 3.6: Spatial distribution of the mills according to their cost-supply classification (left) and their respective supply curves (right): HCHS – High Costs and High Supply; HCLS - High Costs and Low Supply; LCHS – Low Costs and High Supply; LCLS – Low Costs and Low Supply.

LCHS mills (i.e. 23 mills labeled with blue circles and the blue line in figure 3.6), typically represent the traditional big mills established in the beginning of sugarcane ethanol program in Brazil in the 1970's, and are mostly clustered in the northeast of São Paulo. This region is characterized by optimal agronomic conditions for sugarcane cultivation, in contrast to other regions of the state [130]. LCHS mills have the highest average straw availability ($\bar{x}$ = 6.4 t.ha^{-1}) and reasonable mobilization distances (one-way: $\bar{x}$ = 14.1 km), which assure low recovery costs. Contrasting, HCLS mills (43 mills identified with the red circles), represent a group of small and old distilleries generally located in the western part of the state. HCLS mills are characterized by a considerable mobilization distance (one-way: $\bar{x}$ = 20.5 km) due to the low average straw availability ($\bar{x}$ = 5.3 t.ha^{-1}) in the direct surroundings of the mills.

The other two classes, HCHS and LCLS mills, are scattered across the state and more heterogeneous. In general, HCHS mills are located in the West and Center-West of the state, and refer to new brownfield mills that have been leading the sugarcane expansion in the state. These mills present a very high variation in straw recovery costs (see figure 3.7) because some areas present unsuitable agronomic and operational conditions for straw recovery, which increase the straw recovery costs. Distinctively, great part of the LCLS mills are identified as smaller branches of association of mills, located in regions with affordable straw recovery costs (i.e. the majority of the fields are composed by straw recovery costs lower than 27 US$.t^{-1} - figure 3.7) that are used to supply the main mill of the association, which can be either HCLS or LCHS.

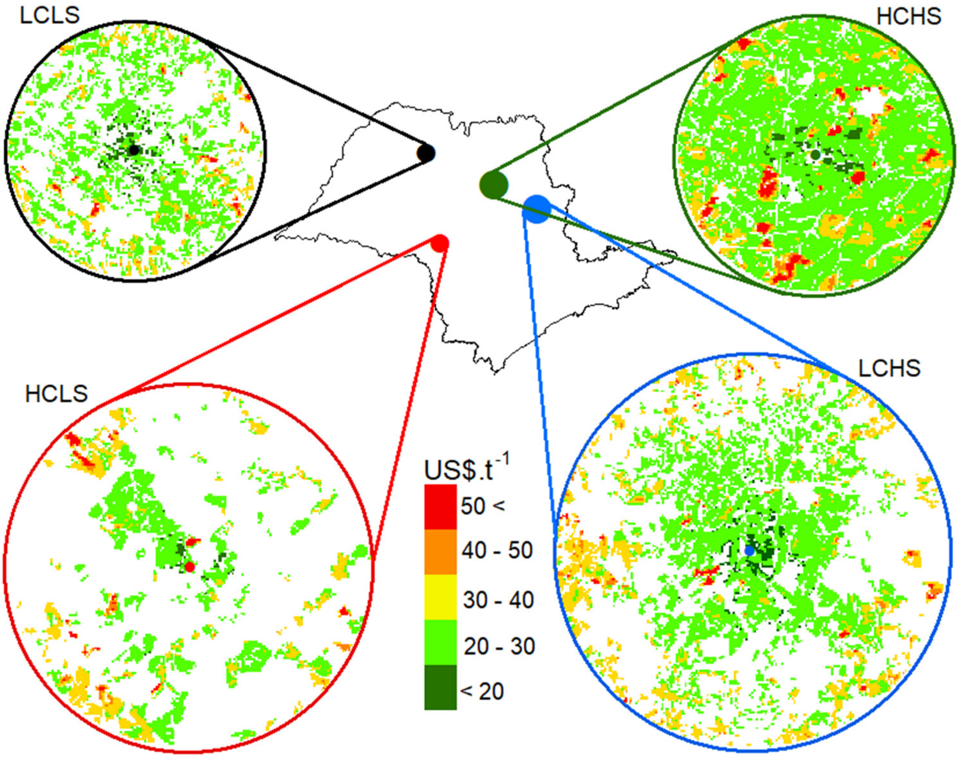

Figure 3.7: Spatial distribution of the straw recovery costs of typical sugarcane mills of the four groups according to the cost-supply classification: HCHS – High Costs and High Supply; HCLS - High Costs and Low Supply; LCHS – Low Costs and High Supply; LCLS – Low Costs and Low Supply.

3.3.2. Bioelectricity production costs

The average bioelectricity production costs at mill level range from 68 to 266 US$.MWh^{-1} (figure 3.8), which represents an average cost at state level of 93 US$.MWh^{-1} in the 2012 crop-year. The total bioelectricity production costs consist of four major cost components: feedstock costs (i.e. straw recovery costs), operational costs, and FCI and transmission costs. The mills with relatively low average bioelectricity costs (shades of blue in figure 3.8), all have a relatively low contribution of transmission costs. High average bioelectricity costs of mills (e.g. > 130 US$.MWh^{-1}) are predominantly caused by high FCI and transmission costs (shades of yellow and red in figure 3.8). This occurs in less than 5% of the mills and are all located in the Southwest of São Paulo. The FCI and transmission costs (i.e. jointly representing the CAPEX costs) show a strong correlation between each other (R^2 0.87) (supplementary material – SM 3.3), because the mills with high FCI costs are often located in regions with sparser grid distribution infrastructure. Across all mills, the FCI costs vary between 20 – 95 US$.MWh^{-1} (figure 3.9), which represents a share of 28% to 45% of the total bioelectricity production cost.

When the share of FCI costs increases beyond 35%, the average bioelectricity production costs increase sharply. These mills are normally characterized by electricity generating capacity lower than 25 MW and high specific investments ranging from 2 to 5 MUS$.MW^{-1}.

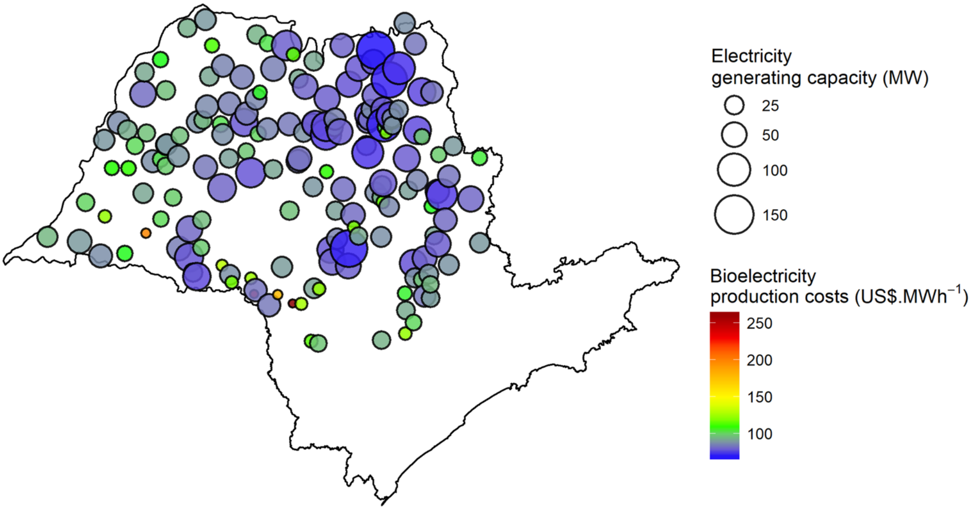

Figure 3.8: Average bioelectricity production costs of the sugarcane mills in São Paulo and their respective electricity generating capacity.

The feedstock costs contribution ranges from 21 to 40 US$.MWh^{-1}, representing a relative contribution of 10% - 34% to the total bioelectricity production costs (figure 3.9). The cost breakdown indicates that just three mills present feedstock costs as the main the cost component. These mills also present high electricity generating capacity that assures low FCI costs, which results in average bioelectricity production costs between 78 - 90 US$.MWh^{-1}. Differently, the operational costs have an absolute contribution fixed at 27 US$.MWh^{-1} as the operational costs is function of the electricity generating capacity of the adjacent plant of each mill. However, the relative contribution of operational costs has the highest variation across the mills (10% – 39%). Consequently, mills with a high electricity generating capacity have generally relatively low bioelectricity production costs with a relatively high contribution of operational cost.

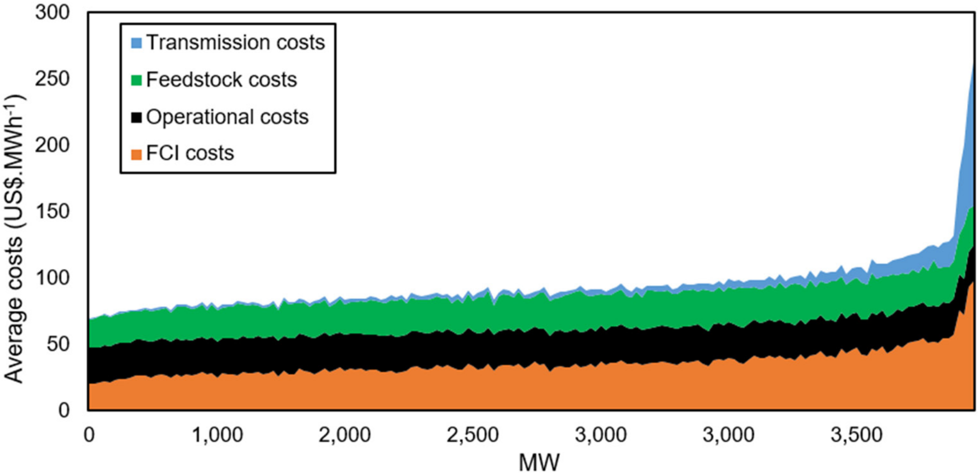

Figure 3.9: Breakdown of the average the cost supply of bioelectricity from sugarcane straw of the 174 sugarcane mills in São Paulo

3.3.3. Techno-economic potential of bioelectricity from sugarcane straw

The results of the techno-economic potential assessment at mill level show that 31 mills present average bioelectricity production costs below 80 US$.MWh^{-1}. The techno-economic potential varies from 273 GWh to 817 GWh per mill, in a total techno-economic potential of 12.5 TWh of bioelectricity from sugarcane straw. These mills are predominantly located in traditional areas of sugarcane production in the Northeast and Center-East of São Paulo (e.g. Ribeirão Preto and Piracicaba region).

When the power plants are optimized based on field level information on the straw cost-supply, scale-efficiency and the scale-cost curves, 37 mills (including those 31 mills before the optimization) present bioelectricity costs lower than 80 US$.MWh^{-1}, resulting in a maximized techno-economic potential of 14.2 TWh (cost-supply curve in figure 3.10). The map in figure 3.10 indicates the mills that contribute to the techno-economic potential of bioelectricity from sugarcane straw. The economically viable mills have a large range of straw availability (206 – 632 kt per mill) and are characterized by straw recovery costs below 34 US$.t^{-1}. These mills present an optimal electricity generating capacity between 41 MW and 154 MW for an overall electrical conversion efficiency ranging from 27% to 35%. This high variability shows that not only the large mills with high input capacity contribute to the techno-economic bioelectricity potential. Mills with medium capacity but located in regions with good agronomic conditions and high infrastructure availability (e.g. hubs of electricity distribution) are likely to be economically viable.

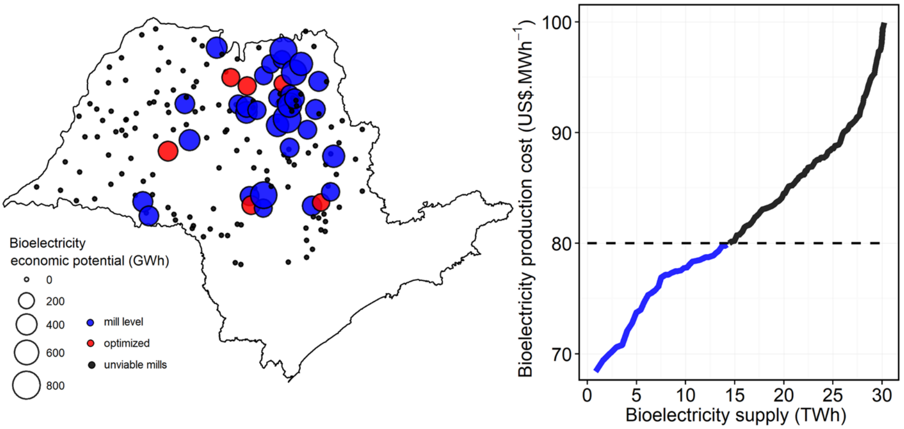

Figure 3.10: Left: the circles in the map indicates the size and the location sugarcane mills contributing to the techno-economic potential of bioelectricity from sugarcane straw. Blue and red circles refer to the techno-economic potential at mill level and optimized at mill level, respectively. The small black circles are the remaining sugarcane mills with no techno-economic potential (i.e. bioelectricity production costs > 80 US\$.MWh^{-1}). Right: cost-supply curve of bioelectricity form sugarcane straw in São Paulo for the 2012 crop year. The blue part of the graph indicates the techno-economic potential when the scale of the adjacent plants is optimized, i.e. the amount of bioelectricity that can be produced below the cut-off prince of 80 US\$.MWh^{-1}.

3.3.4. Sensitivity analysis

The variation in the techno-economic parameters of bioelectricity production from sugarcane straw results in a wide range of uncertainty in the optimized techno-economic potential (figure 3.11). The sensitivity analysis shows that the bioelectricity potential is most sensitive for variations in the bioelectricity price. For prices below 56 US\$.MWh^{-1}, there is no techno-economic potential of bioelectricity, whereas prices higher than 104 US\$.MWh^{-1} result in a potential of more than 30 TWh. Another crucial economic parameter is the discount rate: if the discount rate is reduced to 8.4%, the techno-economic potential of bioelectricity increases to 26 TWh. Conversely, the techno-economic potential declines smoothly, being less sensitive for discount rates over 12%. Variations in the FCI and OPEX affect the techno-economic potential of bioelectricity in a similar way.

The variability of straw mulching levels results in a large variation in the techno-economic potential as it affects both the availability of straw as well as key techno-economic variables (e.g. straw farm-gate costs, electricity generating capacity). Variations in the conversion efficiency highly affects the bioelectricity production: a 5% increase in the electrical efficiency of the adjacent plants almost double the bioelectricity potential.

In case of straw being available on a dry basis (i.e. no moisture content), the techno-economic potential is estimated at 20 TWh. For straw with moisture content of 40%, the bioelectricity potential reduces to less than 1 TWh. Differently, the techno-economic potential of bioelectricity is much less sensitive for bagasse availability, presenting the narrowest variation of 10 – 16 TWh (figure 3.11). Moreover, if the bagasse available present an opportunity cost of 6 US$.t^{-1}, the bioelectricity potential decreases to 3 TWh.

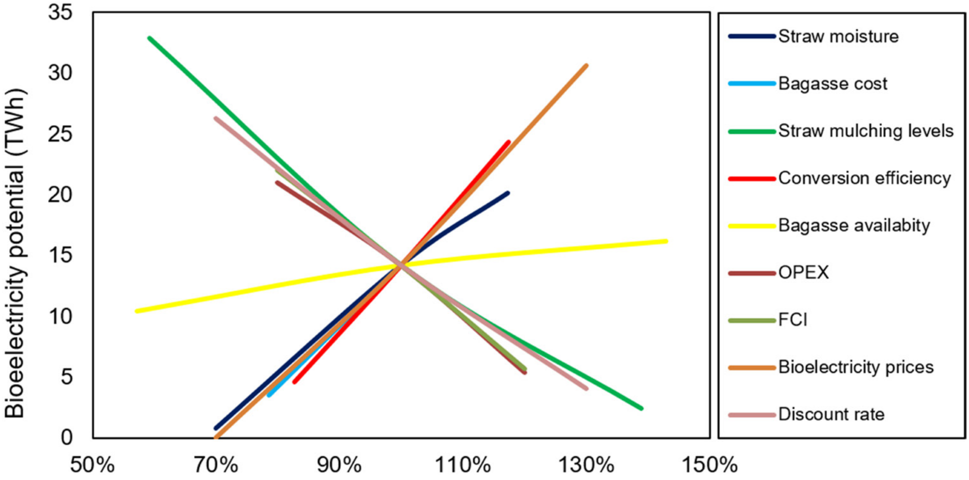

Figure 3.11: Sensitivity analysis of the optimized techno-economic potential of bioelectricity from sugarcane straw in Sao Paulo for the crop year 2012.

3.4. DISCUSSION

3.4.1. Straw recovery costs

The average straw recovery costs at mill level found in this study range from 21 to 35 US$.t^{-1}. This is in line with the range of 22 - 36 US$.t^{-1} found by Cardoso et al. [123] and with the average of 30 US$.t^{-1} observed in practice (Raízen/Shell mill, *pers. comm.* [156]). The mills with high straw supply and low costs are located in the traditional sugarcane areas characterized by suitable agro-ecological conditions. The mills with relatively high straw costs are located in the western part of the state with a lower density of sugarcane fields and/or lower agro-ecological suitability for sugarcane cultivation. These geographical constraints result in long transportation distances, increasing straw transportation costs. Despite that, the straw transportation costs usually have a lower contribution to the total recovery costs in baling systems because of the costly on-farm operations.

The straw recovery costs are highly impacted in areas with low straw availability. To reduce the straw recovery costs in those areas, the deployment of an integral harvest system instead of baling system can be more economically viable. The integral harvest system could be more appropriate for areas with low availability, as the straw is transported together with the harvested sugarcane [119]. Therefore, differentiate the straw recovery route according to straw availability of a given field could potentially improve the techno-economic feasibility of bioelectricity from sugarcane straw [106]. Moreover, we assume that each mill recovers all straw available within the collection radius of the mill and produces bioelectricity at the location of the mill. Instead, analysis at sub-regional level is required to assess potential interactions among mills in order optimize the use of straw and minimize its recovery costs.

3.4.2. Bioelectricity production costs

The average bioelectricity production costs vary from 68 to 266 US$.MWh^{-1} across the mills. However, for more than 95% of the mills, the average bioelectricity production costs range from 68 to 130 US$.MWh^{-1}. These average bioelectricity costs agree with the majority of bioelectricity prices found in the literature and regular bioelectricity auctions [16,147]. For the mills with relatively low bioelectricity costs (i.e. > 100 US$.MWh^{-1}), the feedstock, operational and FCI have about equal contributions to the total costs and very low transmission costs. These mills have generally a high electricity generating capacity, are located in the regions with high agro-ecological suitability for sugarcane cultivation, and with high availability of transmission infrastructure. On the other hand, very high bioelectricity costs are mainly the result of a low electricity generating capacity and high transmission costs associated with long distances to the distributor substations. As long connection distances highly affects the total bioelectricity costs, this has to be taken into account in the allocation planning of future power plants at the mills [65]. In parallel, investments from the energy distributors and dealers in grid infrastructure (e.g. new substations and transmission lines) are required to improve the economic feasibility of bioelectricity projects in sugarcane mills [152].

The mills with a very low electricity generating capacity are largely concentrated in the Southwest and West of São Paulo. As no decrease in the FCI is expected for the adjacent power plant system in the coming years [124], the FCI costs reduction must rely on economies of scale, increasing the electricity generating capacity by using more bagasse or gathering alternative biomass sources, such as forestry residues. The latter has yet been used as supplementary source for bioelectricity production in small sugarcane mills [164]. Therefore, the integration with other biomass chains (e.g. pulp and paper industry) close to the mills can be a strategy to improve the techno-economic potential of bioelectricity at regional level [165].

The bagasse surplus sourced from the cogeneration system in the main mill is assumed to supply the adjacent power plant to accomplish a process design consistent with the current technical stage of power plants in the sugarcane mills. Currently, it is strongly recommended to mix straw with bagasse in order to reduce the boiler corrosion due to presence of mineral impurities in the straw [101]. In the future, the adoption of biomass gasification systems may allow the use of higher rates of sugarcane straw. The bioelectricity production costs are linked with the design of the adjacent power plants (based on Seabra et al. [121]), which uses all the straw available in the mill's surroundings. Alternatively, other scenarios of straw power plant (e.g. stand-alone plants) can be spatially explicit modeled to assess whether the techno-economic potential can be improved.

3.4.3. Techno-economic potential of bioelectricity from sugarcane straw

The optimized techno-economic potential of bioelectricity from sugarcane straw is estimated at 14.2 TWh produced from more than 11 Mt of straw, which represents around 10% of the electricity consumption of the São Paulo in 2012 [166]. In 2012, approximately half of bioelectricity (7.2 TWh) was produced by the whole sugarcane industry in the same crop-year in the state of São Paulo [110]. The 37 mills that contribute to the techno-economic potential could supply more than the total amount of bioelectricity surplus in Brazil in 2012 (12.2 TWh) [120]. Compared to the environmental potential of bioelectricity from sugarcane straw in Cervi et al. [153], the techno-economic constraints reduce the bioelectricity potential by 55% in the 2012 crop-year in São Paulo. The techno-economic potential relies on the scale of the adjacent power plants modeled, which are based on the straw available given the milling capacity of the mill. However, in reality, the scale of sugarcane power plant is not fully dependent on the actual sugarcane milling capacity. This also varies according to the energy policy adopted by the company (mill), the importance of bioelectricity business in the mills' overall revenues and other local contextual factors.

The sensitivity analysis addresses the variations in many (local contextual) techno-economic parameters on the bioelectricity potential. Of the technical aspects, the variation in straw moisture content shows the largest effect on the bioelectricity potential. Hence, more than investing in a very efficient system to operate with straw, mills have to foremost assure the low moisture content of the straw recovered [100]. The bioelectricity potential is also highly sensitive for changes in the discount rate and in the bioelectricity cut-off prices. We have now assumed a variation of 30% in the bioelectricity prices. However, variations could even be much higher as part of the bioelectricity surplus is currently sold in the demand-driven free market at much higher prices [99]. If even higher bioelectricity prices are assumed, the techno-economic potential of bioelectricity from sugarcane straw is much higher.

To enable the realization of the techno-economic potential, the bioelectricity from sugarcane straw should be better exploited in periods of high demand (between April and October) when the hydropower supply is usually lower [167]. However, in practice, the mills with high potential of bioelectricity from sugarcane straw (e.g. large scale traditional mills) are still progressing towards high efficient boilers [127]. Additionally, the bioelectricity market in Brazil still requires regulatory strategies to strength the economic competitiveness [146,152]. As a positive side, straw can be stored and bioelectricity can be produced on demand, which is the main advantage compared to other renewable sources in Brazil, such as wind and solar. Moreover, electricity market projection indicates the increase of distributed generation close to the large demand centers in order to reduce large investments in long transmission systems [168]. This could be beneficial to the sugarcane industry given the location of the sugarcane mills in Brazil. Therefore, comprehending the spatial distribution of the techno-economic potential of bioelectricity from sugarcane straw could contribute in addressing the appropriate energy planning for the sugarcane mills based on their regional characteristics.

3.5. CONCLUSION

This is the first study that combines spatial datasets at different geographical scales to assess the potential and the production costs of bioelectricity from sugarcane straw. We assess the techno-economic potential of 174 operating sugarcane mills in the state of São Paulo (Brazil) for 2012 crop-year. In total, 37 mills are able to produce bioelectricity with production costs below 80 US\$.MWh^{-1}. This corresponds to a techno-economic potential of 14.2 TWh (which is almost twice as high as the bioelectricity production in 2012 in the entire state of Sao Paulo). These economically viable mills have a large electricity generating capacity and are mostly located in the Northeast of São Paulo, which is characterized by suitable agro-ecological conditions, and high density of electricity distribution network. The results could support stakeholders in local decisions at farm and mill level, and policy making at state level. It is recommended that further dedicated studies focused on local resource assessment explore the spatial variability in straw mulching levels and optimal recovery routes, and also investigate the technical specifications of the cogeneration systems in the sugarcane mills.


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Spatial modeling of techno-economic potential of biojet fuels in Brazil

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Abstract. It is expected that Brazil could play an important role in biojet fuel (BJF) production in the future due to the long experience in biofuel production and the good agro-ecological conditions. However, it is difficult to quantify the techno-economic potential of BJF because of the high spatio-temporal variability of available land, biomass yield, and infrastructure as well as the technological developments in BJF production pathways. The objective of this research is to assess the recent and future techno-economic potential of BJF production in Brazil and to identify location specific optimal combinations of biomass crops and technological conversion pathways. In total, thirteen production routes (supply chains) are assessed through the combination of various biomass crops and BJF technologies. We consider temporal land use data to identify potential land availability for biomass production. With the spatial distribution of the land availability and potential yield of biomass crops, biomass production potential and costs are calculated. The BJF production cost is calculated by taking into account the development in the technological pathways and in plant scales. We estimate the techno-economic potential by determining the minimum BJF total costs and comparing this with the range of fossil jet fuel prices. The techno-economic potential of BJF production ranges from 0 to 6.4 EJ in 2015 and between 1.2 – 7.8 EJ in 2030, depending on the reference fossil jet fuel price, which varies from 19 US$/GJ to 65 US$/GJ across the airports. The techno-economic potential consists of a diverse set of production routes. The Northeast and Southeast region of Brazil present the highest potentials with several viable production routes, whereas the remaining regions only have a few promising production routes. The maximum techno-economic potential of BJF in Brazil could meet almost half of the projected global jet fuel demand towards 2030.

Keywords. aviation; biofuels; renewable jet fuels; bioenergy potential; land availability; land use; GIS; bioenergy costs; techno-economic assessment

4.1. INTRODUCTION

With the agreement established in 2015 at COP 21 in Paris, it is expected that biofuels have a large contribution to curb greenhouse gas (GHG) emissions in Brazil in the next decade [18]. Currently, biofuels for road transportation, largely represented by sugarcane ethanol and soybean biodiesel, are the main options to reduce the fossil fuel dependence in Brazil in the coming years [169]. At a global level, biofuels for aviation, known as biojet fuels (BJF), are seen as an important emerging option to reduce the GHG emissions from the transportation sector [20,170]. Approximately 12% of the global GHG emissions of the transportation sector is caused by the aviation sector [170], and this share is expected to grow strongly towards 2050 [171]. Given its significant experience with the production of biofuels and the potentially large availability and suitability for biomass production, Brazil has great potential to develop a BJF industry and mitigate GHG emissions in the aviation sector [77].

The emission reduction target of 50% in 2050 relative to 2005 plus the carbon neutral growth from 2020 onward required by the International Air Transport Management (IATA) [20] have led to voluntary targets for BJF consumption [172]. Airline companies have committed to use BJF sourced from sustainable biomass crops [23]. However, for large scale application, it is rather difficult to quantify the potential of biomass to BJF due to uncertainties regarding land availability, the variety of biomass crops and yield variability. In addition, there are important techno-economic barriers concerning the conversion of biomass to BJF, such as the current production cost gap with fossil jet fuel, technological risks, and high capital costs related to the development of new BJF technologies [173,174].

The project “Flightpath for aviation biofuels in Brazil” provides an extensive review of the aforementioned constraints in the Brazilian context [77,78]. Furthermore, some studies assessed promising biomass feedstock for BJF production in Brazil [82,83]. However, none of them quantified the land availability that could be used for biomass production for BJF. The land availability largely determines the potential supply of biofuels [175] and its assessment is of great concern to avoid GHG emissions due to Indirect Land Use Change (ILUC) [176]. Taking into account legal restrictions and biophysical parameters, Martini et al. [80] mapped more than 3 Mha of land suitable for producing sugarcane derived jet fuel in Brazil. In that study, the spatial variability on the sugarcane yields was not considered, which could have great impact on the potential and the production costs. Murphy et al. [38] found that in the short-term, BJF may require extensive amounts of land with significant biomass production costs. The same authors [177] also mapped the potential of biomass to BJF production that could co-exist with other land use functions as an alternative to optimize the land use while reducing biomass costs. However, none of these studies analyzed the spatial variation of the biomass production costs and their effect on the overall BJF production costs.

Differently from traditional bioenergy systems (e.g. sugarcane ethanol), biomass costs may not be the principal cost component of BJF supply chains [37]. Several studies have assessed the techno-economic performance of various BJF supply chain options for Brazil [85,178–180]. These studies highlight the potential contribution of the existing traditional biofuel industry to reduce the capital intensity in BJF production. Furthermore, Alves et al. [174] show that BJF supply chains from uncommon biomass crops (e.g. macaw palm) may lead to competitive BJF production costs. However, these studies did not consider the variability in biomass yields and costs across regions and the impact on the economic viability of BJF.

Very few studies have been addressed the spatial distribution of biomass resources for assessing the techno-economic performance of BJF production. Carvalho et al. [76] carried out a resource focused assessment on production cost of different BJF supply chains in Brazil. However, the analysis is given temporally static and in a spatial aggregate level, which avoid a detailed spatio-temporal representation of the BJF cost components. De Jong et al. [87] spatially explicitly optimized the location of potential BJF plants to minimize the production costs of BJF from forestry systems in Sweden. The authors recommended the use of temporal variable information on biomass cost-supply, infrastructure, and BJF technology development to increase the accuracy of the techno-economic assessment. To date, no study has assessed the techno-economic performance of BJF supply chains by integrating spatial and temporal data of various biomass crops while taking into account the development in different BJF technologies over time.

The objective of this paper is to assess the spatio-temporal production costs of BJF supply chains (hereafter named as BJF production routes) in Brazil and to quantify the techno-economic potential of location specific optimal combinations of biomass crops and conversion pathways depending on local agro-ecological conditions. We focus on 2015 (reference year) and 2030 to address recent and short-term expected techno-economic developments in BJF production routes. Although there might be a considerable potential of BJF produced from biomass residues, this paper focuses solely on BJF production from dedicated biomass crops. The study consists of three main steps: i) selection of BJF production routes; ii) spatial assessment of land available to grow dedicated BJF biomass; iii) assessment of the techno-economic potential of the BJF production routes.

4.2. BJF PRODUCTION ROUTES

BJF production routes are composed by biomass crops and BJF conversion technologies (so-called "technological pathways" or just "BJF technologies") (figure 4.1). This study covers eight potential biomass crops from three different feedstock groups: corn, sugarcane and sweet sorghum (starch and sugar); soybean, sunflower, macaw palm and oil palm (oil crops); and eucalyptus (lignocellulosic). Brazil has ample experience with the cultivation and processing of most of these crops. In general, these biomass crops present desirable characteristics for biofuel production, compatibility with Brazilian agro-ecological conditions resulting in relatively high biomass yields, and are often produced in proximity to the main consumer spots. Furthermore, for most of these crops there are spatially explicit and cost data available. The compliance of the biomass crops with these selection criteria is provided in the supplementary material – SM 4.1 and the main characteristics of the biomass crops are described in table 4.1.

Table 4.1: Key characteristics of the selected biomass crops for BJF in Brazil.

Biomass crop	Current production (2015)	Average biomass yield (2015)	Typical feedstock yield	Regions with highest agro-ecological suitability in Brazil	Common biofuel application in Brazil	Sources
Corn	85 Mt of grain	5.5 t/ha	660 kg of starches/t of grain	South, Center-West and Northeast	1G Ethanol	[117,181]
Sugarcane	750 Mt of stalks	74 t /ha	145 kg of sugars/t	Southeast, Center-West and Northeast	1G 2G Ethanol	[108,182]
Sweet sorghum*	unknown	-	120 kg of sugars/t	Northeast and Center-West	1G Ethanol	[182,183]
Eucalyptus	130 Mt of wood	30 t/ha	1:1	South and Southeast	2G Ethanol (not currently employed)	[184,185]
Soybean	97 Mt of grain	3 t/ha	200 kg of oil/t of grain	South and Center-West	Biodiesel	[117,186]
Sunflower	0.15 Mt of grain	1.3 t/ha	450kg of oil/t of grain	South and Center-West	Biodiesel	[117,186]
Oil palm	1.6 Mt of FFB	11 t/ha	220 kg of oil/t of FFB	North and Northeast coast	Biodiesel (1%-3% of the national production in 2018)	[117,186,187]
Macaw palm*	unknown	-	220 kg of oil/t of FFB	Center-West	Biodiesel (not currently employed)	[188]

* Sweet sorghum and macaw palm are emerging potential biomass options for bioenergy and are not currently produced at large scale. Thus far, no national official survey has quantified the annual production of these biomass crops in Brazil.

Although there are many potential technological pathways for converting biomass to BJF, we select those currently certified by the American Society for Testing and Materials (ASTM) [189], accounting for their advanced fuel and technology readiness level (FRL and TRL). The technologies produce drop-in BJF with blending levels with fossil jet fuel varying from 10 to 50% depending on the technological pathway. Currently, four technological pathways are already certified by ASTM: HEFA (hydro-processed esters and fatty acids), FT (Fischer-Tropsch), DSHC (direct sugars to hydrocarbons) and ATJ (alcohol to jet). Additionally, we also select HTL (hydrothermal liquefaction) because of the high conversion yield and the promising techno-economic results found by de Jong et al. [90]. All these technological pathways are owned by different companies and are in various development stages. In supplementary material – SM 4.1, we briefly describe the technical characteristics of the selected technological pathways.

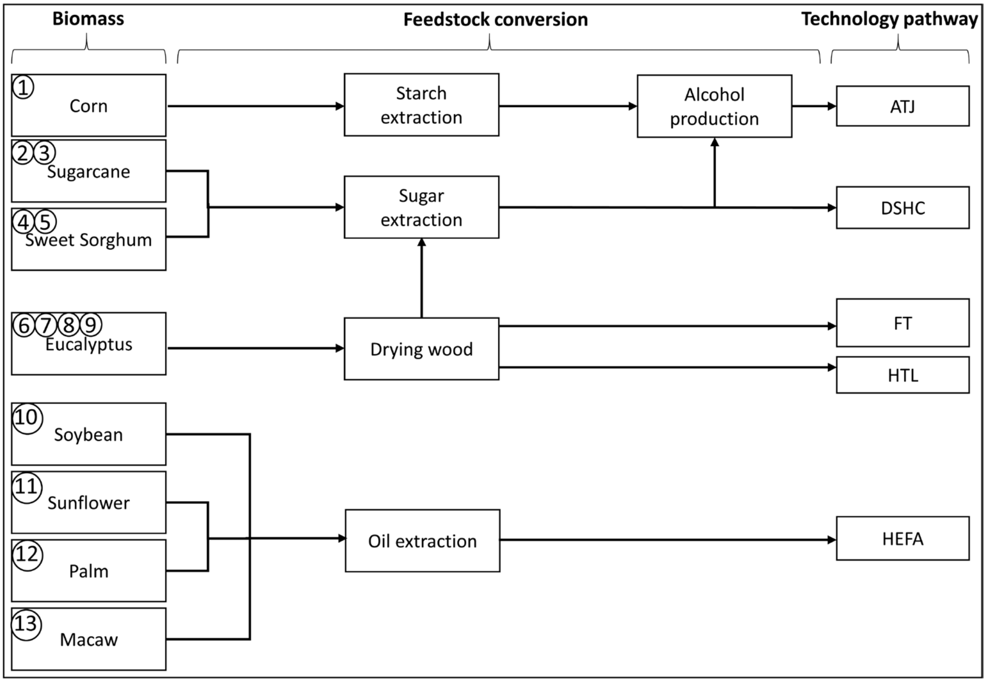

Figure 4.1: BJF production routes: 1) BJF from corn ethanol via ATJ (C_ATJ); 2) BJF from 1G sugarcane ethanol via ATJ (SC_ATJ); 3) BJF from sugarcane sugars via DSHC (SC_DSHC); 4) BJF from sweet sorghum ethanol via ATJ (SS_ATJ); 5) BJF from sweet sorghum sugars via DSHC (SS_DSHC); 6) BJF from 2G eucalyptus ethanol via ATJ (EC_ATJ); 7) BJF from 2G eucalyptus sugars via DSHC (EC_DSHC); 8) BJF from eucalyptus via FT (EC_FT); 9) BJF from eucalyptus via HTL (EC_HTL); 10) BJF from soybean oil via HEFA (SB_HEFA); 11) BJF from sunflower oil via HEFA (SF_HEFA); 12) BJF from palm oil via HEFA (PO_HEFA); 13) BJF from macaw oil via HEFA (MP_HEFA).

4.3. METHODS

We assess recent and future techno-economic potential of BJF production routes in Brazil taking into account the spatio-temporal developments in biomass potential and technical developments in the BJF production routes. The techno-economic assessment focuses on 2015 and 2030 time horizons, and analyzes the development in potential land availability for biomass for BJF production, given the development in other land use functions, and the spatial variation in agro-ecological suitability for the cultivation of different biomass crops. The resulting spatial distribution of biomass potential is used to calculate the biomass production costs (i.e. farm-gate plus transportation costs). The BJF production costs are calculated considering an integrated greenfield feedstock production plant with a BJF biorefinery which converts the raw biomass to BJF. The BJF transportation costs are calculated assuming the shortest route from the BJF plant to the nearest airport in Brazil. Finally, the techno-economic potential is determined by selecting the location specific minimum BJF total costs (BJF production cost plus the BJF transportation cost) across the production routes and compare this to the location specific fossil jet fuel price range. All economic values are expressed in 2015 US dollars, and the exchange rate assumed are 1 USD = 3 BRL and 1 USD = 0.9 EUR.

4.3.1. Land availability for BJF production

The assessment on the development of land availability over time is based on the study of Van der Hilst et al. [59]. In that study, scenarios on the development of sugarcane ethanol expansion and the land demand for food, feed and fiber in Brazil were modelled spatially explicitly. As a result, annual land use maps at 5 km grid cell resolution were generated for the period 2012 to 2030.

In this study, we make use of a reference scenario including an increase in ethanol production, see [59]. We assume that all land not in use for other land use functions (i.e. cropland, pasture, rangeland, sugarcane, forest plantations, natural forest, urban areas, and conservation areas) are residual land that could potentially be used for biomass production for BJF. Hence, abandoned agricultural land (e.g. bare fallow), and shrubs and grasslands are the remaining land use types assumed to be potentially available for BJF production. These land use classes expand or contract over time as consequence of the development in other land use functions [59].

4.3.2. Yield developments

Biomass yield levels (*Y*) are calculated by combining the land availability (*A*) with their respective agro-ecological suitability (*S*) for a specific biomass crop (*b*), and the maximum attainable yield (*M*) (Equation 4.1). The land use maps of [59] for the year 2015 and 2030 are converted to binary land availability maps (*A*), in which 0 refers to “not available land” and 1 to “available land” for biomass cultivation for BJF production.

Equation 4.1

$$Y_{b,a,y} = A_{a,y} \times S_{b,a} \times M_{b,y}$$

Item	Description	Unit
Y_{bya}	Yield of biomass *b* at location *a* in year *y*	t/ha
A_{ay}	Residual land availability at location *a* in year *y*	0, 1
S_{ba}	Agro-ecological suitability for biomass *b* at location *a*	%
M_{by}	Maximum attainable yield of biomass *b* in year *y*	t/ha

The spatially explicit agro-ecological suitability (*S*) data for sugarcane, sweet sorghum, corn, soybean, sunflower and palm are acquired from IIASA - GAEZ (International Institute for Applied Systems Analysis - Global Agro-Ecological Zones). This data refers to a baseline estimation based on historical climate data from 1960 to 1990 (see supplementary material – SM 4.2 and [190]). Due to the absence of specific agro-ecological suitability data for eucalyptus and macaw palm, their suitability levels are estimated using species distribution modeling (SDM). Hence, Maxent model is used to measure the probability of presence of a given species based on environmental variables (e.g. climate, slope, soil) and the location of species occurrence data [191] (supplementary material – SM 4.3). The model output gives a probability range of 0 to 1, which indicates the suitability levels [192]. Also, other studies used SDM to assess the suitability for the cultivation of eucalyptus and macaw palm in Brazil and South America [193,194]. Lastly, the maximum attainable yield (*M*) of each biomass crop is presented in table 4.2 from various sources, and their respective historical trends of annual yield growth rate (see [59]) used to calculated yield levels in 2030.

Table 4.2: Maximum attainable yield for 2015 and the average annual yield increase up to 2030 for each biomass crop.

Biomass	2015 maximum att. yield (t/ha/y)	Source	Energy values (GJ/t) [a]	Annual yield growth rate (%/y) [b]
Corn grain	12	[117]	18.5	1.4
Sugarcane stalks	130	[108]	19.6	0.8
Sweet sorghum stalks	104	[183]	19.6	1.4
Eucalyptus wood	40	[195]	18.4	1.4
Soybean grain	4.2	[117]	23.5	0.9
Sunflower grain	3	[117]	26.4	0.9
Palm FFB	25	[196]	24	0.9
Macaw FFB	25.5	[197]	24	0.9

[a] Biomass energy content based on BioGrace [198].
[b] Annual yield increase based on [59,117]

4.3.3. Biomass production costs

The biomass production costs are calculated by summing the biomass farm-gate costs and biomass transportation costs (Equation 4.2). The biomass production costs vary over space (*a*) and time (*y*) due to spatio-temporal variations in biomass yield and transportation costs.

Equation 4.2

$$BC_{b,a,y} = FC_{b,a,y} + TC_{b,a,y}$$

Item	Description	Unit
BC_{ay}	Biomass production cost of biomass *b* at location *a* in year *y*	US$/t
FC_{ay}	Biomass farm-gate cost of biomass *b* at location *a* in year *y*	US$/t
TC_{ay}	Biomass transportation cost of biomass *b* at location *a* in year *y*	US$/t

The biomass farm-gate costs comprise expenses for land clearing (i.e. from grasslands or shrublands to cropland; no land clearing is required for abandoned agricultural land), land costs, soil preparation, agricultural inputs (fertilizers and agrochemicals), crop management, harvest and storage (for grains) (supplementary material – SM 4.4). The farm-gate costs include fixed costs per hectare (i.e. cultivation management practices, e.g. soil preparation, planting and herbicides) and variable costs per tonne of biomass (e.g. fertilizer application and harvest costs) (equation 4.3) [182]. To allow for a cost comparison between annual crops (e.g. soybean, corn) and perennial crops (e.g. macaw, eucalyptus), the Net Present Value (NPV) is calculated of all cost items and biomass yields throughout the biomass cycle (i.e. lifetime plantation). Towards 2030, the biomass farm-gate costs reduce as function of projected yield increase. In this study, the available land is assumed to be new agricultural areas. Hence, we use cost data from biomass production systems representative for agricultural expansion areas in Brazil (supplementary material – SM 4.4).

Equation 4.3
$$FC_{b,a,y} = \frac{\sum_{t=1}^{t=x} \frac{\sum_{n=1}^{N}\left(O_{n,b,t} \times C_{n,b,t}\right) + \sum_{m=1}^{M}\left(O_{m,b,t} \times C_{m,b,t} \times Y_{b,a,t,y}\right)}{(1+r)^{t}}}{\sum_{t=1}^{t=x} \frac{Y_{b,a,t,y}}{(1+r)^{t}}}$$

Item	Description	Unit
$FC_{b,a,y}$	Biomass farm-gate cost of biomass *b* at location *a* in year *y*	US$/t
$O_{n,b,t}$	Occurrence of biomass fixed cost *n* of biomass *b* in lifetime *t*	#
$C_{n,b,t}$	Cost of biomass fixed cost *n* of biomass *b* in lifetime *t*	US$/ha
$O_{m,b,t}$	Occurrence of biomass variable cost *m* of biomass *b* in lifetime *t*	#
$C_{m,b,t}$	Cost of biomass variable cost *m* of biomass *b* in lifetime *t*	US$/t
$Y_{b,a,t,y}$	Yield of biomass *b* at location *a* in lifetime *t* and year *y*	t/ha
r	Annuity rate	%
t	Annuity period (lifetime plantation)	years

The biomass transportation costs include truck depreciation costs, diesel, lubricants and labor, which are directly related to the distance from the field to the BJF plant [45]. As we do not determine the location of the potential BJF plant, the transportation distance is based on the relative biomass density (*D*) within the gathering radius around each grid cell. This gathering radius is defined by the area required to support the input capacity (*I*) of the BJF plant (i.e. production route *p*) (see table 4.3). The average transportation distance represents 2/3 of the gathering radius [199]. The biomass transportation cost per tonne-km (*C*) of 0.092 refers to secondary roads (i.e. mix of paved and non-paved roads) in good conditions [42], and it is assumed to be equal for all the biomass crops in 2015 and 2030. Equation 4.4 describes the biomass transportation costs calculation.

Equation 4.4

$$TC_{p,b,a,y} = C \times \frac{2}{3} \times I_{p,y}^{0.5} \times (Y_{b,a,y} \times D_{b,a,y})^{-0.5}$$

Item	Description	Unit
TC_{pbay}	Biomass transportation cost of production route *p* and biomass *b* at location *a* in year *y*	US$/t
C	Biomass unit transportation cost	US$/t km
I_{py}	Input capacity of production route *p* in year *y*	t
Y_{bay}	Yield of biomass *b* at location *a* in year *y*	t/ha
D_{bay}	Density of biomass *b* within the radius at location *a* in year *y*	%

4.3.4. Biojet fuel production costs

The BJF production costs assessment is based on de Jong et al. [90] who assessed the economic feasibility of BJF plants in different development stages (i.e. pioneer plant and *n*th plant) and for various co-production strategies (e.g. greenfield, retro-fitting). As our study exclusively deals with "new agricultural land" for BJF production, we assess only hypothetical greenfield BJF plants. The BJF plants convert raw biomass into feedstock and then to BJF. Hence, the production routes entail a BJF feedstock production plant (i.e. central upstream facility) and a BJF biorefinery (i.e. downstream facility) (figure 4.2). To address the current TRL, the assessment in 2015 comprises technological pathways in BJF pioneer biorefineries. Each technological pathway has a different cost growth factor that estimates the capital costs in BJF pioneer biorefineries considering the risks and shortfalls of building the "first of kind BJF biorefinery" (table 4.4) [90,200,201]. Hence, all the BJF biorefineries have a higher capital intensity in 2015 compared to 2030. The cost growth factor is not applied in most of the feedstock production plant as these technologies are already mature, except for the 2G sugar/ethanol plant (table 4.3). In 2030, the BJF biorefineries are assessed as *n*th biorefineries, i.e. assuming that all the technologies would be available at commercial scale with similar TRL.

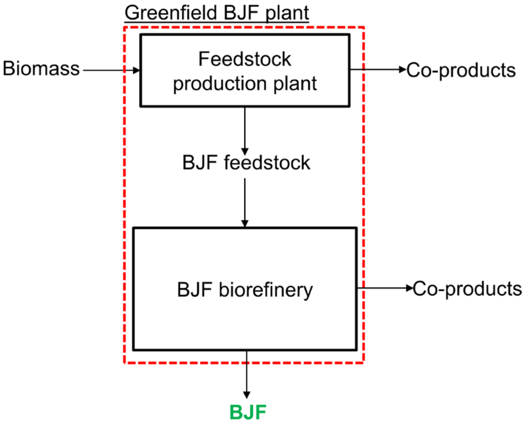

Figure 4.2. Schematic representation of the greenfield BJF plant

The BJF plants are assumed to operate at full capacity (i.e. process the entire input capacity), whereby all the feedstock produced is dedicated to supply the BJF biorefinery. Additionally, all the BJF plants have an operating time range of 300 - 330 days per year with constant BJF feedstock supply (e.g. ethanol and vegetable oil). The assumed input capacities of the BJF plants in 2015 are based on either typical scales of existing feedstock production plants in Brazil or approximations from simulated bioenergy plants in Brazil (see each footnote in table 4.3). Some of these scales could considered to be very optimistic for a new BJF plant. However, these scales are not necessarily high considering the current bioenergy industry in Brazil (e.g. sugarcane ethanol and biodiesel soybean plants). Hence, we assess the techno-economic potential of greenfield BJF plants within the national bioenergy context. The greenfield BJF plants are projected to increase their input capacities towards 2030 driven by technological development, biomass yield and the introduction of BJF in the market [202] (see the details for each production route in table 4.3).

4.3.4.1. Biomass to BJF conversion

The conversion of raw biomass into BJF is done in two steps: the conversion of biomass to dedicated feedstock and feedstock to BJF. The latter consists of the distillation fraction into hydrocarbon products (e.g. green diesel, BJF). The amount of BJF output depends on the downstream characteristics of the final fractioning step, which is to some extent determined by the demand of a given hydrocarbon fuel [203]. In this study, we assume BJF as the main hydrocarbon output product, and therefore a maximum BJF output per *tonne* of feedstock input remains constant for both periods (table 4.4). The developments of biomass to BJF conversion over time are exclusively driven by improvements in the upstream conversion of biomass to dedicated feedstock (table 4.3).

Table 4.3: Biomass input capacity of the BJF feedstock production plant, pre-processing steps required (table footnotes) to convert raw biomass into dedicated feedstock for BJF production, the feedstock yield per unit of biomass input and their main co-products:

Production routes ID	Raw biomass input capacity (Mt/year)		Input biomass	Feedstock conversion yield (t of feedstock/t of biomass)			FCI (US$/t input)		OPEX (US$/t input/yr)	Source
	2015	2030		2015	2030	Source	2015	2030	2015 - 2030	
C_ATJ [a]	0.42	0.65	Corn grain	0.33	0.37	[204]	445	390	143	[205]
SC_DSHC [b]	4	5.5	Sugarcane stalks	0.15	0.16	[182]	63	57	14	[182]
SC_ATJ [b]	4	5.5	Sugarcane stalks	0.06	0.07	[182]	63	57	14	[182]
SS_DSHC [c]	4	5.5	Sweet sorghum stalks	0.12	0.14	[182]	63	57	14	[182]
SS_ATJ [c]	4	5.5	Sweet sorghum stalks	0.04	0.05	[182]	63	57	14	[182]
EC_DSHC [d]	0.72	1.5	Wood chips	0.45	0.5	[182]	1079	459	251 - 133	[4]
EC_ATJ [d]	0.72	1.5	Wood chips	0.22	0.29	[182]	1079	459	251 - 133	[4]
EC_FT [e]	0.6	1	Wood chips	1	1	-	52	44	5	[206]
EC_HTL [e]	0.35	0.8	Wood chips	1	1	-	60	55	5	[206]
SB_HEFA [f]	0.66	0.95	Soybean grain	0.19	0.19	[207]	185	166	20	[208]
SF_HEFA [g]	0.2	0.73	Sunflower grain	0.43	0.43	[207]	266	180	25	[208]
PO_HEFA [h]	0.65	1	FFB	0.25	0.25	[207]	94	83	13	[196]
MP_HEFA [i]	0.35	0.7	FFB	0.25	0.25	[197]	113	92	13	[196]

[a] The input capacity of 2015 is assumed a bit lower than the first greenfield corn ethanol plant established in 2016 in Brazil [209]. From 1999 to 2014, the scale of corn ethanol plants in US increased by 6%/yr on average [210]. In our study, we assume a moderate increase of 3%/yr, as the increase of corn ethanol in Brazil is more linked with the flexibility of sugarcane mills in producing corn ethanol during the sugarcane off-season (through corn grain storage), rather than greenfields corn ethanol plants [25]. The major upstream processes of the corn ethanol plant are grinding, cooking, liquefaction and 1G ethanol production. The corn ethanol cost is calculated by accounting the revenues of DDGS (Dried Distillers Grain Soluble) co-product.

[b] A medium to high input capacity of a current typical sugarcane mill in Brazil is assumed for 2015 [182]. In 2030, the scale moves to 5.5 million tonnes input (i.e. 37.5%), highly affected by the increasing biomass yield (acc. rate of 12%) [182]. We assume that the scale of sugarcane mills do not increase beyond 5.5 million tonnes because studies have shown the ethanol expansion in Brazil is mainly facilitated by decentralized sugarcane mills [211]. The sucrose (and other fermentable sugars) production are fully dedicated for BJF production in both technologies: ethanol in ATJ and sugars in DSHC. The major upstream processes are the sugarcane milling, juice extraction and 1G ethanol production (only for ATJ plants). As co-product, the sugarcane mill cogenerates bioelectricity from sugarcane bagasse, which is used in the sugar/ethanol cost calculation accounting for the revenues from bioelectricity sales.

[c] For sweet sorghum, the same scale, configuration and feedstock cost calculation method as for a typical sugarcane

mill is assumed [182]. As co-product, bioelectricity is produced from bagasse.

[d] The 2G ethanol plant from eucalyptus is considered as pioneer plant as "none of kind" is currently operating in Brazil. Hence, a cost growth factor of 0.53 in the feedstock production plant is assumed [212]. The input capacity of eucalyptus 2G plant in 2015 is based on Jonker et al [45]. The 2G ethanol as BJF feedstock is selected due to high potential for Brazil and the high availability of techno-economic data. The woody residues (lignin) are assumed as feedstock to cover bioelectricity demand of the plant and the surpluses are dispatched to the national grid [182]. The progress on scale is less optimistic than the 2030 projected by Jonker et al. [45] for dedicated 2G ethanol plants. As ethanol is not our main product, a conservative 1.5 Mt of wood input is assumed aligned with the expected development of the pulp and paper industry [213]. Therefore, biomass yield development and learning effects on both biomass pre-treatment and ATJ technology are the main drivers for increasing the scale towards 2030. The major upstream processes are the biomass pretreatment, hydrolysis and 2G ethanol production (only for ATJ plant).

[e] In the feedstock production plant, the eucalyptus wood is grinded, chopped and dried [214]. All the forthcoming processes belongs to the FT and HTL biorefineries (e.g. gasification, bio-crude production). The 2015 scale for both FT and HTL are based on approximations of dedicated studies [214–216]. By 2030, HTL may achieve a scale of 800 kt biomass input, close to the maximum capacity projected by de Jong et al. [5] while for the FT process, 1 Mt of dry wood is assumed according to the projections developed in the UK [217]. No co-product is considered in the feedstock processing plant.

[f] A scale of (2200 t/day) is assumed, equal to the capacity of 20% of the soybean pressing plants in Brazil. A 2.3%/yr historical progress rate of soybean processing plants is verified at [218] and extrapolated to 2030. The learning effects is not considered for HEFA, which is already a mature technology [173]. The major upstream processes are the grain pressing, cleaning and oil extraction. To calculate the soybean oil cost, the soybean meal is considered as co-product.

[g] The maximum input capacity of the largest sunflower oil plant in Brazil (i.e. operating with a daily input capacity of 600t of grain/day in 11 months) is assumed for 2015 [219]. In the company's projection, the insertion of sunflower oil in the biodiesel industry shall be higher, thereby more than doubling the current scale. In both soybean and sunflower, we consider the similar upstream process. In addition, sunflower meal co-product is considered at half (175 US$/t) of soybean meal prices due to lower protein content.

[h] A typical scale for palm fruit processing plants in Brazil is assumed based on the study of Andrade [220]. In Southeast Asia, the capacity of palm oil mills increased by 15-20% in line with the trends of the palm oil industry [221]. In addition, it is expected that palm oil will contribute 8% to the Brazilian biodiesel production in 2030 [26]. Based on these drivers, we assume that the scale of palm oil processing plants will increase to 1 Mt of FFB by 2030, similar to the largest Biopalma greenfield plant (to be built in the coming years in Pará/Brazil) [222]. The major upstream processes are the fruit sterilization and pressing, and palm oil extraction. The kernel press-cake is used for animal feed [196], whereas the kernel oil co-product is used by the food industry [223].

[i] For macaw palm, the same industrial process and co products as for oil palm are assumed [85]. To the best of our knowledge, no large scale macaw oil extraction plant is currently operating in Brazil nor anywhere else in the world. Hence, we assume a hypothetical input capacity half of the palm oil plant scale in 2015. This represents the current medium size palm oil plants in Brazil [220]. We assume the scale will double towards 2030, due to expected investments in R&D for macaw palm in the coming years [188].

4.3.4.2. BJF production costs calculation

The BJF production costs are calculated using the Levelized Cost of Energy (LCOE). First, we calculate the feedstock costs based on the Fixed Capital Investment (FCI; i.e. all the initial installation costs plus the working capital to start up the plant), operational expenditures (OPEX; annual costs for industrial maintenance, labor and utilities) (see footnotes of table 4.3) and biomass costs (section 4.3.3). The revenues from co-products (e.g. soybean meal, DDGS) are accounted for by applying economic allocation (i.e. based on feedstock market prices) (see footnotes of table 4.3) (for the market prices assumed, supplementary material – SM 4.5). Secondly, we calculate the BJF production cost at the BJF biorefinery gate (equation 4.5), which comprises the FCI (i.e. all the initial installation costs plus the working capital to start up BJF biorefinery) and the OPEX (e.g. maintenance, labor, electricity, yeasts, hydrogen supply) (table 4.4). As the outputs of the BJF biorefinery are hydrocarbons (table 4.4), we simplify the BJF production costs calculation using mass allocation method for all the production routes, except for FT technology that also yields electricity surplus, thereby accounting revenues from electricity sales. In the BJF production cost calculation, important economic assumptions (e.g. discount rate, project finance) are adapted to the reality of bioenergy projects in Brazil (supplementary material – SM 4.5).

Equation 4.5

$$BJFC_{B,P,y} = \frac{\sum_{t=1}^{n} (I_{B,P,y} + M_{B,P,y} + FC_{B,P,y} - Rev_{B,P,y}) \times (1+r)^{-t}}{\sum_{t=1}^{n} Output_{B,P,y} \times (1+r)^{-t}}$$

Item	Description	Unit
$BJFC_{BPy}$	BJF costs of Biorefinery *B* in production route *P* in year *y*	US$.t^{-1}
I_{BPy}	FCI of Biorefinery *B* in production route *P* in year *y*	US$
M_{BPy}	OPEX of Biorefinery *B* in production route *P* in year *y*	US$
FC_{BPy}	Feedstocks costs of Biorefinery *B* in production route *P* in year *y*	US$
Rev_{BPy}	Non-hydrocarbon revenues of Biorefinery *B* in production route *P* in year *y*	US$
$Output_{Bpy}$	Hydrocarbon outputs of Biorefinery *B* in production route *P* in year *y*	t
t	Plant lifetime	year
r	Discount rate	%

The FCI and OPEX for the BJF biorefinery used as economic input data are mostly sourced from de Jong et al. [90], Diederichs [206] and Diederichs et al. [215] (table 4.4). These input cost data are rescaled to the input capacity of the BJF biorefinery by using a general scale factor of 0.7. Moreover, the Brazilian inflation index (IGP-DI) [154] is employed to standardize all the outdated costs to 2015 year (supplementary material – SM 4.5).

Table 4.4: Conversion yield of and co products of BJF production and Input capacity, FCI and OPEX of the BJF biorefineries:

ID	BJF input capacity (kt of feedstock)[a]		Conversion yield (t BJF/t feed.) [b]		Cost growth factors (pioneer biorefineries)	FCI [d] (US$/t)		OPEX [d] (US$/t)		Sources	Co-products[e]
	2015	2030	2015/ 2030	Source		2015	2030	2015	2030		
C_ATJ [f]	139	241	0.523	[178]	0.42	589	210	122	51	[90]	D
SC_DSHC [g]	600	913	0.136	[178]	0.42	602	387	41	30	[90,206,215]	D, N
SC_ATJ [f]	252	390	0.523	[178]	0.73	493	181	122	51	[90,206,215]	D
SS_DSHC [g]	500	770	0.136	[178]	0.42	636	408	41	30	[90]	D, N
SS_ATJ [f]	189	303	0.523	[178]	0.73	537	196	122	51	[90]	D
EC_DSHC [g]	324	750	0.136	[178]	0.42	724	411	41	30	[90,206,215]	D, N
EC_ATJ [f]	164	437	0.523	[178]	0.73	560	175	122	51	[90,206,215]	D
EC_FT [h]	600	1000	0.151	[174]	0.47	2061	831	68	30	[90,206,215]	N, E
EC_HTL [i]	350	800	0.15	[216]	0.40	2704	844	263	91	[90,216]	D, G
SB_HEFA [j]	129	185	0.494	[224]	0.86	1659	1279	177	152	[90,206,215]	D, N
SF_HEFA [j]	87	317	0.494	[224]	0.86	1866	1088	177	152	[90,206,215]	D, N
PO_HEFA [j]	162	250	0.494	[224]	0.86	1547	1169	177	152	[90,206,215]	D, N
MP_HEFA [j]	87	175	0.494	[224]	0.86	1863	1301	177	152	[90,206,215]	D, N

[a] The input capacities of the BJF biorefineries are equal to the total feedstock output from the feedstock production plants.

[b] Maximum BJF distillation (i.e. t of BJF/t of feed input) is in line with the literature, and is assumed to remain constant over time.

[c] Cost growth factors of the BJF technological pathways. Sourced from the techno-economic assessment of de Jong et al. [90].

[d] The cost growth factors are only applied to the FCI and OPEX of the BJF pioneer biorefineries.

[e] Co-products from the BJF conversion plant: D – Diesel; N – Naphtha; E - Electricity; G – Gasoline.

[f] Main downstream processes: Dehydration, oligomerization and hydrogenation (off-site hydrogen supply) [90].

[g] Main downstream processes: Separation, hydrocracking and fermentation. Off-site hydrogen supply is assumed [90].

[h] Main downstream processes: syngas production, gas cleaning, upgrading and separation. In this design, the hydrogen is produced on-site with a hydrocracker recovery plant [206].

[i] Main downstream processes: biocrude production and upgrading. The hydrogen is produced on-site through steam reform [90].

[j] Main downstream processes: hydrotreating, hydrocracking and separation. Off-site hydrogen supply is assumed [90].

4.3.5. Biojet fuel transportation cost

Currently, the jet fuel transportation in Brazil is predominantly done by trucks, as the pipelines from oil refineries are only connected to the major international airports in São Paulo and Rio de Janeiro. To standardize the assessment of the BJF transportation costs, we assume that the BJF transportation is entirely deployed by trucks, from the BJF facility to the nearest airport, where a blending terminal is located.

In a GIS environment, we calculate the least-cost distance from each biomass grid cell to the nearest existing airport that currently have jet fuel storage terminals (supplementary material – SM 4.6). The distance is multiplied by the unit BJF transportation cost of the two road classes: primary roads in good conditions (road network) (supplementary material – SM 4.6) and secondary roads in poor conditions (i.e. all the areas that have no intersection with road network) (table 4.5). For 2030, we add the planned and under construction road network while the airports we assume to be the same, as no relevant airport is planned to be built in the next years. Instead, it is expected that current small airports increase their departures due to the upscaling of regional aviation in Brazil [225].

Table 4.5: Road transportation characteristics and BJF transportation cost

Road type	BJF transportation cost (US$/t km) [c]
Primary roads [a]	0.054
Dirty roads [b]	0.22

[a] Paved highways at national or regional scale.
[b] Local roads in poor conditions and segments with gravel road.
[c] [42,87]

4.3.6. Techno-economic potential assessment

The techno-economic potential is defined by the minimum BJF total cost (i.e. lowest BJF total cost at the airport) for each grid cell across the production routes in 2015 and 2030. This criterion also determines which production route achieved the minimum BJF total cost for each grid cell. The minimum BJF total cost is compared to the range of current fossil jet fuel prices at the airports in Brazil (19 – 65 US$/GJ) [226] to assess the techno-economic potential. In reality, these jet fuel prices also contain other components (e.g. profits, income and state taxes). However, these are not accounted for the BJF total cost calculation due to high uncertainty of local contextual factors and limited data availability. Finally, for each grid cell we assess if multiple production routes can achieve viable BJF total costs compared to the fossil jet fuel price of the nearest airport. Therefore, we assess the range of production routes that could potentially achieve BJF total costs lower than the fossil price counterpart.

4.3.6.1. Sensitivity analysis of techno-economic potential

A sensitivity analysis is carried out for assessing the uncertainty of the techno-economic potential in three different scenarios. In the first scenario, we exclude MP_HEFA and EC_HTL production routes as they represent the most uncertain biomass and technological pathway, respectively. Currently, macaw palm is not produced on a large scale, there is limited experience in cropping it as monoculture, and it has not been used as an energy crop [227]. These factors make its successful deployment far more uncertain than all other biomass crops considered in this paper. With regard to the selected technological pathway, HTL has the lowest TRL with only two pilot plants currently available in the world, whereas many of the others (e.g. HEFA, ATJ) are either already deployed or near to market deployment [173]. The second scenario assesses the effect of using current biomass market prices on the techno-economic potential of BJF (see the biomass market prices in the supplementary material – SM 4.5). Although the objective of this study is to modeling biomass and BJF production costs in integrated supply chains, it is likely that farmers (i.e. biomass producers) will sell their biomass to the highest bidder, and thus the production costs used may be too optimistic. In the third scenario, we assume a conservative approach with no biomass yield growth towards 2030. This scenario takes into account the uncertainty in projecting biomass yield developments, which can be largely affected by climate effects, land quality and management factors [159].

4.4. RESULTS

4.4.1. Biomass potential and costs

Due to the increase in land demand for other functions (food, feed and fiber), the land availability for biomass cultivation for BJF decreases from 121.5 Mha in 2015 to 108.1 Mha in 2030. However, due to the projected yield increase of the selected biomass crops, biomass potentials increase and biomass production costs generally decrease towards 2030 (figure 4.3). The biomass costs in 2030 are on average 4% lower than in 2015. Especially, the annual crops (i.e. corn, soybean and sunflower) present significant biomass cost reduction in the future (figure 4.4) with high potentials and relatively low production costs at the border of the North[2] and Northeast regions (figure 4.4). The soybean and sunflower supply potential increases very little up to 2030, whereas the contraction of available land does not constrain the corn supply potential in 2030 (figure 4.3). The eucalyptus potential has a little cost-supply variation between 2015 and 2030. In this case, there is a trade-off between the reduction in land availability, which reduces the amount of suitable land for eucalyptus and the transportation costs, and the increasing eucalyptus yield, which reduces the farm-gate costs. Similarly, for sugarcane the agro-ecological suitable land is projected to be already occupied by sugarcane for conventional ethanol production for road transportation by 2030. Hence, sugarcane cultivation for BJF at the available less suitable land results in higher costs in 2030.

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[2] The spatial distribution of the results normally refers to the administrative division of Brazilian macro-regions and states. For a clearer comprehension (see supplementary material – SM 4.7).

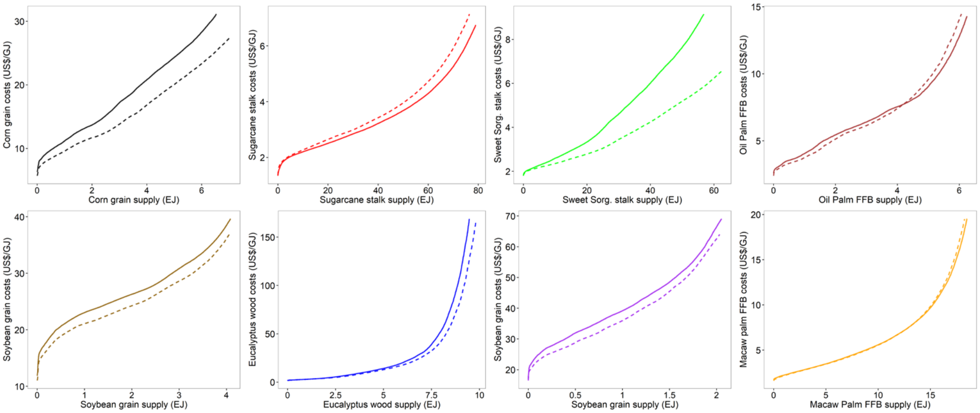


Figure 4.3: Biomass cost-supply curves of corn, sugarcane, sweet sorghum, oil palm, soybean, eucalyptus, sunflower and macaw palm projected to be cultivated on available land for BJF production in 2015 (solid line) and 2030 (dashed line).

The potential location for low cost sugarcane production remains located in the Southeast region; while those of eucalyptus can be found in areas from the South to the Northeast (figure 4.4). The main advantage of sweet sorghum is the good agro-ecological conditions for growing on marginal lands in the North of Minas Gerais and South of Bahia (figure 4.4). In these regions, sweet sorghum has competitive farm-gate costs compared to the sugarcane in 2030. The macaw palm and oil palm are able to grow over highly suitable areas in the Cerrado (Savannah) and Amazon biomes, respectively (figure 4.4). Their cost-supply curves present the narrowest variation over time of the biomass crops assessed. If no major on-farm improvement is introduced, the production costs for these palm trees can be higher in the coming years as the dynamics of land availability are projected to negatively affect the suitable areas of these perennial crops.

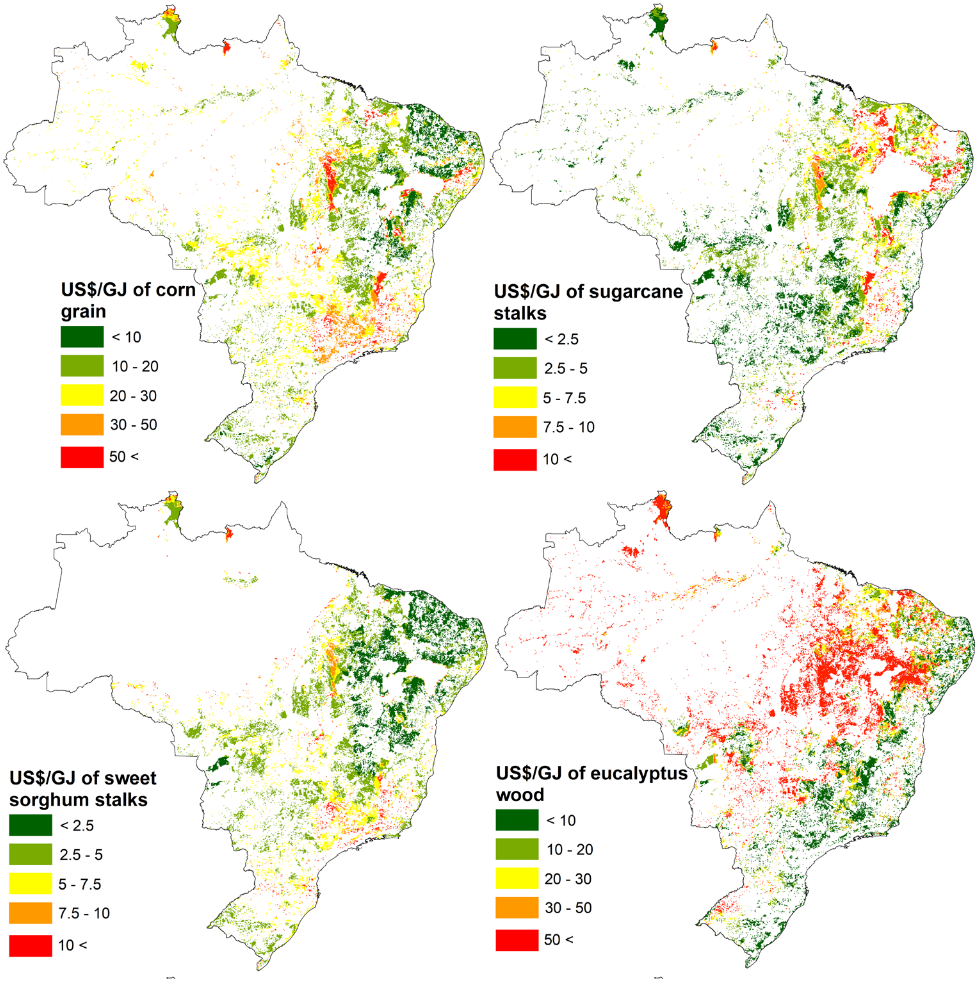
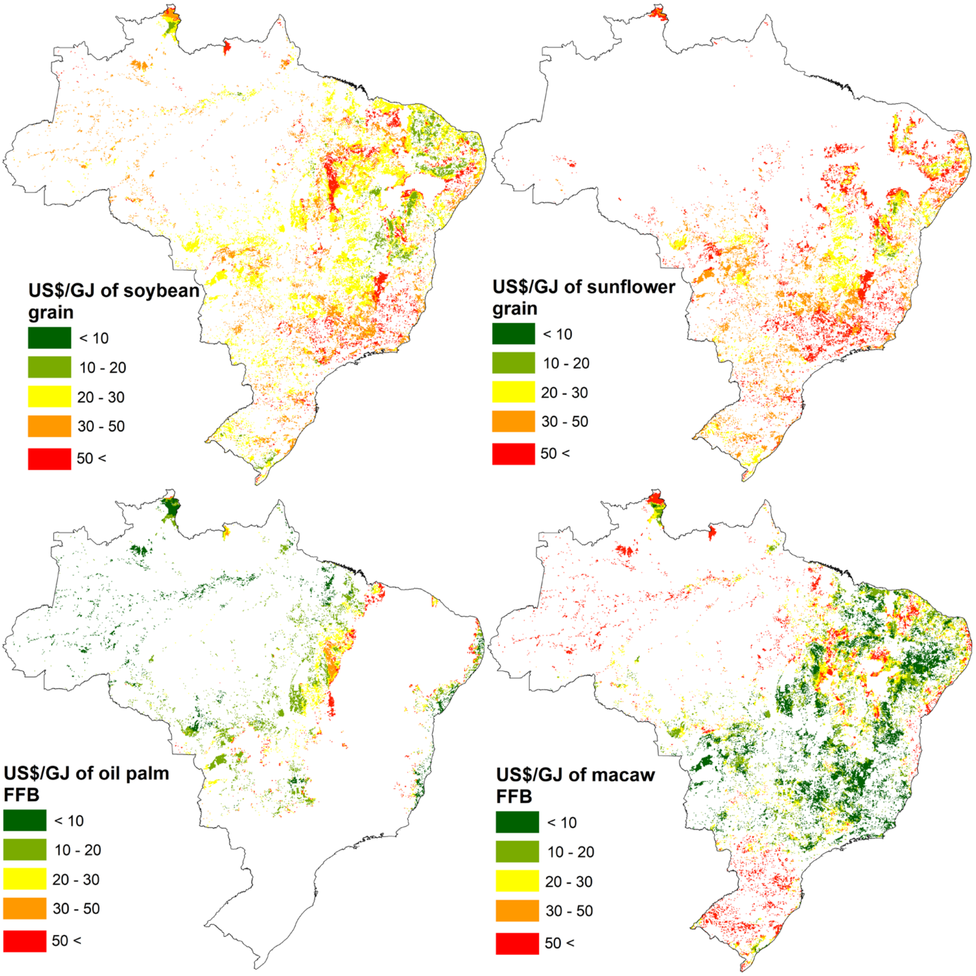


Figure 4.4: Spatial distribution of production costs of biomass crops for BJF production in 2030. The land availability is the same for all crops, but areas where the agro-ecological suitability for a specific crop equals zero are excluded from the analysis for that crop.

4.4.2. BJF production costs

The average BJF plant gate production cost of the first quartile (i.e. 25% of the land availability pixels with the lowest BJF production cost) ranges from 23 US$/GJ to 185 US$/GJ in 2015 and from 20 US$/GJ to 102 US$/GJ in 2030 depending on the production route (figure 4.5). The remaining 75% of the pixels involves costly biomass production areas, which result in very high BJF production costs. As shown in figure 4.5, we find high BJF production costs variability in EC_DSHC and EC_ATJ as a result of sparse suitable land available (i.e. high yield



variability). These production routes also have a very high conversion costs mainly in 2015 due to investments required in the 2G plant and BJF biorefinery. The highest BJF production costs are from production routes with DSHC technology, whereas the lowest production costs are found for HEFA based production routes. The difference in BJF distillation yield is the primary reason for the difference in BJF production costs between these production routes. Comparing the cost reductions over time, the most relevant ones are EC_DSHC, EC_ATJ, EC_FT, EC_HTL due to learning effects for 2G plant (EC_DSHC and EC_ATJ) and for the BJF thermochemical pathways (EC_FT and EC_HTL). On the other hand, the HEFA based production routes present the least cost reduction over time because of the already high readiness of technology.

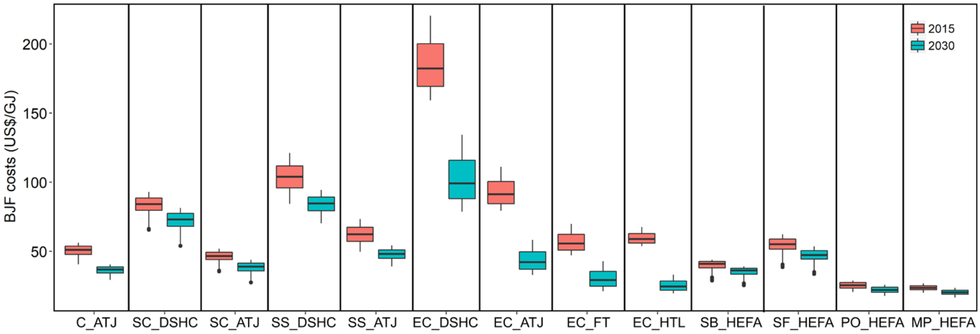


Figure 4.5: BJF production costs variability in first quartile for each production route in 2015 and 2030. This first quartile consists of the 25% pixels with the lowest BJF production cost for each route.

The overall BJF production costs aggregated in figure 4.5 consist of four major cost components: biomass costs (i.e. biomass farm-gate and transportation costs), biomass to feedstock conversion costs in the upstream plants, and capital and operational costs of the BJF biorefinery. In figure 4.6, the cost breakdown of BJF at plant gate in 2015 and 2030 is depicted for the production routes assessed. All production routes present cost reductions towards 2030, as result of the decrease in biomass costs, feedstock conversion yield improvements and the technological learning through the BJF production in *n*th BJF biorefineries. In general, the biomass costs represent the largest contribution to the BJF production cost (figure 4.6), with the exception of FT and HTL routes.

In 2015 and 2030, the EC_DHSC present the highest BJF production costs due to low sugar to farnesene yield and the high investment needed for the upstream 2G plant that converts the dry wood into fermentable sugars. The production routes based on the ATJ technological pathway have the lowest BJF capital cost contribution as all the biomass input is converted to ethanol, thereby increasing the feedstock input capacity of ATJ biorefineries. In 2015, the lowest BJF production cost is achieved by the production routes from macaw palm and oil palm using HEFA technology. This is explained by low initial investments required for the HEFA biorefinery, and also the high oil content of FFB. Hence, the specific investments in macaw and palm oil plants are much lower than the plants fueled by annual oilseed crops (e.g. soybean and sunflower). Thermochemical pathways (FT and HTL technologies) display a high capital intensity. However, they show decreasing BJF production costs towards 2030, due to the increasing scale and the high output of hydrocarbon co-products (e.g. diesel and gasoline).

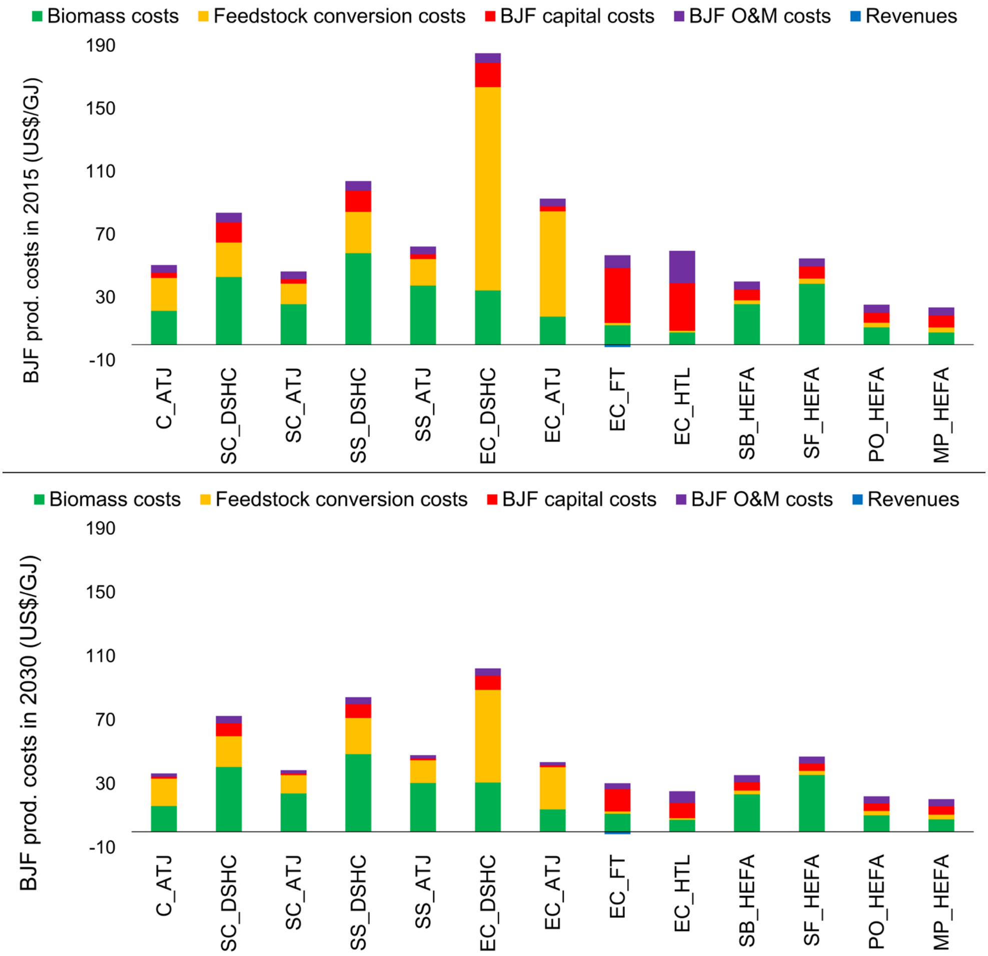


Figure 4.6: BJF production cost breakdown at plant gate in 2015 and 2030. The costs included in this figure represent the average of the first quartile of the pixels for each production route assessed.

4.4.3. BJF transportation cost

The BJF transportation costs have a low contribution to the total BJF total costs, representing an average range of 1% - 7% of the BJF total cost composition regardless of the year and the production route. The BJF transportation costs vary across the production routes due to the spatial variability of biomass production areas and their proximity to the road network and airports. On average, the BJF transportation costs from the BJF plant to the nearest airport ranges from 0.29 to 0.4 US$/GJ over Brazilian territory in 2015. With the expected full paving of important federal highways (e.g. BR-163) and the construction of planned roads towards

2030, the BJF transportation costs decrease by 20% on average, ranging between 0.23 and 0.3 US$/GJ of BJF transportation cost range.

Figure 4.7 shows the spatial variation of the BJF transportation cost in Brazil for four production routes for 2015 and 2030. The SC_DSHC and SC_ATJ production routes (A) have low BJF transportation costs (i.e. < 0.5 US$/GJ) in the Southeast region due to the land availability for sugarcane and the high density of airports. This is also true for corn, soybean and sunflower (B) based production routes, which also have land available in the South/Southeast regions of Brazil. In these regions, the BJF transportation costs do not have major influence on the BJF total costs. Differently, regionally concentrated PO_HEFA (C) has a limited land available in the Amazon area and there is also low infrastructure availability in that region. Therefore, it is projected to be rather costly to distribute (by road) oil palm based BJF to the surrounding airports in the great Amazon area.

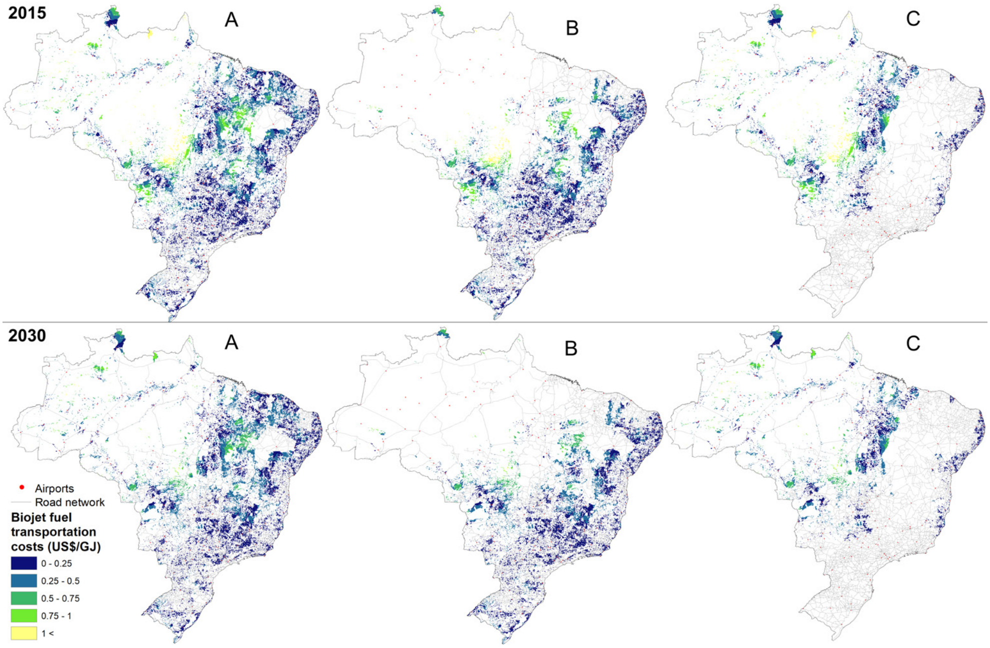


Figure 4.7: Spatial variation in BJF transportation cost in 2015 and 2030. A) SC_DSHC and SC_ATJ; B) SF_HEFA production route; C) PO_HEFA production route.

4.4.4. BJF total costs and techno-economic potential

The techno-economic potential is calculated by selecting the minimum BJF total costs per grid cell across the 13 production routes assessed in 2015 and 2030. The minimum BJF cost-supply curves are drawn (figure 4.8) representing the amount of BJF that can be supplied for minimum BJF total costs lower than the maximum fossil jet fuel price (65 US$/GJ). More than

99% (i.e. 6.4 EJ of BJF in 2015 and 7.8 EJ of BJF in 2030) could be produced at cost below the maximum fossil jet fuel price of 65 US$/GJ. The majority of the techno-economic potential of BJF can be supplied at costs below the average fossil jet fuel price in Brazil (i.e. < 32.4 US$/GJ) (figure 4.8). In total, the techno-economic potential is represented by eight production routes, dominated by contributions from PO_HEFA and MP_HEFA in 2015 (figure 4.8 - right hand side), complemented with EC_HTL in 2030. The other production routes each only have (very) minor shares and contribute less than 10% to the total BJF potential.

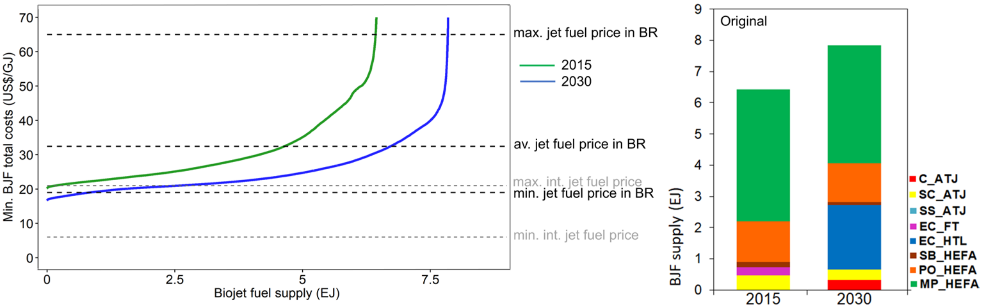


Figure 4.8: Left: BJF cost-supply curves of the minimum BJF total cost produced at the potential available land for BJF in 2015 and 2030. The horizontal dashed lines are the fossil jet fuel price range in the Brazilian airports (in black) [226], of which the maximum represents the cut-off point of the techno-economic potential of BJF. The gray lines are the amplitude of international jet fuel prices not in the airports (i.e. U.S. Gulf Coast kerosene jet fuel spot price) [228]. On the right hand side: corresponding production routes of the techno-economic potential of BJF.

MP_HEFA and EC_HTL production routes are the two most dominant production routes in 2030 (see the cost-supply curve of each individual production route in figure 1 of supplementary material – SM 4.8). However, while HEFA technology is already mature, large-scale macaw palm monocultures have not been commercially employed. Vice versa, while eucalyptus (the biomass crop assumed for HTL) is well established, the current TRL level of HTL ranges between 3 and 5 [217]. Therefore, for these two production routes the projected BJF production costs in 2030 are subject to large uncertainty. To test the robustness of our techno-economic potential, a sensitivity analysis is performed by excluding EC_HTL and MP_HEFA production routes (figure 2 in supplementary material – SM 4.8).

The exclusion of EC_HTL and MP_HEFA leads to an increase of both the SC_ATJ and EC_FT production routes in 2015. These production routes could supply the same amount of BJF at similar BJF totals costs (figure 1 in supplementary material – SM 4.8). In 2030, the impact of excluding these routes is less severe as the competitiveness of the MP_HEFA route already decreased in the original assessment. In addition, by 2030 the EC_FT production route produce BJF at costs close to those of EC_HTL (figure 1 in supplementary material – SM 4.8) with similar yields. The three alternative production routes that most increase their share in the overall techno-economic potential at the expense of the excluded ones in 2030 are EC_FT, SC_ATJ and C_ATJ. Therefore, even when promising production routes for BJF development in Brazil are excluded, there are still several options to provide a diversified and significant techno-economic potential of BJF in 2030 (figure 2 in supplementary material – SM 4.8).

Two other sensitivity scenarios are explored: the use of biomass market prices rather than production costs and the impact of no yield increase until 2030. The impact of using biomass at market prices may decrease the BJF total costs. In the original assessment, the techno-economic potential presents a range of average BJF total costs of 28 - 33 US$/GJ of BJF over time, whereas the introduction of biomass at market prices decreases to 23 - 26 US$/GJ. This cost reduction only occurs because the largest part of the techno-economic potential (i.e. > 2.5 EJ) containing high biomass costs are overshadowed by the use of fixed biomass market prices (figure 3 in supplementary material – SM 4.8). In reality, using biomass market prices for assessing the techno-economic performance of emerging bioenergy system can be misleading as the increasing demand for a given biomass may completely change the existing price. Lastly, assuming no biomass yield growth towards 2030, the techno-economic potential reduces by 1 EJ compared to the original assessment, hampering the BJF total cost reduction over time (figure 4 in supplementary material – SM 4.8). This highlights the importance of selecting the appropriate biomass crop for a given production route, taking into account its potential yield development in order to reduce BJF costs and to support the planning of BJF expansion.

The spatial variation of the minimum BJF total costs for 2015 and 2030 is presented in figure 5.9. Costly areas with a high minimum BJF total costs (shades of yellow, orange and red) are mostly located in the Northeast of Brazil, which is characterized by limited agro-ecological suitability for all biomass crops assessed. In 2030, the minimum BJF total costs below 20 US$/GJ are achieved mainly in the Southeast region (particularly in Minas Gerais state due to low cost MP_HEFA production). On the right hand side, figure 4.9 presents the corresponding production routes to the minimum BJF costs. The production routes PO_HEFA and MP_HEFA are dominant in 2015. In addition, PO_HEFA could be a promising option in the Amazon region (e.g. Pará state and East of Amazonas) as it presents minimum BJF total costs twice as low as all other production routes in that region. On the other hand, MP_HEFA is surpassed by other production routes in the Center-West towards 2030 (e.g. EC_HTL, SC_ATJ, C_ATJ), as the macaw palm cultivation costs are not expected to reduce. Therefore, different than macaw palm, the fact that costs of oil palm are not strongly reduced by 2030 does not affect its consolidation as a promising biomass source for BJF production in the North of Brazil.

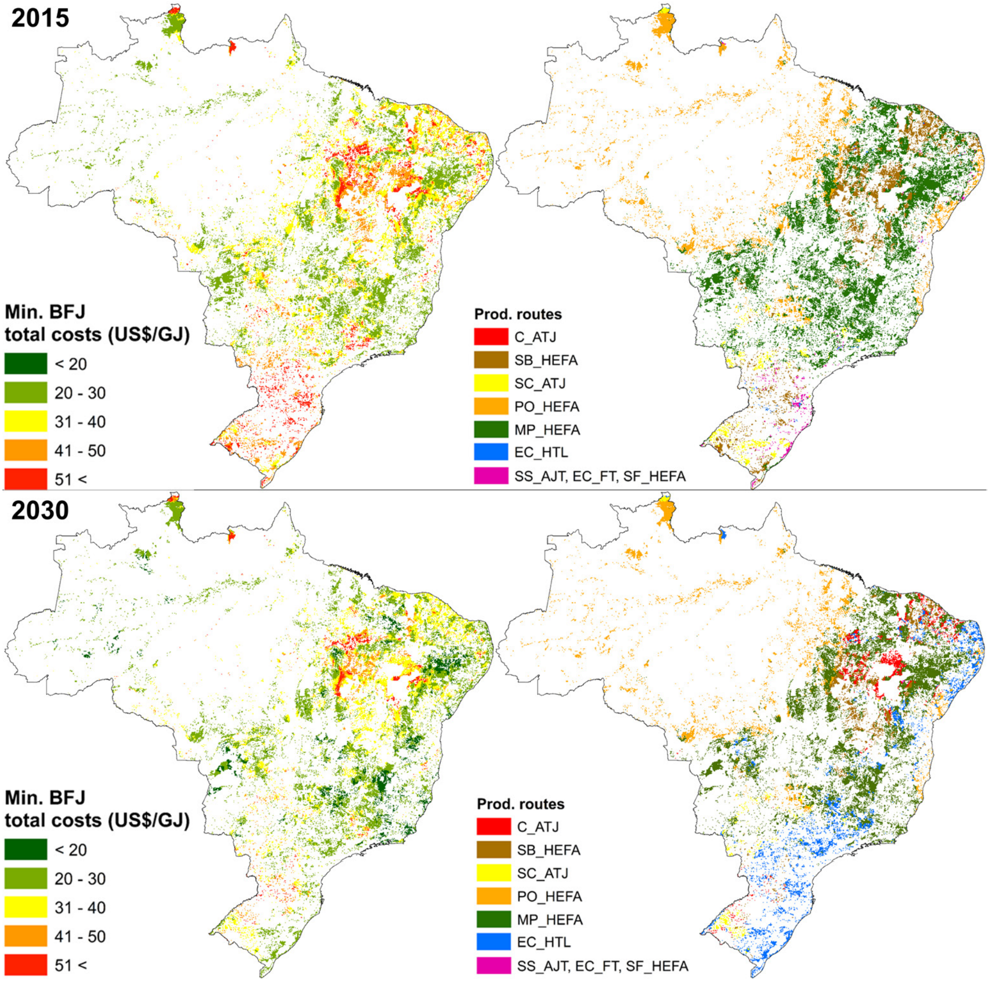


Figure 4.9: Minimum BJF total cost of the 13 production routes assessed and the corresponding production route.

The BJF total costs of C_ATJ are expected to decrease towards 2030, and are projected to outcompete SB_HEFA in the Northeast mainly. This is explained by the relatively high agro-ecological suitability for corn in this region and the expected significant improvements of C_ATJ compared to SB_HEFA (e.g. increasing ethanol conversion yield and capital cost reduction). Moreover, the decreasing amount of suitable areas for sugarcane production in 2030 may also benefit C_ATJ and EC_HTL. The latter is expected to be very relevant in 2030, being concentrated mainly in the South and the Northeast, as well as some inland areas (e.g. Paraná state).

The other production routes that achieve the minimum BJF total costs (figure 4.9; e.g. SS_ATJ, SF_HEFA and EC_FT) present significant coverage in the South of Brazil in 2015, but are progressively outperformed by EC_HTL towards 2030. Overall, the MP_HEFA production route has the highest potential in both 2015 and 2030 with 4.2 and 3.7 EJ, respectively. The EC_HTL, presents the steepest increase from 0 to 2 EJ between 2015 and 2030, and largely outcompetes SC_ATJ, even in typical sugarcane production areas (e.g. state of São Paulo).

We compare the BJF total costs of each production route in 2015 and 2030 to the fossil jet fuel selling price (figure 4.10). The size of the bars in figure 4.10 indicate the quantity of BJF that each production route can supply with BJF total costs below the fossil jet fuel price per Brazilian macro-region. In practice, a single grid cell of potentially available land for biomass cultivation for BJF production can be suitable for multiple production routes to achieve BJF total costs below the fossil counterpart. In 2030, depending on the region, up to 10 production routes may achieve competitive BJF total costs, although their potential varies between a few PJ and close to 2 EJ in Northeast and Southeast regions. Despite the high fossil jet fuel prices, the North region presents the lowest heterogeneity of competitive production routes: in most areas in this region PO_HEFA and MP HEFA are the only production routes with competitive BJF total costs. Differently, in some areas of the Northeast and Southeast regions, a high diversity of viable production routes is found due to the suitability of the available land for various biomass crops. Therefore, instead of selecting the best production route based on the lowest BJF cost, it is important to explore a broader portfolio of viable BJF production routes to comprehend the capabilities of a specific region.

4.5. DISCUSSION AND CONCLUSIONS

4.5.1. Land availability and biomass supply costs

Several of the assumptions made on land availability and possible deployment of new biomass crops have impacts on supply chain potential costs. Although we assume that all the residual land available is dedicated for BJF production, we did not account for the potential land competition with emerging biobased activities (e.g. bioproducts, biomaterials), which could limit techno-economic potential of BJF. Between 2015 and 2030, the residual land available is projected to decrease from 121.5 to 108.1 Mha. This affects the biomass costs, both positively and negatively, depending on the suitability of the available land for each biomass crop. In addition, the biomass cost data used in this study are sourced from various studies, which made different assumptions in terms of e.g. agricultural systems, expansion areas, system boundaries and cost items. Therefore, the reported biomass costs should be interpreted with care.

The typical Brazilian annual crops (i.e. soybean and corn) present the highest suitability for most of the available land and their costs decrease over time. Their utilization in the coming

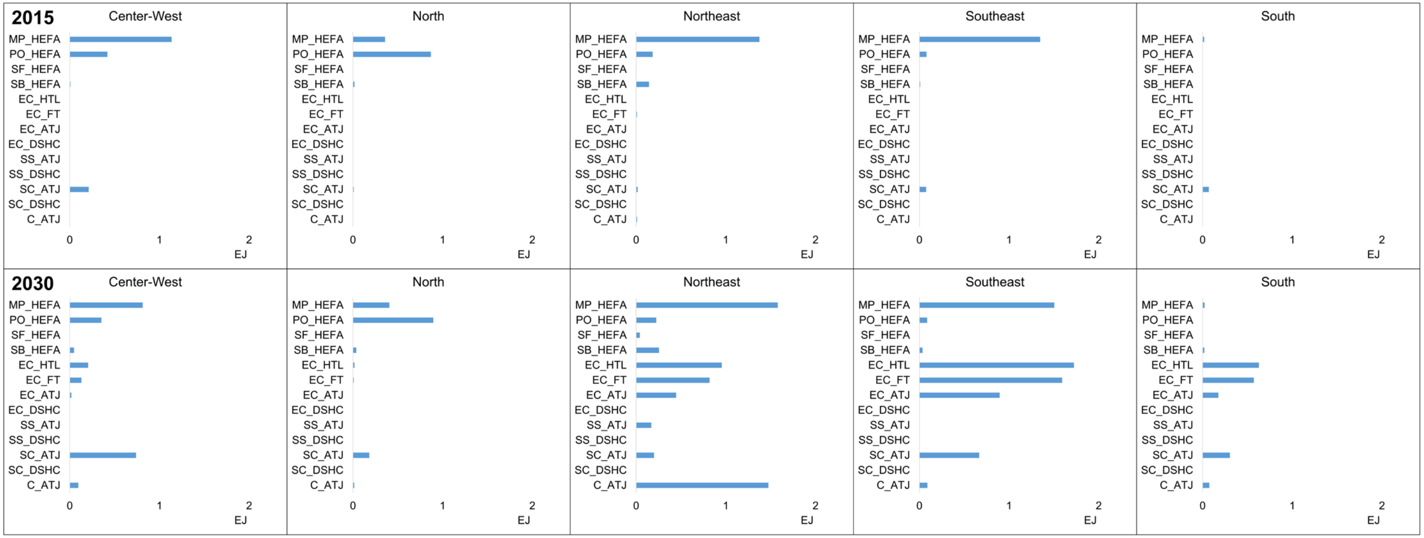


Figure 4.10: BJF supply potential from production routes that present BJF total costs below the fossil jet fuel price in 2015 and 2030 displayed per region. Note that the supply potentials per production route cannot be summed to the total potential per region, as each grid cell could accommodate multiple production routes with BJF cost below fossil jet fuel prices.

years could be an initial driver for scaling up BJF technologies, as the use of alternative biomass crops (e.g. oil palm and macaw) may take time to develop. Differently, the suitable areas for sugarcane cultivation for BJF production are limited as most of the suitable agro-ecological areas for sugarcane are already occupied by the projected expansion of 1G ethanol in 2030 [59]. As an alternative sugar/ethanol source, sweet sorghum has relatively low production costs and it could be a supplementary source of sugars in marginal areas in the Northeast. Even so, efforts are needed for the development of new varieties and management practices to be cultivated closer to the sugarcane industry to realize the cost reductions projected in the results [229].

Although regionally concentrated, perennial oil crops (i.e. macaw and oil palm) are of interest due to high agro-ecological suitability in their respective regions and the significant average oil yield per hectare compared to annual oilseed crops [197]. The development in land availability is a constraint for their cost reductions as part of their suitable areas are projected to be used by other land uses in 2030 [59]. Moreover, these perennial crops require high initial agricultural investments and their yield peak is only achieved 5 to 10 years after planting, which represents an additional risk for the large capital invested in the BJF project. For both 2015 and 2030, macaw palm shows lower FFB costs compared to oil palm due to the higher agro-ecological suitability. However, this is also a result of the assumption that both are cultivated under the same traits, while, in practice oil palm is currently cultivated in large scale monoculture systems, whereas macaw is only cultivated at small scale combined with other land uses (e.g. pasture, shrubs, forest) [188]. Therefore, the data to assess the biomass production cost of macaw palm is highly uncertain [230].

4.5.2. Technological pathways and BJF production costs

The BJF production costs at plant gate have a large range (23 US$/GJ - 180 US$/GJ) in 2015 (BJF pioneer biorefinery). By 2030, the range is smaller (20 US$/GJ - 97 US$/GJ) as it is assumed that BJF is produced at *n*th BJF biorefineries, which reduces capital costs disparities across the production routes [90]. Note that these BJF production costs represent the average of 25% of the land availability with the highest biomass yields and presumably have the best conditions for BJF production. Reference studies, such as Diedrichs et al. [215] found a range of BJF minimum selling prices between 50 US$/GJ – 77 US$/GJ across different production routes, whereas de Jong et al. [90] observed a minimum selling price reduction from 33 US$/GJ (BJF pioneer plant) to 23 US$/GJ (BJF *n*th plant). In hypothetical Brazilian biorefineries, the studies of Klein et al. [85] found a range of 9 US$/GJ – 32 US$/GJ, and Santos et al. [178] verified 2G production routes with minimum prices between 39 US$/GJ and 81 US$/GJ. The comparison with other studies must be carefully interpreted as the BJF production costs assessed herein are within the Brazilian context, sourced from high biomass yields, and take into account the location effect on the BJF cost components (e.g. biomass costs, transportation costs).

We find that the production routes using DSHC technology have the highest BJF production costs, even when dedicating all the fermentable sugars to the BJF plant. This is also illustrated in practice as Amyris produced BJF from SC_DSHC in Brazil, but techno-economic barriers hampered its commercialization [173]. Of the biochemical production routes, SC_ATJ has the lowest BJF production costs due to low capital costs required. This is line with the findings of Santos et al.[178] and Alves et al. [174]. When it comes to ATJ in 2G plants, the BJF production cost reduction over time is more relevant than 1G plants due to expected learning effects that may reduce the capital intensity of the feedstock production plant.

The lowest BJF production costs are achieved by PO_HEFA and MP_HEFA, as a result of low biomass and feedstock production costs, and low conversion cost to BJF. However, these results should be carefully interpreted given the current status of the palm and macaw oil market in Brazil. Although they have high potential oil yields, these biomass crops marginally contribute to the current biofuel industry (e.g. biodiesel) [187]. The opportunity cost of producing BJF from these oil crops is high considering the spectrum of high added value bio-products (e.g. biochemicals, food industry) that can be produced from these vegetable oils [188,231]. Furthermore, a key advantage of producing BJF in Brazil from energy crops is the low BJF feedstock costs (e.g. vegetable oil, ethanol) due to the high biomass yield and the land availability around existing infrastructure. However, we do not account for possible options of decentralized BJF biorefineries supplied by feedstock at market prices, which may change the BJF production costs.

Promising results are also achieved by EC_HTL, which shows significant BJF production cost reduction in 2030 as a result of the assumed technological learning of the BJF biorefinery. Despite not being approved by ASTM so far, the recent established "Steeper plant" in Norway is an example that HTL technology has been recognized as a technically viable option. However, its future development highly depends on investments that are needed to overcome techno-economic barriers and enable technological learning and associated cost reductions in the coming years. As an example, two decades ago, the expected progress for thermochemical pathways (e.g. FT) [232] did not materialize until today. Hence, more empirical information (i.e. more plants to be built) is needed to support the projections on techno-economic development of thermochemical pathways [5]. In addition, BJF production costs could decrease if alternative low-cost residual biomass (e.g. sugarcane bagasse, woody residues) is available as supplementary biomass source. The availability of residual biomass for BJF production is assessed in a forthcoming work [233].

4.5.3. Techno-economic potential of BJF in Brazil

Our spatially explicit approach provides location-specific information on the techno-economic potential of BJF production routes. The techno-economic potential is based on the minimum BJF total cost for each pixel of available land achievable through the 13 production routes included in the analysis. Compared to the range of jet fuel price in Brazil (19 - 65 US$/GJ), the techno-economic potential ranges between 0 – 6.4 EJ in 2015 and from 1.2 EJ to 7.8 EJ in 2030. This wide range is explained by the fossil jet fuel prices used in our assessment, which is based on the price data of all airports in Brazil. Depending on the airport location, fossil jet fuel prices could be up to three times higher than the Brazilian average prices at the refineries, due to differences in profit margins, logistic costs, state taxes (7% - 25% across the states), and import taxes [234]. This implies that niches may exist, where a combination of low BJF costs and high fossil kerosene prices may offer opportunities for (near) competitive deployment of first BFJ production plants.

The techno-economic potential and its variations addressed in the sensitivity analysis are comparable with the projected technical potential of BJF in the Sub-Saharan Africa in 2050, which varies from 4 EJ to 11.4 EJ [52]. Our results are well beyond the recent annual jet fuel demand of 0.26 EJ in Brazil [235] and the expected consumption of 0.38 EJ around 2030 [236]. The projected techno-economic BJF potential of Brazil could also contribute to the global jet fuel demand of 12 EJ in 2015 and 19 EJ in 2040 [237]. Given that, it is recommended that future studies also consider the BJF distribution to international markets.

The techno-economic potential should not be restricted to the production route of the minimum BJF total costs. The results show that up to 10 production routes could produce BJF total costs below the fossil jet fuel price depending on the region. The heterogeneity of viable production routes suggests higher chances for BJF development in a given region. Unlike in the United States and Europe, where the demand for jet fuel is geographically more distributed; in Brazil, the regions with higher demand are concentrated in the Southeast and Northeast regions, which together account for more than 75% of the jet fuel consumed in Brazil [238]. In these regions, the land availability to grow dedicated biomass for BJF is assumed to become scarcer over time due to the development in other land use functions (e.g. food demand increase) [59]. Hence, demand-driven assessments should be further explored as the BJF may be supplied from other regions, thereby impacting techno-economic results. This study only quantifies the potential of BJF under techno-economic constraints and at a large geographical scope. This is relevant for decentralizing energy policies towards a specific region for certain production routes. However, the introduction of BJF in the market requires a more detailed comprehension of local contextual factors (e.g. agronomic, infrastructure), which have to be addressed in future studies. In addition to the techno-economic aspect, the acceptance of BJF also relies on its environmental performance. Therefore, it is highly recommended to assess the effect of environmental constraints on BJF potentials.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Mapping the environmental and techno-economic potential of biojet fuel production from biomass residues in Brazil

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This chapter has been submitted

Abstract. Using agricultural residues as feedstock for production of advanced biojetfuels (BJF) is often regarded as a promising strategy to limit environmental impacts. However, it is difficult to quantify the environmental and techno-economic potential for BJF production from biomass residues due to the high spatial variability on biomass residues availability and infrastructure, as well as the uncertain development in BJF technological pathways. This study assesses the recent and future environmental potential of crop residues and the techno-economic potential of BJF production in Brazil. Different production routes (supply chains) are evaluated from two types of biomass residues (sugarcane straw and eucalyptus harvest residue), and four different technological pathways (Alcohol To Jet, Fischer-Tropsch, HydroThermal Liquefaction and Pyrolysis). The environmental potential of biomass residues is determined, making use of spatio-temporal projections of land use change in Brazil and by modelling the erosion risk and the Soil Organic Carbon balance spatially explicitly. The assessment of the techno-economic potential of BJF production from the environmental potential of sugarcane straw (SCS) and eucalyptus harvest residues (EHR) considers the BJF total costs, which results from the summation of biomass residue recovery costs, BJF conversion costs and BJF transportation costs. These BJF total costs are compared to the range of fossil jet fuel prices at Brazilian airports to quantify the techno-economic potential. The environmental potential of biomass residues varies from 70 Mt in 2015 to 102 Mt in 2030, with SCS being highly constrained by SOC, whereas EHR are more constrained by the high erosion risk. These quantities can generate a techno-economic BJF potential ranging from 0.45 EJ in 2015 (46 US$/GJ – 65 US$/GJ) to 0.67 EJ in 2030 (19 US$/GJ – 65 US$/GJ). In 2030, several BJF production routes can be competitive with fossil jet fuel prices. The Northeast and Southeast regions have the highest potentials, especially in 2030.

Keywords. biomass residues, straw, aviation biofuels, GIS, bioenergy potential, sugarcane, eucalyptus, erosion, soil organic matter.

5.1. INTRODUCTION

Aviation biofuel (hereafter called biojet fuel - BJF) is foreseen as an emerging bioenergy supply chain, which could require large amounts of biomass resources in the coming years [77]. Although globally BJF production is currently in an early development stage, many dedicated initiatives and upcoming policies have already suggested the conditions for biomass utilization for this purpose. For example, the International Civil Aviation Organization (ICAO) has indicated that biomass crops for BJF should not compete with food crops [239]. In addition, the Sustainable Aviation Fuel Users Group (SAFUG) emphasized the importance of using biomass sources without compromising water availability or biodiversity [23].

Historically, conventional so-called 1st generation biofuels, e.g. sugarcane ethanol and soybean biodiesel thrived in Brazil because of low production costs, land availability and suitability, and government incentives [240,241]. However, there are major sustainability concerns related to the use of (food) crops for BJF production (e.g. deforestation, food insecurity) [82,83]. Recently, 2nd generation biofuels from lignocellulosic biomass residues have gained momentum in Brazil, as it could avoid the competition for highly suitable land and related potential negative effects [64]. Previous studies have indicated that the Brazilian agricultural sector produces 1.6 - 4 EJ/yr of biomass residues that can be recovered from the field for non-agronomic applications (e.g. bioenergy, animal feed) [149,242]. However, the removal of biomass residues for bioenergy use could have major agronomic and environmental implications (e.g. impacts on soil organic carbon, soil erosion, and nutrient availability) [36]. Hence, many studies have been conducted to quantify the amount of biomass residues that can be recovered without compromising the forthcoming cropping seasons [102,118,138,243].

Sustainable residue removal rates highly depend on a series of agronomic and environmental variables (e.g. soil, climate, terrain) which present high spatial and temporal variability [36,69,102]. Many studies quantified the biomass residue potential considering spatial variation in environmental constraints [30,46,50,149,150,159,244–246]. At a global level, Daioglou et al. [46] projected an ecological potential from crop and forestry residues of 70 - 100 EJ/yr, by applying fixed removal rates to account for environmental constraints. Monforti et al. [30] estimated a potential of 2.3 EJ/yr of biomass residues in Europe considering Soil Organic Carbon (SOC) conservation as a constraint for crop-residue removal. Muth et al. [34] quantified the potential of biomass residues at county level in US, using soil erosion risk as a constraint. Portugal-Pereira et al. [67] mapped the ecological and economic potential of agricultural residues for bioelectricity production in Brazil. Also at country level, other studies have also assessed the environmental potential of biomass residues [55,159,247]. Of all these studies, a more limited number [30,70,244,248] have used a bottom-up approach to model the environmental constraints spatially explicitly to estimate the biomass residues removal rate at field level. All the aforementioned studies contributed to different extents to the understanding on how the spatial heterogeneity in agro-ecological conditions affect the environmental potential of biomass residues for bioenergy. However, these assessments do not link the spatial variability of biomass residues potential for estimating biomass and bioenergy supply chain costs.

Several studies have assessed the techno-economic performance of BJF production from biomass residues [90,174,249]. In Brazil, studies have addressed the (aggregated) spatial distribution of biomass residues to quantify the techno-economic potential and costs of BJF supply chains [76,250]. However, these studies do not account for the spatially explicit variation in biomass residue availability as they do not consider the spatial heterogeneity of biomass yields and sustainable removal rates. However, biomass yields and removal rates highly effect biomass potentials and costs, and therefore the techno-economic potential of BJF [123]. Thus far, no study has included the implications of environmental constraints in quantifying the potential and cost of biomass residues, and the techno-economic potential of BJF production spatially and temporally explicitly. Therefore, the outcomes from a techno-economic assessment of BJF supply chains considering the environmental constraints and resulting spatial variability of biomass residues are of high relevance for the broader bioenergy community and more specificly to the BJF industry stakeholders in Brazil.

The objective of this study is to assess the spatio-temporal environmental and techno-economic potential of BJF production from biomass residues in Brazil. We assess the environmental potential of biomass residues spatially explicitly as the yield as well as the environmental constraints for residue removal depend on various spatially heterogeneous agro-ecological conditions. The environmental and techno-economic potential is quantified for a baseline (2015) and near future (2030) scenarios to account for the effect of land use change on biomass residues potential, and for the effect of expected technological improvements on the techno-economic potential of BJF supply chains (hereafter named as BJF production routes).

5.2. SELECTED RESIDUES

The potential of biomass residues for bioenergy depends on several parameters, such as the type of crop, crop area, crop yield, residue to crop ratio, residue removal rate and the non-agronomic competitive uses [251,252]. In this study, two types of biomass residues are considered: sugarcane straw and eucalyptus harvest residues. These biomass residues are selected because of the large production of sugarcane and eucalyptus in Brazil, the potential large availability of their residues, the availability of data, and also because they have been identified as promising bioenergy resources in previous studies [84,149,153,253]. In the following sections (5.2.1 and 5.2.2 as well as in table 5.1), key characteristics of the selected biomass residues and their current status in Brazil are described.

Table 5.1: General information about sugarcane straw and eucalyptus harvest residues in Brazil

Biomass	National production in 2015 (Mt)	Current average yield (t/ha/yr)	Residue type	Residues to crop ratio (%)	Sources
sugarcane	750	80	sugarcane straw	14	[69,117]
eucalyptus	130	30	harvest residues (e.g. barks, branches)	15	[149,184]

5.2.1. Sugarcane straw

The sugarcane ratoon cycle usually comprises 5 to 6 years. In sugarcane systems, the sugarcane straw (hereafter named as SCS) is left on the field after mechanical harvest. This brings many agronomic and environmental advantages such as increasing soil organic carbon, recycling of nutrients, and controlling soil erosion [69,102]. However, SCS is composed by lignocellulosic material with high calorific value, which has great potential in the bioenergy industry [100]. Currently, in some modern sugarcane mills SCS is marginally used for producing bioelectricity and/or 2G ethanol production[142,143].

Assuming an average straw to sugarcane ratio of 14% [68], 105 Mt of SCS was theoretically available in Brazil in 2015 [117]. This potential is mainly found in the Southeast and Center-West region of Brazil (see supplementary material SM 4.7 for Brazilian macro-region division). However, some of the available straw should be left on the field to preserve soil quality. Some studies have explored the maximum amount of sugarcane straw that can be removed without impeding soil quality in Brazil, but all of them are site specific [138,139].

5.2.2. Eucalyptus harvest residues

Eucalyptus plantations are found in the South and Southeast region of Brazil, around the main pulp and paper facilities. Eucalyptus plantations generally have a 21-year cycle with harvests after every 7 years. Usually, wood management operations (e.g. debarking) are executed on the field to facilitate wood transportation, and also for silvicultural reasons (e.g. residues acting as a soil amendment) [254]. These operations result in the availability eucalyptus harvest residues (hereafter named as EHR), which could amount around 15% of the cumulated wood yield (average of 270 t of wood per hectare after 7 cultivation years) [255]. However, these residues also play an important role in maintaining soil quality. Very few studies have explored the environmental effect of EHR removal [256].

5.3. PRODUCTION ROUTES

Four technological pathways for drop-in BJF are included in the assessment of the techno-economic potential of BJF from biomass residues: Pyrolysis (PYR), Hydrothermal Liquefaction (HTL), Fischer-Tropsch (FT) and Alcohol to Jet (ATJ). These technologies are chosen because of their current fuel and technology readiness level (FRL and TRL) (see the studies of de Jong et al and E4tech [171,217] for further information on technology status), their positive techno-economic performance in previous studies, and cost data availability [87,90].

PYR and HTL have not yet been certified by ASTM (American Society of Testing Materials) for commercial BJF production. These technologies directly convert biomass to liquid fuels through thermo-chemical reactions (see Gollakota et al. and Wang & Tao [257,258] for a detailed description of these pathways). Currently, the companies Steeper Energy and Licella (HTL), and UOP (PYR) are developing these pathways for BJF production at pilot scale [259,260]. Moreover, both technologies have shown promising techno-economic results in the study of Jong et al. [31]. FT is also a thermo-chemical pathway, which is relatively mature and is already used in the conversion of fossil resources into liquid fuels [261]. In the bioenergy case, lignocellulosic biomass is converted to synthetic gas and then into hydrocarbons through FT reactions [232]. This technology received ASTM acceptance in 2009 with permission for 50% blend with conventional jet fuel [20]. The ATJ biochemical pathway produces BJF from alcohols (e.g. ethanol, butanol and methanol). Recently, ASTM approved an increase from 30% to 50% drop-in of ATJ in conventional jet fuel [262]. The companies Gevo and Lanzatech are currently leading the ATJ development [173,262], If more plants are commissioned in the coming years, the readiness level is likely to increase.

In this study, the BJF production routes are combinations of the biomass residues and the BJF technologies. In total, eight production routes are assessed (four from SCS and four from EHR), see figure 5.1.

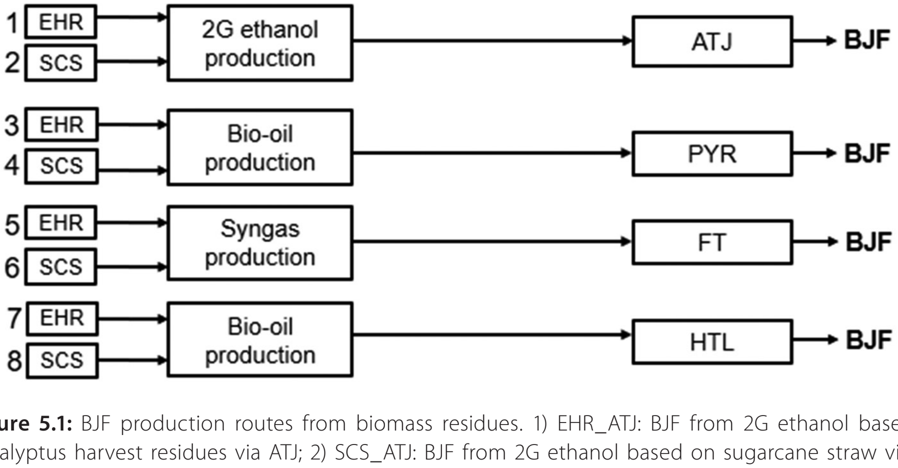

Figure 5.1: BJF production routes from biomass residues. 1) EHR_ATJ: BJF from 2G ethanol based on eucalyptus harvest residues via ATJ; 2) SCS_ATJ: BJF from 2G ethanol based on sugarcane straw via ATJ 3) EHR_PYR: BJF from eucalyptus harvest residues via PYR; 4) SCS_PYR: BJF from sugarcane straw via PYR; 5) EHR_FT: BJF from eucalyptus harvest residues via FT; 6) SCS_FT: BJF from sugarcane straw via FT; 7) EHR_HTL: BJF from eucalyptus harvest residues via HTL; 8) SCS_HTL: BJF from sugarcane straw via HTL.

5.4. METHODS

For the assessment of the environmental and techno-economic potential of BJF from biomass residues, the approach is divided in two main components: the spatially explicit modeling of the environmental potential of biomass residues and the techno-economic assessment of BJF from these biomass residues (figure 5.2).

The environmental potential of biomass residues is the part of the theoretical potential (i.e. the total amount of biomass residues produced in the field), that could be removed given environmental constraints [27,153]. In this study, two environmental criteria are applied for the assessment of the environmental potential of biomass residues: the erosion risk and SOC balance. Several studies indicated the importance of water erosion control for eucalyptus and sugarcane residue management in order to avoid soil losses through run-off [244,263,264]. Potential erosion risk caused by wind is not considered in this study, as it is assumed to be negligible compared to water erosion in Brazilian arable areas [265]. Maintaining or improving SOC levels is assumed crucial as it is generally the main source of organic matter in agricultural soils which is key for soil productivity [36,266]. In this study, the risk of soil erosion is considered by excluding all (potential) sugarcane and eucalyptus areas for residue removal where the annual soil loss already exceeds the location specific tolerable limits for soil loss. A SOC balance approach is applied to assess the amount of residues that can be removed without comprising SOC levels. The erosion risk and SOC constraint are combined to assess the spatial distribution of SCS and EHR for two points in time (2015 and 2030); see Equation 5.1. In this study, we do not account for the non-agronomic competitive uses for the biomass residues.

The techno-economic potential of BJF from biomass residues refers to the share of the theoretical potential that can be achieved given a certain economic constraint [159]. In this study, the production costs of BJF production routes sourced from the environmental potential of SCS and EHR in 2015 and 2030 are assessed. The BJF production costs (expressed in US$/GJ) include the costs for biomass residue recovery, BJF production (i.e. conversion) and BJF transportation. At last, we quantify the amount and determine the spatial distribution of BJF potential from biomass residues that could be produced at costs below the fossil counterpart.

Equation 5.1

$$EPr_{p,y} = Er_{p,y} \times ER_{p,y}$$

Item	Description	Unit
$EPr_{p,y}$	Environmental potential of biomass residues in pixel *p* in year *y*	t/ha
$Er_{p,y}$	Residue availability according to SOC balance in pixel *p* in year *y*	t/ha
$ER_{p,y}$	Erosion Risk in pixel *p* in year *y*	0, 1

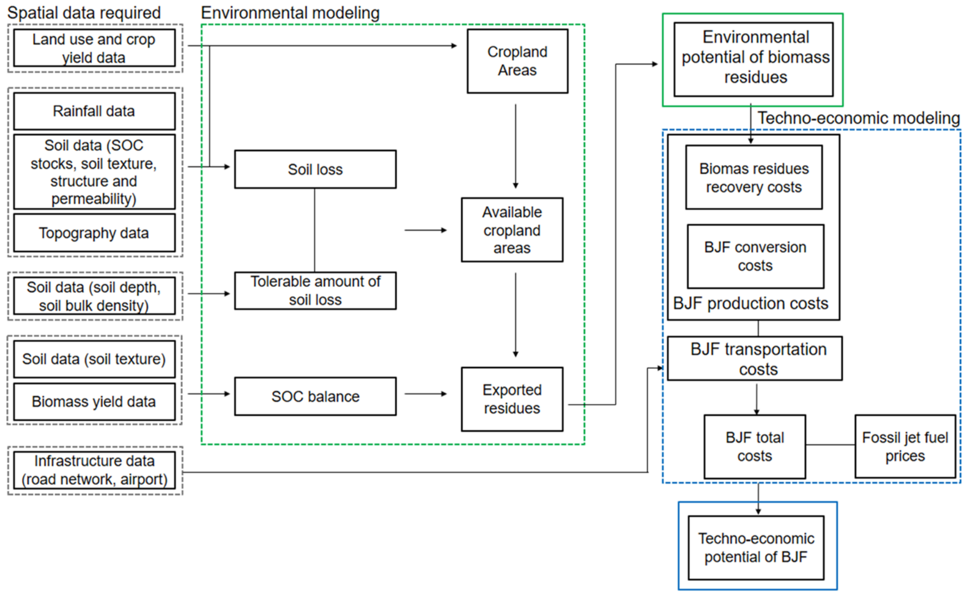

Figure 5.2: Workflow for estimating the environmental potential of biomass residues (green solid outline box) and techno-economic potential of BJF from biomass residues (blue solid outline box). The spatial data (dashed grey outline boxes) are used as input for both environmental modeling (green dashed outline box) and the techno-economic modeling (blue dashed outline box).

5.4.1. Crop data and yield levels

The assessment of the potential of biomass residues is based on the spatial distribution of sugarcane for SCS and planted forest (i.e. areas occupied with eucalyptus plantations) for EHR sourced from maps of current and future land use of Brazil modeled by Van der Hilst et al. [59] at a 5x5 km pixel resolution. These projections of land use developments in Brazil towards 2030 are based on scenario analyses making use macro-economic and land use models, see Van der Hilst et al. [59]. The spatial variation of crop yield levels is calculated by multiplying the spatial variable agro-ecological suitability levels (*S*) by the time-specific maximum attainable yield (*M*) (equation 5.2) in areas of sugarcane and planted forest (*A*). The agro-ecological suitability map for sugarcane is derived from IIASA – GAEZ [190], and the suitability map for eucalyptus is based on Cervi et al. [267]. The data on current maximum attainable yield is derived from national agricultural statistics [117] for sugarcane and from Stape et al. [195] for eucalyptus. Development of sugarcane and eucalyptus yield over time is based on historical trends (i.e. annual increase of 0.8% for sugarcane and 1.4% for eucalyptus, in line with Van der Hilst et al. [59]).

Equation 5.2

$$Y_{b,p,y} = A_{b,p,y} \times Su_{b,p} \times M_{b,y}$$

Item	Description	Unit
$Y_{b,p,y}$	Yield of biomass *b* in pixel *p* in year *y*	t ha^{-1}
$A_{b,p,y}$	Area in use for biomass *b* in pixel *p* in year y	0, 1
$Su_{b,p}$	Agro-ecological suitability for biomass *b* in pixel *p*	%
$M_{b,y}$	Maximum attainable yield of biomass *b* in year *y*	t ha^{-1}

5.4.2. Erosion risk constraint for biomass residues recovery

The areas that in use for sugarcane or eucalyptus in 2015 or 2030, that are already facing erosion risks beyond the spatially explicit tolerable limits for soil loss, are excluded for biomass residue removal. The Revised Universal Soil Loss Equation (RUSLE) [268] (equation 5.5) is employed to calculate the potential annual amount of soil loss (t/ha/yr) by water erosion (table 5.2). Using the same approach as Muth and Bryden [70], we compare the annual amount of potential soil loss in a given biomass area is to the tolerable limits (*T* value) of soil losses (equation 5.3). The tolerable limits of soil loss are defined as the maximum amount that a given soil can lose while maintaining productivity [269]. It is calculated through the multiplication of soil bulk density with the soil depth (equation 5.4), in line with Muth and Bryden [70]. The areas where the potential soil loss are below the tolerable limits, are considered available for residue recovery (1), whereas areas exceeding this limit are considered as “no-go” (0) areas [70] (equation 5.3). In the areas available for biomass residue recovery, we assume 2 t/ha/yr of biomass residues are retained on the field for erosion control, in line with Andrews [270]. Table 5.2 describes the variables used in RUSLE equation as well as the sources of the spatially explicit data and the supplementary material – SM 5.1 describes all the input equations for each RUSLE parameter.

Equation 5.3

$$ER_{p,y} = \begin{cases} 0, An_{p,y} > T_p \\ 1, An_{p,y} \leq T_p \end{cases}$$

Item	Description	Unit
$ER_{p,y}$	Erosion Risk in pixel *p* in year *y*	0, 1
$An_{p,y}$	Annual soil loss in pixel *p* in year *y*	t ha^{-1}
T_p	Tolerable soil loss limit in pixel *p* in year *y*	t ha^{-1}

Equation 5.4

$$T_p = \frac{Hp \times Dp}{1000}$$

Item	Description	Unit
T_p	Tolerable soil loss limit in pixel *p*	t ha^{-1}
H_p	Soil depth in pixel *p*	m
D_p	Soil bulk density in pixel *p*	kg m^{3}

Equation 5.5

$$An_{b,p,y} = R_p \times K_p \times L_p \times S_p \times C_{b,p,y} \times P_p$$

Item	Description	Unit
$An_{p,y}$	annual soil loss in biomass area *b* in pixel *p* in year *y*	t/ha/yr
R_p	rainfall erosivity factor in pixel *p*	MJ/mm/ha/h/y
K_p	soil erodibility factor in pixel *p*	t/ha/h/ha/MJ/mm
L_p	slope length factor in pixel *p*	-
S_p	slope steepness factor in pixel *p*	-
$C_{b,p,y}$	cover management factor in biomass area *b* in pixel *p* in year *y*	-
P_p	control practice factor in pixel *p*	-

Table 5.2: Description of RUSLE variables and the spatial datasets used for its calculation

RUSLE variable	**R Rainfall erosivity**[1]	**K Soil erodibility**[2]	**L and S Slope length and steepness**[3]	**C Land cover management**[4]	**P Control practice**[5]
Unit	MJ mm ha^{-1} h^{-1} y^{-1}	t ha h ha^{-1} MJ^{-1} mm^{-1}	dimensionless	dimensionless	dimensionless
Data required	rainfall	topsoil texture, topsoil organic carbon (0 -30 cm)	slope and flow accumulation	land use	slope
Data source	European Centre for Medium-Range Weather Forecasts (ECWMF)	World Soil Grids (International Soil Reference and Information Centre - ISRIC) and Global Soil Organic Estimates (Joint Research Centre - JRC)	Shuttle Radar Topographic Mission (SRTM)	Brazilian land use scenarios (PLUC model)	Shuttle Radar Topographic Mission (SRTM)
Variability	Spatial	Spatial	Spatial	Spatial and temporal	Spatial

[1] The R factor refers to the ability of water to detach and transport soil particles [271]. We assume the same erosivity values for 2015 and 2030 to avoid the complexity of climate models to project future rainfall.

[2] The K factor represent the susceptibility of a given soil to erosion [271].

[3] The L factor is defined as the horizontal distance from the original point of overland sediment flows to the point where the slope decreases and the sediment deposition begins, or where the runoff flows into a given channel. The S factor represents the influence of slope gradient on erosion [271].

[4] The C factor is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled [77]. It addresses the cover characteristics of a given land use over the entire year. In agricultural land use, the C factor is very sensitive to variations of crop canopy, type of cultivar and possible crop rotations throughout the year [273]. For sugarcane and to a lesser extent for eucalyptus, there is a large number of studies seeking to determine the C factor in different cultivation systems and agro-ecological conditions. In this study, we use the average of C factors (sugarcane: 0.17; eucalyptus: 0.08) reported in different studies for sugarcane and eucalyptus in Brazil (see details in the supplementary material – SM 5.1).

[5] The P factor gives the ratio between the soil loss expected from a certain soil conservation practice to that increasing/decreasing surface slope [271].

5.4.3. Modeling the residue removal rate through SOC balance

To estimate the amount of residues that can be removed for BJF production without decreasing soil organic carbon levels, we quantify the SOC dynamics by adapting the VDLUFA Humus Balance tool [274]. This is a simple agronomic spreadsheet model that has been used to assess soil fertility in crop rotation systems in Germany [275]. The model quantifies the humus input and output from crop rotation systems. However, the downside of VDLUFA humus balance is the use of dimensionless humus values (i.e. humus equivalent unit) that are specific for the German context, which limits the application in a broader context [276]. For this reason, we use more general physical Organic Carbon (OC) values to quantify the SOC dynamics. The use of OC values in humus balance tools has been already applied in the study of Kolbe [277] for different crop types (e.g. roots, tuber, fodder, grasses). To quantify the impact of biomass management on SOC dynamics, we assess the changes in SOC over the lifetime of sugarcane (6 years) and eucalyptus (21 years), and it is hereafter called SOC balance. We assess SOC variations after each ratooning/harvesting cycle (i.e. three harvest cycles for eucalyptus and six for sugarcane). The SOC balance quantifies the SOC inputs and outputs to the soil for each harvest cycle within the timeframe (crop lifetime) (see the supplementary material – SM 5.2). The sources of SOC input considered in this study are above and below ground biomass and organic fertilizers, whereas the SOC outputs (i.e. SOC depletion) are due to SCS and EHR removal and belowground SOC decomposition. These factors are affected by crop management, and by the interaction with agro-ecological factors (e.g. soil texture and biomass yield) [139], which are spatially heterogeneous. As no other study assessed the SOC dynamics in sugarcane and eucalyptus systems in a spatially explicit manner, in this study the SOC dynamics are quantified by upscaling the results found in different site specific experiments (see the key references in the supplementary material – SM 5.2) to pixel level. These studies provide data of SOC increase/decrease in the crop lifetime of the biomass systems assessed under different agro-ecological conditions. Using information on soil texture and biomass yield, the SOC dynamics observed in these site specific studies are upscale spatially explicitly. The rule of the SOC balance model works with an "if-else" conditional statement, i.e. if the amount of SOC at the end of each harvest cycle is lower than the previous year, all the residue must be left on the field; or else all the residues can be removed. Hence, there are both harvest cycles with all residues being recovered and harvest cycles in which all the residues are kept on the field. After calculating the SOC balance of each harvest cycle over the entire timeframe, the average annual amount of removed residues over the timeframe is estimated.

Equation 5.6 describes the general SOC balance calculation accounting the SOC inputs and outputs; equation 5.7 shows the model rule (i.e. decision on whether or not recover the residues based on the SOC balance); and equation 5.8 quantifies the biomass residues exported from the field (i.e. environmental potential). The data required for the SOC balance calculations, the model assumptions and constraints, and the reference studies are described in the supplementary material – SM 5.2. For a deeper understanding of SOC balance, this data repository (SOC balance) provides the raw data (e.g. amount of fertilizer, mass of above and belowground biomass), all the equations and a simple demonstration (in a spreadsheet format) of the calculations required in model framework for both biomass systems.

Equation 5.6

$$OCB_{t,p,y} = BAGC_{t,p,y} + TFer_{t,p,y} + \begin{cases} 0, t = 0 \\ CO_{t-1,p,y}, t > 0 \end{cases}$$

Item	Description	Unit
$OCB_{t,p,y}$	Soil Organic Carbon Balance in harvest cycle *t* in pixel *p* in year *y*	t C/ha
$BAGC_{t,p,y}$	Belowground and/or Aboveground contribution to OC in harvest cycle *t* in pixel *p* in year *y*	t C/ha
$TFer_{f,t,p,y}$	Total OC from fertilizer applied in harvest cycle t in pixel p in year y	t/ha
$CO_{t-1,p,y}$	SOC carried over from previous harvest cycle t-1 in pixel p in year y	0, t C/ha

Equation 5.7

$$Dr_{t,p,y} = \begin{cases} 0, OCB_{t,p,y} < OCB_{t-1,p,y} \\ 1, OCB_{t,p,y} \geq OCB_{t-1,p,y} \end{cases}$$

Item	Description	Unit
$Dr_{t,p,y}$	Decision on recover (1) or not recover (0) residues in harvest cycle *t* in pixel *p* in year *y*	0, 1
$OCB_{t,p,y}$	SOC balance in harvest cycle t in pixel p in year y	t C/ha
$OCB_{t-1,p,y}$	SOC balance in previous harvest cycle t-1 in pixel p in year y	t C/ha

Equation 5.8

$$TR_{t,p,y} = ER_{t,p,y} \times Dr_{t,p,y}$$

Item	Description	Unit
$TR_{t,p,y}$	Total amount of residues in harvest cycle *t* pixel *p* in year *y*	t/ha
$ER_{t,p,y}$	Exported residues in harvest cycle *t* pixel *p* in year *y*	t/ha
$Dr_{t,p,y}$	Decision on recover (1) or not recover (0) in harvest cycle *t* in pixel *p* in time *y*	0, 1

5.4.4. Techno-economic potential assessment

5.4.4.1. Biomass residues recovery costs

Biomass residue recovery is assumed to be carried out some time after harvest in order to allow for natural drying in the field. SCS and EHR are assumed to have the same moisture content of 15%, which has also been used in other studies [4,153,278]. For SCS, the baling system is selected as recovery route [123]. In the baling system, the straw available on the field is windrowed, baled and loaded onto a truck [119]. For EHR, the chipping system is selected as it is generally employed in both pulpwood and forestry residues harvest [279], and it has already been tested for EHR in Brazil [278]. The EHR are collected in the field by a forwarder, are chipped and then loaded into a truck container at roadside. Figure 5.3 presents the field operations of both residue recovery systems.

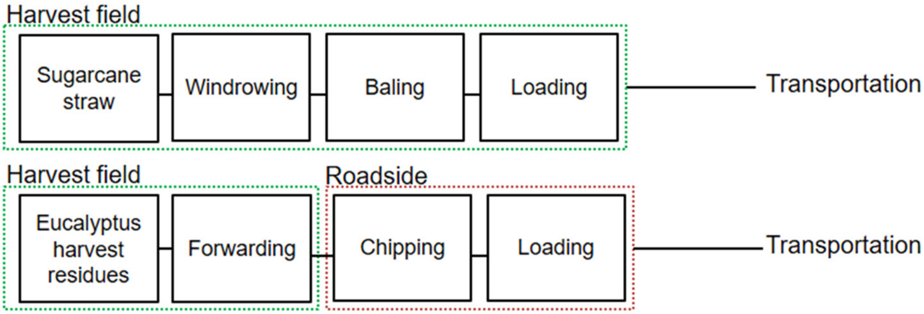

Figure 5.3: Schematic representation of biomass residue recovery systems. For EHR the system takes place at the harvest area (green box) and also at roadside (brown box). For SCS, the entire system is carried at the harvest area.

The biomass residue recovery costs (US$/t) are the result of the summation of farm-gate costs and transportation costs. The first is composed by operational costs (e.g. machinery, depreciation, diesel and labor), and for SCS it also includes a marginal cost for agricultural inputs required to compensate the nutrient losses of residue removal [119,123]. The farm-gate costs depend on the available biomass residue per hectare, see (equation 5.9) and Cervi et al. [280]. For EHR, the farm-gate costs also depend on yield (Equation 5.10).This relationship is estimated as a function of machinery costs per hour (US$/h) and machine productivity (t/h) [279] (see supplementary material – SM 5.3). The transportation costs of biomass residues, including costs of diesel, lubricants, labor and truck depreciation are fixed at 0.052 US$/t. km, which is an average for different road types.(i.e. highway, secondary and dirt roads), sourced from Jonker (2017) [281]. Similarly to Van der Hilst et al. [83], the transportation costs are calculated in a GIS environment by estimating the biomass density within a hypothetical radius, which varies according to the input capacity of the BJF plants (see table 5.3), and the spatial availability of biomass residues (equation 5.11).

Equation 5.9

$$SCS\_Cf = 71.88 \times EPr^{-0.631}$$

Item	Description	Unit
SCS_Cf	SCS farm-gate cost	US$/t
EPr	Environmental potential of SCS	t/ha

Equation 5.10

$$EHR\_Cf = 339.47 \times EPr^{-0.869}$$

Item	Description	Unit
EHR_Cf	EHR farm-gate cost	US$/t
EPr	Environmental potential of EHR	t/ha

Equation 5.11

$$TC_{P,r,p,y} = C_{P,r,y} \times \frac{2}{3} \times I_{Py}^{0.5} \times (EPr_{r,p,y} \times D_{r,p,y})^{-0.5}$$

Item	Description	Unit
$TC_{P,r,p,y}$	Biomass transportation cost of production route *P* and biomass residue *r* in pixel *p* in year *y* of	US$/t
$C_{P,r,y}$	Unit biomass transportation cost of production route *P* and biomass residue *r* in year *y*	US$/t km
I_{Py}	Input capacity of production route *P* in year *y*	t
$EPr_{r,p,y}$	Environmental potential of biomass residues *r* in pixel *p* in year *y*	t/ha
$D_{r,p,y}$	Density of biomass residues *r* within the radius in pixel *p* in year *y*	%

5.4.4.2. BJF production costs

In line with the studies of Jong et al. [90] and Cervi et al. [267], the techno-economic potential of BJF production is assessed for a greenfield BJF plant in two development stages: a pioneer plant and a *n*th plant. For 2015, a pioneer plant is assumed, and its production costs are largely affected by the techno-economic risks of building the first of kind BJF plant [90,214]. These risks are addressed by the cost growth factor based on the RAND Method [201], which accounts for the technological risks and the associated potential cost increase because of unforeseen problems to start up a first of a kind BJF plant [90]. It is applied as denominator for estimating the Fixed Capital Investment (FCI) and the operating expenditures (OPEX) of BJF pioneer plants in 2015. For almost all BJF production routes, this data is sourced from Jong et al. [90] (table 5.3). However, it has to be considered that the use of SCS for BJF has more technical constraints due to impurities (e.g. dust) and high ash and chlorine content, which can lead to a high degradation mainly in thermochemical technologies [217,250]. To address these constraints, the cost growth factor of SCS based pioneer plants has been adjusted (see the cost growth factor in table 5.3). For the *n*th plant in 2030, the expected development of the technological pathways at commercial scale is taking into account. Table 5.3 describes the techno-economic characteristics of the BJF production routes for 2015 and 2030 and all input data.

To calculate the BJF production costs at the plant gate of each production Route *P* in year y, the discounted annual biomass residues recovery costs (BC), FCI (I), annual operational – OPEX - costs (M) and annual revenues (Rev) from non-hydrocarbon co-products (e.g. electricity) are accounted over the plant years (t). The BJF production costs at plant gate are determined by dividing all the discounted costs and revenues by the discounted mass of hydrocarbon outputs (e.g. BJF, diesel, naphtha) as they present similar mass density [282], i.e. mass allocation.

Equation 5.12

$$BJFC_{Py} = \frac{\sum_{t=1}^{n}(I_{Py} + M_{Py} + BC_{Py} - Rev_{Py}) \times (1+r)^{-t}}{\sum_{t=1}^{n} Output_{Py} \times (1+r)^{-t}}$$

Item	Description	Unit
$BJFC_{Py}$	BJF costs of Production route *P* in year *y*	US$/t
I_{Py}	FCI of Production route *P* in year *y*	US$
M_{Py}	OPEX of Production route *P* in year *y*	US$
BC_{Py}	Biomass costs of Production route *P* in year *y*	US$
Rev_{Py}	Non-hydrocarbon revenues of Production route *P* in year *y*	US$
$Output_{py}$	Hydrocarbon outputs of Production route *P* in year *y*	t
t	Years	year
r	discount rate	%
n	BJF plant lifetime	-

The total BJF production costs (hereafter named as BJF total costs) are calculated by summing the BJF production costs at plant gate (i.e. equation 5.12) and the BJF transportation costs. The latter is calculated by using the spatial distribution of the airports in Brazil, and the current (2015) and planned (2030) highways (see Cervi et al. [267]). We assume that the BJF is transported by trucks to the nearest airport (see supplementary material – SM 4.6). The distances are estimated in a GIS environment and multiplied by the unit BJF transportation costs per road type expressed in tonne-kilometers, i.e. 0.054 US$/tkm for primary roads (i.e. inter-regional paved roads) and 0.22 US$/tkm for secondary roads (i.e. paved roads in poor conditions) [42,87].

Table 5.3: BJF conversion yield, techno-economic characteristics and input cost data of the BJF plants

Production route (ID)	BJF input capacity (Mt of biomass) [a]		BJF conversion yield (t of biomass / t of BJF) [b]			Cost-growth factor [c]	FCI [d] (US$/t biomass)		OPEX (US$/t biomass)		Source	Co-products [e]
	2015	2030	2015	2030	Source		2015	2030	2015	2030		
SCS_ATJ [f]	0.72	1.5	0.119	0.152	[178,182]	0.59	1207.7	510.3	279.6	148.3	[90,178,182]	D, El
SCS_PYR [g h]	0.6	0.8	0.065	0.065	[206]	0.35	3536.2	1229.7	224.8	86.4	[90,283]	N, D
SCS_FT [g i]	0.6	1	0.151	0.151	[178]	0.43	2113.7	875.3	73.4	35.8	[90,215]	N, El
SCS_HTL [g j]	0.35	0.8	0.15	0.15	[216]	0.38	2764.7	899.3	268.9	96.3	[216]	D, G
EHR_ATJ [f]	0.72	1.5	0.119	0.152	[178,182]	0.59	1207.7	510.3	279.6	148.3	[90,178,182]	D, El
EHR_PYR [g h]	0.6	0.8	0.065	0.065	[206]	0.37	3536.2	1229.7	224.8	86.4	[90,283]	N, D
EHR_FT [g i]	0.6	1	0.151	0.151	[174]	0.47	2113.7	875.3	73.4	35.8	[90,215]	N, El
EHR_HTL [g j]	0.35	0.8	0.15	0.15	[216]	0.4	2764.7	899.3	268.9	96.3	[216]	D, G

[a] The input capacities of the BJF plant are considered to be equal for both types of biomass residue.

[b] The BJF conversion yield, we assume a constant maximum BJF distillation/upgrading verified in the literature for both 2015 and 2030. In ATJ production routes, there is a slightly change over time due to improvements in the upstream processes of 2G ethanol production [182].

[c] The cost growth factors are sourced from de Jong et al. [90], which set the six main variables of the RAND Method (***pctnew, impurities, complexity, inclusiveness, commercialization status*** and ***project definition***) based on an extensive survey of the BJF market worldwide in 2015. In this study, we change the ***impurities*** variable from 4 to the maximum 5 level in all SCS based BJF pioneer plants due to higher impurity level of SCS [100], except the downstream ATJ plant, which is fed by ethanol from the upstream 2G plant. The cost growth factor of the 2G plant is set at 0.53, based on Kazi et al. [212]. As the ATJ technology has been commercialized aviation biofuels since 2016 [284], we also change the commercialization status from 0.06361 to 0.04011. See supplementary material – SM 5.3.

[d] A scale factor of 0.7 is used to adjust the FCI to the scale of the BJF plant. The original FCI data is updated to 2015 values by using the Brazilian inflation index (IGP-DI).

[e] Co-products from the BJF plant: D – Diesel; N – Naphtha; El - Electricity; G – Gasoline. The electricity in ATJ plants is supplied by the power plant from the 2G ethanol plant, which uses unfermented materials (lignin) to feed the boiler [45]. In the FT plants, the electricity is sourced from off-gases [206].

[f] The input capacity and progress development over time are aligned with the studies of Cervi et al.[267]. In their study, despite using eucalyptus pulpwood as feedstock, the same scale is applied herein to allow for a fair BJF production cost comparison. Moreover, no distinction between biomass residues pre-treatment are assumed between 2G from EHR and 2G from SCS. The main downstream processes in ATJ plants are dehydration, oligomerization and hydrogenation (i.e. off-site hydrogen supply).

[g] The 2015 scale for the thermochemical routes (PYR, FT and HTL) are based on other studies [214–216,283]. By 2030, HTL and PYR achieve the maximum scale of 800 kt/year input projected by Jong et al. [5]; while FT is expected to process 1 Mt/year of dry biomass according to the projections developed by E4tech [217].

[h] Main downstream processes: crude bio-oil production and upgrading. The hydrogen is produced on-site through steam reform [206].

[i] Main downstream processes: syngas production, gas cleaning, upgrading and separation. In this design, the hydrogen is produced on-site with hydrocracker recovery plant [206].

[j] Main downstream processes: biocrude production and upgrading. The hydrogen is produced on-site through steam reform [90].

5.4.5. Techno-economic potential of BJF

The techno-economic potential of BJF from biomass residues is defined as the amount of BJF that can be produced at cost below the Brazilian fossil jet fuel prices. For each grid cell, the minimum BJF production costs (hereafter named as min. BJF costs) across the production routes are determined for 2015 and 2030. The same approach was used in Cervi et al. [267] for assessing the techno-economic potential of BJF from energy crops. Firstly, we compare the min. BJF costs from biomass residues to the range of current fossil jet fuel prices at Brazilian airports (19 - 65 US$/GJ) [226] to quantify the range of the techno-economic potential. The fossil jet fuel price data includes additional components (e.g. profits, income and state taxes) that are not accounted for in the BJF cost calculation due to high uncertainty and limited data availability. Secondly, BJF production costs from all production routes are assessed to identify alternative options competitive with fossil jet fuel prices. Lastly, we quantify the regional techno-economic potential (i.e. macro-regional level) of each production route by comparing the BJF production costs of each pixel with the fossil jet fuel price of the nearest airport.

5.4.5.1. Sensitivity analysis

We develop a sensitivity analysis to account for the uncertainty in the potential and the costs of BJF production from biomass residues. As this study is divided in two main components (i.e. environmental potential of biomass residues and techno-economic potential of BJF from biomass residues), we assess the uncertainty of key parameters in each of these components. For the environmental modeling, we assumed biomass yield developments towards 2030 based on historical yield developments. However, yield developments are uncertain and may not follow the historical yield growth rate as it can be rather affected by climate, land quality, management factors and technology development [159]. To account for this, we include the conservative assumption of stagnant yield levels (at the level of 2015) in this sensitivity assessment.

For the techno-economic assessment, we originally apply the cost growth factor to address the technological progress of the BJF production routes between 2015 to 2030. However, in the past two decades little progress has been made in reducing capital costs, especially in the thermochemical pathways [232]. Therefore, in this sensitivity analysis we also account for a more conservative assumption on technological progress, assuming no difference in BJF technology deployment between 2015 and 2030. Hence, it is assumed that the BJF plants in 2030 are also pioneer plants (instead of *n*th plants).

5.5. RESULTS

5.5.1. Environmental potential of biomass residues

The environmental potential of biomass residues is estimated at approximately 70 Mt/yr (0.9 EJ/yr) in 2015 and 102 Mt/yr (1.4 EJ/yr) in 2030. The SCS accounts for 62% (43 Mt/yr) of the biomass residues potential in 2015 and for 70% (71 Mt/yr) in 2030. The increase in SCS availability towards 2030 is aligned with the projected overall increase in sugarcane production of 63%. Hence, the expansion of sugarcane areas mostly take place in areas with similar agro-ecological suitability, with comparable risk of erosion and/or SOC depletion. The EHR potential increases by 17%, from 26 Mt/yr in 2015 to 31 Mt/yr in 2030. This exceeds the projected increase in eucalyptus production (13%) in this time period. The expansion of eucalyptus areas in Brazil is expected to take place around the current eucalyptus areas, and therefore in similar conditions

The increase of SCS supply over time is largely related to the expansion of sugarcane areas in the Center-West of Brazil, see in Figure 5.4 which shows the spatial distribution of the environmental potential of SCS in 2015 and 2030. The areas with high SCS availability are concentrated in few Center-South states (i.e. mainly São Paulo and Goias), whereas the areas with moderate to low availability (< 6 t/ha/yr) are scattered in the Center-South and in the Northeast. For EHR, the areas with low residue availability (< 3 t/ha/yr) are widely distributed from the Northeast cost to the border of Amazon regions, while areas with high residue availability (> 5 t/ha/yr) are clustered in the extreme South and at the border of the states of Bahia and Minas Gerais.

For both 2015 and 2030, the erosion risk reduces the theoretical potential of SCS (i.e. 85 Mt/yr in 2015 and 141 Mt/yr in 2030) by 30%, whereas the theoretical potential of EHR (i.e. 41 Mt/yr - 48 Mt/yr of SCS) is reduced by 35% (figure 5.5). This means the expansion areas face a similar erosion risk as current sugarcane and eucalyptus production areas. Nonetheless, it is clear that an important share of the EHR potential is limited by erosion risk in both 2015 and 2030. Furthermore, the theoretical potential of SCS is decreased by 18% (in 2015) and 21% (in 2030), because of the SOC balance constraint, which is negatively affected by the expansion of sugarcane on sandy soils. For EHR, in both 2015 and 2030, the theoretical potential is reduced by less than 1% because of the SOC balance constraint. This is mainly due to the recurrent annual input of SOC from litterfall, which positively impact SOC dynamics. Therefore, for SCS the two environmental constraints have about similar impact on the SCS potential, with a significant reduction from the SOC constraint, whereas the EHR potential is mostly constraint by erosion risk.

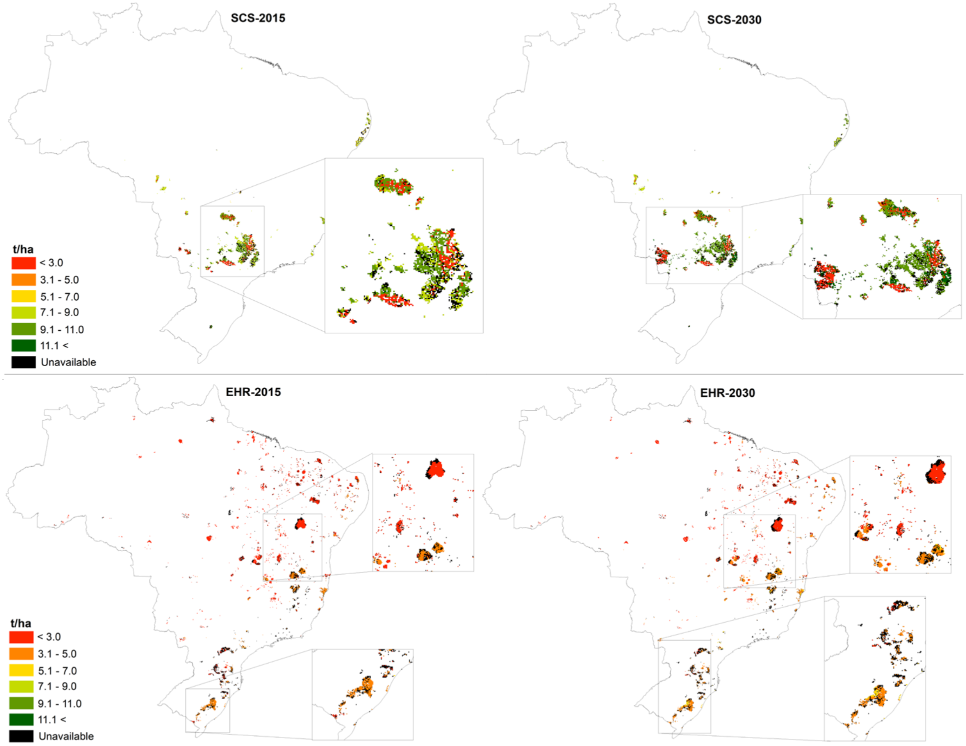

Figure 5.4: Spatial distribution of the environmental potential (removal rate – t/ha) of SCS and EHR in Brazil in 2015 and 2030.

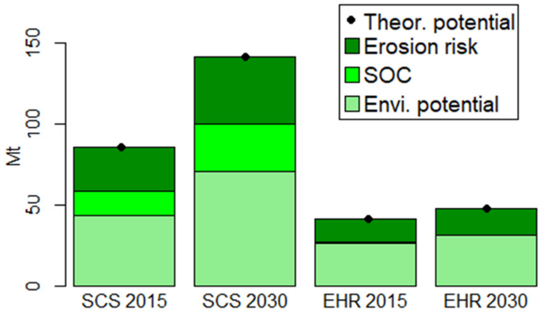

Figure 5.5: The effect of environmental constraints (erosion risk and SOC balance) on the environmental potential of SCS and EHR in 2015 and 2030.

5.5.2. Techno-economic potential of BJF from biomass residues

5.5.2.1. Biomass residues recovery costs

The majority of the environmental potential of SCS and EHR is available at 30 US$/t to 100 US$/t of biomass residues total recovery costs (figure 5.6 – left hand side). Regardless the type of biomass residue and the time horizon, very little is supplied beyond 100 US$/t (figure 5.6 – left hand side). For SCS, 40 Mt (2015) and 60 Mt (2030) is available below 50 US$/t, whereas the EHR shows a smaller variation as it accounts for 10 Mt (2015) and 7 Mt (2030). Fig 6 (right hand side) displays the cost-breakdown of biomass residues. On average, the farm-gate costs of SCS are slightly higher than EHR due to the complexity of the baling system and to a lesser extent the fertilizer cost related to nutrient compensation. In 2015, farm-gate cost comprises about 40% (EHR) - 60% (SCS) of biomass residues recovery costs (figure 5.6 – right hand side). By 2030, the biomass residues transportation costs increase considerably due to a larger radius required to recover a higher amount of biomass residues used as input in the BJF plant. In addition, there is increasing expansion of both sugarcane and eucalyptus to areas with poorer agro-ecological conditions, thereby affecting even more the transportation distances. The transportation costs are even more relevant for EHR, as it encompasses 60% (in 2015) - 66% (in 2030) of the total residue recovery costs, due to the relatively large service areas of logging operations. These results correspond to the ATJ production routes, which are the plants with the largest input capacity. In the remaining production routes, biomass residue transportation costs are slightly lower.

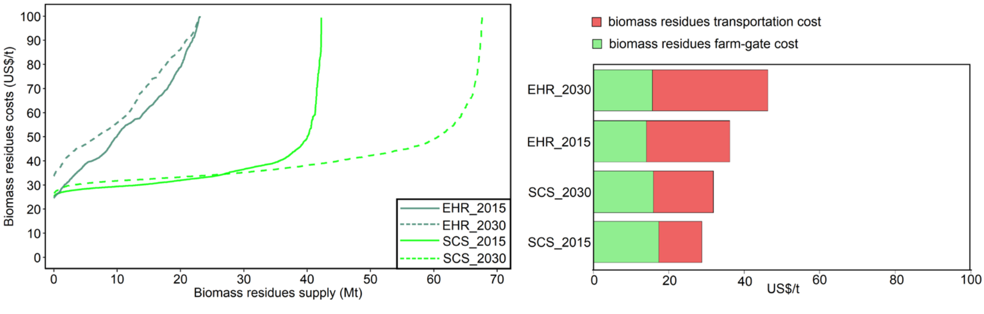

Figure 5.6: On the left hand side: biomass residues cost supply curves for SCS and EHR in 2015 and 2030. On the right hand side: biomass residue recovery cost breakdown with the share of the farm-gate and transportation costs for SCS and EHR.

5.5.2.2. BJF production costs

The BJF production costs present a spatial variability range between 46.5 US$/GJ and 247 US$/GJ in 2015 and between 19.6 US$/GJ and 135 US$/GJ in 2030 (figure 5.7). The BJF production routes based on SCS have a higher spatial variability than EHR, which is caused by the presence of areas with very high SCS recovery costs (figure 5.7). These SCS areas often require high mulching levels to maintain SOC levels, resulting a low availability to be recovered. On average, the production costs of BJF based on SCS are slightly lower than BJF from EHR. This is mainly caused by lower biomass residue recovery cost. The BJF production routes with the lowest average costs in 2015, are those from FT technology (SCS_FT and EHR_FT), which currently has the second best TRL, and also high conversion yields. In 2030, the average BJF production costs are reduced by half because of the lower cost of the *n*th plant compared to pioneer plant. The HTL production routes stand out with the lowest production costs due to high conversion yields and the projected sharp decrease of the capital intensity towards 2030. PYR based production routes are characterized by the highest production cost reduction, due to the high projected technological development of their *n*th plants.

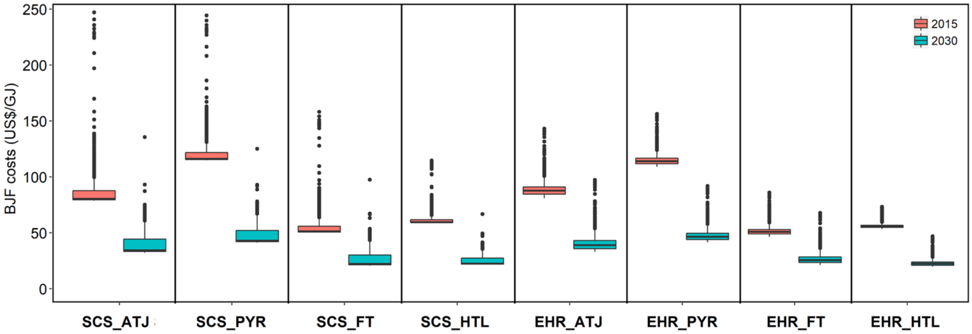

Figure 5.7: Boxplots displaying the BJF production costs variability of each production route in 2015 and 2030. Note that there is a high number of outliers at the higher end, which indicates the presence of areas with very high biomass residues recovery costs (i.e. very low biomass residue availability). For SCS based production routes, the boxplot median is very close to the lower limit, which indicates large number of areas with high and homogeneous levels of SCS availability.

In figure 5.8, we detail the BFJ cost-breakdown for each production route. For 2015, the biomass cost component has a low contribution to the overall BJF production cost. Because of the high capital demanding technologies (e.g. HTL, FT and PYR), the biomass costs are often low compared to the conversion costs. The share of biomass residues costs increases towards 2030 mainly due to a strong reduction in the capital costs, and only to a marginal extent to the increase in biomass residues costs in some locations. The operational cost contribution is significantly high in ATJ plants due to 2G ethanol production needed, and also in PYR plants due to high utility requirements (e.g. natural gas). Moreover, the electricity revenues in the ATJ and FT plants only marginally (1 - 3%) reduce BJF production costs. Finally, as expected, the BJF transportation cost contributes very little to the total BJF production costs. The areas of biomass residues supply are often close to the main highways as well as to the main Brazilian airports. The BJF transportation costs of SCS based routes remains constant over time around 0.1 US$/GJ and varies between 0.32 US$/GJ and 0.26 US$/GJ for EHR based routes in 2015 and 2030.

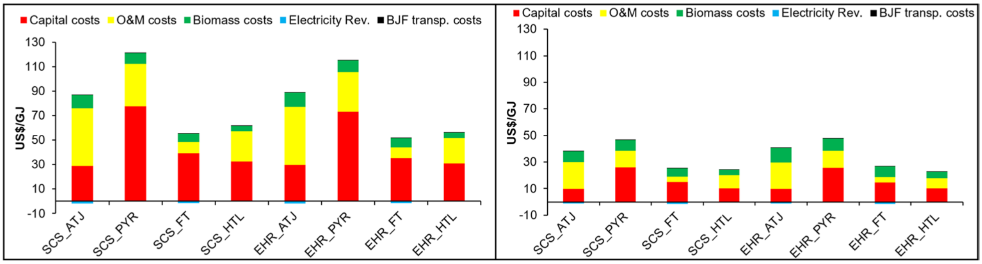

Figure 5.8: Average BJF production cost breakdown showing the contribution of biomass, capital, operational and BJF transportation costs to the BJF production costs of each routes in 2015 and 2030.

5.5.2.3. Techno-economic potential assessment

The techno-economic potential of BJF is defined as the volume of BJF that can be produced from SCS and EHR at cost below fossil jet fuel prices. For each pixel with SCS or EHR availability, the lowest (min.) cost BJF production route is selected. The techno-economic potential of BJF from SCS and EHR is composed by SCS_FT, EHR_FT, SCS_HTL and EHR_HTL production routes with a BJF supply ranging from 0.45 EJ/yr in 2015 to 0.67 EJ/yr in 2030. These quantities are delivered with min. BJF total costs below the maximum fossil jet fuel price of 65 US$/GJ at Brazilian airports. The BJF cost-supply curve of the techno-economic potential highlights the significant difference between the BJF total costs in 2015 and in 2030 (left hand side of figure 5.9). In 2015, the min. BJF total costs vary spatially between 46 US$/GJ and 65 US$/GJ. The BJF potential consists mainly of SCS_FT and EHR_FT production

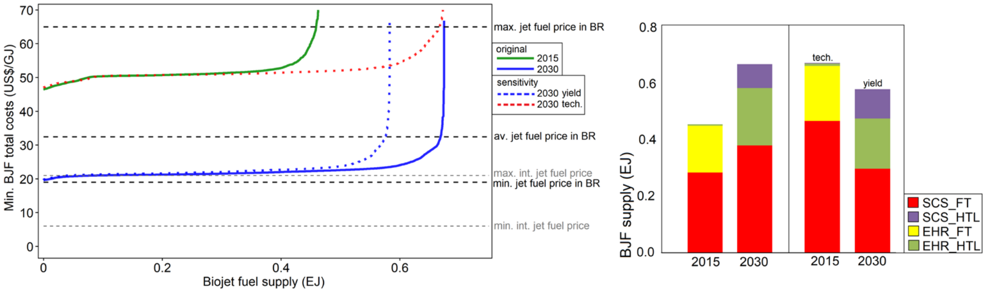

Figure 5.9: On the left hand graph, the solid lines show cost supply curves of the techno-economic potential of BJF from biomass residues in 2015 and 2030, and the dashed lines show the sensitivity scenarios (tech. and yield). The dashed gray lines show the range of the international jet fuel price at the refinery (U.S. Gulf Coast kerosene jet fuel spot price) [228]. The dashed black lines represent the range of jet fuel prices commercialized in the Brazilian airports [226], which is used to measure the techno-economic potential of BJF from biomass residues. On the right hand graph, the stack bars show the BJF production routes that contribute to techno-economic potential.

routes, with a small contribution from SCS_HTL (right hand side of figure 5.9). Compared to the current fossil jet fuel prices, the techno-economic potential of BJF from biomass residues in 2015 is in between the average and maximum jet fuel prices in Brazil (figure 5.9). In 2030, the min. BJF total costs range from 19 US$/GJ to 49 US$/GJ, which indicates that BJF from crop residues could reach costs comparable with the fossil jet fuel prices of the largest airports in Brazil (e.g. Sao Paulo, Rio de Janeiro, Brasilia). The SCS_FT production route remains dominant in the techno-economic potential of 2030. However, SCS_HTL and EHR_HTL show a substantial increase compared to 2015, which shows the large projected technologic improvements in HTL technology in the coming decade.

In the sensitivity analysis, the results show that assumptions on yield and technology improvement have a significant effect on the BJF total costs and on the techno-economic potential in 2030. Assuming a BJF pioneer plant in 2030 (instead of BJF *n*th plant), the minimum BJF total costs are in line with the BJF total cost in 2015 (sensitivity tech. in figure 5.9) until a supply of 0.4 EJ. The increase of biomass recovery cost towards 2030 is marginal mainly for SCS, with no large effect on the minimum BJF total costs. In this scenario, the techno-economic potential of BJF in 2030 is the same as the original assessment. Hence, when considering the availability of biomass resources and the maximum fossil jet fuel price in Brazil as a cut-off for determining the techno-economic potential, the deployment of hypothetical BJF pioneer plants in 2030 may not represent a lower BJF supply, even though the costs of production in pioneer plants is a factor of two higher than in *n*th plants. In the other sensitivity assessment (yield), in which we assume no biomass yield increase towards 2030, the BJF total costs vary between 19 US$/GJ and 57 US$/GJ in 2030 (sensitivity yield – figure 5.9), This is in line with the cost range for 2030 assuming a biomass yield increase, due to the very little effect of biomass residues costs on the BJF total costs for the production routes that contribute to the techno-economic potential. However, assuming no yield increase towards 2030, decreases the techno-economic BJF potential by 0.1 EJ, as less BJF is produced.

Figure 5.10 shows the spatial distribution of the techno-economic BJF potential with the min. BJF total costs for 2015 and 2030. For 2015, it is relatively easy to detect the most promising regions to produce the cheapest BJF ranging from 40 to 50 US$/GJ (shades of orange) in the South and few areas of the state of Bahia (i.e. Northeast region), which are characterized by the high EHR availability. The majority of SCS based production routes is produced at higher costs in in the Southeast of Brazil due to the current technical challenges of converting SCS into BJF. In 2030, however, it is projected that almost all areas where EHR or SCS are available could produce BJF between 20 and 30 US$/GJ.

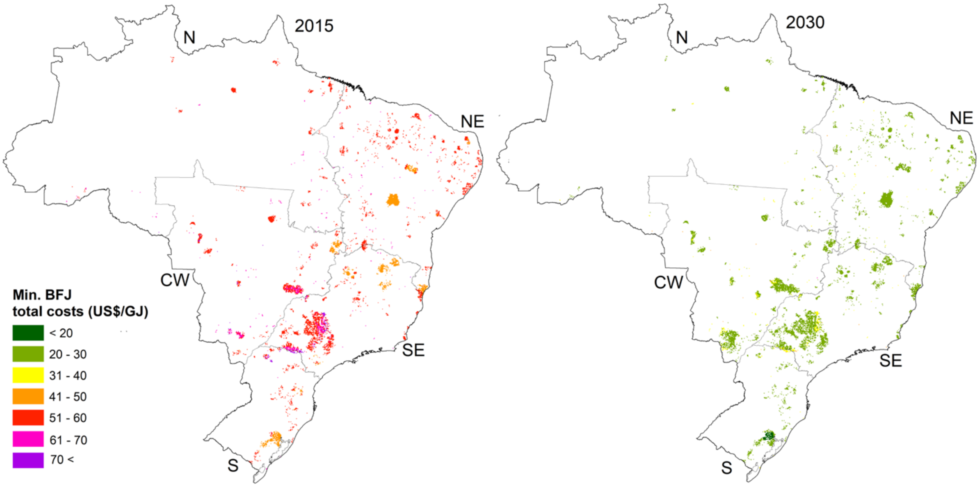

Figure 5.10: Spatial distribution of the min. BJF costs from biomass residues in 2015 and 2030 in the Brazilian macro-regions. N: North; NE: Northeast; SE: Southeast; CW: Center-West; S: South.

In figure 5.11, we plot the cost supply curves for all the BJF production routes that present at least in one location BJF total costs below the maximum fossil jet fuel price in Brazil (65 US$/GJ). Most of these BJF production routes do not contribute to the techno-economic potential (i.e. these production routes do not present the lowest BJF production cost at any location), which is only formed by the HTL and FT based production routes (see figure 5.9). However, it should be noted that other production routes also present a very good performance either in producing BJF total lower than the fossil prices (e.g. SCS_HTL in 2015) or with large possibility of BJF supply (e.g. EHR_ATJ and SCS_ATJ in 2030). At several locations, many production routes could produce BJF below the fossil jet fuel price.

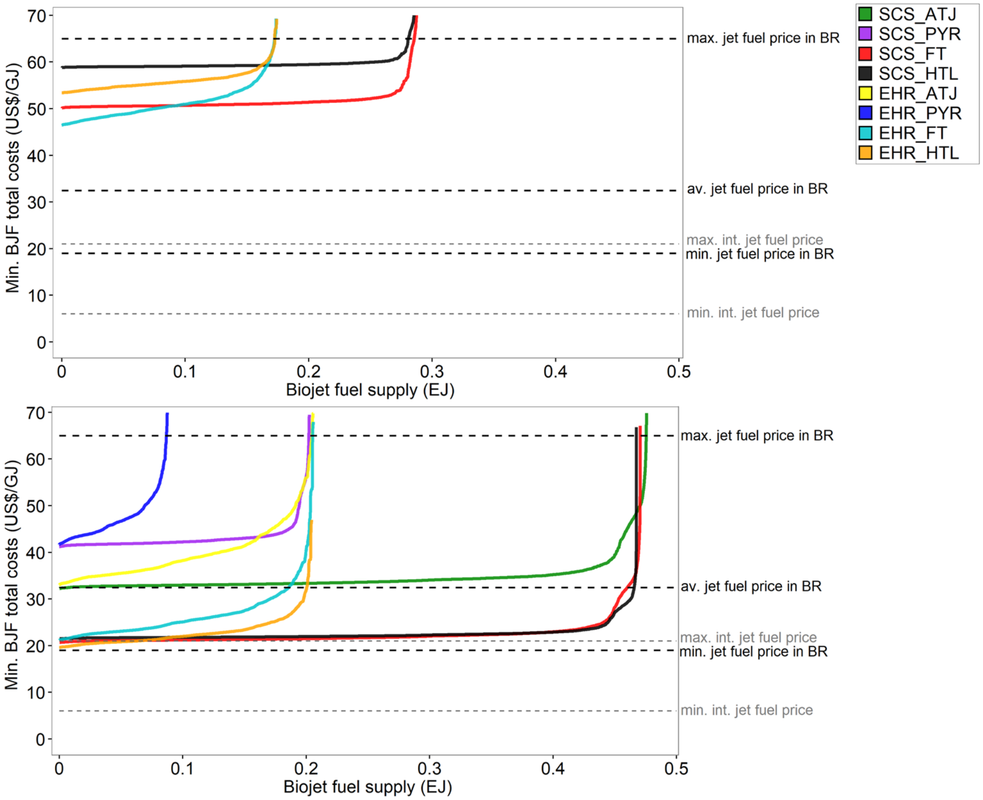

Figure 5.11: BJF cost-supply curves of all the production routes assessed in 2015 and 2030.

Figure 5.12 shows for every macro-region, which production route could produce BJF below the fossil jet fuel price at the nearest airport. It should be noted that fossil jet fuel prices vary across airports within the macro-regions. We assess that only EHR_PYR is not able to supply BJF production costs below the fossil jet fuel prices, whereas the remaining seven production routes could achieve production cost below this threshold in various regions. Particularly, the Center-West and Southeast regions present a high diversity of production routes that can produce up to 0.35 EJ/yr of BJF at costs below the fossil jet fuel prices.

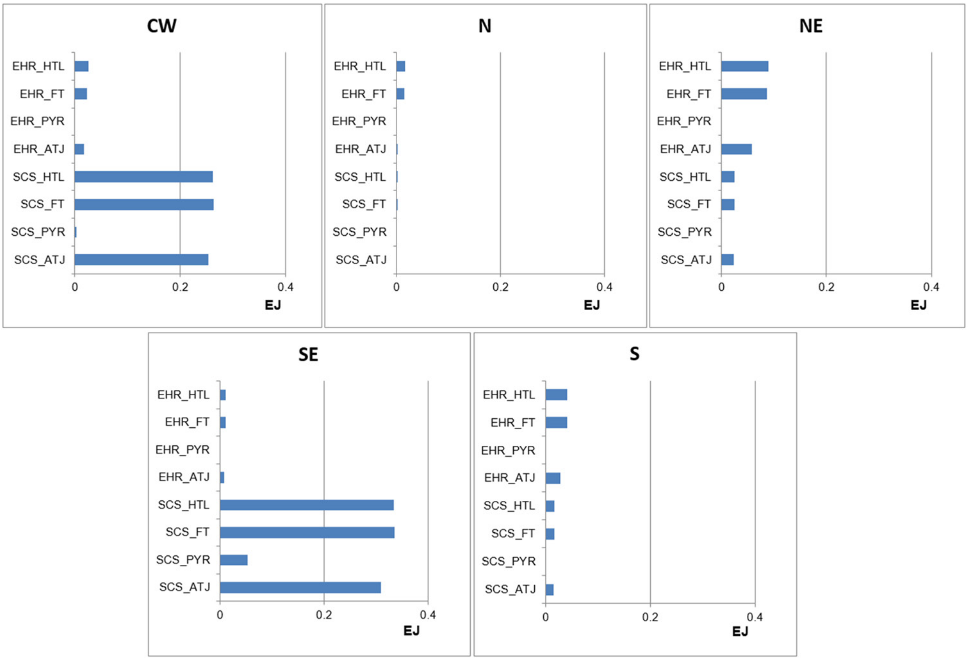

Figure 5.12: Techno-economic potential of BJF from biomass residues from each production routes in 2030 at Brazilian macro-regional level (i.e. South - S, Southeast - SE, Northeast - NE, North - N and Center-West - CW). Note that the potentials provided for each macro-region partly overlap (i.e. available biomass residues could reach BJF total cost below fossil yet fuel prices via several production routes), and should therefore not be summed.

5.6. DISCUSSION AND CONCLUSIONS

5.6.1. Environmental potential of biomass residues for BJF production

The environmental potential of biomass residues is projected at 43.3 Mt/yr in 2015 and 70.8 Mt/yr in 2030 for SCS, and 26.4 Mt/yr and 30.9 Mt/yr for EHR. The increase of the environmental potential over time is primarily a result of the crop yield development and the expansion of eucalyptus and sugarcane areas. The majority of the SCS potential is found in the Southeast and Center-West regions, due to presence of the sugarcane ethanol industry. Potential areas for SCS in the Northeast coast are also available, which already has a 2G ethanol plant based on SCS in Alagoas state (Granbio SA) [285]. For EHR, the South and Northeast regions present the highest environmental potential in some specific states (Paraná and south of Bahia). The results also show that SOC is a major constraint affecting the environmental potential of SCS, mainly in the expansion areas (Western of São Paulo and Center-West region). In general, we find that the SOC balance tool can easily be applied in sugarcane systems and it is easily combined with spatial datasets (i.e. soil and crop-yield data). However, the reliability of the results needs to be further improved by calibrating the model on in-depth field data of specific case studies at local level. For long term projections on SOC dynamics, more detailed simulations are needed (e.g. making use of biogeochemical models) – especially for eucalyptus, and additional environmental factors should be included (e.g. climate data) [286,287]. The environmental potential of EHR is more constrained by the erosion risk (spatially heterogeneous), as the litterfall from eucalyptus trees positively affect the SOC balance. This high risk of erosion in eucalyptus can be critical if eucalyptus monoculture expands over marginal lands (e.g. degraded pasturelands) in the coming years. Implementing agroforestry systems instead of monoculture eucalyptus plantations could potentially mitigate these problems and may offer higher changes for EHR recovery [288]. The reliability of our results on soil loss can be increased by including more spatial detailed data (e.g. slope, soil), long term projections on e.g. the effect of climate change on rainfall erosivity), as well as local, more detailed studies in different agro-ecological conditions to calibrate the soil loss estimations.

Previous studies estimated the potential supply of SCS in Brazil ranging from 42.77 Mt/yr in 2010's [149] to 135.6 Mt/yr in 2020's [105,107]. These estimations are primarily based on projections of sugarcane production, combined with a fixed country-wide SCS removal rate to address the soil and agronomic constraints. In our study we developed a more refined approach as the annual removal rate varies for each grid cell and over time driven by the SOC balance calculation. However, competitive uses and practical restrictions (e.g. crop features and treatments, density of the fields, transportation distance), which may affect the SCS that can be mobilized for BJF, are not considered in this study. For EHR, only Roozen [149] has quantified the environmental potential in Brazilian Center-South from 6 Mt/yr (in 2012) to 11 Mt/yr (in 2030), applying a fixed removal rate of 52%. The limited number of studies on EHR potential in Brazil can be explained by the still very limited use of these residues in the pulp and paper industry, but also due to the current lack of integration of this industry with bioenergy supply chains. However, there is a large EHR potential, i.e. the theoretical potential of a single harvested field is around 45 t/ha of EHR. Currently, some sugarcane mills use EHR as a supplementary resource for bioelectricity production in high demanding periods (e.g. high bioelectricity market prices) [164]. Given that, we expect that the potential application of biomass residues in the BJF industry is likely mainly based on SCS and supplemented with HER.

In this study, we focused on SCS and EHR only. However, considering that Brazil is one of the leading agricultural producers in the world, other agricultural residues could have large potentials as well. The majority of environmental impacts of producing bioenergy from biomass residues are related to agricultural management and recovery operations. In this study, SOC and erosion risk related to biomass residue removal is considered. However, other environmental impacts (such as GHG emissions, impact on water availability and biodiversity) and impacts related to the rest of the supply chain (i.e. transport, conversion, distribution and use) should also be quantified for a holistic view on the environmental potential of BJF from residues. The spatio-temporal approach demonstrated in this study is an important step in that direction.

5.6.2. Techno-economic potential of BJF from biomass residues

The techno-economic potential of BJF from biomass residues is significantly higher in 2030 (i.e. 0.67 EJ/yr for a range of min. BJF total costs between 19 US$/GJ and 66 US$/GJ) than 2015 (i.e. 0.45 EJ/yr for a much higher range of min. BJF total costs between 46 US$/GJ and 114 US$/GJ). In Cervi et al. [267], part of the techno-economic potential sourced from eucalyptus wood based FT and HTL greenfield plants in Brazil achieved min. BJF total costs of 47 – 64 US$/GJ for FT in 2015, and 20 – 102 US$/GJ for HTL in 2030. Using wheat straw from Europe as feedstock in BJF technologies, de Jong et al. [90] found a range of min. BJF selling prices between 32 – 88 US$/GJ in BJF *n*th plants, with HTL leading the lower costs, whereas ATJ resulted in the highest costs. However, Klein et al. have shown that FT and ATJ from SCS could reach a minimum selling prices (at plant gate) between 10 - 19 US$/GJ if BJF production is integrated with existing biorefineries in Brazil [85]. Therefore, different co-production scenarios can be also further explored spatially explicitly.

Currently, the demand for fossil jet fuel in Brazil is close to 0.26 EJ/yr [235] with jet fuel prices between 19 US$/GJ and 65 US$/GJ, with an average of 32 US$/GJ [226]. Based on our results, it is unlikely that the BJF from residues can compete with fossil jet fuel in the most demanding regions in 2015 (or in a 2030 in absence of technological learning as demonstrated in the sensitivity analysis) due to the low fossil jet fuel price. However, due to the large extent of the country and the current lack of infrastructure for fuel distribution to remote areas in the Center-West and North of Brazil (see Carvalho et al. [76] for analyzing the location of refineries and airports in Brazil), niches for the development of competitive BJF from biomass residues may exist and should be also explored in more specific case studies. For a current wide implementation of BJF from biomass residues, more incentives (e.g. lower interest rates, carbon saving credits), other strategies to lower production costs (e.g. lowering the residue supply cost, integration with existing biorefineries) and BJF technologies development are needed to increase the competitiveness of BJF.

For 2030, all production routes are assessed as *n*th plants. This is based on the premise that these technologies will mature over the next decade, largely due to deployment also outside Brazil. The results show that under these assumptions, BJF from biomass residues becomes much more competitive, with production costs very close to the minimum Brazilian fossil jet fuel price. Apart from the increase of HTL technology potential, we also see alternative BJF production routes having competitive BJF costs in the Southeast and Center-West regions, where biomass residues are available. For 2030, it is projected that the

Brazilian fossil jet fuel demand increases to almost 0.4 EJ [236], while the global demand is projected to increase to 15 EJ [237]. By that time, we expect that – depending also on policy incentives and other factors – a part of the projected BJF techno-economic potential of 0.8 EJ may be supplied. Meanwhile, efforts are needed to enable the realization of the techno-economic potential, thereby optimizing the BJF plants location and scale and increasing overall infrastructure development of fuel distribution hubs, supply of utilities (e.g. electricity, hydrogen, yeasts) as well as human resources.

Conclusions

6

6.1. THESIS BACKGROUND

Developing transition pathways from fossil to renewable energy sources is of paramount importance to mitigate greenhouse gas (GHG) emissions [2]. Brazil is one of the largest producers of renewable energy [9] due to the abundance of natural resources. Currently, a significant share (~45%) of its primary energy consumption is supplied by renewable sources, of which 1.6 EJ is supplied by hydropower and 3.6 EJ by biomass [10]. Of modern renewable energy resources, biomass for bioenergy is one of the most flexible options to reduce fossil energy dependency as it provides a diversified portfolio for different uses, e.g. biofuels, heat, electricity, chemicals [3]. Bioenergy in Brazil is mostly represented by the sugarcane ethanol industry, which is projected to increase by 5%/year towards 2030 [25]. The sugarcane ethanol sector also supplies bioelectricity produced from sugarcane residues. Bioelectricity currently represents approximately 7% of the national electricity mix [10,15,16]. Energy outlooks for Brazil project biomass and other renewables to substitute part of the fossil resources in the coming decade, as well as to supply part of the growing electricity demand [17]. In parallel, emerging bioenergy systems, notably biojet fuels (BJF), have also gained momentum due to ambitious GHG reduction targets established by the aviation sector. BJF production could possibly demand large amounts of biomass resources depending on the market development. In Brazil, it could be mostly sourced from energy crops and biomass residues, and should be aligned with the most recent international standards of sustainable bioenergy production, e.g. GHG emission reduction, ecological preservation and social welfare [23]. Considering that the demand for current bioenergy applications is already projected to grow, and that emerging BJF use may further increase the demand for biomass resources, it is pivotal to monitor and quantify the biomass resources and bioenergy potentials.

Bioenergy potentials can be quantified at various levels: theoretical, technical, economic (techno-economic or market), environmental (or ecological), and implementation potential. The majority of studies on bioenergy potentials have investigated environmental impacts and economic factors. The environmental potential is the share of the technical potential that can be obtained under several environmental constraints such as carbon and water footprint, soil quality and biodiversity [289]. The techno-economic potential represents the share of the technical potential which meets economic criteria, such as competitiveness with fossil fuel [27]. However, it is difficult to quantify environmental and techno-economic potentials of bioenergy production due to the spatial and temporal variability of environmental impacts and techno-economic factors. Therefore, a key research challenge on bioenergy potential quantification is to address environmental impacts and techno-economic factors in a spatially and temporally explicit manner.

Bioenergy potentials can be evaluated spatially explicitly at different geographical scales. Based on a literature review, three main knowledge gaps are highlighted when assessing the potentials of bioelectricity and BJF in Brazil. Firstly, spatially and temporally explicit variation of land availability, yields from energy crops and biomass residues availability are often lacking in bioenergy potential assessments. Secondly, most studies do not account for the spatial and temporal variation of biomass and land availability, biomass production costs and the developments in technology and infrastructure availability to quantify the techno-economic and environmental impacts and potentials of bioenergy. Lastly, bioenergy potentials are affected by the interplay of local and regional factors. Therefore, it is important to assess both scales simultaneously.

6.2. AIM AND RESEARCH QUESTIONS

The objective of the thesis is to spatially explicitly assess the current and future environmental and techno-economic potential of bioenergy in Brazil at different geographical scales. To meet this objective, the following research questions were addressed:

- I - How to spatially explicitly quantify the environmental and techno-economic potential from biomass residues and energy crops?
- II – How to spatially explicitly quantify the environmental and techno-economic potential of bioenergy supply chains given the development of conversion technologies and infrastructure?
- III - What is the current and future environmental and techno-economic potential of bioelectricity and BJF supply chains in Brazil from energy crops and biomass residues, and what is the spatial distribution?

Table 6.1: Overview of the research questions addressed in each chapter of the thesis. Light green indicates that the chapter partially addresses the research question. Dark green indicates that the chapter fully addresses the research question.

Chapter	Title	Research questions		
		I	II	III
2	Bioelectricity potential from ecologically available sugarcane straw in Brazil: A spatially explicit assessment	▨	▨	▨
3	Spatial assessment of the techno-economic potential of bioelectricity from sugarcane straw	▨	■	▨
4	Spatial modeling of techno-economic potential of biojet fuel production in Brazil	▨	▨	▨
5	Mapping the environmental and techno-economic potential of biojet fuel production from biomass residues in Brazil	▨	■	▨

6.3. SUMMARY OF THE CHAPTERS

In chapter 2, the bioelectricity potential from ecologically available sugarcane straw in the state of Sao Paulo (Brazil) in 2012 is assessed at multiple scales. A spatially explicit approach is employed taking into account the spatial distribution of sugarcane fields, the spatial variation of sugarcane yield based on remote sensing data, and the location and capacity of each sugarcane mill. A business as usual, a moderate and a high scenario are generated, in which the amount of straw that can be removed given environmental constraints is varied. The estimated environmental potential of bioelectricity from sugarcane straw ranges between 18.7 and 45.8 TWh depending on the scenario. This equals to 22% – 58% of the total electricity produced in São Paulo in 2012. The results show large geographical differences, with generally higher potentials and shorter collection radiuses for the mills in the traditional sugarcane areas in the Northeast of Sao Paulo state then for the mills in the expansion areas in the West region of Sao Paulo state. Bioelectricity from sugarcane straw could have a significant contribution to the electricity supply in Brazil, but economic constraints need to be further investigated. The identification of regions and sugarcane mills with the highest potentials for bioelectricity could support local and regional decision making on bioenergy planning.

Chapter 3 follows up on chapter 2 and aims to spatially assess the techno-economic potential of bioelectricity from sugarcane straw of the mills in São Paulo state (Brazil). The cost of the bioelectricity supply chain is quantified spatially explicitly. It is assumed that all 174 mills in Sao Paulo are equipped with an adjacent power plant, and that all sugarcane straw within the collection radius of the mill can potentially be used in this adjacent power plant. The bioelectricity costs are calculated taking into account the spatial variation in biomass costs, the scale of the power plant, the scale-dependent efficiency, the investments and operational costs, and the cost of connecting to the nearest transmission infrastructure. The straw costs are assessed making use of the spatial information on straw availability and the collection radius of the mills derived from chapter 2 considering the moderate scenario on the environmental potential of sugarcane straw. The bioelectricity costs range between 68 and 266 US$/MWh across the mills. The mills with high bioelectricity potential and low costs are generally large mills located in traditional sugarcane areas in the Northeast of Sao Paulo State, characterized by suitable agro-ecological conditions. Assuming a cut-off price of 80 US$/MWh, the techno-economic potential of bioelectricity from sugarcane straw in Sao Paulo is 14.2 TWh, which equals 10% of total electricity consumption of the state in 2012.

The objective of chapter 4 is to assess the recent and future techno-economic potential of BJF production in Brazil and to identify location specific optimal combinations of energy crops and technological conversion pathways. In total, thirteen BJF production routes (hereafter named as supply chains) are assessed through the combination of various crops (corn, sugarcane, eucalyptus, sweet-sorghum, soybeans, sunflower, oil palm and macaw palm) and BJF conversion technologies (Alcohol To Jet - ATJ, Direct Sugar to HydroCarbons – DHSC, Fischer-Tropsch – FT, HydroThermal Liquefaction – HTL, Hydroprocessed Esters and Fatty Acids – HEFA). Spatially explicit projections of future land use change are considered to identify potential land availability for biomass production. With the spatial distribution of the land availability, spatial variation of agro-ecological suitability for energy crops, and temporal yield developments, biomass production potential and costs are calculated. The BJF production costs are calculated by taking into account the development in the technological pathways and in plant scales. The techno-economic potential is determined by calculating the minimum BJF total costs across all production pathways for each location of available land and comparing this with the range of fossil jet fuel prices. The techno-economic potential of BJF ranges from 0 to 6.4 EJ in 2015 and between 1.2 – 7.8 EJ in 2030, depending on the reference fossil jet fuel price, which varies from 19 US$/GJ to 65 US$/GJ across airports. The techno-economic potential is composed of various supply chains. The Northeast and Southeast region of Brazil present the highest potentials with several viable BJF supply chains (e.g. ATJ from sugarcane, HTL from eucalyptus, ATJ from corn), whereas the remaining regions only have a few promising BJF supply chains (e.g. HEFA from oil palm). The maximum techno-economic potential of BJF in Brazil could meet almost half of the projected global jet fuel demand in 2030.

Chapter 5 assesses the recent and future environmental potential of crop residues and techno-economic potential of BJF production in Brazil. Different BJF supply chains are evaluated from sugarcane straw (SCS) and eucalyptus harvest residue (EHR) as biomass residue, and four different technological pathways (Alcohol To Jet – ATJ, Fischer-Tropsch – FT, HydroThermal Liquefaction – HTL, Pyrolysis - PYR). For the assessment of the environmental potential of SCS and EHR, the erosion risk and the Soil Organic Carbon (SOC) balance are taken into account, as these are considered the key constraining factors for biomass residues removal. The environmental potential is determined, making use of spatio-temporal projections of land use in Brazil and by modelling the erosion risk and the SOC balance spatially explicitly. This results in maps of the environmental potential of SCS and EHR at pixel level. The assessment of the techno-economic potential of BJF of SCS and EHR considers the BJF total costs, which is resulted from the summation of biomass residues recovery costs, BJF conversion costs and BJF transportation costs. These BJF total costs are compared to the range of fossil jet fuel prices at Brazilian airports to quantify the techno-economic potential. The environmental potential of biomass residues varies from 70 Mt in 2015 to 102 Mt in 2030, with sugarcane straw being highly constrained by SOC, whereas eucalyptus harvest residues are more constrained by the high erosion risk. These quantities can generate a techno-economic potential of BJF ranging from 0.45 EJ in 2015 (46 US$/GJ – 65 US$/GJ) to 0.67 EJ in 2030 (19 US$/GJ – 65 US$/GJ). In 2030, several BJF production routes can be competitive with fossil BJF prices. The Northeast and Southeast regions have the highest potentials, especially in 2030. However, the current techno-economic potential is much smaller due to high conversion costs. Thus, in the short term, large scale production of BJF could only be realized with favorable policies (e.g. lower taxes, carbon credits).

6.4. ANSWERING THE RESEARCH QUESTIONS

How to spatially explicitly quantify the environmental and techno-economic potential from biomass residues and energy crops over time?

To answer this research question, the different methods used in this thesis to assess the spatial distribution of the environmental potential and production costs of biomass residues and energy crops are discussed. These assessments are developed considering different research boundaries, geographical scales, temporal coverages and levels of complexity in chapters 2 - 5.

To assess the ***environmental potential*** of biomass residues (sugarcane straw), the location of all the sugarcane mills (bioenergy facilities) in São Paulo is considered. The main advantage of considering the location of the mills is that it allows for bottom up analysis, in which the mills are assessed individually, and their potentials are compared among each other in a state level analysis. In chapter 2, the spatial distribution of sugarcane areas is combined with remote sensing data at high spatial resolution to determine the sugarcane yield levels and total sugarcane production in São Paulo. For assessing past and current spatial distribution of biomass yield levels, remote sensing is generally considered a reliable source, as it can generate different indexes well correlated with biomass yield (e.g. vegetation and dry matter indexes for yield and crop residue estimation) [115,290–292]. Because of the high spatial resolution of these data sources, the results on the potentials express a detailed picture of the biomass resource availability of each sugarcane mill. However, it should be mentioned that the computational cost increases considerably with larger amounts of grid (pixel) data, and the number of scenarios and aggregation levels. Therefore, no complex environmental modeling is employed at pixel level for calculating the environmental potential of sugarcane straw in chapter 2. Instead, fixed mulching levels of sugarcane straw left on the field are assumed to comply with environmental services (e.g. soil loss reduction and soil organic matter preservation). Following this approach, the environmental potential of sugarcane straw is exclusively dependent on the yield levels of sugarcane.

In chapter 5, the spatially explicit assessment of the environmental potential of biomass residues (sugarcane straw and eucalyptus harvest residues) at national level in 2015 and 2030 requires a different approach. Different than chapter 2, environmental constraining factors (i.e. erosion risk and Soil Organic Carbon – SOC) are modeled spatially explicitly. Erosion risk and SOC are of high relevance for biomass residue removal, as they are ultimately related to ecosystem preservation in biomass production systems. They depend on a series of agro-ecological factors (e.g. soil characteristics, topography, biomass yield, climate), which can be modelled spatially explicitly. As a downside, the spatial distribution of biomass (sugarcane and eucalyptus) yield levels are far more uncertain than in chapter 2, as the distribution is based on agro-ecological suitability maps, current and future maximum attainable yield data, and land use projections of current and future sugarcane and planted forestry (i.e. eucalyptus). Hence, when new land becomes available, the agro-ecological conditions are different, which affects biomass yields. From the environmental perspective, this approach is much more refined than the approach applied in chapter 2. It allows for mapping areas where the biomass residues can be removed due to a low risk of erosion, and how much should be retained on the soil to preserve soil organic carbon stocks. At the same time, the spatial resolution is much coarser (5x5 km pixel), decreasing reliability for decision-making at local level. Therefore, exploring the trade-off between the spatial resolution and the complexity of the assessment of environmental impacts is important. Nevertheless, this yields significant benefits over using simplified exogenous assumptions (e.g. fixed mulching levels) and improves the understanding of the spatial distribution of biomass resources.

In the ***techno-economic potential*** assessment, the costs of biomass residues include the farm-gate and transportation costs, which are strongly related to yield levels and transport distances. Hence, more detailed information on biomass yield and transportation distances allows for more reliable estimations of biomass residue recovery cost. The biomass residues farm-gate cost refers to variable operational costs (e.g. machinery, diesel, labor) related to the amount of residue that is recovered. The same approach on the biomass residue farm-gate cost calculation is employed in chapters 3 and 5, based on the non-linear relationship between yield and operational costs sourced from empirical studies. The approach on the biomass residue transportation costs is different, as it fully depends on the transport distance. In chapter 3, the transportation distances vary spatially explicitly, based on the Euclidean distance from a given pixel to a given sugarcane mill. The distance information is multiplied by the unit transportation cost (i.e. US$/tkm), which is largely based on truck performance (fuel consumption and cost) and labor. In chapter 5, as no information on BJF plant location and distances are available, the biomass residues transportation costs are estimated at pixel level assuming that each pixel can be a potential location for a BJF plant. Hence, a hypothetical distance is estimated according to the input capacity/scale of each (hypothetical) BJF plant and the density of biomass available (i.e. environmental potential of biomass residues). This distance is multiplied by the unit biomass transportation costs. Therefore, the biomass residues transportation costs vary spatially and temporally.

Chapter 4 focuses on the spatio-temporal assessment of the techno-economic potential of BJF production from energy crops. Current and future land use scenarios are used for Brazil to prospect residual land (i.e. available land) that could be used for energy crops and subsequent BJF production. Grasses, shrubs and abandoned agricultural areas are assumed to be the land use classes able to accommodate the production of energy crops. This selection does not consider any environmental constraints, and therefore the results on the techno-economic potential should be interpreted with care. Using the same approach of chapter 5, the spatial variation of biomass yield levels combines agro-ecological suitability maps, current and future maximum attainable yield data, and current and future land availability map. The spatial variation and temporal development of biomass yield levels allow for the calculation of the spatially explicit biomass farm-gate costs. Different than chapter 5, the estimation of energy crop production costs in chapter 4 accounts for fixed costs per hectare (e.g. administrative costs, land costs) and variable costs per yield (e.g. fertilizer and harvest costs). For the eight energy crops assessed, the Net Present Value (NPV) is calculated for estimating the fixed and variable farm-gate costs. For the biomass transportation costs, the same approach as in chapter 5 is applied, as no information on the location of BJF plants is assumed.

In conclusion: spatially explicit assessments on biomass potentials have an important advantage compared to statistical or spatially aggregated assessments, as they are able to include location specific information on land availability and biophysical conditions. These factors are crucial for evaluating different environmental impacts (e.g. carbon and water footprint, biodiversity) and techno-economic factors (biomass production costs and logistics) of bioenergy production. The assessment of these impacts and factors present various levels of complexity and different geographical scales, from a sub-field (e.g. precision agriculture for reducing fertilizer costs) to a regional level (e.g. hydrological impacts in watersheds), and time scales from hours (e.g. in case of meteorological events) to years (e.g. in case of major SOC dynamics). Therefore, attention needs to be paid on the research assumptions (e.g. residue-to-crop ratio), methods (e.g. soil loss equation for modelling soil erosion risk) and quality of information (e.g. spatial resolution of the pixels). Finding an optimal combination of these factors is good modelling practice for assessing environmental and techno-economic potential of biomass production systems.

How to spatially explicitly quantify the environmental and techno-economic potential of bioenergy supply chains given the development of conversion technologies and infrastructure?

While the first research question focuses on the biomass resource potentials, research question II considers the spatial and temporal distribution of the environmental and techno-economic potential of the entire bioenergy supply chains. Similar to research question I, the methods developed in this study are chosen to be specific for the assessment of bioelectricity and BJF supply chains in Brazil. Similar approaches can be used to assess the potentials of other bioenergy supply chains, but the specific contextual factors should be considered.

In the assessment of the potentials of bioelectricity from sugarcane straw, the electricity generating capacity and the electrical conversion efficiency are estimated at mill level, based on the environmental potential of straw available for each sugarcane mill (shown schematically in figure 6.1.). These factors highly impact the specific investment costs required to build a power plant dedicated to export bioelectricity from sugarcane straw to the national grid (network) system. The medium to high pressure Condensing Extraction Steam Turbines power plants assessed in chapter 2 and 3 are a mature conversion technology, and therefore, no technological development until 2030 is considered. Together with biomass production, the bioenergy conversion step is the most important supply chain component, as it encompasses the majority of the capital costs. For the export of electricity to the grid, it is important to consider the availability of electricity distribution infrastructure. In chapter 3, the spatial distribution of the electrical substations is used to better estimate the investments in transmission lines that each mill must own to distribute the bioelectricity produced. Depending on the distance from the mill to a given substation, the investments costs can be very high, which can make the bioelectricity project not feasible. Using spatial infrastructure data to estimate bioenergy supply chain costs can provide more reliable information for investors, and also for policy makers to set up a regional strategy with other stakeholders (e.g. distribution companies, other renewable energy companies). By summing the straw recovery costs available in each pixel, the mill specific bioelectricity capital and operational (conversion) costs, and cost of grid/network connection, the total bioelectricity production costs are estimated using the Levelized Cost Of Energy (LCOE) at pixel level for each sugarcane mill (figure 6.1). In this regard, other micro-economic metrics could also be used to quantify the techno-economic potential, such as Return On Investments (ROI) and Energy Return On Investments (EROI). Nonetheless, the relevancy of these metrics depend on the economic research questions addressed in a given study. In chapter 3, the bioelectricity production costs are compared to a reference regular market price of bioelectricity, in order to identify the mills with techno-economic potential (i.e. bioelectricity costs < 80 US$/MWh). A reference price is selected to observe the overall spatial patterns of the best mills to invest in bioelectricity from sugarcane in São Paulo, as shown in figure 6.3.

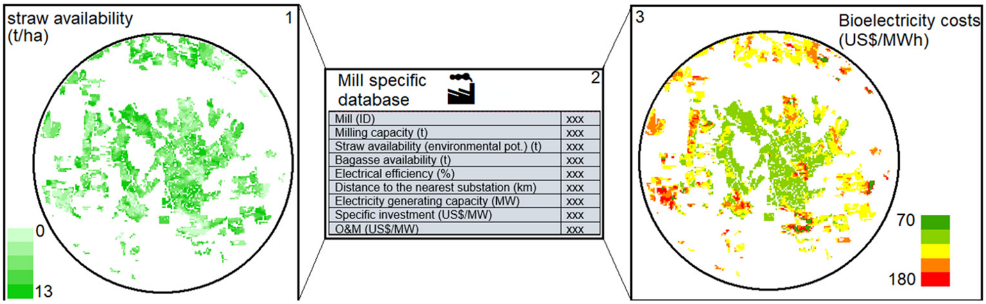

Figure 6.1. a schematic representation of: 1) aggregation of the environmental potential of sugarcane straw from pixel to mill level; 2) analysis of the mill specific techno-economic factors; 3) calculation of bioelectricity costs at pixel level based on LCOE. The straw recovery costs at pixel level is also an input for the bioelectricity cost calculation, but it is not aggregated per mill.

For supply chain assessments where the bioenergy facility location is neither available or estimated, the conversion costs of bioenergy are constant over space (chapter 4 and 5), unless different scales are assumed across regions. Different than in chapter 3, conversion costs analyzed in chapters 4 and 5 vary over time (and not over space) due to technological development and increasing scales assumed in each BJF supply chain. In the BJF transportation cost calculation, the infrastructure availability is considered, including the current and future spatial distribution of road network, and current operating airports in Brazil. However, the impact of BJF transportation costs on the total BJF costs is much smaller than the impacts of the large investments in transmission lines required by the sugarcane mills. Regarding infrastructure, it should be also noted that not only affordable logistic conditions should be considered. Rather, planning the installation of future BJF plants should also account for the availability of affordable utility supply (e.g. natural gas, hydrogen, electricity, among others) as well as availability of human resources, which are not considered in this thesis. In chapters 4 and 5, LCOE is also used to calculate the total BJF costs at pixel level by summing the biomass costs (spatial and temporal variable) of either biomass residues or energy crops, BJF conversion (i.e. capital and operational) costs (temporal variable) and BJF transportation costs (spatial and temporal variable). A breakdown of the BJF costs to the main components is available at pixel level for both 2015 and 2030 (see figure 6.2). For the techno-economic potential, the total BJF costs for 2015 and 2030 are compared to the current airport specific jet fuel prices (spatial variable), which can vary up to three-fold across the Brazilian regions due to logistic issues and state level taxes. This high spatial variation of jet fuel prices can help identify promising areas in which potential BJF supply chains can compete with fossil jet fuel prices.

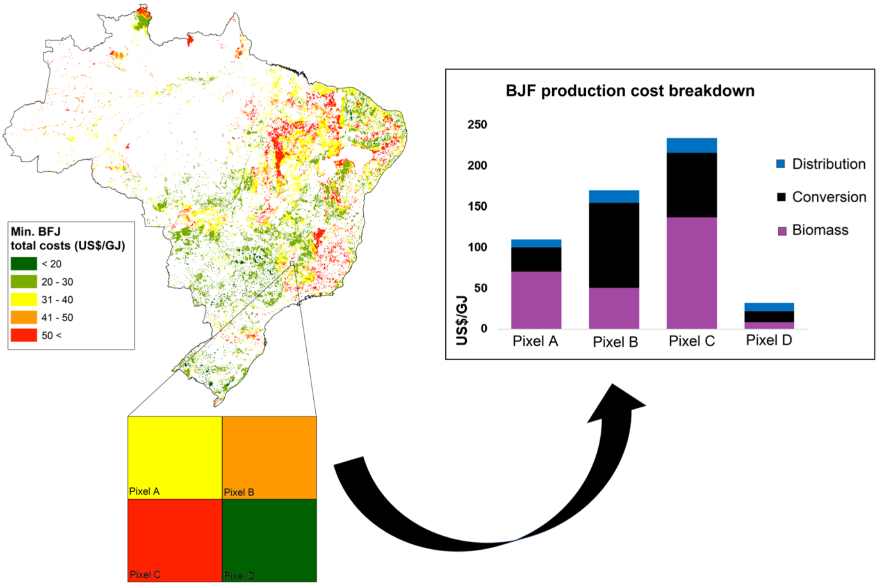

Figure 6.2. Schematic representation of the spatially explicit cost breakdown of BJF production. Note that this example indicates the BJF production costs from the techno-economic potential (i.e. multiple BJF supply chains), which explain the difference among the BJF conversion costs per pixel.

Refining environmental and techno-economic constraints of bioenergy supply chains to pixel level is a key methodological contribution of this thesis. Although the approach is demonstrated for specific supply chains in Brazil, the process of combining information to pixel level can be reproduced elsewhere (different regions and supply chains). A reliable spatially explicit representation of bioenergy impacts also strongly depends on other factors, e.g. on how detailed the modeling methods are for environmental impacts of bioenergy supply chains (e.g. determining global warming potentials in Life Cycle Assessments), as well as the techno-economic simulation (e.g. characterization of process design of downstream process). The results of these assessments (e.g. energy conversion efficiency) can be combined with spatial attributes (e.g. biomass yield, distances), which allows for the calculation of the spatial variability of the environmental and techno-economic performance of bioenergy systems, and the quantification of the potentials.

What is the current and future environmental and techno-economic potential of bioelectricity and BJF supply chains in Brazil from energy crops and biomass residues, and what is the spatial distribution?

By addressing both research questions I and II, the environmental and techno-economic potentials of bioenergy supply chains in Brazil are quantified. Moreover, the spatial distribution of the potentials is mapped to identify the hotpots for bioenergy potential from energy crops and biomass residues in Brazil.

In the 2012 crop-year, the environmental potential of bioelectricity from sugarcane straw was up to 45.8 TWh in São Paulo. For comparison, this corresponds to around 50% of the fossil-based (e.g. coal, natural gas) electricity currently produced in the whole Brazil. This potential is sourced from an environmental potential of sugarcane straw ranging from 16.7 Mt to 40 Mt over 5.6 Mha. Across the mills, the environmental potential ranges between 2.5 - 508.2 GWh in the BAU scenario, 4.2 - 817 GWh in the Moderate scenario, and 5.9 - 1144 GWh in the High scenario. The high variation of these numbers are based on the large range in electricity generating capacity (1 MW – 154 MW), and a proportional electrical conversion efficiency ranging from 20% to 35% in the 174 sugarcane mills in Sao Paulo. The techno-economic potential of bioelectricity from sugarcane straw is estimated at 14.2 TWh produced from more than 11 Mt of straw, which represents around 10% of the electricity consumption of São Paulo state in 2012 [166]. The techno-economic potential is achieved with average bioelectricity production costs per mill varying from 68 US$/MWh to 80 US$/MWh (i.e. cut-off bioelectricity price), but in the assessment at pixel level, the minimum bioelectricity production costs can be found at 61 US$/MWh. In total, 37 mills could contribute to the techno-economic potential, which altogether are capable to supply more than the total amount of bioelectricity surplus that was produced mostly from bagasse in Brazil in 2012 (12.2 TWh). The sugarcane mills with the highest environmental and techno-economic potential of bioelectricity from sugarcane straw are located in the Northeast of São Paulo (see blue circles in figure 6.1), where mills with medium to high capacity are located and the agro-ecological conditions for sugarcane cultivation are optimal. In general, São Paulo also presents a relative high density of electrical substations, thereby contributing to a reduction of capital costs of new bioelectricity systems. The spatial distribution of the environmental and techno-economic potential of bioelectricity from sugarcane straw is presented in figure 6.3.

The environmental and techno-economic potential of biomass residues (sugarcane straw and eucalyptus harvest residues) for BJF production is quantified for 2015 and 2030 in chapter 5. The techno-economic potential is significantly higher in 2030 (i.e. 0.67 EJ/yr for a range of total BJF costs between 19 US$/GJ and 66 US$/GJ) compared to 2015 (i.e. 0.45 EJ/yr for a much higher range of total BJF costs between 46 US$/GJ and 114 US$/GJ) (see figure 6.5). These potentials are mostly composed by Fischer-Tropsch (FT) and HydroThermal Liquefaction (HTL) technological pathways, which achieved the minimum BJF total costs. Although these technologies are very capital demanding, their expected technological development are assumed to reduce the BJF costs significantly towards 2030. The largest share of the techno-economic potential is sourced from sugarcane straw, as the environmental potential is much larger than eucalyptus harvest residues. However, the

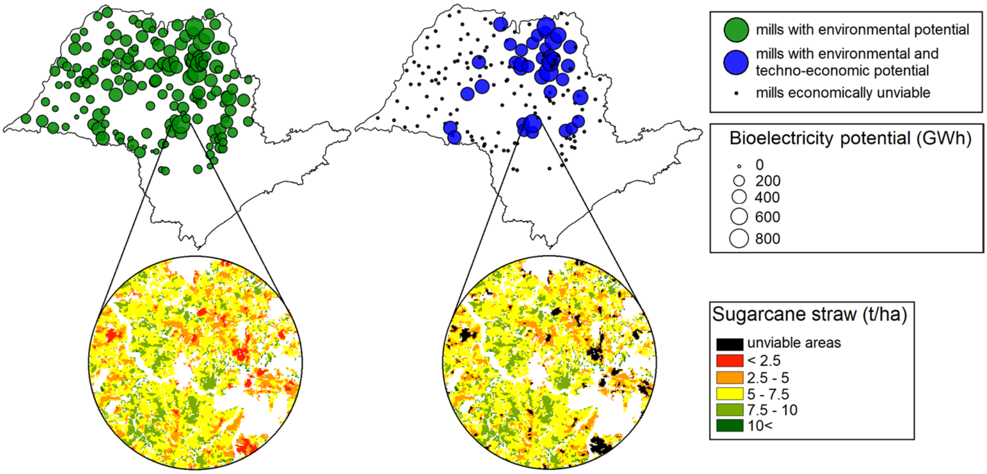

Figure 6.3: Spatial distribution of the environmental and techno-economic potential of bioelectricity from sugarcane straw on state and mill level. The enlarged circles show an example of the spatial distribution and yield levels of sugarcane straw.

demand for sugarcane straw in other bioenergy supply chains (e.g. bioelectricity, cellulosic ethanol) may be higher compared to eucalyptus harvest residues as it is often located close to bioenergy/sugarcane mills, which may decrease the availability for BJF production. The majority of the environmental and techno-economic potential of BJF from eucalyptus harvest residues is identified from the South to the Northeast region of Brazil, whereas the largest share of the BJF potential from sugarcane straw can be found in traditional sugarcane areas in the Southeast and also towards Center-West of Brazil in 2030 (figure 6.4).

The techno-economic potential of BJF from energy crops is also quantified for 2015 and 2030. It can reach up to 6.4 EJ in 2015 (23 US$/GJ – 65 US$/GJ), and up to 7.8 EJ in 2030 (20 US$/GJ - 65 US$/GJ) (figure 6.3). Despite the reduced amount of land available in 2030 (from 121 Mha to 108 Mha[3]), the techno-economic potential is much higher in 2030 due to improvements in energy crop yields (biomass costs reduction); technological learning and scale gains (conversion costs reduction); and distribution infrastructure (BJF transportation costs reduction). In total, all eight energy crops assessed could contribute to the techno-economic potential of BJF, which shows that the high variability of agro-ecological conditions is not a restriction for techno-economic viable bioenergy production in Brazil. Of the five BJF technologies assessed, only Direct Sugars to HydroCarbon (DSHC) technology cannot achieve any techno-economic potential due to low conversion efficiency. The majority of the techno-economic potential is dominated by four BJF supply chains: Hydroprocessed

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[3] For comparison, the current cropland area in Brazil (2019) is around 65 Mha (less than 10% of the national territory) [349].

Ester from Fatty Acids (HEFA) from macaw palm and oil palm, HTL from eucalyptus and ATJ from corn. HEFA production is mostly promising in the North and Center West region of Brazil in both 2015 and 2030, HTL can be relevant from the South to the Northeast region, and ATJ in some areas of the Northeast.

The environmental and techno-economic potential of bioelectricity and BJF are quantified spatially explicitly. Chapter 2 and 3 show that the techno-economic potential is much lower than the original environmental potential (figure 6.1). This reduction occurs in sugarcane mills that present at least one of these three major drawbacks: high sugarcane straw cost-supply, low electricity generating capacity, and long distances to distributors' substations. It should be noted that the techno-economic potential of energy crops and

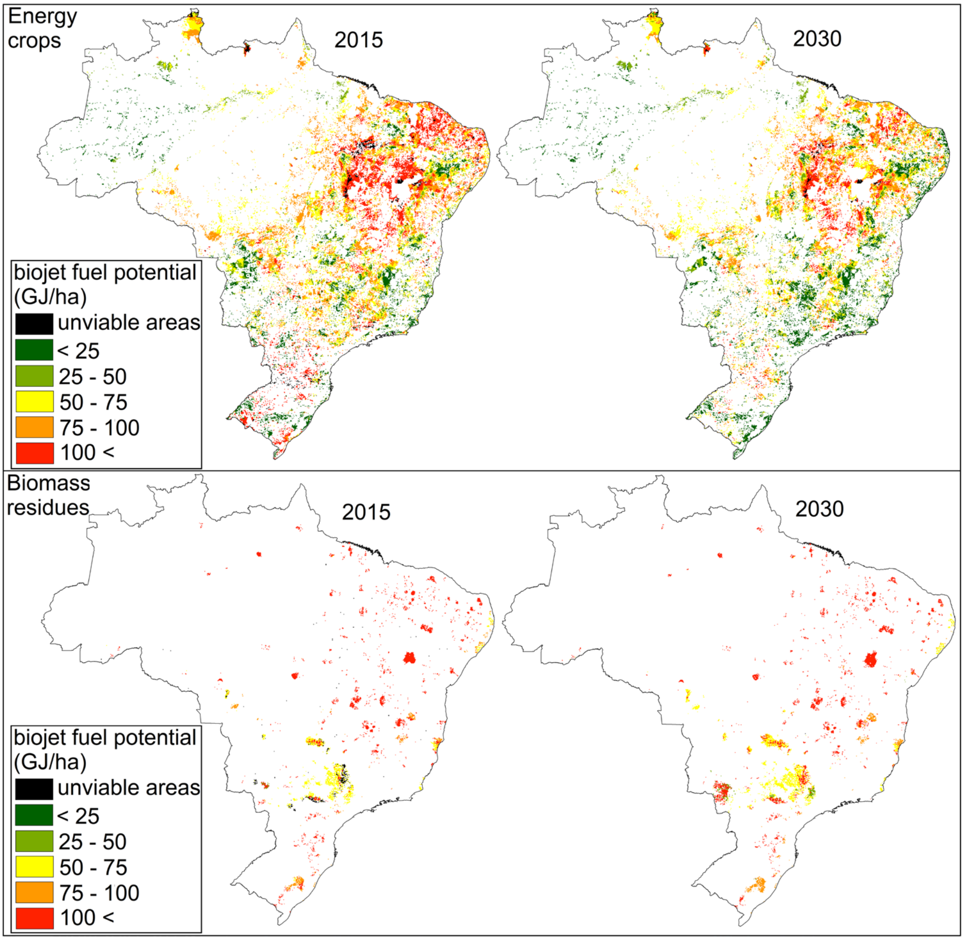

Figure 6.4: Spatial distribution of the techno-economic potential of BJF from energy crops and from the environmental potential of biomass residues in 2015 and 2030 in Brazil.

biomass residues presented in chapter 4 and 5 cannot be compared, as the estimation of the biomass residue potential also accounts for important environmental restrictions (soil erosion and SOC). For both energy crops and biomass residues, multiple BJF supply chains achieve competitive production costs across different regions, which shows the possibilities to develop various BJF supply chains in Brazil.

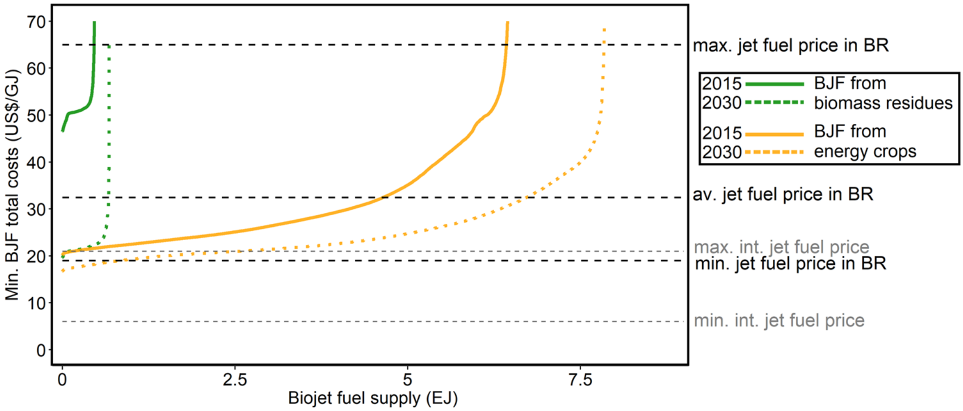

Figure 6.5: Spatio-temporal cost-supply curves of the environmental and techno-economic potential of BJF from biomass residues and the techno-economic potential of BJF from energy crops. The dashed gray lines show the range of the international jet fuel price at the refinery (U.S. Gulf Coast kerosene jet fuel spot price) [228]. The dashed black lines represent the range of jet fuel prices at the Brazilian airports [226], which is used to quantify the techno-economic potential of BJF.

6.5. MAIN MESSAGES

- ***Refining environmental and techno-economic constraints of bioenergy supply chains to grid/pixel level is a major methodological challenge for quantifying bioenergy potentials spatially explicitly.***

Combining the environmental impacts and techno-economic factors of bioenergy supply chains at pixel level requires multiple scientific disciplines. Although chapters 2 and 3 are dealing with a single bioelectricity supply chain, it is laborious from the operational perspective, as the integration of different geographical scales require iterative data processing (e.g. aggregating and disaggregating data from pixel to mill level and vice-versa). On the other hand, in chapters 4 and 5, a detailed characterization of the multiple BJF supply chains is required to assess the environmental and techno-economic potential. This demands an important multi-disciplinary comprehension of various aspects of the agricultural, industrial and distribution stages of the supply chains. Therefore, the environmental and techno-economic variables mapped at pixel level are highly sensitive to the assumptions taken (e.g. residue-to-crop ratio, plant input capacity, technological progress).

- ***The sugarcane mills in Sao Paulo with the highest environmental and techno-economic potentials of bioelectricity from sugarcane straw are mostly in regions with optimal agro-ecological conditions, have a medium to high milling capacity and have high accessibility to the electricity distribution network.***

In chapter 2, it is shown that the sugarcane mills with the highest environmental bioelectricity potential are located in the Northeast region of Sao Paulo. This region presents optimal agro-ecological conditions for sugarcane cultivation and also for straw recovery. From the techno-economic perspective explored in chapter 3, it is also noted that the sugarcane mills with a high milling capacity do not necessarily produce bioelectricity from sugarcane straw at low costs. Depending on the location of the mill and the environmental conditions for straw recovery within the collection radius, medium to high milling capacity typically possess the optimal conditions to invest in an additional power plant. Bioelectricity production costs depend on the straw recovery costs, which are mostly affected by the farm-gate costs, and also by the environmental potential of sugarcane straw per hectare. Investments in transmission infrastructure have a marginal effect on the overall bioelectricity costs for the majority of the sugarcane mills, as the state of São Paulo is well covered by electrical substations from the distribution companies. However, areas like the Southwest of the state, with low population density, the need for new transmission lines could represent a large share of the capital costs of a new power plant.

- ***The development of BJF industry should not only focus on the supply chain that achieves the lowest BJF total costs. There are regions in Brazil in which up to 10 supply chains could produce BJF total costs below the fossil jet fuel price.***

In chapters 4 and 5, the techno-economic potential of BJF in Brazil is calculated through the summation of all pixels that achieved minimum BJF total costs below the maximum fossil jet fuel prices in Brazil. This generates the spatial distribution and cost-supply curves of the optimal combination of supply chains with the lowest BJF costs. It should be mentioned, however, that for many regions in Brazil, more than one supply chain can achieve BJF total costs below the fossil counterpart. In regions, such as the Southeast and Northeast of Brazil, up to 10 BJF supply chains are projected to achieve BJF total costs below the fossil jet fuel prices of the nearest airport in 2030. Therefore, more than selecting a single BJF supply chain, it is important understanding which BJF supply chains are promising in a given region. This supports a better decision on which production routes should be further developed given the regional characteristics.

- ***Currently, BJF is not competitive with fossil jet fuel in the (central) regions of Brazil with highest demand for aviation fuels. Nonetheless, due to the large size of the country and the high fossil jet fuel prices in airports located in (remote) regions of Brazil, niches for the development of competitive BJF may exist.***

The techno-economic development of BJF supply chains in Brazil should consider that the jet fuel price in the country is very high, with high variability across the national airports due to different state taxes applied, logistics and infrastructure conditions, and fuel distributors companies. In (central) regions with high jet fuel demand, such as the states of São Paulo and Rio de Janeiro, it is unlikely that BJF can currently compete with fossil jet fuel prices. To increase the competitiveness of BJF in these (central) regions, mechanisms (e.g. Renovabio and CORSIA) are required to support BJF development. On the other hand, in other (remote) regions (e.g. western part of the North and Center-West regions) where the fossil jet fuel is usually significantly more expensive in combination with low-cost biomass availability, the chances for introduction of BJF may be higher. However, this also depends on whether the expected demand of the nearest airport(s) can assure a viable BJF plant scale. Moreover, the development of advanced biofuels in remote regions also requires an assessment on the infrastructure availability of the region, not solely focused on fuel distribution hubs, but also supply of utilities (e.g. electricity, hydrogen, yeasts) as well as human resources. Lastly, if the production costs of BJF in remote regions are lower than in central regions, other logistics options (e.g. short-sea and rail) should be considered to assess the feasibility of supplying large airports (in central regions).

- ***Brazil has a large techno-economic and environmental potential of bioenergy (bioelectricity and BJF), but implementation is limited by additional factors.***

In chapter 3, 37 sugarcane mills are identified with a joint techno-economic bioelectricity potential of 14.2 TWh. However, more refined information of these mills is needed to understand their willingness to invest in this business model. Policy makers and energy planners can use this techno-economic potential to make projections for bioelectricity and related energy security in Brazil. Nonetheless, several other factors influence the ultimate implementation potential such as socio-political conditions, electricity price volatility, and competitive demand for sugarcane straw.

In chapter 5 and (mainly) 4, a very large potential of BJF is found (around 8 EJ in 2030, combining both energy crops and biomass residues). This large potential shows that Brazil is indeed a relevant country for investing in BJF production due to favorable agro-ecological conditions and high fossil jet fuel prices. However, in chapter 4, the techno-economic potential is achieved due to diverse combinations of multiple BJF supply chains across Brazil, which are unlikely to be developed simultaneously. In addition, no environmental restrictions are taken into account (e.g. biodiversity, GHG emissions), which will most likely reduce the BJF potential significantly. The current techno-economic BJF potential is based on land availability which is almost twice the current cropland area in Brazil – most likely, only a fraction of this may actually be implemented. Furthermore, no competition for both biomass and the available land with other bio-based applications is considered in the assessment of the BJF potential.

6.6. RECOMMENDATIONS

In this thesis, the environmental and techno-economic potential of bioelectricity and BJF are assessed spatially explicitly on different geographical scales. To reduce the high complexity of these assessments, important generalizations and research boundaries are assumed throughout the chapters. In this section, recommendations for follow up studies are addressed to increase the reliability and the completeness of environmental and techno-economic assessments. Moreover, recommendations for different stakeholders are provided on how they could support the realization of the bioelectricity and BJF potentials.

6.5.1. Recommendation for future research

- Assuming that all sugarcane areas within the gathering radius belong to a given sugarcane mill can be deemed realistic for isolated sugarcane mills in the West of São Paulo, where the competition for sugarcane areas is lower. However, it is less likely in regions of clusters of mills in the Northeast of São Paulo, where the competition for land, and the dynamics of land ownership and lease varies across the mills. In this regard, a spatial optimization exercise seeking to minimize the straw recovery costs may yield a different allocation of sugarcane straw to the sugarcane mills. This can give a different perspective to the decision maker mainly at mill level to search for areas with low straw recovery costs.
- ·The environmental potential of bioelectricity from sugarcane straw determined in this thesis only considers restrictions on straw removal. However, other environmental impacts such as carbon and water footprint need to be evaluated. Although the environmental burdens of bioenergy from biomass residues is mostly linked with residue removal, it is recommended that environmental impacts throughout the supply chain are also considered, as well as impacts related to the implementation of long transmission lines.
- Sugarcane straw is assumed to be recovered using a baling system. However, the baling system can be costly depending on the amount of straw recovered and transported from the field, and can also be harmful to the sugarcane ratoons due to machinery operations in the fields. Furthermore, it can cause technical issues in the bioelectricity conversion facility (boilers) due to the presence of dust in the straw recovered from the ground. It would be recommended to investigate the effect of an integral harvest

system, where the sugarcane straw is harvested together with sugarcane stalks, as well as a combination of an integral harvest system and a baling system on the environmental and techno-economic performance of bioelectricity from sugarcane straw. Moreover, mills currently face multiple technical challenges of post-harvest operations that also require improvements and further studies, such as the high complexity of straw collection (damaging the machinery), storage (high risk of fire) and the use of straw in the boilers (impurities degrading the boilers).

- In this thesis, all sugarcane mills in Sao Paulo are assumed to have an adjacent power plant to produce bioelectricity, with scale and efficiency relying on the amount of straw available (i.e. environmental potential) within the collection radius. This is assumed because no information on current sugarcane mills' boiler status is publicly available. According to bioelectricity selling data, large mills do not necessarily sell more bioelectricity than smaller mills. In general, investments in high efficient boilers are made by modern medium size mills that have bioelectricity as a core business model (together with sugar and ethanol). Hence, a study describing the current availability and characteristics of the boilers (and a potential transition to high efficient boilers) of the mills would be of high relevance to energy planners. This can also be relevant for very short-term energy planning in seasonal circumstances (e.g. in case of drought effects in hydropower, a large bioelectricity supply would be required, increasing the bioelectricity prices).
- Soil Organic Carbon (SOC) balance and erosion risk are modelled spatially explicitly to estimate the impact on the amount of biomass residues that can be sustainably removed for BJF production. Simulating soil erosion and SOC in biomass production systems involves complex biogeochemical processes, which also vary at sub-field level. Chapter 5 should be seen as a first attempt to quantify the availability of sugarcane straw and eucalyptus harvest residues by carrying out spatially explicit environmental modelling. To improve our results, spatially explicit process-based assessments on the soil erosion and (mainly) SOC of sugarcane and eucalyptus systems should be carried out mainly at local and regional levels to understand the dynamics of these environmental constraints in different agro-ecological conditions.
- Similar to the assessment of the bioelectricity potential, the BJF potential is quantified in chapter 5 by assessing environmental potential of biomass residues. However, BJF production should comply with many other socio-economic and environmental criteria, and therefore, it is of high importance that other impacts are also considered in future studies, such as carbon and water footprint, and biodiversity impacts. Especially for energy crops with high potential for BJF production, such as eucalyptus and macaw palm, the integration with other land uses in agroforestry systems (instead of monoculture)

and smallholder participation should be further explored to assess the sustainability of biojet fuel supply chains.

- In chapter 4 and 5, BJF production is assumed to take place in greenfield plants, and considers linear technology development. However, the BJF development in Brazil could also be realized at brownfields plants, where part of the infrastructure needed is already available. Therefore, forthcoming studies considering the location of potential facilities for BJF production (e.g. sugarcane mill, biodiesel plants, pulp and paper mill) could provide more reliable cost estimations in a current scenario.
- The potential of BJF production from energy crops and from biomass residues are assessed in two different studies (chapters 4 and 5). In reality, BJF producers will likely look for a combination of the most cost effective biomass sources. For lignocellulosic feedstock, scenarios of mixing biomass sources (e.g. sugarcane straw and eucalyptus wood) to supply BJF plants are also possible depending on the spatial distribution and costs, and should be further explored. Moreover, chapter 4 also considers that all BJF supply chains have an integrated biomass processing plant and a BJF biorefinery. It should be noted that another option for BJF development Brazil is a decoupled production of intermediates (e.g. sugarcane ethanol, or vegetable oils) and BJF because of low feedstock market prices.
- Given the expected development in demand for BJF in the next years, integrating macro-economic models and land use projections to explore demand driven scenarios for BJF as well as other advanced fuels (e.g. marine biofuels) can be further assessed in case studies. This can be done by using spatial proxies for land use allocation, such as existing bioenergy facilities, airports, refineries, harbors, among others. This type of assessment may provide more reliable information on future land availability, as well as on the environmental and techno-economic impacts.
- In this thesis, the environmental and techno-economic potential of sugarcane straw is quantified in different chapters for the application in different end-uses: bioelectricity and BJF supply chains. However, the potential competition for the same sugarcane straw for different end uses is not quantified. In principle, policy makers are advised that a further increase of sugarcane straw valorization could be realized by exploring its use in new BJF technologies, instead of burning it for bioelectricity. That can be advantageous for scaling up the BJF industry in Brazil and it can be incorporated in brownfield plants. In addition, the electricity sector currently has alternative renewable sources to decarbonizing the sector (e.g. solar and wind), whereas the aviation industry would be more dependent on BJF in the coming years. At the same time, it should also be pointed out that bioelectricity prices can be very high due to rainfall shortages (especially if extreme climate events are considered), which could be highly attractive to the investors. Given that, further demand driven studies should incorporate competing

end-uses for sugarcane straw, as well as energy system models that compare the techno-economic and environmental performance of different bioenergy systems.

6.5.2. Recommendation for stakeholders

- ·In the biomass resource potential assessment, areas with limited biomass supply are identified based on the spatial distribution of biomass yield levels and environmental constraints (e.g. SOC depletion and erosion risk). This type of information is of high relevance to decision makers at local level (e.g. farmers, agronomists, environmental consultants) to design the appropriate solutions in a given area for improving biomass yields and the ecological availability of straw (e.g. by soil conservations practices). However, given the spatial resolution of the land use data in chapter 4 and 5 (5km x 5km), a more specific spatial assessment is required to comprehend the dynamics of biomass residues at field and sub-field level.
- ·The spatially explicit assessment of the techno-economic potential of bioenergy can be an important approach for guiding investment decisions from the public and private sector. Currently, sugarcane mills have limited, and often subjective, information on the potential biomass and bioenergy costs for areas that are not owned by the mills. For the sugarcane mill manager, this type of information is of utmost importance to plan investments in bioelectricity capacity, and also to understand the potentials of other mills in the surroundings, explore potential agreements of biomass supply and partnerships with electricity distribution companies to reduce the investments costs of transmissions lines. Moreover, the spatial identification of the hotspots for future BJF production can also guide investments, especially from the public sector, in the short-term infrastructure required to enable the realization and scale up BJF production.
- To support investors in bioelectricity and BJF production, energy planners at state or federal level from government bodies (e.g. Ministries and Secretariats) have to size and project the demand and potential supply of biomass in a given region, accounting for technology development and also assess the feasibility. Currently, government bodies in Brazil rarely assesses the spatial distribution of biomass resources, land availability and quantify environmental impacts of bioenergy production spatially and temporally explicitly. These assessments are often carried out by academia and research institutes (national or international) often with more limited funding and/or outreach. Therefore, national and international energy government bodies should support the development of theoretical studies on bioenergy potentials.
- Currently, mechanisms such as CORSIA (specific for BJF) and Renovabio (for different biofuels) can provide incentives to sustainable bioenergy producers. However, these mechanisms still rely very little on spatially explicit assessments. In this context, spatially explicit assessments of the environmental potential of bioenergy can assist these

mechanisms to produce more refined information for the monitoring of sustainable bioenergy. For example, a more detailed assessment of the environmental potential of biomass residues mapped in chapter 5 would allow for identifying areas that are identified as ecologically available, but in reality are highly susceptible to SOC depletion and/or erosion risk. Additionally, agricultural and forest certification systems (e.g. BONSUCRO, ISCC, FSC and PEFC) could also benefit from spatially explicit assessments of bioenergy systems. Currently, the monitoring of certified supply chains is based on evidence provided by bioenergy producers and local audits by accredited certification bodies. Several forestry systems also use so-called risked-based assessments (e.g. FSC controlled wood), where an entire area (e.g. a state or a region) is assessed to meet specific sustainability criteria. Spatially explicit assessment using high quality spatial information would allow for a more detailed quantification of such risks and the likelihood of compliance of bioenergy production with various sustainability criteria.

Samenvatting

INTRODUCTIE

Brazilië is een van de grootse producenten van hernieuwbare energie dankzij de grote hoeveelheid natuurlijke hulpbronnen die het land rijk is. Van alle hernieuwbare energiebronnen is biomassa voor bio-energie een van de meest flexibele opties om de afhankelijkheid van fossiele brandstoffen te reduceren omdat het een divers portfolio van verschillende toepassingen kent zoals biobrandstoffen, warmte, elektriciteit, en chemicaliën. De huidige bio-energie sector in Brazilië bestaat voornamelijk uit de suikerriet-ethanol industrie, maar het wordt verwacht dat in de komende jaren nieuwe bio-energie productie systemen zullen opkomen. Omdat de vraag naar huidige energietoepassingen van biomassa zeer waarschijnlijk zal groeien en omdat opkomende bio-energie systemen de vraag wellicht verder zal doen toenemen, is het van groot belang om biomassa en bio-energie potentiëlen te kwantificeren en te monitoren.

Verschillende typen bio-energie potentiëlen kunnen worden gekwantificeerd: theoretisch, technisch, economisch (techno-economisch of markt-), milieu- (of ecologisch), en implementatie potentieel. Het merendeel van de studies naar biomassapotentiëlen heeft het ecologisch of economisch potentieel onderzocht. Deze potentiëlen zijn lastig te kwantificeren door de ruimtelijke en temporele variatie in milieueffecten en economische factoren. Het ruimtelijk en temporeel expliciet onderzoeken van milieueffecten en de techno-economische karakteristieken van bio-energie productie is daarom een belangrijke uitdaging.

Het doel van deze thesis is om huidige en toekomstige ecologische en techno-economische potentiëlen van bio-energie productieketens in Brazilië ruimtelijk expliciet te onderzoeken op verschillende geografische niveaus. In deze thesis worden de ecologische en techno-economische potentiëlen van twee veelbelovende bio-energie systemen in Brazilië onderzocht: elektriciteit geproduceerd van suikerrietstro en biokerosine geproduceerd van verschillende soorten biomassa. De volgende onderzoeksvragen worden in deze thesis behandeld:

I. Hoe kunnen ecologische en techno-economische potentiëlen van biomassa residuen en energiegewassen gekwantificeerd worden?
II. Hoe kunnen de ecologische en techno-economische potentiëlen van bio-energie productieketens worden gekwantificeerd, rekening houdend met de ontwikkelingen in conversietechnologieën en infrastructuur?
III. Wat is het huidig en toekomstig ecologisch en techno-economisch potentieel van elektriciteit en biokerosine gemaakt van energiegewassen en biomassaresiduen in Brazilië, en wat is de ruimtelijke verdeling hiervan?

Onderzoeksvragen I, II en III worden in hoofdstuk 2 t/m 5 op verschillende geografische niveaus, termijnen, en mate van complexiteit behandeld. In hoofdstuk 2 en 3 wordt het potentieel van elektriciteit geproduceerd van suikerrietstro in de staat São Paulo (Brazilië) voor het gewasjaar 2012 ruimtelijk expliciet onderzocht. In hoofdstuk 4 en 5 worden verschillende biokerosine productieketens van energiegewassen en biomassaresiduen onderzocht om het ecologische en techno-economische biokerosine potentieel voor 2015 en 2030 in kaart te brengen en te kwantificeren.

SAMENVATTING VAN DE HOOFDSTUKKEN

In hoofdstuk 2 wordt het potentieel van elektriciteit van suikerrietstro dat in 2012 in de staat São Paulo (Brazilië) onder ecologische restricties beschikbaar is onderzocht op verschillende geografische niveaus. Er is een ruimtelijke expliciete benadering gebruikt waarbij rekening wordt gehouden met de ruimtelijke distributie van suikerrietvelden, de ruimtelijke variatie in suikerriet opbrengsten, en de locatie en capaciteit van alle suiker- en ethanolfabrieken. Drie scenario's met betrekking tot de hoeveelheid stro dat gegeven ecologische restricties van het veld kan worden afgevoerd worden onderzocht. Het geschatte potentieel van elektriciteit van suikerrietstro varieert tussen 18.7 en 45.8 TWh afhankelijk van het scenario. Dat staat gelijk aan 22% tot 58% van de totale elektriciteitsproductie in São Paulo in 2012. De resultaten laten grote geografische verschillen zien, met over het algemeen hogere potentiëlen en kleinere oogstgebieden voor de suiker- en ethanolfabrieken in de traditionele suikerrietgebieden in het noordoosten van de staat São Paulo dan voor de suiker- en ethanolfabrieken in de expansiegebieden in het westen van de staat São Paulo. Elektriciteitsproductie van suikerrietstro kan een significante bijdrage leveren aan de elektriciteitsvoorziening in Brazilië, maar economische haalbaarheid moet nog verder worden onderzocht. De identificatie van de regio's en de suiker- en ethanolfabrieken met de grootste potentie voor elektriciteitsproductie kan bijdragen aan lokale en regionale besluitvorming op het gebied van bio-energie planning.

Hoofstuk 3 bouwt voort of hoofdstuk 2 en heeft als doel het techno-economisch potentieel van elektriciteitsproductie van suikerrietstro van de suiker- en ethanolfabrieken in de staat São Paulo (Brazilië) te onderzoeken. Er is aangenomen dat alle 174 suiker- en ethanolfabrieken in São Paulo zijn uitgerust met een aanliggende elektriciteitscentrale, en dat al het suikerrietstro dat beschikbaar is binnen het oogstgebied van de suiker- en ethanolfabriek kan worden gebuikt in deze aanliggende energiecentrale. De kosten van elektriciteitsproductie van suikerrietstro zijn ruimtelijk expliciet gekwantificeerd rekening houdend met de ruimtelijke variatie in biomassa kosten, de capaciteit van de elektriciteitscentrales, de schaal-afhankelijke conversie efficiency, de investerings- en operationele kosten, en kosten voor de aansluiting op de dichtstbijzijnde transmissie-infrastructuur. De kosten van suikerrietstro zijn onderzocht op basis van de ruimtelijke informatie over de beschikbaarheid van stro en het oogstgebied van de suiker- en ethanolfabrieken verkregen uit hoofdstuk 2, gegeven het gematigde scenario met betrekking tot de ecologische restricties voor het suikerrietstro potentieel. De kosten voor elektriciteitsproductie van suikerrietstro variëren tussen 68 en 266 US$/MWh tussen de verschillende suiker- en ethanolfabrieken. De suiker- en ethanolfabrieken met een hoog potentieel en lage kosten liggen over het algemeen in de traditionele suikerrietgebieden in het noordoosten van de staat São Paulo die gekarakteriseerd wordt door goede agro-ecologische condities. Bij een prijslimiet van 80 US$/MWh is het techno-economisch potentieel van elektriciteit van suikerrietstro in São Paulo 14.2 TWh, wat gelijk staat aan 10% van de totale elektriciteitsconsumptie in de staat in 2012.

Het doel van hoofdstuk 4 is om het recente en toekomstige techno-economisch potentieel van biokerosine in Brazilië te onderzoeken en locatie-specifieke optimale combinaties te vinden van energiegewassen en technologische conversiepaden. Er zijn in totaal dertien biokerosine productieroutes onderzocht bestaande uit combinaties van verschillende energiegewassen (mais, suikerriet, eucalyptus, sorghum, soja, zonnebloemen, oliepalm, en coyolpalm) en biokerosine conversietechnologieën (Alcohol To Jet - ATJ, Direct Sugar to HydroCarbons – DHSC, Fischer-Tropsch – FT, HydroThermal Liquefaction – HTL, Hydroprocessed Esters and Fatty Acids – HEFA). Ruimtelijk expliciete projecties van toekomstig landgebruik zijn gebruikt om potentieel beschikbaar land voor biomassaproductie te identificeren. Biomassapotentieel en -kosten zijn berekend op basis van de ruimtelijke distributie van landbeschikbaarheid, de ruimtelijke variatie in agro-ecologische geschiktheid voor de verschillende energiegewassen, en de temporele ontwikkelingen in gewasopbrengsten. De kosten van biokerosine productie zijn berekend rekening houdend met de ontwikkelingen in technologische conversiepaden en in de schaal van de fabrieken. Het techno-economisch potentieel is bepaald door voor alle locaties waar land beschikbaar is de totale biokerosine productiekosten te berekenen van alle productieroutes en de laagste biokerosine productiekosten te vergelijken met de variatie in fossiele kerosine prijzen. Het techno-economisch potentieel van biokerosine varieert van 0 tot 6.4 EJ in 2015 en van 1.2 tot 7.8 in 2030, afhankelijk van de referentieprijs voor fossiele kerosine, welke tussen de verschillende luchthavens varieert tussen 19 US$/GJ en 65 US$/GJ. Het techno-economisch potentieel bestaat uit verschillende productieketens. Het noordoosten en het zuidoosten van Brazilië hebben de grootste potentiëlen en daar zijn verscheidene productieketens economisch haalbaar (e.g. ATJ van suikerriet, HTL van eucalyptus, ATJ van mais), terwijl in de rest van Brazilië maar enkele producties routes veelbelovend zijn (bijvoorbeeld HEFA van oliepalm). Het maximale techno-economisch biokerosine potentieel in Brazilië in 2030 zou aan bijna de helft van de verwachte mondiale vraag naar vliegtuigbrandstof kunnen voldoen.

In hoofdstuk 5 wordt het recente en toekomstig ecologisch en techno-economisch potentieel van biokerosine uit biomassa residuen in Brazilië onderzocht. Verschillende productieketens bestaande uit twee soorten biomassa residuen (suikerrietstro – SCS en oogstresiduen van eucalyptus -EHR) en vier verschillende technologische conversiepaden (Alcohol To Jet – ATJ, Fischer-Tropsch – FT, HydroThermal Liquefaction – HTL, Pyrolysis – PYR) zijn onderzocht. Voor het bepalen van het ecologisch potentieel van SCS en EHR, is gekeken naar het erosie risico en organische koolstof in de bodem, omdat deze als de belangrijkste limiterende factoren worden beschouwd voor het weghalen van biomassa residuen. Het ecologisch potentieel is bepaald aan de hand van de spatiotemporele projecties van landgebruik in Brazilië en door het erosie risico en de organische koolstofbalans in de bodem ruimtelijk expliciet te modelleren. Dit resulteert in kaarten van het ecologisch potentieel van SCS en EHR op pixel niveau. De analyse van het techno-economisch potentieel van biokerosine van SCS en EHR is gebaseerd op de totale biokerosine productie kosten. Deze worden verkregen door de som van de kosten van het verzamelen van de residuen, de biokerosine conversiekosten en de biokerosine transportkosten. Deze totale biokerosine productiekosten worden vergeleken met de bandbreedte van de prijs van fossiele kerosine van de Braziliaanse luchthavens om het techno-economisch potentieel te kwantificeren. Het ecologisch potentieel van biomassa residuen varieert van 70 Mt in 2015 tot 102 Mt in 2030, waarbij de beschikbaarheid van suikerrietstro vooral wordt gelimiteerd door de organische koolstofbalans terwijl de beschikbaarheid van oogstresiduen van eucalyptus met name worden beperkt door het erosie risico. Deze hoeveelheden kunnen een technisch biokerosine potentieel genereren variërend van 0.45 EJ in 2015 (46 US$/GJ – 65 US$/GJ) tot 0.67 EJ in 2030 (19 US$/GJ – 65 US$/GJ). De projecties laten zien dat in 2030 verschillende biokerosine productieroutes kunnen concurreren met fossiele kerosine. Het noordoosten en zuidoosten hebben de hoogste potentiëlen, vooral in 2030. Het huidige techno-economische potentieel is echter veel kleiner, met name door de hoge conversiekosten. Daarom kan op de korte termijn grootschalige biokerosine productie alleen gerealiseerd worden met gunstig beleid (bijvoorbeeld lagere belastingen en carbon credits).

BEVINDINGEN EN CONCLUSIES

· *Het verfijnen van de ecologische en techno-economische restricties van bio-energie productieketens naar grid/pixel niveau is een grote methodologische uitdaging om bio-energie potentiëlen ruimtelijk expliciet te kwantificeren.*

Het combineren van de milieueffecten en techno-economische factoren van bio-energie productieketens op pixelniveau vereist meerdere wetenschappelijke disciplines. Ondanks dat hoofdstuk 2 en 3 maar één bio-energie productieketen behandelen, is het behoorlijk arbeidsintensief omdat de integratie van verschillende geografische niveaus iteratieve data verwerking vereist (e.g. aggregeren en desaggregeren van data van pixel naar fabrieksniveau en vice versa). In hoofdstuk 4 en 5 is een gedetailleerde karakterisering van meerdere biokerosine productieketens vereist om het ecologisch en techno-economisch potentieel te onderzoeken. Dit vraagt om multidisciplinair inzicht in de verschillende aspecten van de agrarische-, industriële- en distributiefasen van de productieketens. De ecologische en techno-economische variabelen die op pixel niveau in kaart worden gebracht zijn erg gevoelig voor de verschillende aannames die gemaakt worden (e.g. residu-gewas verhouding, capaciteit van de fabriek, technologische ontwikkeling).

· *De suiker- en ethanolfabrieken in São Paulo met de grootste ecologische en techno-economische potentiëlen van elektriciteit van suikerrietstro zijn voornamelijk gelegen in regio's met optimale agro-ecologische condities, hebben een gemiddelde tot hoge invoer capaciteit en hebben goede toegang tot het elektriciteitsnetwerk.*

In hoofdstuk 2 wordt aangetoond dat de suiker- en ethanolfabrieken met de hoogste ecologisch potentiëlen van elektriciteit uit suikerrietstro zich in de noordoostelijke regio van São Paulo bevinden.

Deze regio heeft optimale agro-ecologische omstandigheden voor de teelt van suikerriet en voor het verwijderen van stro. Vanuit het techno-economische perspectief dat in hoofdstuk 3 is onderzocht, kan worden opgemerkt dat de suiker- en ethanolfabrieken met een grote capaciteit niet noodzakelijkerwijs tegen lage kosten elektriciteit uit suikerrietstro produceren. Afhankelijk van de locatie van de suiker- en ethanolfabriek en de ecologische condities voor het verwijderen van stro binnen het oogstgebied, verkeren fabrieken met gemiddelde tot grote capaciteit doorgaans in de optimale omstandigheden om te investeren in een extra elektriciteitscentrale. De productiekosten van elektriciteit van suikerrietstro zijn afhankelijk van de kosten voor stro, die voornamelijk worden bepaald door de kosten van het verzamelen van het stro en door het ecologisch potentieel van suikerrietstro per hectare. Voor de meeste suiker- en ethanolfabrieken hebben de investeringen in transmissie-infrastructuur een marginaal effect op de totale kosten voor elektriciteitsproductie, aangezien het elektriciteitsnetwerk in São Paulo een hoge dekkingsgraad heeft. Echter, in gebieden met een lage bevolkingsdichtheid zoals in het zuidwesten van de staat, kan een noodzakelijke transmissielijn een groot deel uitmaken van de kapitaalkosten van een nieuwe elektriciteitscentrale.

· *De ontwikkeling van de biokerosine-industrie moet niet alleen gericht zijn op de productieketens met de laagste totale biokerosine productiekosten. Er zijn regio's in Brazilië waar tot wel 10 productieketens biokerosine zouden kunnen produceren tegen kosten lager dan de prijs van fossiele kerosine.*

In de hoofdstuk 4 en 5 wordt het techno-economische potentieel van biokerosine in Brazilië berekend door de som te nemen van alle pixels waar de totale productiekosten van biokerosine onder de maximale fossiele brandstofprijzen in Brazilië ligt. Dit genereert de ruimtelijke spreiding en kosten-aanbodcurven van de optimale combinatie van productieketens met de laagste biokerosine productiekosten. Er moet echter worden vermeld dat in veel regio’s in Brazilië meer dan één keten productiekosten kan behalen die onder de fossiele referentie liggen. In regio’s zoals het zuidoosten en noordoosten van Brazilië kunnen in 2030 naar verwachting tot wel 10 biokerosine productieketens gerealiseerd worden tegen kosten die onder de fossiele brandstofprijzen van de dichtstbijzijnde luchthaven liggen. Daarom is het belangrijker om te begrijpen welke biokerosine productieketens in een bepaalde regio veelbelovend zijn, dan om een enkele biokerosine productieketen te selecteren. Dit helpt bij een betere besluitvorming over welke productieroutes verder ontwikkeld moeten worden rekening houdend met regionale karakteristieken.

· *Momenteel kan biokerosine niet concurreren met fossiele kerosine in de (centrale) regio's van Brazilië waar de grootste vraag naar kerosine is. Desalniettemin kunnen er, vanwege de grote omvang van het land en de hoge prijzen voor fossiele kerosine op luchthavens in (afgelegen) regio's van Brazilië, niches bestaan voor de ontwikkeling van concurrerende biokerosine.*

Bij de techno-economische ontwikkeling van de biokerosine productieketens in Brazilië moet rekening gehouden worden met de hoge kerosine prijzen in het land en de grote variatie tussen de nationale luchthavens als gevolg van verschillen in staatsbelastingen, logistiek en infrastructuur en brandstofdistributeurs. In (centrale) regio’s met een grote vraag naar kerosine, zoals de staten van São Paulo en Rio de Janeiro, is het onwaarschijnlijk dat biokerosine op korte termijn kan concurreren met fossiele kerosine. Om het concurrentievermogen van biokerosine in deze (centrale) regio’s te vergroten, zijn beleidsinstrumenten (e.g. Renovabio en CORSIA) nodig om de ontwikkeling van biokerosine te ondersteunen. Aan de andere kant, in andere (afgelegen) regio’s (bijv. het westelijk deel van de Noord- en Midden-West-regio’s) waar de fossiele kerosine doorgaans aanzienlijk duurder is in combinatie met een grote beschikbaarheid van goedkope biomassa, kan de slagingskans van de introductie van biokerosine mogelijk hoger zijn. Dit hangt echter ook af van of de verwachte biokerosine vraag van de dichtstbijzijnde luchthaven(s) een rendabele schaal van de biokerosinefabriek kan garanderen. Bovendien vereist de ontwikkeling van geavanceerde biobrandstoffen in afgelegen regio’s ook een evaluatie van de beschikbaarheid van infrastructuur in de regio, niet alleen gericht op brandstofdistributiehubs, maar ook op de levering van nutsvoorzieningen (bijv. elektriciteit, waterstof, gist) en de beschikbaarheid van personeel. Ten slotte, als de productiekosten van biokerosine in afgelegen regio's lager zijn dan in centrale regio's, moeten andere logistieke opties (bv. scheepvaart en spoor) worden overwogen om de haalbaarheid van levering aan grote luchthavens (in centrale regio's) te evalueren.

· *Brazilië heeft een groot techno-economisch en ecologisch bio-energie potentieel (elektriciteit en biokerosine), maar de implementatie wordt beperkt door bijkomende factoren.*

In hoofdstuk 3 worden 37 suiker- en ethanolfabrieken geïdentificeerd met een gezamenlijk techno-economisch potentieel van elektriciteit uit suikerrietstro van 14,2 TWh. Er is echter meer gedetailleerde informatie over deze fabrieken nodig om te begrijpen of ze bereid zijn te investeren in elektriciteitsproductie uit biomassaresiduen. Beleidsmakers en energieplanners kunnen dit techno-economische potentieel gebruiken om projecties te maken voor elektriciteit uit biomassaresiduen en de leveringszekerheid in Brazilië. Toch zijn er verschillende andere factoren die het uiteindelijke implementatiepotentieel beïnvloeden, zoals de sociaal-politieke omstandigheden, de volatiliteit van de elektriciteitsprijzen en de concurrerende vraag naar suikerrietstro.

In hoofdstuk 5 en (voornamelijk) 4 wordt een zeer groot biokerosine potentieel gevonden (ongeveer 8 EJ in 2030, waarbij zowel energiegewassen als biomassa-residuen worden gecombineerd). Dit grote potentieel laat zien dat Brazilië inderdaad een relevant land is om in biokerosine productie te investeren vanwege de gunstige agro-ecologische omstandigheden en de hoge prijzen voor fossiele kerosine. In hoofdstuk 4 wordt het techno-economische potentieel echter bereikt dankzij een combinatie van diverse biokerosine productieketens in Brazilië, die waarschijnlijk niet gelijktijdig zullen worden ontwikkeld.
Bovendien wordt er geen rekening gehouden met ecologische restricties (e.g. biodiversiteit, broeikasgasemissies), waardoor het biokerosine potentieel hoogstwaarschijnlijk aanzienlijk lager is. Het huidige techno-economische biokerosine potentieel is gebaseerd op de beschikbaarheid van land, wat bijna het dubbele is van het huidige akkerland in Brazilië - hoogstwaarschijnlijk zal slechts een fractie hiervan daadwerkelijk kunnen worden gerealiseerd. Bovendien wordt bij het onderzoek naar het biokerosine potentieel de concurrerende vraag naar biomassa en land voor andere biobased toepassingen niet meegenomen.

AANBEVELINGEN VOOR VERDER ONDERZOEK

- In dit proefschrift wordt aangenomen dat alle suiker- en ethanol fabrieken in São Paulo een aangrenzende elektriciteitscentrale hebben om elektriciteit uit suikerrietstro te produceren, waarbij schaal en efficiëntie afhangen van de beschikbaarheid van suikerrietstro (d.w.z. het ecologisch potentieel) binnen het oogstgebied. Dit wordt aangenomen omdat er geen informatie openbaar beschikbaar is over de huidige status van de boilers van suiker- en ethanolfabrieken. Volgens de verkoopcijfers van bio-elektriciteit verkopen grote suiker- en ethanolfabrieken niet noodzakelijkerwijs meer elektriciteit dan kleinere fabrieken. Over het algemeen wordt er in hoogrendementsketels geïnvesteerd door moderne middelgrote fabrieken voor welke de verkoop van elektriciteit (naast suiker en ethanol) een belangrijkste bedrijfsstrategie is. Daarom zou een studie naar de huidige beschikbaarheid en kenmerken van de boilers van de suiker- en ethanolfabrieken (en een mogelijke overgang naar hoogrenderende ketels) van groot belang zijn voor energieplanners. Dit kan ook relevant zijn voor korte termijn energieplanning met betrekking tot seizoensgebonden omstandigheden. Zo zal in geval van verminderde elektriciteitsproductie uit waterkracht door droogte een grotere elektriciteitsproductie uit biomassa nodig zijn, waardoor prijzen van elektriciteit uit biomassa stijgen.

- Net als bij het onderzoek naar het potentieel van elektriciteitsproductie uit suikerrietstro, wordt in hoofdstuk 5 het biokerosine potentieel gekwantificeerd door het ecologisch potentieel van biomassa-residuen te onderzoeken. Biokerosine productie moet echter aan andere sociaaleconomische en ecologische criteria voldoen. Het is daarom van groot belang dat in toekomstige studies ook rekening wordt gehouden met andere effecten, zoals de koolstof- en watervoetafdruk en de impact op de biodiversiteit. Vooral voor energiegewassen met een hoog potentieel voor biokerosine productie, zoals eucalyptus en coyolpalm, moet de integratie met ander landgebruik in agroforestry-systemen (in plaats van monocultuur) en participatie van kleine boeren verder worden onderzocht om de duurzaamheid van de toeleveringsketens van biokerosine productieketens te evalueren.
- In dit proefschrift wordt in verschillende hoofdstukken het ecologisch- en techno-economisch potentieel van suikerrietstro gekwantificeerd voor toepassing in verschillende eindgebruiken: elektriciteit en biokerosine. De potentiële concurrentie voor suikerrietstro voor de verschillende toepassingen wordt echter niet gekwantificeerd. In principe wordt beleidsmakers geadviseerd dat een verdere toename van de valorisatie van suikerrietstro kan worden gerealiseerd door het gebruik ervan in nieuwe biokerosine conversietechnologieën te onderzoeken, in plaats van het te verbranden voor elektriciteit. Dat kan bevorderlijk zijn voor het opschalen van de biokerosine industrie in Brazilië en kan worden geïntegreerd bij het renoveren van bestaande fabrieken. Bovendien zijn er voor de elektriciteitssector momenteel alternatieve hernieuwbare bronnen om de broeikasgasemissies in de sector te reduceren (bijvoorbeeld zon- en windenergie), terwijl de luchtvaartsector daarvoor de komende jaren meer afhankelijk zal zijn van biokerosine. Tegelijkertijd moet er ook op worden gewezen dat de prijzen voor elektriciteit zeer hoog kunnen zijn als gevolg van een tekort aan regenval (vooral als extreme weersomstandigheden worden meegenomen), wat zeer

aantrekkelijk zou kunnen zijn voor investeerders. Daarom zou in toekomstige studies concurrerende toepassingen voor suikerrietstro moeten worden meegenomen, evenals in energiesysteemmodellen die de techno-economische en ecologische prestaties van verschillende bio-energiesystemen vergelijken.

AANBEVELINGEN VOOR STAKEHOLDERS

- Om investeerders te ondersteunen in de productie van bio-energie en biokerosine moeten energieplanners van overheidsinstanties op staats- en/of federaal niveau (bijv. Ministeries en secretariaten) een prognose maken van de potentiele vraag en aanbod van biomassa in een bepaalde regio, rekening houdend met technologische ontwikkeling en de haalbaarheid. Momenteel worden de ruimtelijke verdeling van biomassa, landbeschikbaarheid en milieueffecten van bio-energieproductie zelden ruimtelijk- en temporeel expliciet onderzocht door overheidsinstanties in Brazilië. Deze onderzoeken worden vaak uitgevoerd door universiteiten en onderzoeksinstellingen (nationaal of internationaal), vaak met beperkte financiering en / of valorisatie. Daarom moeten nationale en internationale overheidsinstanties op het gebied van energie de ontwikkeling van theoretische studies over bio-energiepotentiëlen ondersteunen.
- Momenteel kunnen beleidsinstrumenten zoals CORSIA (specifiek voor biokerosine) en Renovabio (voor verschillende biobrandstoffen) een stimulans bieden voor duurzame bio-energieproducenten. Deze mechanismen zijn echter nog steeds weinig gebaseerd op ruimtelijk expliciete evaluaties. In deze context kunnen ruimtelijk expliciete onderzoeken naar het ecologisch potentieel van bio-energie deze beleidsinstrumenten helpen door meer gedetailleerde informatie te genereren voor de monitoring van duurzame bio-energie. Een meer gedetailleerde evaluatie van het ecologisch potentieel van biomassa-residuen in hoofdstuk 5 zou het bijvoorbeeld mogelijk maken om gebieden te identificeren die als ecologisch beschikbaar zijn aangemerkt, maar in werkelijkheid zeer vatbaar zijn voor uitputting van bodemkoolstof en / of erosie. Bovendien zouden certificeringssystemen voor land- en bosbouw (bijvoorbeeld BONSUCRO, ISCC, FSC en PEFC) ook kunnen profiteren van ruimtelijk expliciete evaluatie van bio-energiesystemen. Momenteel is de monitoring van gecertificeerde productieketens gebaseerd op bewijs dat geleverd wordt door bio-energieproducenten en door lokale audits die gedaan worden door geaccrediteerde certificatie-instellingen. Verschillende bosbouwsystemen maken ook gebruik van zogenoemde 'risk-based' benadering (bijv. FSC-gecertificeerd hout), waarbij een heel gebied (bijv. een staat of een regio) wordt beoordeeld op specifieke duurzaamheidscriteria. Een ruimtelijk expliciete beoordeling met behulp van hoogwaardige ruimtelijke informatie zou een meer gedetailleerde kwantificering van dergelijke risico's mogelijk maken en beter inzicht kunnen geven over de waarschijnlijkheid dat bio-energieproductie aan verschillende duurzaamheidscriteria voldoet.

Sumário executivo

INTRODUÇÃO

Brasil é um dos maiores produtores de energias renováveis no mundo em razão da abundância de recursos naturais. Das fontes modernas de energias renováveis, a bioenergia é uma das opções mais flexíveis para a reduzir a dependência de energias fósseis, dado que oferece um portfólio diversificado para diferentes usos, como biocombustíveis, eletricidade e produtos químicos. Atualmente, a produção de bioenergia no Brasil é amplamente representada pelo etanol de cana de açúcar, porém novas cadeias de produção estão projetadas para crescer nos próximos anos. Considerando o aumento da demanda por bioenergia nos próximos anos, incluindo o surgimento de novas cadeias de produção, é essencial monitorar e quantificar os potenciais de bioenergia.

Os potenciais de bioenergia podem ser quantificados em vários níveis: teórico, técnico, econômico (tecno-econômico ou de mercado), ambiental (ou ecológico) e potencial de implementação. A maioria dos estudos sobre potenciais de bioenergia são voltados aos impactos ambientais e fatores tecno-econômicos. Esses potenciais são difíceis de se quantificar devido à variabilidade espacial e temporal dos impactos ambientais e de fatores tecno-econômicos. Portanto, um desafio-chave de pesquisa é abordar os impactos ambientais e os fatores tecno-econômicos de maneira espacial e temporal.

O objetivo desta tese é avaliar espacialmente os atuais e futuros potenciais ambientais e tecno-econômicos da produção de bioenergia no Brasil em diferentes escalas geográficas. Nesta tese, avalia-se o potencial ambiental e tecno-econômico de dois promissores sistemas de bioenergia para o Brasil: bioeletricidade da palha de cana e biocombustíveis de aviação (bioquerosene) a partir de várias fontes de biomassa. Para atingir o objetivo desta tese, são abordadas as seguintes questões de pesquisa.

I - Como quantificar espacialmente o potencial ambiental e tecno-econômico de resíduos agrícolas e culturas energéticas ao longo do tempo?

II - Como quantificar espacialmente o potencial ambiental e tecno-econômico das cadeias de produção de bioenergia, dado o desenvolvimento de tecnologias e infraestrutura de conversão?

III - Qual é o atual e futuro potencial ambiental e tecno-econômico de bioeletricidade e bioquerosene no Brasil a partir de culturas energéticas e resíduos agrícolas, bem como suas distribuições espaciais?

As questões de pesquisa I, II e III são abordadas nos capítulos 2 a 5, em várias escalas geográficas, níveis temporais e de complexidade. Nos capítulos 2 e 3, os potenciais de bioeletricidade da palha de cana são avaliados espacialmente no estado de São Paulo (Brasil), considerando a safra 2012. Nos capítulos 4 e 5, várias cadeias de produção de bioquerosene a partir de culturas energéticas e resíduos agrícolas são avaliadas para mapear e quantificar os potenciais ambiental e tecno-econômico no Brasil em 2015 e 2030.

RESUMO DOS CAPÍTULOS

No capítulo 2, o potencial ambiental de bioeletricidade da palha de cana disponível no estado de São Paulo (Brasil) em 2012 é avaliado em diferentes escalas. Uma abordagem espacialmente explícita é empregada considerando a distribuição espacial das áreas de cana de açúcar, a variabilidade espacial da produtividade da cana com base em dados de sensoriamento remoto, e a localização e capacidade de cada usina de cana de açúcar. São gerados cenários ***business as usual***, moderado e elevado, nos quais a quantidade de palha a ser removida por restrições ambientais é variada. O potencial ambiental estimado de bioeletricidade a partir da palha de cana varia entre 18,7 e 45,8 TWh, dependendo do cenário analisado. Isso equivaleria a 22% - 58% do total de eletricidade produzida em São Paulo em 2012. Os resultados mostram grandes diferenças espaciais, com potenciais geralmente mais altos e raios de coleta mais curtos para as usinas em áreas tradicionais de cana de açúcar, no nordeste do estado de São Paulo, do que para as usinas nas áreas de expansão na região oeste do estado de São Paulo. A bioeletricidade da palha de cana pode ter uma contribuição significativa para o suprimento de eletricidade no Brasil, porém as restrições econômicas precisam ser mais bem investigadas. A identificação de regiões e usinas com os maiores potenciais de bioeletricidade poderia apoiar a tomada de decisões locais e regionais no planejamento de bioenergia.

O capítulo 3 é baseado no capítulo 2, e tem como objetivo avaliar espacialmente o potencial tecno-econômico da bioeletricidade a partir da palha de cana das usinas do estado de São Paulo (Brasil). O custo de produção de bioeletricidade é quantificado espacialmente. Para tanto, assumiu-se que todas as 174 usinas em São Paulo são equipadas com uma planta adjacente/adicional, e que toda a palha de cana dentro do raio de coleta da usina possa potencialmente ser utilizada na planta adjacente. Os custos de bioeletricidade são calculados considerando a variação espacial nos custos de biomassa (palha), a escala e a eficiência da planta, os investimentos e os custos operacionais e o custo de conexão com a infraestrutura de transmissão mais próxima. Os custos da palha são avaliados utilizando as informações espaciais sobre a disponibilidade de palha e o raio de coleta das usinas levantadas no capítulo 2, relativo ao cenário moderado do potencial ambiental da palha de cana. Os custos de bioeletricidade variam entre 68 e 266 US$/MWh nas usinas. As usinas com alto potencial de bioeletricidade e baixo custo são geralmente grandes usinas localizadas em áreas tradicionais de cana de açúcar no nordeste do Estado de São Paulo, caracterizadas por condições agro-ecológicas adequadas. Supondo um preço de corte de 80 US$/MWh, o potencial tecno-econômico da bioeletricidade pela palha de cana em São Paulo é de 14,2 TWh, o que equivaleria a 10% do total de eletricidade consumida no estado em 2012.

O objetivo do capítulo 4 é avaliar o atual e futuro potencial tecno-econômico da produção de bioquerosene no Brasil, e identificar combinações ótimas de localizações de culturas energéticas e tecnologias de conversão. Ao todo, treze rotas de produção de bioquerosene são avaliadas através da combinação de várias culturas energéticas (milho, cana, eucalipto, sorgo-sacarino, soja, girassol, dendê e macauba) e tecnologias de conversão de bioquerosene (*Alcohol **To Jet*** - ATJ, *Direct Sugar to HydroCarbons* – DHSC, *Fischer-Tropsch* – FT, *HydroThermal Liquefaction* – HTL, *Hydroprocessed Esters and Fatty Acids* – HEFA). Projeções espaciais de mudanças de uso da terra são consideradas para identificar a disponibilidade do potencial de terra para a produção de biomassa até o ano de 2030. Com a distribuição espacial da disponibilidade de terra, é calculado a variabilidade espacial da aptidão agroecológica para as culturas energéticas e a estimativa de evolução produtividade até 2030, o potencial de produção de biomassa e os custos. Os custos de produção da bioquerosene são calculados considerando o desenvolvimento das tecnologias de conversão e também da escala. O potencial tecno-econômico é determinado a partir do menor custo de bioquerosene dentre todas as rotas de produção e comparando-o com a faixa de preços de querosene fóssil nos aeroportos do Brasil. O potencial tecno-econômico do bioquerosene varia de 0 a 6,4 EJ em 2015 e entre 1,2 - 7,8 EJ em 2030, dependendo do preço de referência do querosene fóssil, que varia de 19 US$/GJ a 65 US$/GJ nos aeroportos. O potencial tecno-econômico é composto por várias rotas de produção que atingiram o menor custo. As regiões Nordeste e Sudeste do Brasil apresentam os maiores potenciais com várias rotas viáveis de bioquerosene (por exemplo, ATJ de cana de açúcar, HTL de eucalipto, ATJ de milho), enquanto as demais regiões possuem apenas poucas rotas de produção promissoras (por exemplo, HEFA de dendê). O potencial tecno-econômico máximo de bioquerosene no Brasil poderia atender quase metade da demanda global projetada de querosene de aviação em 2030.

O capítulo 5 avalia o potencial ambiental dos resíduos agrícolas e o potencial tecno-econômico da produção de bioquerosene a partir desses resíduos no Brasil em diferentes horizontes temporais. Diferentes rotas de produção de bioquerosene são avaliadas a partir da palha de cana de açúcar (PCA) e resíduo de colheita de eucalipto (RCE) e quatro tecnologias de conversão (*Alcohol To Jet* – ATJ, *Fischer-Tropsch* – FT, *HydroThermal Liquefaction* – HTL, *Pyrolysis* - PYR). Para a avaliação do potencial ambiental de PCA e RCE, são considerados o risco de erosão e o balanço de Carbono Orgânico do Solo (COS), pois são fatores determinantes para a remoção de resíduos agrícolas. O potencial ambiental é determinado, utilizando projeções espaço-temporais de cana de açúcar e eucalipto no Brasil, e modelando o risco de erosão e o balanço de COS em sistemas de manejo de resíduo. Isso resulta em mapas do potencial ambiental de PCA e RCE. A avaliação do potencial tecno-econômico do bioquerosene da PCA e RCE considera os custos totais do bioquerosene, resultantes da soma dos custos de recuperação dos resíduos de agrícolas, custos de conversão do bioquerosene e custos de transporte do bioquerosene. Esses custos totais da bioquerosene são comparados com a faixa de preços do querosene fóssil nos aeroportos brasileiros para quantificar o potencial tecno-econômico. O potencial ambiental dos resíduos agrícolas varia de 70 Mt em 2015 a 102 Mt em 2030, com a PCA sendo altamente restringida pelo COS, enquanto o RCE é mais limitado pelo alto risco de erosão. Essas quantidades podem gerar um potencial tecno-econômico de bioquerosene variando de 0,45 EJ em 2015 (46 US$/GJ - 65 US$/GJ) a 0,67 EJ em 2030 (19 US$/GJ - 65 US$/GJ). Em 2030, várias rotas de produção de bioquerosene podem ser competitivas com os preços do querosene fóssil. As regiões Nordeste e Sudeste têm os maiores potenciais, especialmente em 2030. No entanto, o potencial tecno-econômico atual é muito menor devido aos altos custos de conversão. Assim, no curto prazo, a produção em larga escala de bioquerosene só poderia ser realizada com políticas favoráveis (por exemplo, impostos mais baixos, créditos de carbono).

PRINCIPAIS MENSAGENS

- *A análise de restrições ambientais e tecno-econômicas em cadeias de produção de bioenergia ao nível de pixel é um grande desafio metodológico para se quantificar espacialmente os potenciais de bioenergia.*

Combinar impactos ambientais e fatores tecno-econômicos na avaliação do potencial em cadeias de produção de bioenergia no nível de pixel requer a integração de várias disciplinas. Embora os capítulos 2 e 3 avaliem exclusivamente a cadeia de produção de bioeletricidade, o estudo se mostrou bem mais trabalhoso do ponto de vista operacional/computacional, pois integra diferentes escalas geográficas, exigindo um processamento iterativo de dados (por exemplo, agregar e desagregar análises do nível de pixel para o nível de usina e vice-versa). Por outro lado, nos capítulos 4 e 5, foi necessária uma caracterização mais detalhada das múltiplas rotas de produção da bioquerosene para avaliar o potencial ambiental e tecno-econômico. Isso exige uma importante compreensão multidisciplinar de vários aspectos dos estágios agrícola, industrial e de distribuição das cadeias de suprimentos. Portanto, as variáveis ambientais e tecno-econômicas mapeadas no nível de pixel são altamente sensíveis às premissas adotadas (por exemplo, relação resíduo-cultura, capacidade instalada da planta, progresso tecnológico).

- *As usinas de cana de açúcar em São Paulo que possuem os maiores potenciais ambientais e tecno-econômicos de bioeletricidade pela palha de cana estão principalmente em regiões com ótimas condições agroecológicas, com capacidade de moagem média, e alta acessibilidade à rede de distribuição de energia elétrica.*

O capítulo 2 mostrou que as usinas de cana com maior potencial ambiental de bioeletricidade estão localizadas na região nordeste de São Paulo. Esta região apresenta ótimas condições agroecológicas para o cultivo da cana de açúcar e também para a recuperação da palha. Na perspectiva tecno-econômica explorada no capítulo 3, nota-se também que as usinas de cana com alta capacidade de moagem não necessariamente produzem bioeletricidade a baixo custo. Dependendo da localização da usina e das condições ambientais para a recuperação da palha dentro do raio de coleta, usinas com capacidade de moagem média-alta normalmente possuem condições ideais para investir em uma planta adjacente para produção de bioeletricidade. Os custos de produção de bioeletricidade dependem dos custos de recuperação da palha, que são afetados principalmente pelos custos na "porteira da fazenda" e também pelo potencial ambiental da palha de cana por hectare. Os investimentos em infraestrutura de transmissão têm um efeito marginal nos custos gerais de bioeletricidade para a maioria das usinas de cana, pois o estado de São Paulo possui alta disponibilidade de subestações elétricas das distribuidoras. No entanto, em áreas como o sudoeste do estado, com baixa densidade populacional, a necessidade de novas linhas de transmissão pode representar uma grande parcela dos custos de capital de uma nova usina.

- *O desenvolvimento da indústria de bioquerosene não deve se concentrar apenas na rota de produção que atingir os menores custos totais de produção de bioquerosene. Existem regiões no Brasil em que até 10 rotas de produção poderiam (em 2030) produzir bioquerosene com custos abaixo do preço do querosene fóssil.*

Nos capítulos 4 e 5, o potencial tecno-econômico da bioquerosene no Brasil foi calculado através da soma de todos os pixels que atingiram os menores custos de produção de bioquerosene, abaixo dos preços querosene fóssil no Brasil. Isso gerou as curvas de suprimento oriundo da combinação ideal de rotas de produção com os menores custos de bioquerosene. Deve-se mencionar, no entanto, que em muitas regiões do Brasil, mais de uma rota de produção pode atingir os custos de bioquerosene abaixo do equivalente fóssil. Em regiões como o Sudeste e o Nordeste do Brasil, projeta-se que até 10 rotas de produção de bioquerosene atinjam custos abaixo dos preços de querosene fóssil em 2030. Portanto, mais do que selecionar uma única rota de produção de bioquerosene, é importante entender quais rotas de bioquerosene são promissoras em uma determinada região. Isso poderia apoiar uma melhor decisão sobre quais rotas de produção devem ser desenvolvidas, conforme as características regionais.

- *Atualmente, o bioquerosene não é competitivo com o querosene fóssil nas regiões (centrais) do Brasil, com maior demanda por combustíveis para aviação. No entanto, devido ao tamanho do país e os altos preços querosene fóssil em aeroportos localizados em regiões (remotas) do Brasil, nichos para o desenvolvimento de bioquerosene com custos competitivos podem existir.*

O desenvolvimento tecno-econômico das rotas de produção de bioquerosene no Brasil deve considerar que o preço do combustível para aviação no país é muito alto, com alta variabilidade nos aeroportos nacionais pelos diferentes impostos estaduais aplicados, condições de logística e infraestrutura, e empresas distribuidoras de combustível. Nas regiões (centrais) com alta demanda de combustível de aviação, como os estados de São Paulo e Rio de Janeiro, é improvável que o bioquerosene possa competir atualmente com os preços do querosene fóssil. Para aumentar a competitividade do bioquerosene nessas regiões (centrais), são necessários mecanismos (por exemplo, Renovabio e CORSIA) para apoiar o desenvolvimento do bioquerosene. Entretanto, em outras regiões (remotas) (por exemplo, oeste das regiões Norte e Centro-Oeste), onde o querosene fóssil é significativamente mais caro, mas que há uma disponibilidade de biomassa a baixo custo, as chances de introdução de bioquerosene podem ser maiores. No entanto, isso também depende se a demanda esperada do(s) aeroporto(s) mais próximo(s) possa garantir uma escala viável de produção de bioquerosene. Além disso, o desenvolvimento de biocombustíveis avançados em regiões remotas também exige uma avaliação da disponibilidade de infraestrutura da região, não apenas focada nos centros de distribuição de combustível, mas também no fornecimento de utilidades (por exemplo, eletricidade, hidrogênio, leveduras) e recursos humanos. Por fim, se os custos de produção da bioquerosene em regiões remotas forem mais baixos do que nas regiões centrais, outras opções de logística (por exemplo, cabotagem e ferroviário) devem ser consideradas para avaliar a viabilidade do fornecimento para grandes aeroportos (nas regiões centrais).

- *O Brasil possui um grande potencial tecno-econômico e ambiental de bioenergia (bioeletricidade e bioquerosene), mas a implementação é limitada por fatores adicionais*.

No capítulo 3, ao todo 37 usinas de cana de açúcar foram identificadas com um potencial tecno-econômico de bioeletricidade de 14,2 TWh. No entanto, são necessárias informações mais detalhadas dessas usinas para entender de fato sua condição de investir nesse modelo de negócio. Os formuladores de políticas e planejadores energéticos podem utilizar esse potencial tecno-econômico para fazer projeções de bioeletricidade e segurança energética no Brasil. No entanto, vários outros fatores influenciam um processo de implementação da atividade, como condições sócio-políticas, volatilidade dos preços da eletricidade e a competição pela palha de cana.

No capítulo 5 e (principalmente) 4, foi encontrado um potencial muito alto de bioquerosene (cerca de 8 EJ em 2030, combinando culturas energéticas e resíduos de biomassa). Esse alto potencial mostra que o Brasil é de fato um país relevante para se investir na produção de bioquerosene devido às condições agroecológicas favoráveis e aos altos preços querosene fóssil para aviação. No entanto, no capítulo 4, o potencial tecno-econômico foi alcançado em razão das diversas combinações de múltiplas rotas de produção de bioquerosene em todo o Brasil, que dificilmente serão desenvolvidas simultaneamente. Além disso, nenhuma restrição ambiental foi considerada (e.g. biodiversidade, emissões de GEE), o que provavelmente reduziria significativamente o potencial de bioquerosene. O atual potencial tecno-econômico de bioquerosene foi baseado na disponibilidade de terra, que é o dobro das atuais áreas cultiváveis no Brasil – mas que provavelmente, apenas uma fração dessa terra poderia ser realmente utilizada. Além disso, nenhuma competição pela biomassa e pela terra disponível para outros fins foi considerada na avaliação do potencial da bioquerosene.

RECOMENDAÇÕES PARA FUTUROS ESTUDOS

- Nesta tese, assumiu-se que todas as usinas de cana de açúcar em São Paulo tinham uma usina adjacente para a produção comercial de bioeletricidade, com escala e eficiência dependentes da quantidade de palha disponível (i.e. potencial ambiental) dentro do raio de coleta. Esta premissa foi assumida porque nenhuma informação sobre a condição atual das caldeiras das usinas de cana está disponível publicamente. De acordo com os dados de venda de bioeletricidade, as grandes usinas não necessariamente vendem mais bioeletricidade. Em geral, os investimentos em caldeiras de alta eficiência para fins de comercialização de bioeletricidade são feitos por usinas modernas de médio porte que têm a bioeletricidade como principal modelo de negócios (juntamente com açúcar e etanol). Portanto, estudos que descrevam a disponibilidade e as características atuais das caldeiras das usinas seriam de grande relevância para o planejamento energético do setor. Isso também pode ser relevante para o planejamento energético de curtíssimo prazo em circunstâncias sazonais (por exemplo, no caso de efeitos da seca na produção de energia hidrelétrica, seria necessário um grande suprimento de bioeletricidade, aumentando os preços da bioeletricidade).

- Semelhante à avaliação do potencial de bioeletricidade, o potencial de bioquerosene foi quantificado no capítulo 5, avaliando o potencial ambiental de resíduos agrícolas. No entanto, a produção de bioquerosene deve cumprir outros critérios socio-econômicos e ambientais e, portanto, é de grande importância que outros impactos também sejam considerados em estudos futuros, como pegada de carbono e hídrica e impactos na biodiversidade. Especialmente para culturas energéticas com alto potencial de produção de bioquerosene, como eucalipto e macaúba, a integração com outros usos da terra em sistemas agroflorestais (ao invés da monocultura), juntamente com a participação de pequenos produtores devem ser mais exploradas para avaliar a sustentabilidade das rotas de produção desses biocombustíveis.

- Nesta tese, o potencial ambiental e tecno-econômico da palha de cana foi quantificado em diferentes capítulos para aplicação em diferentes usos: bioeletricidade e bioquerosene. No entanto, a potencial competição pela mesma palha de cana para esses diferentes usos não foi quantificada. Em princípio, recomenda-se aos formuladores de políticas públicas que um aumento adicional da valorização da palha de cana de açúcar possa ser realizado explorando seu uso em novas tecnologias de bioquerose, ao invés de sua queima para bioeletricidade. Isso pode ser vantajoso para a expansão da indústria de bioquerosene no Brasil e pode ser incorporado em indústrias já existentes. Além disso, o setor elétrico atualmente possui outras fontes renováveis para sua descarbonização (e.g. solar e eólica), enquanto o setor de aviação será mais dependente do bioquerosene nos próximos anos. Ao mesmo tempo, deve-se destacar também que os preços da bioeletricidade podem ser muito altos devido à escassez de chuvas (principalmente se eventos climáticos extremos forem considerados), o que pode ser atrativo para os investidores. Portanto, considerando esse contexto, novos estudos focados na demanda desses bioprodutos são necessários para analisar a competição dos produtos oriundos da palha de cana, bem como a comparação do desempenho tecno-econômico e ambiental de diferentes sistemas de produção de bioenergia a partir da palha.

RECOMENDAÇÕES PARA STAKEHOLDERS

- Para apoiar os investidores na produção de bioeletricidade e bioquerosene, o planejamento energético no nível estadual ou federal de órgãos governamentais (por exemplo, ministérios e secretarias) precisa dimensionar e projetar a demanda e o potencial de fornecimento de biomassa em uma determinada região, considerando o desenvolvimento tecnológico e também viabilidade econômica. Atualmente, os órgãos governamentais no Brasil dificilmente avaliam a distribuição espacial da disponbilidade de biomassa, bem como a projeção de disponibilidade de terras e quantificação dos impactos ambientais e tecno-econômicos na produção de bioenergia. Essas avaliações são geralmente realizadas por instituições acadêmicas e institutos de pesquisa (nacionais ou internacionais), com financiamento e/ou divulgação mais limitada. Portanto, os órgãos governamentais nacionais e internacionais de energia devem apoiar o desenvolvimento de estudos teóricos sobre os potenciais de bioenergia.

- Atualmente, mecanismos como CORSIA (específico para bioquerosene) e Renovabio (para diferentes biocombustíveis) podem oferecer incentivos para produtores de bioenergia “sustentável”. No entanto, esses mecanismos ainda se baseiam muito pouco em avaliações espacialmente explícitas. Este tipo de avaliação poderia auxiliar esses mecanismos a produzir informações mais precisas no monitoramento da produção “sustentável” de bioenergia. Por exemplo, uma avaliação mais detalhada do potencial ambiental dos resíduos agrícolas mapeadas no capítulo 5 permitiria identificar áreas previamente rotuladas como ecologicamente disponíveis, mas que na realidade são altamente suscetíveis à depleção de carbono do solo e/ou perda de solo. Além disso, os sistemas de certificação agrícola e florestal (por exemplo, BONSUCRO, ISCC, FSC e PEFC) também poderiam se beneficiar de avaliações espacialmente explícitas dos sistemas de bioenergia. Atualmente, o monitoramento de cadeias de produção certificadas é baseado em informações fornecidas por produtores de bioenergia e auditorias locais por organismos de certificação credenciados. Vários sistemas florestais também usam as avaliações baseadas em risco (por exemplo, madeira controlada pelo FSC), onde toda uma área (por exemplo, um estado ou uma região) é avaliada para atender critérios específicos de sustentabilidade. A avaliação espacialmente explícita, utilizando de informações espaciais de alta qualidade, permitiria uma quantificação mais detalhada das condições de produção e da conformidade da produção de bioenergia com vários critérios de sustentabilidade.

Supplementary Material

SM 3.1. - STRAW FARM-GATE COST CALCULATION

Table 1 SM 3.1 shows the required data to calculate the straw farm-gate cost. The variables sugarcane yield, rate of recovery, total straw costs and recovering distance are based on the 15 scenarios (ID) established by Cardoso et al. [123]. In figure 1 SM 3.1, we fit a power trend line between the reference data on farm-gate cost and straw availability to estimate the farm-gate cost at field level.

Table 1: Reference techno-economic data used for estimating straw farm-gate cost.

ID	Sugarcane yield (t.ha^{-1})	Recovery rate (%)	Straw availability (t.ha^{-1})	Total straw cost (US\$.t^{-1})	Recovering distance (km)	Transportation cost (US\$.t^{-1})	Farm-gate cost (US\$.t^{-1})
1	76.1	38.1	4.05	32.87	26.1	5.1156	27.7544
2	76.1	61.9	6.59	26.41	26.1	5.1156	21.2944
3	76.1	38.1	4.05	35.36	43.9	8.6044	26.7556
4	76.1	61.9	6.59	28.9	43.9	8.6044	20.2956
5	93.9	38.1	5.00	28.55	26.1	5.1156	23.4344
6	93.9	61.9	8.13	22.87	26.1	5.1156	17.7544
7	93.9	38.1	5.00	30.77	43.9	8.6044	22.1656
8	93.9	61.9	8.13	25.09	43.9	8.6044	16.4856
9	70	50	4.90	31.57	35	6.86	24.71
10	100	50	7.00	24.82	35	6.86	17.96
11	85	50	5.95	25.95	20	3.92	22.03
12	85	50	5.95	29.88	50	9.8	20.08
13	85	30	3.57	36.32	35	6.86	29.46
14	85	70	8.33	24.82	35	6.86	17.96
15	85	50	5.95	27.9	35	6.86	21.04

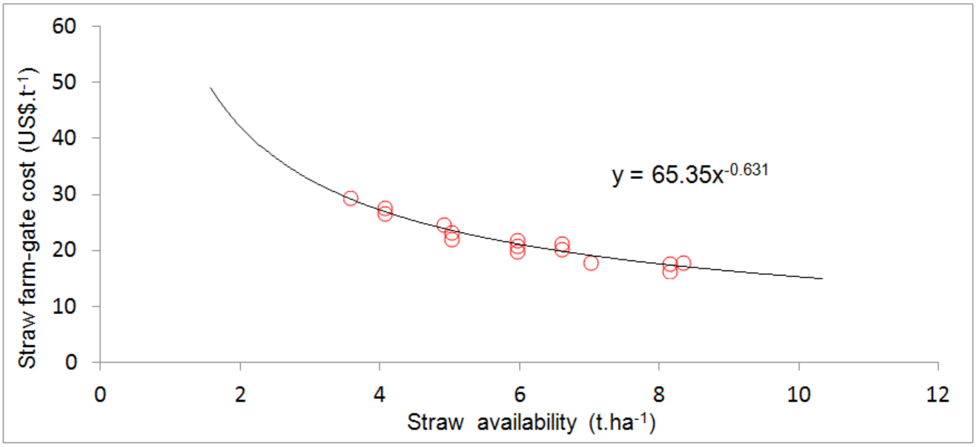

Figure 1 SM 3.1: Power trend line between the sugarcane straw farm-gate cost and the straw availability per hectare

SM 3.2 - ADJACENT POWER PLANT SCALE AND EFFICIENCY

In the study of Cervi [153], a realistic range of electrical efficiency varying from 20% to 35% as function of the electricity generating capacity of the adjacent power plants is established (figure 1 SM 3.2). This is based on the empirical relationship determined by Cutz et al. [125], and a review of studies concerning bioelectricity systems in Brazilian sugarcane mills [126–128].

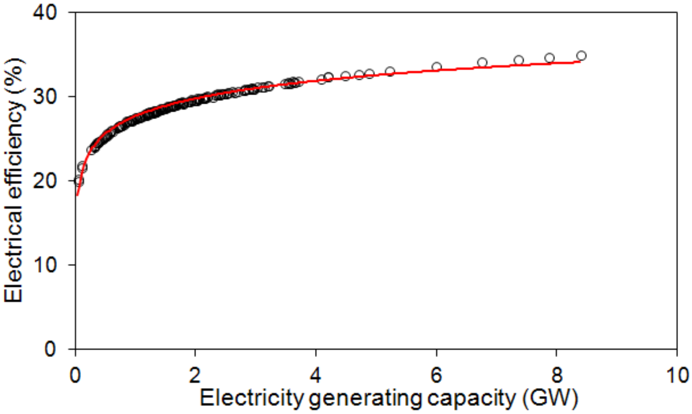

Figure 1 SM 3.2: Assumed relationship between the electrical efficiency and electricity generating capacity of the power plant adjacent to the sugarcane mills. Based on Cutz et al. [125].

SM 3.3 - CORRELATION AMONG THE BIOELECTRICITY COST COMPONENTS

Figure SM - 3.3 shows a correlation matrix to assess the potential spatial dependence among the bioelectricity cost components. By testing all the possible combinations, a strong correlation between FCI costs and transmission costs is verified.

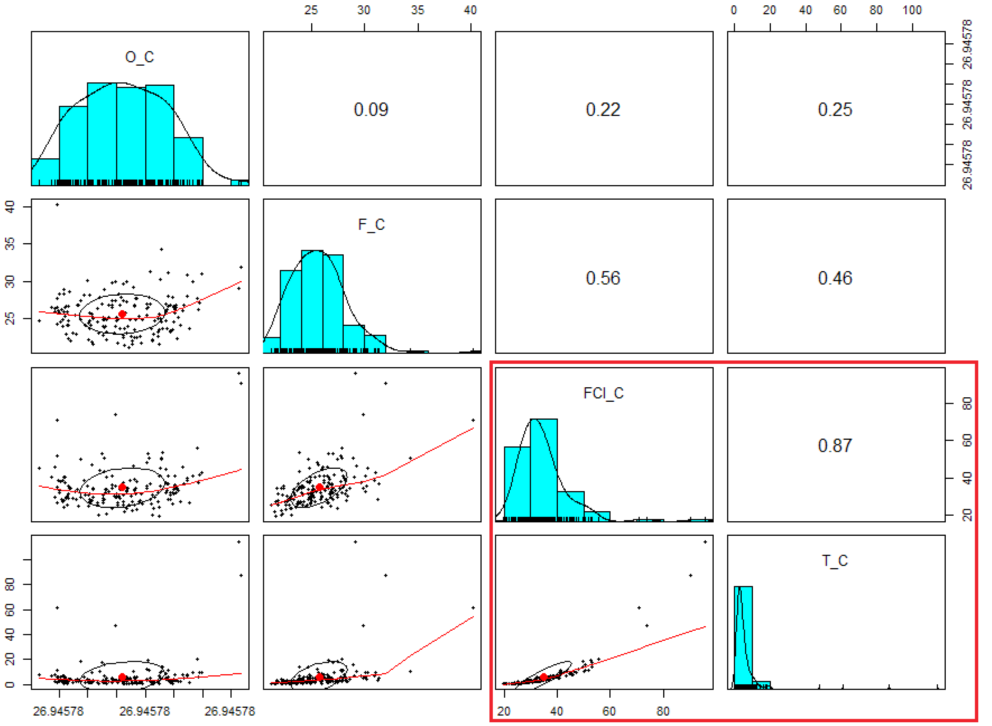

Figure 1 SM 3.3: Exploratory statistical analysis among the major bioelectricity production cost components: O_C: operational costs; F_C: feedstock costs; FCI_C: capital costs; T_C: transmission costs. The red box on the lower right indicates the most significant and strong correlated bioelectricity cost components between the FCI costs and Transmission costs.

SM 4.1 – CHARACTERISTICS OF THE SELECTED BIOMASS CROPS AND BJF TECHNOLOGICAL PATHWAYS

Feedstock group

Sugar and starch crops

The national corn production in 2015 was estimated at 85 Mt and it is predominantly used as animal feed [117]. Currently, the production is largely concentrated in the Center-South region (e.g. states of Mato Grosso and Paraná) with average yield levels of 5.5 t/ha. The key factors for selecting corn as a potential bioenergy source is the suitability to be cultivated in different regions and in various seasons within the crop-year. The current corn production system in Brazil uses a substantial amount of land for short periods (90 – 120 days) either once or twice per crop-year, leading to land use intensification as other fast growing crops (e.g. soybean) can be cultivated in the same area per year.

Currently, Brazil is the world largest sugarcane producer, driven by sugar and ethanol markets. The long standing experience in ethanol production and the high levels of recoverable sugars (ranging from 10 to 15 tonnes per hectare of sugarcane) have drawn the attention of BJF stakeholders [293]. Also, suitable areas for sugarcane plantation are mostly located around the big consumer hubs in the Southeast region of Brazil, which is of significant interest to the BJF market (e.g. proximity to the major airports and oil terminals), as it minimizes the need for large (inter-regional) investments in infrastructure.

Contrasting with corn and sugarcane, sweet sorghum is not produced at a large scale, with a cultivation area of less than 1 Mha [229]. However, it is suitable for a wide range of agro-ecological conditions. Sweet sorghum has already been targeted as a second crop between sugarcane cycles bringing many agronomic and industrial benefits [183]. Sweet sorghum can produce significant amount of fermentable sugars (8 – 12 tonnes per hectare) in very short periods (approx. 4 months) [229]. For these reasons, there is a growing interest in sweet sorghum for future ethanol production either as add in to the current sugarcane ethanol production model or as a standalone bioenergy system [294].

Oil-bearing crops

Soybean is the main feedstock for biodiesel production in Brazil (70% - 80%) with a well-structured supply chain. Although soybean is primary produced to provide protein for animal feed and has a relatively low oil yield (18% - 20% of the mass of soybean grain), it can be a promising crop for BJF production due to techno-economic advantages compared to perennial high yielding oil crops, such as macaw, palm oil and jatropha. Due to the high flexibility of soybean, it can to be cultivated in different geographical regions of Brazil. The current national production is mainly concentrated in the Center-West and South regions. However, soybean expansion can also be found in the North and Northeast in new agricultural borders [117].

Sunflower is seen as an important alternative feedstock to reduce the soybean dependence in biodiesel chains [186]. The oil content (35% - 40%) can be twice as high as soybean, even though new cultivation techniques would be required to ensure higher oil yields per hectare [186]. Moreover, sunflower has higher resistance for water deficit regions and periods which makes it an interesting option for the unproductive marginal and underutilized lands in the Northeast and Southern regions.

Oil palm is an important source of vegetable oil, but current production is limited due to the low agro-ecological suitability for oil palm development. Oil palm production is predominantly located in the North region at Pará state with less than 150 kha of planted area [117]. To enlarge the current production, degraded areas available in the East border of Amazon biome have been targeted by the main palm oil companies [222]. The main interest in oil palm is the high oil yield, which can be ten times higher than soybean [186].

Macaw palm is a native palm species from South America which is suitable for many Brazilian edaphic and climatic conditions [295]. The potentially high fruit and oil productivity has sparked the interest for commercial production. However, the studies concerning macaw palm are still at plot level and there are many uncertainties in the upscaling as a monoculture for commercial applications [296]. Thus, very little information is available on the agro-ecological requirements and production costs. Currently, macaw palm is not produced as a monoculture (such as oil palm), so the cost data is based on projections rather than empirical data. Like palm oil, it takes some years before macaw reaches the peak of the fructification period. Moreover, it has been currently assessed as a complementary option for land use intensification to be grown in integrated agro-forestry systems [188].

Lignocellulosic

The current eucalyptus production is spread over 7 Mha in the Center-South region largely triggered by the national paper and pulp industry [184]. Among other lignocellulosic options (e.g. pines, grasses), we select eucalyptus as it stands out as the best option for Brazil with the highest average wood yield (30 t/ha/year) and the shortest time-length between planting and harvesting [184]. Concerning the development of future biorefineries within the paper and pulp facilities, eucalyptus has a great flexibility as it can be also integrated in sugar-based biochemical and thermochemical routes for BJF production [185].

Technological pathways

The HEFA technological pathway is commonly highlighted as the most promising pathway to produce BJF [21]. It was certified by ASTM in 2011 with a maximum of 50% blend with conventional fossil jet fuel [297]. The HEFA pathway consists of the conversion of lipids sourced from oil crops or animal fats into hydrocarbons through hydro-processing techniques [298]. Besides BJF, this technology yields also a mixture of other desirable hydrocarbons, such as diesel and naphtha at different rates. Most of the BJF currently commercialized are produced via HEFA at competitive production costs [173].

Fischer Tropsch (FT) was the first technology using lignocellulosic materials as feedstock that was certified by ASTM in 2009, with a maximum of 50% drop-in [297]. FT is a relatively mature thermochemical technological pathway, which was already used in the petrochemical industry. For BJF production, the lignocellusic feedstock is primarily transformed into synthetic gas (syngas) and electricity at high temperatures. Then, the syngas is used in the FT reaction: a set of catalytic processes producing liquid hydrocarbons and water [258]. Alternatively, Hydrothermal Liquefaction (HTL) is an emerging thermochemical technological pathway that converts wet lignocellusic feedstock into bio-crude, which is hydrotreated and upgraded to hydrocarbons (e.g. BJF). The main advantage of HTL is the combined process of liquefaction and deoxygenation that leads to high conversion rates [299]. However, the technology readiness level is still low compared to the technological pathways already approved by ASTM. Currently, Steeper Energy and Licella are the companies leading the development of HTL plants [300].

The most recent ASTM certified technologies, Direct Sugars to Hydrocarbons (DSHC) and Alcohol to Jet (ATJ), were respectively approved in 2014 and 2016 [21]. DSHC represents a direct biochemical conversion of fermentable sugars into isoprenoid farnesene through yeast fermentation. Then, hydrogenation processes convert farnesene into farnesane, which can be blended with fossil-derived jet fuel to a maximum of 10% according to ASTM specifications [21,189]. In Brazil, a pioneer DSHC plant is located at a conventional sugarcane mill [173,301]. Differently, ATJ comprises the conversion of any type of alcohol (e.g. ethanol and butanol) to jet fuel by means of dehydration, oligomerization and hydrogenation. These downstream steps are relatively simple with a large potential to scale up, however efforts are required in the upstream phase depending on the pre-treatment needed and the alcohol production process. The recent ASTM approval allowed BJF from ATJ to be blended up to 30% with fossil jet fuels [302], which could certainly increase its readiness level. The American biofuel company Gevo is one of the leaders in ATJ projects to produce BJF from isobutanol [173].

Table 1 SM 4.1: Criteria applied for biomass selection and the respective compliance of the biomass sources selected.

BIOMASS	Sugarcane	Soybean	Macaw Palm	Eucalyptus	Sorghum	Corn	Oil Palm	Sunflower
Feedstock group [a]	sugars	oil	oil	lignocellulosic	sugars	starch	oil	oil
BJF technology available [b]	DSHC, ATJ	HEFA	HEFA	DSHC, ATJ, FT, HTL	DSHC, ATJ	ATJ	HEFA	HEFA
Accessibility [c]	High	High	Medium	High	Medium	High	Low	High
Suitability [d]	High	High	High	High	High	High	High	Medium
Feedstock yield [e]	High	Low	Medium	High	High	Medium	Medium	High
Data availability [f]	High	High	Low	High	Medium	High	Medium	Medium

[a] Group of feedstock that each biomass source belongs.
[b] Technological pathways able to convert the feedstock into biojet fuel.
[c] Current proximity to the main centers (e.g. Brazilian Center-South region).
[d] Biomass suitability in Brazil. Based on spatially explicit agro-ecological data.
[e] Yield of the feedstock from a given biomass (e.g. sucrose content in sugarcane).
[f] Spatial and techno-economic data availability.

SM 4.2 – BIOMASS CROPS SUITABILITY MAPS

The agro-ecological suitability data for the biomass crops are based on the characteristics of the Brazilian agricultural production. Thus, we assume rain fed and high input conditions (i.e. advanced management), in a baseline climate scenario [190,303]. These data are sourced from the GAEZ - Global Agro-Ecological Zones [304].

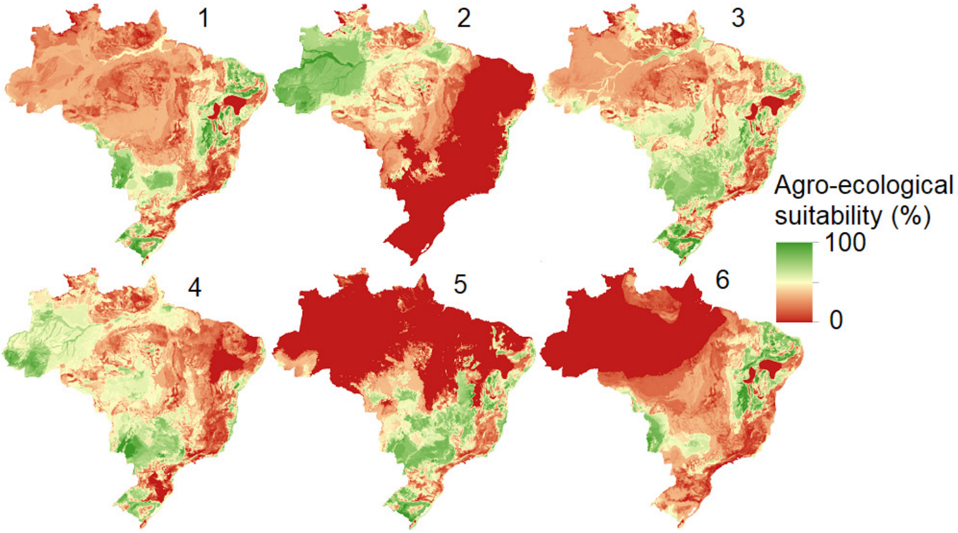

Figure 1 SM 4.2: Agro-ecological suitability maps of biomass crops in Brazil. 1: Corn; 2: Oil palm; 3: Soybean; 4: Sugarcane; 5: Sunflower; 6: Sorghum.

SM 4.3 – EUCALYPTUS AND MACAW PALM SUITABILITY MAPS

In this study, the agro-ecological suitability maps of eucalyptus and macaw palm are generated based on agro-ecological datasets. These consist of bioclimatic variables from WorldClim [305], but also terrain (SRTM - *Shuttle Radar Topographic Mission*) [306] and soil texture dataset (World Soil Information) [307]. First, we retrieve species-location point data for both eucalyptus and macaw from the GBIF (*Global Biodiversity Information Facility*) online database [308]. In total, 54 occurrence points for eucalyptus and 79 for macaw are retrieved. These records are split in training (~3/4 for macaw palm and ~2/3 for eucalyptus) and testing (~1/4 for macaw palm and ~1/3 for eucalyptus) sets. Thereafter, the 21 agro-ecological datasets specific for these location point data for both eucalyptus and macaw palm are modeled in Maxent. The Maxent estimates the probability of presence of macaw and eucalyptus based on the agro-ecological variables across the study region [191,193]. The probability values indicate the relative suitability of a given grid cell for the modeled biomass crops based on the agro-ecological predictors [193]. The model performance is measured by the area under the curve (AUC) metric, which reach 0.92 for eucalyptus and 0.86 for macaw palm. Figure 1 SM 4.3 shows the agro-ecological suitability maps for eucalyptus and macaw palm and table 1 SM 4.3 shows the best bioclimatic predictors and their relative contribution to the model output.

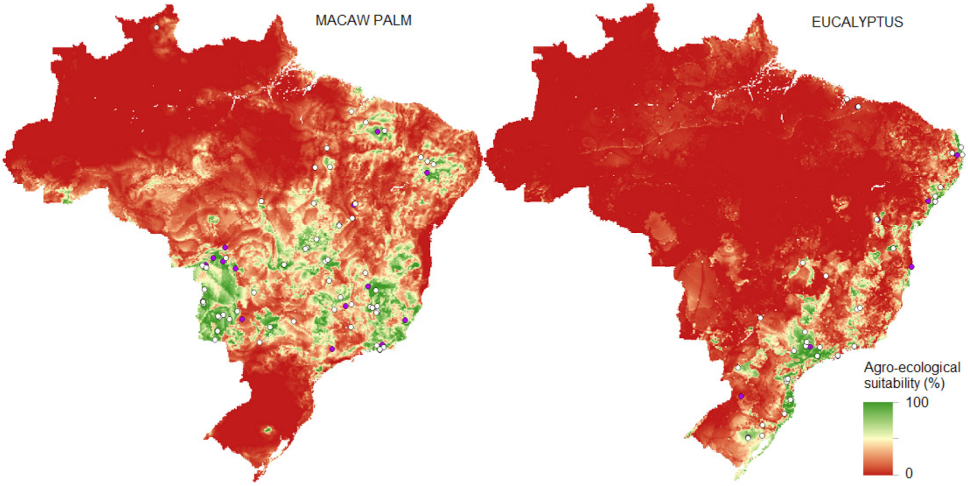

Figure 1 SM 4.3: Agro-ecological suitability maps for eucalyptus (right hand map) and macaw palm (left hand map). Shades of green show areas with better predicted agro-ecological conditions, which represent the probability occurrence of a given species in a 0 – 1 scale range [192]. The white dots show point locations used for training, and violet dots show the testing locations.

Table 1 SM 4.3: The top five bioclimatic predictors and their relative contribution to the suitability of eucalyptus and macaw palm.

Eucalyptus		**Macaw Palm**	
Variable	Rel. contribution (%)	Variable	Rel. contribution (%)
Min temperature of coldest month	20.4	Temperature annual range	16.3
Mean temperature diurnal range	13.7	Precipitation of driest month	15.2
Max temperature of warmest Month	12.2	Isothermality	13
Mean temperature of wettest quarter	9.7	Mean temperature of wettest quarter	7.7
Mean temperature of warmest quarter	7	Mean temperature of driest quarter	6.3

SM 4.4 - BIOMASS PRODUCTION COSTS

Due to the absence of a standardized studies covering the cost data of all the biomass crops assessed, we gather our biomass cost data from various sources in different agricultural systems. This could reflect in a heterogeneity of cost denomination, cost items, cost formation and taxes. Therefore, our biomass cost data should be carefully interpreted when it is used as basis of comparison.

Discount rate	**12%**

Biomass	Sources
Oil palm	[196,310]
Macaw palm	[230]
Sugarcane	[311]
Corn	[312]
Soybean	[312]
Sweet Sorghum	[183]
Eucalyptus	[313,314]
Sunflower	[315]

Perennial biomass	Years (cycle)
Palm oil	31
Macaw	31
Eucalyptus	19
Sugarcane	6

Currency	
BRL/USD	3.00

YEAR	**inflation – IGPDI Ref:** [309]	
2002	rate (n)	1 + n
2003	0.2641	1.2641
2004	0.0767	1.0767
2005	0.012321	1.012321
2006	0.037973	1.037973
2007	0.078984	1.078984
2008	0.091073	1.091073
2009	-0.01436	0.985636
2010	0.113058	1.113058
2011	0.050125	1.050125
2012	0.081121	1.081121
2013	0.055278	1.055278
2014	0.0378	1.0378
2015	0.106786	1.106786
2016	0.0715	1.0715

Land clearing costs (US$/ha)	
290.3	Ref: [316]

This cost data refers to soybean (in no tillage management), located in the state of Mato Grosso do Sul.

Table 1 SM 4.4: Description of each soybean fixed and variable cost items. Adapted from Richetti et al. [312].

Inputs	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Seeds	385.00	114.63	114.63	-
Seeds treatment	-	-	-	-
Inoculant	-	-	-	-
Fertilizers	474.00	141.13	-	29.40
Herbicides	75.18	22.38	22.38	-
Insecticides	110.00	32.75	32.75	-
Fungicides	79.80	23.76	23.76	-
Adjuvants	8.60	2.56	2.56	-
Operations				
Tillage	-	-	-	-
Soil correction	-	-	-	-
Seeds	75.63	22.52	22.52	-
Aerial fert.	-	-	-	-
Pesticides	39.73	11.83	11.83	
Harvest	50.78	15.12		3.15
Administrative				
Technical assistance	27.90	8.31	8.31	-
Administration	27.90	8.31	8.31	-
Insurance	9.49	2.83	2.83	-
Interest	174.06	51.82	51.82	-
Taxes	73.86	21.99	21.99	-
Transport	96.00	28.58	28.58	-
Storage	160.00	47.64	47.64	-
Maintenance				
Improvements	5.13	1.53	1.53	-
Depreciation				
Depreciation	140.30	41.77	41.77	-
Remuneration factors				
Machines	164.52	48.98	48.98	-
Own capital	-	-	-	-

This cost data refers to a sugarcane project in the state of Mato Grosso do Sul (expansion area). In this system, the conventional tillage is carried out in the first year (YEAR 0) for the sugarcane plant establishment. Then, there are 5 more years of sugarcane ratoons with no tillage (straw on the field).

Table 2 SM 4.4: Annualized fixed and variable sugarcane costs (based on table 3 – SM 4.4).

Years	Yield	Fixed costs (US$/ha)	Variable costs (US$/t)	Variable costs (US$/ha)
0	122	1674.74	6.23	760.31
1	104	87.71	6.96	723.92
2	92	87.71	7.58	697.50
3	81	87.71	8.31	673.03
4	71	87.71	9.16	650.53
5	62.5	87.71	3.63	226.85

Table 3 SM 4.4: Description of each sugarcane fixed and variable cost items. Adapted from Pereira et al.[311].

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
YEAR 0				
Inputs for soil				
Glyphosate	31.50	11.48	11.48	
Isoxaflutole	58.06	21.15	21.15	
Lime	72.00	26.23	26.23	
Gypsum	127.00	46.27	46.27	
Phosphate	292.60	106.61	106.61	
Trifuralin	30.00	10.93	10.93	
Soil prep.				
Soil sampling	0.92	0.34	0.34	
Lime app.	15.79	5.75	5.75	
Gypsum app.	15.79	5.75	5.75	
Herbicides_1	14.50	5.28	5.28	
Phosphate app.	15.79	5.75	5.75	
Topography_1	78.94	28.76	28.76	
Topography_2	268.32	97.76	97.76	
Road prep.	73.96	26.95	26.95	
Road prep. 2	226.80	82.64	82.64	
Tillage_1	138.93	50.62	50.62	
Tillage_2	178.71	65.11	65.11	
Tillage_3	24.46	8.91	8.91	
Tillage_4	40.42	14.73	14.73	
Subsolar	138.61	50.50	50.50	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Residues removal	33.74	12.29	12.29	
Fence removal	37.93	13.82	13.82	
Topography_3	11.35	4.14	4.14	
Planting inputs				
Seedlings	715.96	260.87	260.87	
Fertilizers NPK	614.80	224.01		1.84
Insecticides_1	170.00	61.94	61.94	
Herbicides_2	105.56	38.46	38.46	
Herbicides_3	35.52	12.94	12.94	
Herbicides_4	49.00	17.85	17.85	
Planting oper.				
Seedlings (loading)	85.53	31.16	31.16	
Seedlings (transport)	124.18	45.25	45.25	
Labor	205.00	74.69	74.69	
Insecticides_2	140.01	51.01	51.01	
Seedlings coverage	62.07	22.62	22.62	
Tillage_5	42.18	15.37	15.37	
Herbicides_5	16.87	6.15	6.15	
Seedlings handling	161.08	58.69	58.69	
Planting_1	322.16	117.38	117.38	
Planting_2	53.70	19.57	19.57	
Surveillance	138.25	50.37	50.37	
Supervision	243.20	88.61	88.61	
Harvest				
Cut				2.37
Load				2.02
YEAR 1				
Inputs				
Fertilizers NPK	549.00	200.03		1.92
Herbicides_1	90.45	32.96	32.96	
Herbicides_2	3.45	1.26	1.26	
Operation				
Water transport	6.98	2.54	2.54	
Application of herbicides 1	22.36	8.15	8.15	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Application of herbicides 2	67.49	24.59	24.59	
Organic amendments	73.61	26.82		0.26
Harvest				
Cut				2.76
Load				2.02
Administrative				
Expenses	50.00	18.22	18.22	
YEAR 2				
Inputs				
Fertilizers NPK	549.00	200.03		2.17
Herbicides_1	90.45	32.96	32.96	
Herbicides_2	3.45	1.26	1.26	
Operation				
Water transport	6.98	2.54	2.54	
Application of herbicides 1	22.36	8.15	8.15	
Application of herbicides 2	67.49	24.59	24.59	
Organic amendments	73.61	26.82		0.29
Harvest				
Cut				3.09
Load				2.02
Administrative				
Expenses	50.00	18.22	18.22	
YEAR 3				
Inputs				
Fertilizers NPK	549.00	200.03		2.47
Herbicides_1	90.45	32.96	32.96	
Herbicides_2	3.45	1.26	1.26	
Operation				
Water transport	6.98	2.54	2.54	
Application of herbicides 1	22.36	8.15	8.15	
Application of herbicides 2	67.49	24.59	24.59	
Organic amendments	73.61	26.82		0.33
Harvest				
Cut				3.48

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Load				2.02
Administrative				
Expenses	50.00	18.22	18.22	
YEAR 4				
Inputs				
Fertilizers NPK	549.00	200.03		2.82
Herbicides_1	90.45	32.96	32.96	
Herbicides_2	3.45	1.26	1.26	
Operation				
Water transport	6.98	2.54	2.54	
Application of herbicides 1	22.36	8.15	8.15	
Application of herbicides 2	67.49	24.59	24.59	
Organic amendments	73.61	26.82		0.38
Harvest				
Cut				3.94
Load				2.02
Administrative				
Expenses	50.00	18.22	18.22	
YEAR 5				
Inputs				
Fertilizers NPK	549.00	200.03		3.20
Herbicides_1	90.45	32.96	32.96	
Herbicides_2	3.45	1.26	1.26	
Operation				
Water transport	6.98	2.54	2.54	
Application of herbicides 1	22.36	8.15	8.15	
Application of herbicides 2	67.49	24.59	24.59	
Organic amendments	73.61	26.82		0.43
Harvest				
Cut				4.44
Load				2.02
Administrative				
Expenses	50.00	18.22	18.22	

This cost data refers to the sweet sorghum planted between the sugarcane cycles. This can be practice in some sugarcane mills to increase their sugar/ethanol revenues. In summary, after the last ratooning sugarcane year, the sweet sorghum is planted through a conventional tillage system in November (normally) and it is harvested in March.

Table 4 SM 4.4: Description of each sweet sorghum fixed and variable cost items. Adapted from May et al. [183].

	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Soil prep.				
Desiccation	96.74	32.25	32.25	-
Terracing	106.29	35.43	35.43	-
Tillage	61.09	20.36	20.36	-
Lime	331.57	110.52	110.52	-
Disc Harrow	29.97	9.99	9.99	-
Planting				
Seedling operation	175.56	58.52	58.52	-
Fertilizers	446.16	148.72	-	3.72
Seeds	300.00	100.00	100.00	-
Traits				
Herbicides	46.00	15.33	15.33	-
Pesticides	198.38	66.13	66.13	-
Fertilizers	455.58	151.86	-	3.80
Administrative				
Expenses	264.20	88.07	88.07	
Harvest				
Cut	637.64	212.55	-	5.31
Loading	79.20	26.40	-	0.66

The eucalyptus systems usually take around 19-21 years, depending on the yield and other agricultural constraints. The harvest is carried out in seven years' intervals. In this data, the cost of the eucalyptus system covers 19 years, with productive years in the year 6, 12 and 18. We used two different cost data sources from near regions to increase the reliability (and completeness) of the data [313,314].

Table 5 SM 4.4: Annualized fixed and variable eucalyptus costs (based on table 7 – SM 4.4).

Years	Yield	Fixed costs (US$/ha)	Variable costs (US$/t)	Variable costs (US$/ha)
0	0	1945.86	0.00	0.00
1	0	508.81	0.00	0.00
2	0	188.86	0.00	0.00
3	0	188.86	0.00	0.00
4	0	188.86	0.00	0.00
5	0	188.86	0.00	0.00
6	260.4	246.73	4.99	1299.59
7	0	188.86	0.00	0.00
8	0	188.86	0.00	0.00
9	0	188.86	0.00	0.00
10	0	188.86	0.00	0.00
11	0	188.86	0.00	0.00
12	234.3	239.26	5.07	1187.87
13	0	188.86	0.00	0.00
14	0	188.86	0.00	0.00
15	0	188.86	0.00	0.00
16	0	188.86	0.00	0.00
17	0	188.86	0.00	0.00
18	217	95.22	4.28	928.50

Table 6 SM 4.4: Description of each eucalyptus fixed and variable cost items. Adapted from CIF (2007) and IFAG (2017) [313,314].

	Raw data (2017 or 2007 R$/ha)	Value (2015 US$/ha)	Yield(t/ha)	Fixed costs (US$/ha)	Variable costs (US$/t)
YEAR 0			0		
Inputs					
Planting	666.80	206.37		206.37	
Re planting	66.80	20.67		20.67	
Fertilizers					
Phosphate	291.65	90.27		90.27	
Manure	565.32	174.97		174.97	
FTE	340.00	105.23		105.23	
Lime	280.00	86.66		86.66	
Gypsum	138.00	42.71		42.71	
Pesticides					
Ant control_1	150.00	46.43		46.43	
Ant control_2	30.00	9.29		9.29	
Insecticide_1	123.75	38.30		38.30	
Herbicide_1	90.00	27.86		27.86	
Insecticide_2	481.00	148.87		148.87	
Herbicide_2	60.00	18.57		18.57	
Herbicide_3	626.00	193.75		193.75	
Services					
Topography	7.00	2.17		2.17	
Road adequation	166.50	51.53		51.53	
Soil preparation	394.80	122.19		122.19	
OM ants	41.00	12.69		12.69	
Lime	40.60	12.57		12.57	
OM lime	41.00	12.69		12.69	
Glyphosate	41.43	12.82		12.82	
Machine	70.50	21.82		21.82	
OM planting	205.00	63.45		63.45	
Fertilizers	105.10	32.53		32.53	
OM fertilizers	82.00	25.38		25.38	
OM ant control	287.00	88.83		88.83	
OM replanting	16.40	5.08		5.08	
Herbicide_4	166.20	51.44		51.44	

	Raw data (2017 or 2007 R$/ha)	Value (2015 US$/ha)	Yield(t/ha)	Fixed costs (US$/ha)	Variable costs (US$/t)
Herbicide_5	166.20	51.44		51.44	
Org. amendments	105.20	32.56		32.56	
OM Org. amendment	82.00	25.38		25.38	
OM herbicide 1 and 2	164.00	50.76		50.76	
Gen. Maintenance	52.60	16.28		16.28	
Administrative					
Percentage	122.88	38.03		38.03	
Technical assistance	20.38	6.31		6.31	
YEAR 1			0.00		
Forest management					
Roundup	54.00	16.71		16.71	
Chemical carpentry	83.10	25.72		25.72	
Herbicide	30.00	9.29		9.29	
OM herbicide 1 and 2	82.00	25.38		25.38	
Fertilizers					
Potassium chloride	414.46	128.28		128.28	
Ammonium sulfide	266.70	82.54		82.54	
Org. amendment	105.12	32.53		32.53	
OM Org. amendment	82.00	25.38		25.38	
Ant control					
Formicidae	15.00	4.64		4.64	
OM ant control	164.00	50.76		50.76	
Maintenance					
Firebreak	315.36	97.60		97.60	
Administrative					
Technical assistance	32.23	9.98		9.98	
YEAR 2			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 3			0.00		
Forest management					

	Raw data (2017 or 2007 R$/ha)	**Value (2015 US$/ ha)**	**Yield(t/ ha)**	**Fixed costs (US$/ha)**	**Variable costs (US$/t)**
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Adm. costs					
Technical assistance	11.96	3.70		3.70	
YEAR 4			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 5			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 6			260.40		
Fertilizers					
Fertilizers	482.00	149.18			0.57
Harvest					
Harvest	3600.00	1114.20			4.28
Traits					
Inter row tillage	52.98	16.40		16.40	
Herbicides	210.00	65.00		65.00	
Maintenance					
Firebreak	35.32	10.93		10.93	
Services					
Org. amendment	39.00	12.07			0.05
Ant control	52.00	16.09		16.09	
Ratoon management	78.00	24.14			0.09
Inputs					
Herbicides	81.00	25.07		25.07	

	Raw data (2017 or 2007 R$/ha)	Value (2015 US$/ha)	Yield(t/ha)	Fixed costs (US$/ha)	Variable costs (US$/t)
Formicidae	10.00	3.10		3.10	
Other inputs	8.00	2.48		2.48	
Administrative					
Technical assistance	106.40	32.93		32.93	
Taxes	241.50	74.74		74.74	
YEAR 7			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 8			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 9			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 10			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 11			0.00		
Forest management					

	Raw data (2017 or 2007 R$/ha)	Value (2015 US$/ha)	Yield(t/ha)	Fixed costs (US$/ha)	Variable costs (US$/t)
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 12			234.36		
Fertilizers					
Fertilizers	482.00	149.18			0.64
Harvest					
Harvest	3240.00	1002.78			4.28
Traits					
Inter row tillage	52.98	16.40		16.40	
Herbicides	210.00	65.00		65.00	
Maintenance					
Firebreak	35.32	10.93		10.93	
Services					
Org. amendment	39.00	12.07			0.05
Ant control	52.00	16.09		16.09	
Ratoon management	78.00	24.14			0.10
Inputs					
herbicides	81.00	25.07		25.07	
Formicidae	10.00	3.10		3.10	
other inputs	8.00	2.48		2.48	
Administrative					
Technical assistance	106.40	32.93		32.93	
Taxes	217.35	67.27		67.27	
YEAR 13			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative		*0.00*			
Technical assistance	11.96	3.70		3.70	
YEAR 14			0.00		
Forest management					

	Raw data (2017 or 2007 R$/ha)	Value (2015 US$/ha)	Yield(t/ha)	Fixed costs (US$/ha)	Variable costs (US$/t)
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Adm. costs					
Technical assistance	11.96	3.70		3.70	
YEAR 15			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 16			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 17			0.00		
Forest management					
Ant control	60.00	18.57		18.57	
OM	328.00	101.52		101.52	
Machine	210.24	65.07		65.07	
Administrative					
Technical assistance	11.96	3.70		3.70	
YEAR 18			217.00		
Harvest					
Harvest	3000.00	928.50			4.28
Administrative					
Technical assistance	106.40	32.93		32.93	
Taxes	201.25	62.29		62.29	

This cost data refers to corn production (in no tillage management), located in the state of Mato Grosso do Sul.

Table 7 SM 4.4: Description of each corn fixed and variable cost items. Adapted from Richetti et al. [312].

	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Inputs				
Seeds	351.75	104.73	104.73	
Seed treatment	-	-	-	-
Inoculant	3.00	0.89	0.89	
Fertilizers	532.00	158.40	-	44.00
Herbicides	197.25	58.73	58.73	-
Insecticide	95.00	28.29	28.29	-
Fungicide	228.80	68.12	68.12	-
Adjuvants	30.90	9.20	9.20	-
Operations				
Tillage	-	-	-	-
Soil correction	20.27	6.04	6.04	-
Seeds	85.04	25.32	25.32	-
Aerial fertilizers	5.47	1.63	-	0.45
Pesticides	57.80	17.21	17.21	-
Harvest	50.78	15.12	-	4.20
Administrative				
Technical assistance	34.60	10.30	10.30	-
Administration	34.60	10.30	10.30	-
Insurance	19.26	5.73	5.73	-
Interests	163.13	48.57	48.57	-
Taxes	139.01	41.39	41.39	-
Transport	72.00	21.44	21.44	-
Storage	120.00	35.73	35.73	-
Maintainance				
Improvements	10.43	3.11	3.11	-
Depreciations				
Depreciations	146.34	43.57	43.57	-
Remuneration factors				
Machines	180.40	53.71	53.71	-
Own capital	20.13	5.99	5.99	-

This cost data refers to sunflower production in the state of Goias (in crop rotation systems with soybean and no tillage management).

Table 8 SM 4.4: Description of each sunflower fixed and variable cost items. Adapted from IFAG (2017) [315].

	Quantity	unit value ($/ha)	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Pre-planting						
Desiccate	-	-	-	-	-	-
Labor	0.60	86.63	51.98	16.09	16.09	-
Defensives	0.15	8.15	1.22	0.38	0.38	-
Boron 1	2.00	6.45	12.90	3.99	-	2.22
Roundup Original	2.00	13.00	26.00	8.05	8.05	-
Planting						
Machinery	0.60	188.26	112.96	34.96	34.96	-
Seedlings	0.20	8.15	1.63	0.50	0.50	-
Seedlings Treatment	0.20	8.15	1.63	0.50	0.50	-
Seeds	6.25	203.75	1273.44	394.13	394.13	-
Insecticides	0.01	502.50	3.52	1.09	1.09	-
Crop management						
Spray	0.70	86.63	60.64	18.77	18.77	-
Fert. Machine	0.20	83.49	16.70	5.17	5.17	-
Spray. assistance	0.35	8.15	2.85	0.88	0.88	-
Fert. Assistance	0.15	8.15	1.22	0.38	0.38	-
Herbicides	0.80	58.00	46.40	14.36	14.36	-
Inseticide_1	0.20	70.00	14.00	4.33	4.33	-
Fungicide_1	1.00	20.75	20.75	6.42	6.42	-
Fungicide_2	0.15	150.75	22.61	7.00	7.00	-
Inseticide_2	0.35	107.00	37.45	11.59	11.59	-
Fungicide_3	1.00	169.00	169.00	52.31	52.31	-
Mineral oil	1.00	14.00	14.00	4.33	4.33	-
Fertilizers						
Boron 2	2.00	7.00	14.00	4.33	-	2.41
Quantis Syngenta	2.00	25.00	50.00	15.48	-	8.60
Urea	0.10	1460.00	146.00	45.19	-	25.10
Harvest						
Machine	0.60	197.81	118.69	36.73	-	20.41
Labor	0.20	8.15	1.63	0.50	-	0.28

	Quantity	unit value ($/ha)	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Post-harvest						
Storage	1.00	39.40	39.40	13.13	13.13	-
Truck	1.40	120.00	168.00	52.00	52.00	-
Taxes						
ICMS	0.02	1650.00	24.75	7.66	7.66	-
Other taxes	1.00	32.61	32.61	10.09	10.09	-
Administrative						
Tech. assist	1.00	22.80	22.80	7.60	7.60	-
Adm costs	1.00	34.20	34.20	11.40	11.40	-

This is 30-year oil palm project with annual fertilizer input (after year 0) and annual harvest (after year 3).

Table 9 SM 4.4: Annualized fixed and variable oil palm costs (based on table 11 – SM 4.4).

Years	Yield	Fixed costs (US$/ha)	Variable costs (US$/t)	Variable costs (US$/ha)
0	0.00	1094.04	0.00	0.00
1	0.00	444.45	0.00	0.00
2	0.00	510.61	0.00	0.00
3	9.00	403.59	25.44	228.94
4	18.00	614.83	17.39	312.96
5	22.50	485.76	16.40	369.07
6	27.00	487.40	14.27	385.40
7	31.50	489.03	12.75	401.72
8	31.50	489.03	12.75	401.72
9	31.50	489.03	12.75	401.72
10	31.50	489.03	12.75	401.72
11	31.50	489.03	13.40	422.13
12	31.50	489.03	12.75	401.72
13	31.50	489.03	12.75	401.72
14	31.50	489.03	12.75	401.72
15	31.50	489.03	12.75	401.72
16	31.50	489.03	12.75	401.72
17	31.50	489.03	12.75	401.72
18	31.50	489.03	12.75	401.72
19	31.50	489.03	12.75	401.72

Years	Yield	Fixed costs (US$/ha)	Variable costs (US$/t)	Variable costs (US$/ha)
20	31.50	489.03	12.75	401.72
21	31.50	489.03	12.75	401.72
22	31.50	684.92	12.75	401.72
23	31.50	666.96	12.23	385.40
24	31.50	485.76	11.72	369.07
25	31.50	480.87	10.16	320.10
26	30.00	480.87	10.67	320.10
27	28.50	480.87	11.23	320.10
28	27.00	480.87	11.86	320.10
29	25.50	480.87	12.55	320.10
30	24.56	471.75	9.32	228.94

Table 10 SM 4.4: Description of each oil palm fixed and variable cost items. Adapted from Furlan et al. and CODEVASF [196,310].

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
YEAR 0				
Seedlings acquisition				
Area preparation	25.00	10.20	10.20	-
Terrace preparation	50.00	20.41	20.41	-
Seedlings	255.00	104.07	104.07	-
Marking	25.00	10.20	10.20	-
Traits	175.00	71.42	71.42	-
Soil preparation				
Area demarcation	25.00	10.20	10.20	-
Vegetation control	125.00	51.01	51.01	-
Marking	25.00	10.20	10.20	-
Others (roads, windrower, etc)	500.00	204.05	204.05	-
Plantation				
Pit opening	150.00	61.22	61.22	-
Seedling distribution	25.00	10.20	10.20	-
Pit fertilizer	25.00	10.20	10.20	-
Planting	50.00	20.41		-
Traits				
Branch control	300.00	122.43	122.43	-
Organic fertilizer	37.50	15.30	15.30	-
Defensives	25.00	10.20	10.20	-

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Inputs and materials				
Urea	52.92	21.60		-
Fosfate_1	44.00	17.96	17.96	-
KCl	29.30	11.96		-
Fosfate_2	17.16	7.00	7.00	-
Magnesium sulfate	10.73	4.38		-
Fungicide	62.00	25.30	25.30	-
Insecticide	82.00	33.46		-
Knife	11.50	4.69	4.69	-
Digger	12.00	4.90		-
Plastic bags_1	3.60	1.47		-
Plastic bags_2	24.00	9.79	9.79	-
Manual spray	36.00	14.69		-
Lime and Gypsum	50.00	20.41	20.41	-
Herbicides	80.00	32.65	32.65	-
Administrative				
Gen. expenses	160.00	65.30	65.30	-
Post-harvest		0.00		
Organization and management	371.69	151.69	151.69	-
Technical assistance	92.92	37.92	37.92	-
YEAR 1				
Planting				
Planting	50.00	20.41	20.41	-
Traits				
Branch control	400.00	163.24	163.24	-
Organic fertilizer	50.00	20.41	20.41	-
Defensives	25.00	10.20	10.20	-
Inputs and materials				
Urea	86.24	35.20	35.20	-
Superphosphate	62.00	25.30	25.30	-
Potassium Chloride	46.50	18.98	18.98	-
Herbicides	40.00	16.32	16.32	-
Administrative				
Gen. expenses	80.00	32.65	32.65	-
Post-harvest				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Organization and management	199.45	81.40	81.40	-
Technical assistance	49.86	20.35	20.35	-
YEAR 2				
Traits				
Branch control	500.00	204.05	204.05	-
Organic fertilizer	50.00	20.41	20.41	-
Defensives	25.00	10.20	10.20	-
Inputs and materials				
Urea	129.36	52.79	52.79	-
Superphosphate	93.00	37.95	37.95	-
Potassium Chloride	69.75	28.47	28.47	-
Herbicides	40.00	16.32	16.32	-
Administrative				
Gen. expenses	80.00	32.65	32.65	-
Post-harvest				
Organization and management	211.24	86.21	86.21	-
Technical assistance	52.81	21.55	21.55	-
YEAR 3				
Traits				
Branch control	500.00	204.05	204.05	-
Organic fertilizer	50.00	20.41	20.41	-
Defensives	25.00	10.20	10.20	-
Inputs and materials				
Urea	172.48	70.39	-	7.82
Superphosphate	124.00	50.61	-	5.62
Potassium Chloride	93.00	37.95	-	4.22
Knife	11.50	4.69	-	0.52
Herbicides	40.00	16.32	16.32	-
Harvest				
Harvest	160.00	65.30		7.26
Administrative				
Gen. expenses	80.00	32.65	32.65	-
Post-harvest				
Organization and management	235.75	96.21	96.21	-
Technical assistance	58.19	23.75	23.75	-

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ ha)	Variable costs (2015 US$/t)
YEAR 4				
Soil preparation				
Gen maintenance	500.00	204.05	204.05	
Traits				
Branch control	500.00	204.05	204.05	-
Organic fertilizer	50.00	20.41	20.41	-
Defensives	25.00	10.20	10.20	-
Inputs and materials				
Urea	215.60	87.99		4.89
Superphosphate	155.00	63.26		3.51
Potassium Chloride	116.25	47.44		2.64
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	280.00	114.27		6.35
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	249.22	101.71	101.71	
Technical assistance	62.31	25.43	25.43	
YEAR 5				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	-
Organic fertilizer	50.00	20.41	20.41	-
Defensives	25.00	10.20	10.20	-
Inputs and materials				
Urea	215.60	87.99		3.91
Superphosphate	155.00	63.26		2.81
Potassium Chloride	116.25	47.44		2.11
Knife	11.50	4.69		0.21
Digger	6.00	2.45		0.11
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	400.00	163.24		7.26

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ ha)	Variable costs (2015 US$/t)
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	236.22	96.40	96.40	
Technical assistance	59.06	24.10	24.10	
YEAR 6				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	-
Organic fertilizer	50.00	20.41	20.41	-
Defensives	25.00	10.20	10.20	-
Inputs and materials				
Urea	215.60	87.99		3.26
Superphosphate	155.00	63.26		2.34
Potassium Chloride	116.25	47.44		1.76
Knife	11.50	4.69		0.17
Digger	6.00	2.45		0.09
Herbicides	40.00	16.32	16.32	
Irrigation				
Irrigation			0.00	
Harvest				
Harvest	440.00	179.57		6.65
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	239.42	97.71	97.71	
Technical assistance	59.86	24.43	24.43	
YEAR 7				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	-
Organic fertilizer	50.00	20.41	20.41	-
Defensives	25.00	10.20	10.20	-

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 8				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
YEAR 9				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 10				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 11				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Lime	50.00	20.41		0.65
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 12				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 13				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Technical assistance	60.66	24.76	24.76	
YEAR 14				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 15				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ ha)	Variable costs (2015 US$/t)
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 16				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 17				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 18				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 20				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 21				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89		6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 22				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	480.00	195.89	195.89	6.22
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	242.62	99.02	99.02	
Technical assistance	60.66	24.76	24.76	
YEAR 23				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	440.00	179.57	179.57	5.70
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	239.42	97.71	97.71	
Technical assistance	59.86	24.43	24.43	
YEAR 24				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ ha)	Variable costs (2015 US$/t)
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	400.00	163.24		5.18
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	236.22	96.40	96.40	
Technical assistance	59.06	24.10	24.10	
YEAR 25				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.79
Superphosphate	155.00	63.26		2.01
Potassium Chloride	116.25	47.44		1.51
Knife	11.50	4.69		0.15
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	280.00	114.27		3.63
Administrative				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	226.62	92.49	92.49	
Technical assistance	56.66	23.12	23.12	
YEAR 26				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		2.93
Superphosphate	155.00	63.26		2.11
Potassium Chloride	116.25	47.44		1.58
Knife	11.50	4.69		0.16
Digger	6.00	2.45		0.08
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	280.00	114.27		3.81
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	226.62	92.49	92.49	
Technical assistance	56.66	23.12	23.12	
YEAR 27				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		3.09
Superphosphate	155.00	63.26		2.22

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ ha)	Variable costs (2015 US$/t)
Potassium Chloride	116.25	47.44		1.66
Knife	11.50	4.69		0.16
Digger	6.00	2.45		0.09
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	280.00	114.27		4.01
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	226.62	92.49	92.49	
Technical assistance	56.66	23.12	23.12	
YEAR 28				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		3.26
Superphosphate	155.00	63.26		2.34
Potassium Chloride	116.25	47.44		1.76
Knife	11.50	4.69		0.17
Digger	6.00	2.45		0.09
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	280.00	114.27		4.23
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	226.62	92.49	92.49	
Technical assistance	56.66	23.12	23.12	
YEAR 29				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	215.60	87.99		3.45
Superphosphate	155.00	63.26		2.48
Potassium Chloride	116.25	47.44		1.86
Knife	11.50	4.69		0.18
Digger	6.00	2.45		0.10
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	280.00	114.27		4.48
Administrative				
Gen. expenses	80.00	32.65	32.65	
Post-harvest				
Organization and management	226.62	92.49	92.49	
Technical assistance	56.66	23.12	23.12	
YEAR 30				
Soil preparation				
Gen maintenance	200.00	81.62	81.62	
Traits				
Branch control	500.00	204.05	204.05	
Organic fertilizer	50.00	20.41	20.41	
Defensives	25.00	10.20	10.20	
Inputs and materials				
Urea	172.48	70.39		2.87
Superphosphate	124.00	50.61		2.06
Potassium Chloride	93.00	37.95		1.55
Knife	11.50	4.69		0.19
Herbicides	40.00	16.32	16.32	
Harvest				
Harvest	160.00	65.30		2.66
Administrative				
Gen. expenses	80.00	32.65	32.65	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ ha)	Variable costs (2015 US$/t)
Post-harvest				
Organization and management	208.75	85.19	85.19	
Technical assistance	52.19	21.30	21.30	

This is 30-year simulation of macaw palm monoculture project to be established in Minas Gerais.

Table 11 SM 4.4: Annualized fixed and variable macaw palm costs (based on table 13 – SM 4.4).

Years	Yield	Fixed costs (US$/ha)	Variable costs (US$/t)	Variable costs (US$/ha)
0	0.00	1641.42	0.00	0.00
1	0.00	234.62	0.00	0.00
2	0.00	234.62	0.00	0.00
3	0.00	234.62	0.00	0.00
4	16.40	166.72	29.21	478.97
5	16.40	166.72	29.21	478.97
6	16.40	166.72	29.21	478.97
7	16.40	166.72	29.21	478.97
8	16.40	166.72	29.21	478.97
9	16.40	166.72	29.21	478.97
10	24.50	180.72	28.62	701.20
11	24.50	180.72	28.62	701.20
12	24.50	180.72	28.62	701.20
13	24.50	180.72	28.62	701.20
14	24.50	180.72	28.62	701.20
15	24.50	180.72	28.62	701.20
16	24.50	180.72	28.62	701.20
17	24.50	180.72	28.62	701.20
18	24.50	180.72	28.62	701.20
19	24.50	180.72	28.62	701.20
20	24.50	180.72	28.62	701.20
21	24.50	180.72	28.62	701.20
22	24.50	180.72	28.62	701.20
23	24.50	180.72	28.62	701.20
24	24.50	180.72	28.62	701.20
25	24.50	180.72	28.62	701.20

Years	Yield	Fixed costs (US$/ha)	Variable costs (US$/t)	Variable costs (US$/ha)
26	24.50	180.72	28.62	701.20
27	24.50	180.72	28.62	701.20
28	24.50	180.72	28.62	701.20
29	24.50	180.72	28.62	701.20
30	24.50	180.72	28.62	701.20

Table 12 SM 4.4: Description of each macaw palm fixed and variable cost items. Adapted from Pimentel et al. [230].

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
YEAR 0				
Mechanized oper.				
Tillage	40.00	17.64	17.64	
Seedlings distribution	100.00	44.10	44.10	
Fertilizer app.	100.00	44.10	44.10	
Manual oper. soil prep.				
Ant control	40.00	17.64	17.64	
Tillage	40.00	17.64	17.64	
Tillage 2	40.00	17.64	17.64	
Crowning	80.00	35.28	35.28	
Seedlings distribution	120.00	52.92	52.92	
Subsoiling	200.00	88.20	88.20	
Planting	40.00	17.64	17.64	
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Organic amendments	80.00	35.28	35.28	
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	88.00	38.81	38.81	
Nitrogen	38.00	16.76	16.76	
Potassium	68.00	29.99	29.99	
Micronutrients	20.00	8.82	8.82	
Inputs: Phytosanitaires				
Insecticides	20.00	8.82	8.82	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Inputs: seedlings				

Cost item	**Ref. value (R$/ha)**	**Updated value (2015 US$/ha)**	**Fixed costs (2015 US$/ha)**	**Variable costs (2015 US$/t)**
Seedlings	2400.00	1058.41	1058.41	
Administrative				
Project	74.00	32.63	32.63	
YEAR 1				
Mechanized oper.				
Fertilizer app.	50.00	22.05	22.05	
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Organic amendments	80.00	35.28	35.28	
Inputs: Fertilizers				
Phosphorus	44.00	19.40	19.40	
Nitrogen	76.00	33.52	33.52	
Potassium	136.00	59.98	59.98	
Micronutrients	20.00	8.82	8.82	
Inputs: Phytosanitaires				
Insecticides	10.00	4.41	4.41	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
YEAR 2				
Mechanized oper.				
Fertilizer app.	50.00	22.05	22.05	
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Organic amendments	80.00	35.28	35.28	
Inputs: Fertilizers				
Phosphorus	44.00	19.40	19.40	
Nitrogen	76.00	33.52	33.52	
Potassium	136.00	59.98	59.98	
Micronutrients	20.00	8.82	8.82	
Inputs: Phytosanitaires				
Insecticides	10.00	4.41	4.41	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
YEAR 3				
Mechanized oper.				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Fertilizer app.	50.00	22.05	22.05	
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Organic amendments	80.00	35.28	35.28	
Inputs: Fertilizers				
Phosphorus	44.00	19.40	19.40	
Nitrogen	76.00	33.52	33.52	
Potassium	136.00	59.98	59.98	
Micronutrients	20.00	8.82	8.82	
Inputs: Phytosanitaires				
Insecticides	10.00	4.41	4.41	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
YEAR 4				
Mechanized oper.				
Fertilizer app.	50.00	22.05		1.34
Harvest	150.00	66.15		4.03
Manual oper. traits				
Herbicides	80.00	35.28	35.28	2.15
Branch control	40.00	17.64		1.08
Organic amendments	80.00	35.28		2.15
Manual oper. harvest				
Harvest	262.08	115.58		7.05
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	66.00	29.11		1.77
Nitrogen	114.00	50.27		3.07
Potassium	204.00	89.97		5.49
Micronutrients	40.00	17.64		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Taxes	64.05	28.25	28.25	
YEAR 5				
Mechanized oper.				
Fertilizer app.	50.00	22.05		1.34
Harvest	150.00	66.15		4.03
Manual oper. traits				
Herbicides	80.00	35.28	35.28	2.15
Branch control	40.00	17.64		1.08
Organic amendments	80.00	35.28		2.15
Manual oper. harvest				
Harvest	262.08	115.58		7.05
Inputs: Fertilizers			0.00	
Lime	18.00	7.94	7.94	
Phosphorus	66.00	29.11		1.77
Nitrogen	114.00	50.27		3.07
Potassium	204.00	89.97		5.49
Micronutrients	40.00	17.64		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	64.05	28.25	28.25	
YEAR 6				
Mechanized oper.				
Fertilizer app.	50.00	22.05		1.34
Harvest	150.00	66.15		4.03
Manual oper. traits				
Herbicides	80.00	35.28	35.28	2.15
Branch control	40.00	17.64		1.08
Organic amendments	80.00	35.28		2.15
Manual oper. harvest				
Harvest	262.08	115.58		7.05
Inputs: Fertilizers			0.00	
Lime	18.00	7.94	7.94	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Phosphorus	66.00	29.11		1.77
Nitrogen	114.00	50.27		3.07
Potassium	204.00	89.97		5.49
Micronutrients	40.00	17.64		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	64.05	28.25	28.25	
YEAR 7				
Mechanized oper.				
Fertilizer app.	50.00	22.05		1.34
Harvest	150.00	66.15		4.03
Manual oper. traits				
Herbicides	80.00	35.28	35.28	2.15
Branch control	40.00	17.64		1.08
Organic amendments	80.00	35.28		2.15
Manual oper. harvest				
Harvest	262.08	115.58		7.05
Inputs: Fertilizers			0.00	
Lime	18.00	7.94	7.94	
Phosphorus	66.00	29.11		1.77
Nitrogen	114.00	50.27		3.07
Potassium	204.00	89.97		5.49
Micronutrients	40.00	17.64		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	64.05	28.25	28.25	
YEAR 8				
Mechanized oper.				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Fertilizer app.	50.00	22.05		1.34
Harvest	150.00	66.15		4.03
Manual oper. traits				
Herbicides	80.00	35.28	35.28	2.15
Branch control	40.00	17.64		1.08
Organic amendments	80.00	35.28		2.15
Manual oper. harvest				
Harvest	262.08	115.58		7.05
Inputs: Fertilizers			*0.00*	
Lime	18.00	7.94	7.94	
Phosphorus	66.00	29.11		1.77
Nitrogen	114.00	50.27		3.07
Potassium	204.00	89.97		5.49
Micronutrients	40.00	17.64		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	64.05	28.25	28.25	
YEAR 9				
Mechanized oper.				
Fertilizer app.	50.00	22.05		1.34
Harvest	150.00	66.15		4.03
Manual oper. traits				
Herbicides	80.00	35.28	35.28	2.15
Branch control	40.00	17.64		1.08
Organic amendments	80.00	35.28		2.15
Manual oper. harvest				
Harvest	262.08	115.58		7.05
Inputs: Fertilizers			0.00	
Lime	18.00	7.94	7.94	
Phosphorus	66.00	29.11		1.77
Nitrogen	114.00	50.27		3.07
Potassium	204.00	89.97		5.49

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Micronutrients	40.00	17.64		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	64.05	28.25	28.25	
YEAR 10				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 11				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 12				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 13				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 14				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 15				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
YEAR 16				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 17				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 18				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 19				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 20				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 21				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 22				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 23				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 24				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 25				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 26				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 27				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 28				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	
YEAR 29				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	

Cost item	Ref. value (R$/ha)	Updated value (2015 US$/ha)	Fixed costs (2015 US$/ha)	Variable costs (2015 US$/t)
YEAR 30				
Mechanized oper.				
Fertilizer app.	50.00	22.05		0.90
Harvest	200.00	88.20		3.60
Manual oper. traits				
Herbicides	80.00	35.28	35.28	
Branch control	40.00	17.64		0.72
Organic amendments	80.00	35.28		1.44
Manual oper. harvest				
Harvest	392.00	172.87		7.06
Inputs: Fertilizers				
Lime	18.00	7.94	7.94	
Phosphorus	132.00	58.21		2.38
Nitrogen	228.00	100.55		4.10
Potassium	408.00	179.93		7.34
Micronutrients	60.00	26.46		1.08
Inputs: Phytosanitaires				
Fungicides	90.00	39.69	39.69	
Insecticides	90.00	39.69	39.69	
Inputs: Herbicides				
Post emergent	36.00	15.88	15.88	
Administrative				
Taxes	95.80	42.25	42.25	

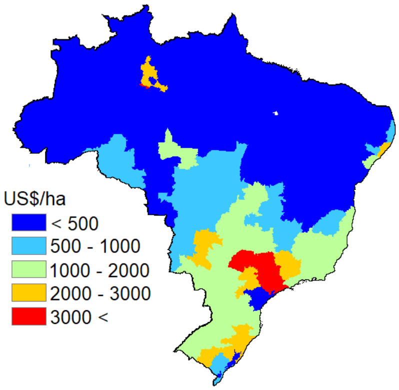

Figure 1 SM 4.4. Land price in Brazil. Source [317].

SM 4.5 - BIOJET FUEL PRODUCTION COSTS (TECHNO-ECONOMIC DATA)

Table 1 SM 4.5: Biomass yield development factor towards 2030. Based on Van der Hilst et al. [59].

Biomass	Factor
Corn	1.23
Sugarcane	1.13
Sweet Sorghum	1.23
Eucalyptus	1.13
Soybean	1.14
Sunflower	1.14
Palm	1.14
Macaw	1.14

Table 2 SM 4.5: Feedstock conversion yields in 2015 and 2030.

Feedstock conversion yields	(w/w)	Reference
cane to sugar 2015	0.15	[182]
cane to sugar 2030	0.166	[182]
sorghum to sugar 2015	0.125	[182]
sorghum to sugar 2030	0.14	[182]
corn to ethanol 2015	0.33138	[204]
corn to ethanol 2030	0.37083	[204]
cane to ethanol 2015	0.06312	[182]
cane to ethanol 2030	0.07101	[182]
sorghum to ethanol 2015	0.04734	[182]
sorghum to ethanol 2030	0.05523	[182]
eucalyptus to sugar 2015	0.45	[182]
eucalyptus to sugar 2030	0.5	[182]
soybean to oil	0.195	[207]
sunflower to oil	0.435	[207]
FFB to oil 2015	0.25	[207]
FFB to oil 2030	0.25	[207]
eucalyptus to ethanol 2015	0.22881	[182]
eucalyptus to ethanol 2030	0.29193	[182]
ethanol massa density	0.789	-

Table 3 SM 4.5: Market prices of biomass crops.

Biomass	Market price (US$/t)	Reference
Corn grain	170	[318]
Sugarcane stalk	25	[136]
Sweet sorghum stalk	27	[174]
Eucalyptus wood	66	[319]
Soybean grain	400	[320]
Sunflower seeds	360	[321]
Palm FFB	80	[322]
Macaw FFB *	80	-

* due to lack of data, it is assumed to be the same as the palm FFB price

Table 4 SM 4.5: Feedstock processing plant: main flowrates.

Feedstock proc. plant main flowrates	Value	Reference
Corn ethanol to DDGS (w/w)	0.80048	[323]
1G Elec. prod./sugarcane input (kWh/t)	117	[182]
DSHC Elec. demand/sugarcane input (kWh/t)	3.652	[90]
1G Elec. demand/sugarcane input (kWh/t)	46	[182]
ATJ Elec. demand/sugarcane input (kWh/t)	1.38864	[90]
2G Elec. demand/dry tonne input (kWh/t)	218	[182]
2G Elec. prod./dry tonne input (kWh/t)	351	[182]
DSHC Elec. demand/dry tonne input (kWh/t)	9.9	[90]
ATJ Elec. demand/dry tonne input (kWh/t)	5.03382	[90]
FFB to press cake (w/w)	0.035	[223]
FFB to Kernel oil (w/w)	0.016	[222]

Table 5 SM 4.5: BJF biorefinery: main flowrates.

BJF biorefineries main flowrates	Value	Reference
FT Elec. prod./dry tonne input (kWh/t)	430.907	[214]
FT Elec. demand/dry tonne input (kWh/t)	264.994	[214]
Diesel Prod ATJ (t/t)	0.064	[178]
Diesel Prod HEFA (t/t)	0.233	[298]
Naphta Prod HEFA (t/t)	0.07	[298]
Dry wood energy value (GJ/t)	19.2	-
DW to biocrude (t/t)	0.375	[216]
Gasoline fraction HTL (t/t biocrude)	0.24	[216]
Diesel fraction HTL (t/t biocrude)	0.14	[216]
Diesel Prod HTL (t/GJ feed)	0.013	[299]

Gasoline Prod HTL (t/GJ feed)	0.0048	[299]
Naphta Prod FT (t/GJ feed)	0.002	[90]
Sugars to farnesene (t/t)	0.18	[178]
Farnesene to diesel (t/t)	0.08	[324]
Farnesene to naphta (t/t)	0.28	[324]
BJF fraction HTL (t/t biocrude)	0.4	[216]

Table 6 SM 4.5: Cost growth factor of pioneer BJF biorefineries.

Cost growth factor	Ref: [90]
2G ethanol plant	0.53
DSHC	0.73
ATJ	0.42
FT	0.45
HTL	0.4
HEFA	0.86

Table 7 SM 4.5: Currency.

Exchange rate	
EUR/USD	1.09
BRL/USD	3.00

Table 8 SM 4.5: Inflation rate based on General Index Prices (IGP-DI).

Inflation - IGPDI	Ref: [309]	
Year	n	1 + n
2003	0.26	1.26
2004	0.08	1.08
2005	0.01	1.01
2006	0.04	1.04
2007	0.08	1.08
2008	0.09	1.09
2009	-0.01	0.99
2010	0.11	1.11
2011	0.05	1.05
2012	0.08	1.08
2013	0.06	1.06
2014	0.04	1.04
2015	0.11	1.11
2016	0.07	1.07

Table 9 SM 4.5: Main economic parameters for BJF production costs calculation.

Economic parameters	Value	Unit
Discount rate	12	%
Lifetime Project	25	years
Plant construction	3	years
Project finance (equity)	100	%

Table 10 SM 4.5: Market prices of BJF feedstocks.

Feedstock	Market price (US$/t)	Reference
Fermentable sugars (juice)	632	[178]
1G ethanol	650	[136]
2G ethanol	725	[325]
Soybean oil	800	[326]
Sunflower oil	800	[327]
Palm oil	1000	[328]
Macaw palm oil *	1000	-

* due to lack of data, it is assumed to be the same as the palm oil price

Table 11 SM 4.5: FCI and input capacity of the feedstock production plants.

Feedstock Proc. Plants	Biomass input	Reference Scales (t)	Reference FCI (MM US$)	Ref.	2015 Input	2015 Updated FCI (2015 US$/t)	2030 Input	2030 Updated value (2015 US$/t)
Palm oil plant	FFB	38000	3.7	[196]	650000	94.5	1000000	83.1
Macaw oil plant	FFB	38000	3.7	[196]	350000	113.8	700000	92.5
Sugar/ethanol plant	Stalks	4000000	279.4	[182]	4000000	63.1	5500000	57.4
2G Sugar/ethanol plant	Fresh wood	360000	280.6	[182]	720000	1079.0	1500000	459.0
Soybean oil plant	Grain	480000	98.2	[208]	660000	185.9	950000	166.7
Sunflower oil plant	Grain	480000	98.2	[208]	200000	266.0	730000	180.4
Wood Proc. Plant for FT	Fresh wood	615000	22.7	[214]	600000	52.4	1000000	44.1
Wood Proc. Plant for HTL	Fresh wood	615000	22.7	[214]	350000	60.5	800000	55.2
Corn ethanol plant	Grain	120000	46.7	[205]	420000	445.5	650000	390.8

Table 12 SM 4.5: FCI and input capacity of the BJF biorefinery.

BJF biorefineries	Biomass input	Reference Scales (t)	Reference FCI (MM US$)	Ref.	2015 Input	2015 Updated FCI (2015 US$/t)	2030 Input	2030 Updated value (2015 US$/t)
SB_HEFA	Soybean oil	120000	174.9	[90]	128700	1659.8	185250	1279.7
SF_HEFA	Sunflower oil	120000	174.9	[90]	87000	1866.7	317550	1088.6
PO_HEFA	Palm oil	120000	174.9	[90]	162500	1547.6	250000	1169.6
MO_HEFA	Palm oil	120000	174.9	[90]	87500	1863.5	175000	1301.7
SC_ATJ	1G ethanol	320000	56.4	[90]	252480	493.4	390555	181.8
SS_ATJ	1G ethanol	320000	56.4	[90]	189360	537.9	303765	196.1
C_ATJ	1G ethanol	320000	56.4	[90]	139179.6	590.0	241039.5	210.1
EC_ATJ	2G ethanol	320000	56.4	[90]	164743.2	560.9	437895	175.7
SC_DSHC	fermentable 1G sugars	600000	241.0	[90]	600000	602.6	913000	387.8
SS_DSHC	fermentable 1G sugars	600000	241.0	[90]	500000	636.5	770000	408.2
EC_DSHC	fermentable 2G sugars	600000	241.0	[90]	324000	724.9	750000	411.4
EC_FT	dry wood	615000	591.4	[90]	600000	2061.3	1000000	831.2
EC_HTL	dry wood	615000	512.9	[216]	350000	2704.3	800000	844.1

Table 13 SM 4.5: OPEX and input capacity of the feedstock production plants.

Feedstock Proc. Plants	Biomass input	Reference Scales (t)	Reference OPEX (US$/t)	Ref.	2015 Input	2015 Updated OPEX (2015 US$/t)	2030 Input	2030 Updated value (2015 US$/t)
Palm oil plant	FFB	131000	10.30	[310]	650000	14.25	1000000	14.25
Macaw oil plant	FFB	131000	10.30	[310]	350000	14.25	700000	14.25
Sugar/ethanol plant	Stalks	4000000	16.09	[182]	4000000	14.54	5500000	14.54
2G Sugar/ethanol plant	Fresh wood	360000	144.77	[182]	720000	251.57	1500000	133.33
Soybean oil plant	Grain	480000	21.9	[208]	660000	20.92	950000	20.92
Sunflower oil plant	Grain	480000	21.9	[208]	200000	25.02	730000	25.02
Wood Proc. Plant for FT	Fresh wood	615000	5.11	[214]	600000	5.11	1000000	5.11
Wood Proc. Plant for HTL	Fresh wood	615000	5.11	[214]	350000	5.11	800000	5.11
Corn ethanol plant	Grain	120000	86.08	[205]	420000	143.48	650000	143.48

Table 14 SM 4.5: OPEX and input capacity of the BJF biorefineries.

BJF biorefineries	Biomass input	Reference Scales (t)	Reference OPEX (US$/t)	Ref.	2015 Input	2015 Updated OPEX (2015 US$/t)	2030 Input	2030 Updated value (2015 US$/t)
SB_HEFA	Soybean oil	120000	95.25	[206]	128700	177.85	185250	152.96
SF_HEFA	Sunflower oil	120000	95.25	[206]	87000	177.85	317550	152.96
PO_HEFA	Palm oil	120000	95.25	[206]	162500	177.85	250000	152.96
MO_HEFA	Palm oil	120000	95.25	[206]	87500	177.85	175000	152.96
SC_ATJ	1G ethanol	320000	35.35	[206]	252480	122.79	390555	51.57
SS_ATJ	1G ethanol	320000	35.35	[206]	189360	122.79	303765	51.57
C_ATJ	1G ethanol	320000	35.35	[206]	139179.6	122.79	241039.5	51.57
EC_ATJ	2G ethanol	320000	35.35	[206]	164743.2	122.79	437895	51.57
SC_DSHC	fermentable 1G sugars	600000	17.13	[206]	600000	41.48	913000	30.28
SS_DSHC	fermentable 1G sugars	600000	17.13	[206]	500000	41.48	770000	30.28
EC_DSHC	fermentable 2G sugars	600000	17.13	[206]	324000	41.48	750000	30.28
EC_FT	dry wood	615000	19.15	[206]	600000	68.35	1000000	30.76
EC_HTL	dry wood	615000	118.74	[90]	350000	263.88	800000	91.29

Table 15 SM 4.5: Co-products of the feedstock production plants.

Feedstock proc. Plants (Prod. Routes)	Co products	Co product A					Co product B				
		2015	2030	Unit	Market unit price	Ref.	2015	2030	Unit	Market unit price	Ref.
Corn ethanol plant (C_ATJ)	DDGS (A)	87902.91	192947.37	t	200.00	[323]	0	0	-	-	-
Sugar/ethanol plant (SC_DSHC)	Electricity (A)	269392.00	370414.00	MWh	80.00	[147]	0	0	-	-	-
Sugar/ethanol plant (SC_ATJ)	Electricity (A)	278445.44	382862.48	MWh	80.00	[147]	0	0	-	-	-
Sugar/ethanol plant (SS_DSHC)	Electricity (A)	269392.00	370414.00	MWh	80.00	[147]	0	0	-	-	-
Sugar/ethanol plant (SS_ATJ)	Electricity (A)	278445.44	382862.48	MWh	80.00	[147]	0	0	-	-	-
2G Sugar/ethanol plant (EC_DSHC)	Electricity (A)	88632.00	184650.00	MWh	80.00	[147]	0	0	-	-	-
2G Sugar/ethanol plant (EC_ATJ)	Electricity (A)	92135.65	191949.27	MWh	80.00	[147]	0	0	-	-	-
Wood Proc. Plant for FT (EC_FT)	-	0.00	0.00	-	-	-	0	0	-	-	-
Wood Proc. Plant for HTL (EC_HTL)	-	0.00	0.00	-	-	-	0	0	-	-	-
Soybean oil plant (SB_HEFA)	Meal (A)	531300.00	764750.00	t	350.00	[329]	0	0	-	-	-
Sunflower oil plant (SF_HEFA)	Meal (A)	113000.00	412450.00	t	175.00	[330]	0	0	-	-	-
Palm oil plant (PO_HEFA)	Press cake (A) Kernel oil (B)	22750.00	35000.00	t	100.00	[85]	10400	16000	t	1300.00	[331]
Macaw oil plant (MP_HEFA)	Press cake (A) Kernel oil (B)	12250.00	24500.00	t	100.00	[85]	5600	11200	t	1300.00	[331]

Table 16 SM 4.5: Co-products of the BJF biorefineries.

BJF biorefinery (Prod. Routes)	Co products	Co product D (t)		Co product N (t)		Co product G (t)		Co product El (MWh)		
		2015	2030	2015	2030	2015	2030	2015	2030	Market unit price (US$/ MWh)
ATJ (C_ATJ)	Diesel (D)	7028.01	12171.53	0	0	0	0	0	0	0
DSHC (SC_DSHC)	Diesel (D), Naphtha (N)	8640.00	13147.20	30240.00	46015.20	0	0	0	0	0
ATJ (SC_ATJ)	Diesel (D)	12749.23	19721.47	0	0	0	0	0	0	0
DSHC (SS_DSHC)	Diesel (D), Naphtha (N)	7200.00	11088.00	25200.00	38808.00	0	0	0	0	0
ATJ (SS_ATJ)	Diesel (D)	9561.92	15338.92	0	0	0	0	0	0	0
DSHC (EC_DSHC)	Diesel (D), Naphtha (N)	4665.60	10800.00	16329.60	37800.00	0	0	0	0	0
ATJ (EC_ATJ)	Diesel (D)	8318.87	22111.95	0	0	0	0	0	0	0
FT (EC_FT)	Naphtha (N), Electricity (El)	0	0	23040.00	38400.00	0	0	99548.22	165913.69	80.00
HTL (EC_HTL)	Diesel (D), Gasoline (G)	18375.00	42000.00	0	0	31500.00	72000.00	0	0	0
HEFA (SB_HEFA)	Diesel (D), Naphtha (N)	29987.10	43163.25	9009.00	12967.50	0	0	0	0	0
HEFA (SF_HEFA)	Diesel (D), Naphtha (N)	20271.00	73989.15	6090.00	22228.50	0	0	0	0	0
HEFA (PO_HEFA)	Diesel (D), Naphtha (N)	37862.50	58250.00	11375.00	17500.00	0	0	0	0	0
HEFA (MP_HEFA)	Diesel (D), Naphtha (N)	20387.50	40775.00	6125.00	12250.00	0	0	0	0	0

SM 4.6 – ROAD NETWORK AND AIRPORTS

The infrastructure data refers to the location of paved highways network and airport point location. The first is sourced from [332], assuming for 2015 only the existing highways and for 2030 also the highways that are planned to be built or those that are currently being constructed. For the airports, we assess only the airports that in theory are able to receive jet fuel (i.e. Jet A-1). As no information on the airport jet fuel storage system is available, we select only those rated as "medium" and "large" scale according to [333]. Of these amount (n=123), we consider only those with take-off information registered at ANAC (Nacional Civil Aviation Agency) [334] (i.e. assuming that these airports are able to refuel aircrafts). In total, 115 airports are assessed.

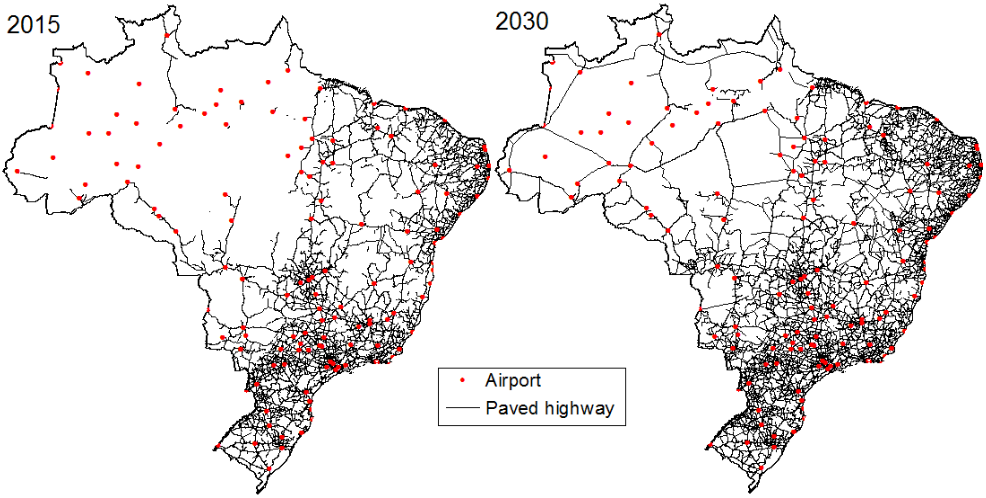

Figure 1 SM 4.6: The spatial distribution of paved highways in Brazil in 2015 and 2030. For 2030, we consider the highways that are currently in construction and planning stages. In both maps, we use the same operating airports that current have jet fuel (i.e. Jet A-1) storage tanks.

SM 4.7 – MACRO REGIONS AND STATE DIVISION

Figure 1 SM 4.7: Brazilian state names per macro region: North Region (green), Northeast Region (blue), Center-West Region (red), Southeast Region (brown), South Region (dark yellow).

SM 4.8 – COMPLEMENTARY RESULTS: TECHNO-ECONOMIC POTENTIAL AND SENSITIVITY ANALYSIS

In SM 4.8, we present complementary figures for a better comprehension of section 4.4.4 (BJF total costs and techno-economic potential). In figure 1, the cost supply curves for all the BJF production routes with BJF total costs lower than maximum verified jet fuel price in Brazil (65 US$/GJ) is presented. These production routes do not necessiraly contribute to

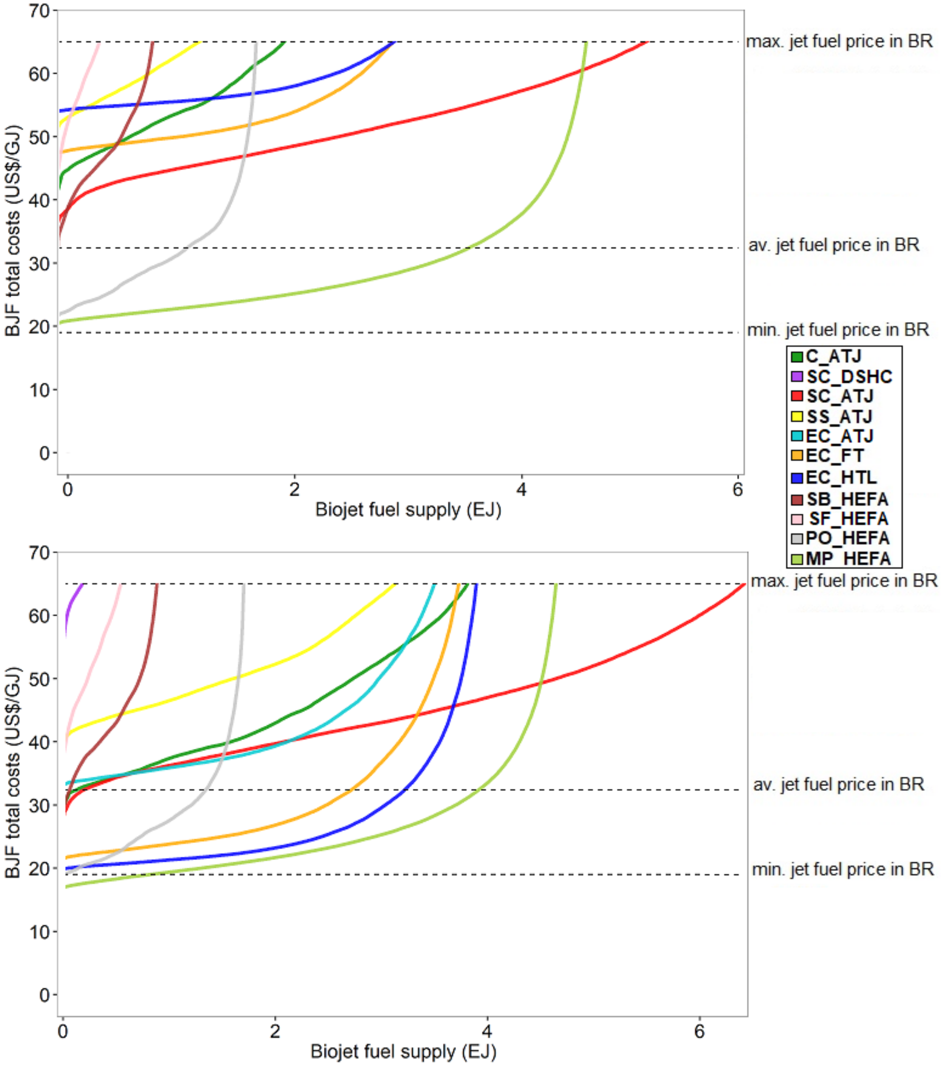

Figure 1 SM 4.8: BJF cost supply curves of the BJF production routes in 2015. BJF cost supply curves of the BJF production routes in 2030.

techno-economic potential, which is formed by the production routes that achieved the lowest BJF total cost at each (pixel) location. Some of the production routes (e.g. SF_HEFA, EC_ATJ) are able to produce affordable BJF (i.e. within the jet fuel price range). However, in the original assessment they are overshadowed by the strong performance of high potential and well developed production routes (e.g. MP_HEFA, SC_ATJ).

In figures 2, 3 and 4, the three scenarios of the sensitivity analysis are presented (dashed lines) and compared to the original assessment (solid lines). Figure 2 shows the impact of excluding the two promising, but rather uncertain EC_HTL and MP_HEFA production routes. Despite the reduction on the techno-economic potential, there still a diversified group of production routes that could produce BJF total costs lower than the highest fossil jet fuel price in Brazil.

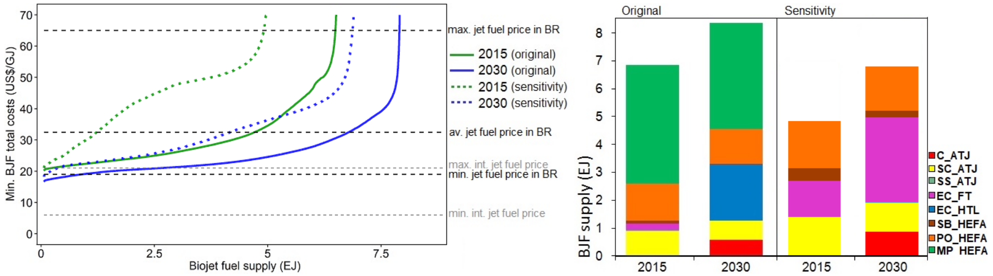

Figure 2 SM 4.8: First scenario of the sensitivity analysis: excluding EC_HTL and MP_HEFA production routes.

Figure 3 compares the cost-supply performance if the techno-economic potential is supplied with fixed biomass market prices instead of the calculated biomass production costs. In this scenario, we did not account for the potential geographical variability of biomass market prices across the Brazilian regions due to limited data availability (see the biomass market prices in supp. material 4). Hence, the cost supply curves in this scenario have a flat behavior with pronounced steeps as the BJF total costs increases among the production routes. This scenario is a valid exercise from the biomass crop producer perspective, which seeks to sell the biomass at the highest price. However, if the hypothetical demand for a given biomass in the BJF market is high, the current biomass prices may change completely. Therefore, the biomass production cost is needed for assessing cost-supply curves analysis of techno-economic potential.

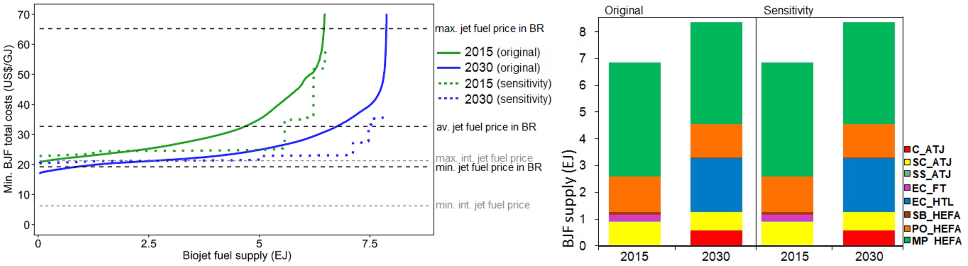

Figure 3 SM 4.8: Second scenario of the sensitivity analysis: using biomass market prices to assess the cost-supply of the techno-economic of BJF.

Figure 4 analyzes the impact on the techno-economic potential in 2030 if no biomass yield improvement is achieved from 2015 onwards. This is a very conservative scenario considering historical yield growth rate of the selected biomass crop, but addresses the high uncertainty of projecting future biomass yields. As a result, we verify an expected reduction on the techno-economic potential compared to the original assessment in 2030. Moreover, in this scenario the cost reduction over time is solely driven by improvements on the BJF conversion. Therefore, selecting the right biomass adapted to the agro-ecological condition of the land available is key for reducing bioenergy costs and planning the expansion of BJF.

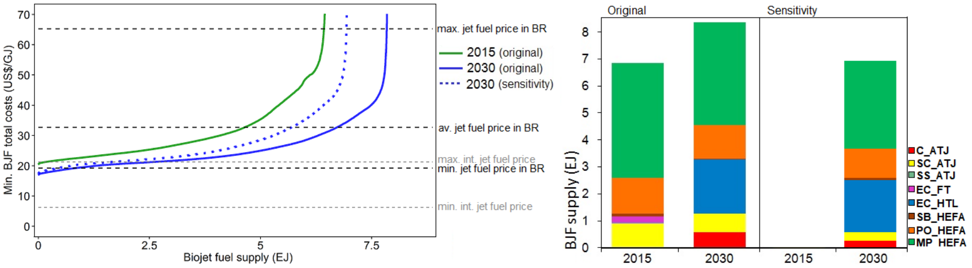

Figure 4 SM 4.8: Third scenario of the sensitivity analysis: no biomass yield growth towards 2030.

SM 5.1 – RUSLE CALCULATION

The erosivity (R) factor accounts for monthly rainfall data from 2005 to 2015. In this study, the R factor is estimated based on Modified Fournier Index (*MFI*) [335], of which *p* represents the average rainfall of the month and *P* is the average annual rainfall. The summation of the MFI of each month is used to estimate the R factor, see Vrieling et al. [336].

$$MFI = p^2 \times P^{-1}$$

$$R = \left(50.7 \times \sum_{i=1}^{12} MFI\right) - 1405$$

The erodibility (K) factor overlaid different soil characteristics based on the equation proposed by Wischmeier and Smith [272]. In this study, the K factor is calculated only for the topsoil layer (0-30cm), by integrating soil organic matter (*OM*), soil texture (*m*), soil structure (*s*) and permeability (*p*). These variables are sourced from [307].

$$K = 0.1317 \times (2.1 \times 10^{-4}) \times (12 - OM) \times m^{1.14} + 3.25 \times (s - 2) + 2.5 \times (p - 3))/100$$

The slope steepness and length (LS) factor is based on Teng et al. [271] and it is entirely calculated in ArcGIS in the Spatial Analyst Tools extension using the DEM (Digital Elevation Model) from SRTM as input data [306]. The *FA* refers to the Flow Accumulation (i.e. refers to where the hypothetical sediments are accumulated) and the *SL* refers to slope (in percentage).

$$LS = \left(\left(\frac{FA \times 947.68}{22.3}\right)^{0.4}\right) \times \left(\sin\left(\frac{SL \times 0.01745}{0.09}\right)^{1.3}\right)$$

The cover management (C) factor is assumed to be the average of a range of existing values available in the literature. These values vary across the studies due to the diversity of crop management, biophysical and agro-ecological conditions. For sugarcane, our study make use of the dedicated extensive literature review (28 records) compiled by Casoni (2017) [273], whereas for eucalyptus, we gather a more limited quantity (9 records) of C factor information in Brazil sourced from [337–341]. In figure 1 – SM 5.1, we summarized the values for each literature source in boxplots for both sugarcane and eucalyptus.

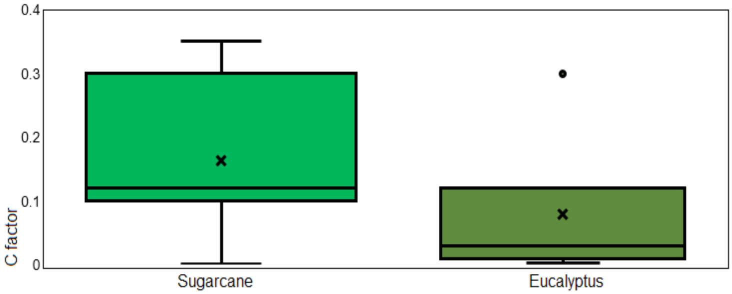

Figure 1 SM 5.1: Variability of C factor values for sugarcane and eucalyptus systems in Brazil. The cross symbol represents the average of these records, which are used as an input in the RUSLE calculation.

The support practice (P) factor is estimated based on slope percent thresholds. The study of Wischmeier and Smith [272] indicated the corresponding P values for each slope thresholds, of which have been used by several studies (e.g. [271,342]).

Table 1 SM 5.1: P values

Slope threshold (%)	P value
1 - 2	0.6
3 – 5	0.5
6 – 8	0.5
9 - 12	0.6
13 – 16	0.7
17 – 20	0.8
21 – 25	0.9

SUPPLEMENTARY MATERIAL SM 5.2

Table 1 SM 5.2 shows the sources of OC inputs and outputs in sugarcane and eucalyptus system with biomass residues management. These values highly depend on several agro-ecological variables (e.g. climate, soil, plant). In this study, we use spatially explicit biomass yield (see section 5.4.1) and soil texture information [307] to assess the SOC dynamics.

Table 1 SM 5.2: Characterization of OC inputs and outputs in sugarcane and eucalyptus systems subjected to harvest residue management.

SOC Dynamic [c]	**Sugarcane** [a]		**Eucalyptus** [b]	
	SOC input range (t C/ha/yr)	**SOC output range (t C/ha/yr)**	**SOC input range (t C/ha/7-yr)**	**SOC output range (t C/ha/7-yr)**
Fertilizers (TFer) [d]	0.21 – 0.47	-	-	-
Belowground biomass (BGC) [e]	0.45 – 0.9	-	2 – 8.6	-
Aboveground biomass (AGC) [f]	0.24 – 0.71	-	6.9 – 13.9	-
100% Residue removal [g]	-	0.19 – 0.71	-	0 – 10.4
Belowground OC decomposition [h]	-	0.35 – 0.47	-	0.9 – 1.57

Legend

■ Crop yield dependent

▨ Crop yield and soil texture dependent

[a] The sugarcane system timeframe comprises 6 to 7 years with 6 harvest periods, with yield decreasing rate of 12% (estimation based on Rocha, 2017) [273]. The SCS is annually available with a fixed residue to crop ratio of 14% [68].

[b] The eucalyptus system timeframe comprises 21 years, of which is harvested only three times in 7 years' interval (i.e. year 7, year 14 and year 21), with yield decreasing rate of 9%. The EHR is available in each harvest period with a residue to crop ratio of 15% [149].

[c] The range of SOC input/output values presented in the table is linked with crop yield range used as example, among the different soil textures and harvest cycles. All the data gathered refers to SOC dynamics happening on the topsoil layer (0 – 30 cm).

[d] Organic Fertilizers have low contribution to SOC and its rate of application is a function of crop yield (see the link SOC balance). For example, in sugarcane systems, filter cake is usually applied during sugarcane planting (year 0) and vinasse in the forthcoming harvest cycles until the end of the timeframe. The OC contribution from these organic amendments is available in Brandani et al. [343]. In eucalyptus systems, no organic fertilizer is assumed to be applied as mineral fertilizer (e.g. urea) comprises the majority of inputs in eucalyptus management [344]. We do not account the potential OC input from mineral fertilizers, as they have an indirect effect on the SOC through the increase of the plant biomass, which is linked with crop yield data. In eucalyptus systems, the main source of organic amendments is the annual litterfall (i.e. leaves and small branches), which is incorporated in the SOC balance calculation (in eucalyptus) as an organic fertilizer variable.

[e] The OC input from belowground biomass has great spatial variability due to crop yield linked with the root system growth and soil texture, which affects the resistance of root penetration [345]. In this study, input of OC from belowground biomass is calculated using the root to shoot ratio, derived from Carvalho et al. [139] for sugarcane Ryan et al. [346] for eucalyptus in different soil types, and the turnover effect (i.e. the amounts of belowground C that are incorporated in the soil).

[f] For both eucalyptus and sugarcane, the contribution of aboveground biomass to the SOC decreases over time according to the decreasing yield rate. In sugarcane systems, the aboveground biomass contributing to the SOC

is the SCS that can be either 100% removed or 100% maintained according to SOC balance in a given harvest cycle. Due to the large amount of studies and data available for sugarcane, OC from aboveground biomass varies among different soil texture and yield levels. In eucalyptus systems, EHR is an important source of aboveground OC, which can be removed or maintained in each harvest cycle. In addition, eucalyptus systems also account for the aboveground OC sourced from the annual litterfall, which is not recovered from the field, has a high decomposition rate, and plays an important role in preserving the SOC stocks [256]. Due to the limited amount of studies for eucalyptus, OC from aboveground biomass varies only among different yield levels.

[g] For each positive SOC balance harvest cycle, we assume 100% of residues recovery, which necessarily leads to a SOC depletion in the forthcoming harvest cycle as the uncovered soil leads to higher soil organic matter losses. In sugarcane systems, the SOC depletion varies throughout the harvest cycles as function of the amount of residue recovered [138]. For eucalyptus, the dynamics from SOC depletion due to residue removal is sourced from Cook et al. [347], which did not include residue management in their experiments. As a result, an intensified SOC depletions after two harvest cycles of EHR removal (see the link SOC balance), in line with the studies of Rocha et al. [256] and Epron et al. [348].

[h] The natural belowground SOC loss is related to the decreasing yield and natural organic matter decomposition throughout the harvest cycles. These losses are primarily linked with the diminishing of belowground biomass (i.e. root system reduction) and consequently a lower SOC turnover. In sugarcane systems, the annual belowground depletion rate varies from 0.35 to 0.47 depending on the soil texture and crop yield [139]. In eucalyptus, the depletion from belowground biomass was estimated by Ryan et al. [344] with no distinction among soil textures, thereby varying only as function of yield levels.

SM 5.3 - BIOJET FUEL PRODUCTION COSTS (TECHNO-ECONOMIC DATA)

Table 1 SM 5.3: BJF plant: main upstream flowrates.

Upstream conversion yields	(w/w)	Reference
ethanol massa density	0.789	-
biomass residue to ethanol 2015	0.22881	[182]
biomass residue to ethanol 2030	0.29193	[45]

Table 2 SM 5.3: BJF plant: main flowrates.

BJF biorefineries main flowrates	Value	Reference
FT Elec. prod./dry tonne input (kWh/t)	430.907	[214]
FT Elec. demand/dry tonne input (kWh/t)	264.994	[214]
Diesel Prod ATJ (t/t)	0.064	[178]
Dry wood energy value (GJ/t)	19.2	-
DW to biocrude (t/t)	0.375	[216]
Gasoline fraction HTL (t/t biocrude)	0.24	[216]
Diesel fraction HTL (t/t biocrude)	0.14	[216]
Diesel Prod HTL (t/GJ feed)	0.013	[299]
Gasoline Prod HTL (t/GJ feed)	0.0048	[299]
Naphta Prod FT (t/GJ feed)	0.002	[90]
BJF fraction HTL (t/t biocrude)	0.4	[216]
BioOil fraction PYR (t/t feed)	0.75	[206]
Diesel fraction PYR (t/t feed)	0.0359	[206]
Naphtha fraction PYR (t/t feed)	0.0877	[206]
2G Elec. demand/dry tonne input (kWh/t)	218	[182]
2G Elec. prod./dry tonne input (kWh/t)	351	[182]
ATJ Elec. demand/dry tonne input (kWh/t)	5.03382	[90]

Table 3 SM 5.3: Main economic parameters for BJF production costs calculation.

Economic parameters	Value	Unit
Discount rate	12	%
Lifetime Project	25	years
Plant construction	3	years
Project finance (equity)	100	%

Table 4 SM 5.3: Currency.

Exchange rate	
EUR/USD	1.09
BRL/USD	3.00

Table 5 SM 5.3: Inflation rate based on General Index Prices (IGP-DI) [309].

Inflation - IGPDI		
Year	n	1 + n
2003	0.26	1.26
2004	0.08	1.08
2005	0.01	1.01
2006	0.04	1.04
2007	0.08	1.08
2008	0.09	1.09
2009	-0.01	0.99
2010	0.11	1.11
2011	0.05	1.05
2012	0.08	1.08
2013	0.06	1.06
2014	0.04	1.04
2015	0.11	1.11
2016	0.07	1.07

Table 6 SM 5.3: Variables of RAND method and the resulting cost growth factor. Adapted from de Jong et al.[90]

Production routes	**SCS_FT**	**SCS_HTL**	**SCS_PYR**	**SCS_ATJ**	**EHR_FT**	**EHR_HTL**	**EHR_PYR**	**EHR_ATJ**
1.1219	-	-	-	-	-	-	-	-
0.00297	-	-	-	-	-	-	-	-
PCTNEW	37	71	77	32	37	71	77	32
0.02125	-	-	-	-				
IMPURITIES	5	5	5	3	4	4	4	3
0.01137	-	-	-	-	-	-	-	-
COMPLEXITY	9	5	6	15	9	5	6	15
0.00111	-	-	-	-	-	-	-	-
INCLUSIVESS	66	66	66	66	66	66	66	66
C1	0.06361	0.06361	0.06361	0.04011	0.06361	0.06361	0.06361	0.04011
PROJECT DEFINITION	7	7	7	7	7	7	7	7
COST GROWTH FACTOR	0.43142	0.37592	0.34673	0.58505	0.45267	0.39717	0.36798	0.58505

Table 7 SM 5.3: FCI and input capacity of the BJF plant.

BJF plants	Reference Scales (t)	Reference FCI (MM US$)	Ref.	2015 Input	2015 Updated FCI (2015 US$/t)	2030 Input	2030 Updated value (2015 US$/t)
SCS_ATJ	320000	56.4	[90]	720000	843.0	1500000	765.5
SCS_PYR	660000	826.8	[283]	600000	2241.3	800000	983.8
SCS_FT	615000	591.4	[90]	600000	1383.3	1000000	875.3
SCS_HTL	615000	512.9	[216]	350000	1017.5	800000	719.5
EHR_ATJ	320000	56.4	[90]	720000	869.6	1500000	765.5
EHR_PYR	660000	826.8	[283]	600000	2121.9	800000	983.8
EHR_FT	615000	591.4	[90]	600000	1268.2	1000000	875.3
EHR_HTL	615000	512.9	[216]	350000	967.7	800000	719.5

Table 8 SM 5.3: OPEX and input capacity of the BJF plant.

BJF plants	Reference Scales (t)	Reference OPEX (US$/t)	Ref.	2015 Input	2015 Updated OPEX (2015 US$/t)	2030 Input	2030 Updated value (2015 US$/t)
SCS_ATJ	320000	35.5	[206]	720000	195.5	1500000	222.6
SCS_PYR	660000	32.9	[206]	600000	142.3	800000	69.1
SCS_FT	615000	19.5	[206]	600000	46.0	1000000	35.9
SCS_HTL	615000	118.7	[90]	350000	111.2	800000	99.1
EHR_ATJ	320000	35.5	[206]	720000	201.4	1500000	222.6
EHR_PYR	660000	32.9	[206]	600000	134.9	800000	69.1
EHR_FT	615000	19.5	[206]	600000	44.1	1000000	35.9
EHR_HTL	615000	118.7	[90]	350000	94.1	800000	77.1

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I had never chosen a career to follow, but at a certain young age, if you're not doing well in the sports, you really need to think what you will do for the rest of your life. In my case, the year was 2006 with 16/17 years old. By that time, my life was completely shuffled as my dad passed away that year. In the end of 2006, I applied for the faculties of business administration, law and geography. I failed in all of them! In the beginning of 2007, after serious talks with my mother, instead of applying for private universities, she suggested me to do one more year of studies and re-apply for a public university (usually the good ones in Brazil). With two conditions: I needed to move out from home and to decide only one career.

So in 2007 I moved to Franca/SP to study for Geography (the subject that I never had problem in the school). Here I start to acknowledge my first roommate: Igor (one of my best friends since I was 3) during the ***cursinho*** (~prep. school) times. That year, I had for the first time, the sensation of "what a good decision I made". In the middle of 2007, I got my first faculty approval, which gave me peace and confidence for the upcoming tests. After being accepted in two public universities, I choose for the University of Londrina/PR (UEL). With 18, I moved 550 km away from my hometown and started the Bachelor times. Five years of learning, good grades, bad grades, parties and lot of self-questions. The main one: am I enjoying what I am doing? In the second year (2009) of university I was completely uncertain of my decision. Luckily, in that year I was invited by my initial mentors (thank you Laerte Ferreira and Manuel Ferreira) for a winter course in the GIS lab of the Federal University of Goias/GO. That was really important to give me sense of direction during the Bachelor.

In 2011, I was doing well at the Bachelor and well established in my internship in the secretariat of agriculture of Londrina (special thanks to Osvaldo – advisor – for the patience and the field works). By that time, I was aware of my strengths and weakness, and at the end of 2011 I decided to spend 4 months (during summer breaks) in US to work and study. That (intense/hectic) experience gave so much confidence to face the final year of Bachelor (2012) and also for the coming years. Between 2008 and 2012 (bachelor times), I want to make a special thanks to my friends Igor (roommate for the 2nd time), Giagio, Iuri, Daniel (BH), Pedro, Glauco e Eduardo and advisors Luciano, Osvaldo(s) and Eliane.

In 2013, I started my Masters in Agricultural Engineering at University of Campinas/SP (Unicamp). My main focus was to work with remote sensing for agriculture, but I suddenly realized that my background was taking me to other areas (here a special thanks to Rubens and Jansle, my supervisors that also realized that). Within our research group, big projects were happening in the field of sugarcane/bioenergy. In my Masters, I analyzed several data sources to prospect spatial information for bioenergy supply chains in the state of São Paulo (many of these data were reused in this thesis). During the Masters, I started making contacts with Dutch colleagues through the BeBasic project (thank you Fabiana and Ernst).

In 2015, I started my PhD in Bioenergy (a new program that integrates the main universities of Sao Paulo for R&D in bioenergy). Until 2017, I was the students' representative in the program, which was a really important experience (in this phase, thank you Camila and Andrea). In august of 2015, my great colleague and friend Ramses Molijn (thank you, pal) told me that Floor would be in Brazil for a week and would be nice to talk with her. Floor and I had a nice first talk at Unicamp, and since then we have been exchanging emails quite lot. Together we established the first Dual Degree agreement between Unicamp and Utrecht University (by that time I was not even sure what that means and the requirements involved). In April of 2017, I travelled for the first to the Netherlands to meet Floor and Martin. This trip would be repeated six times up to 2019. During these trips, I had several productive days with my new colleagues: thank you Ana, Anand, Anna, Blanca, Gert Jan, Hu Jing, Ioanna, Ivan, Jorge, Judith, Lotte, Marnix, Paul, Ric, Sierk, Steven and Will to make feel at home and for the support and the good meetings we had. In addition, I cannot forget all the support that I received from Aisha, Siham, Fiona and Rinske. From the Unicamp side, really big thanks to Johinislam and Juliana that took care of all the administrative stuffs of all these trips. Lastly, Marinel and Frank, owners of the room that I stayed in Utrecht – thanks for being so nice with me.

Now at the end of this journey, I want to make a huge thanks to all colleagues/friends from the GIS and Data Science Labs of the School of Agriculture Engineering of Unicamp: Victor, Bocca, Marcio, Carlos, Talita, Diego, Monique, Danilo, Valeria, Cecilia and Yane. Their resilience to work during the hard times and make high-quality research really inspires me. To my colleagues Rafael (FEM), Bruna and Ricardo (LNBR/CTBE), many thanks for your help. Lorenzo, my friend, thanks for hosting me many times in Delft. WEcR team, thanks for supporting the development of this thesis. Big thanks to my co-supervisor Joaquim Seabra – always open to talk since the beginning of my Masters. My supervisors, Floor, Rubens and Martin, thank you for your patience, interest and willingness to help whenever I asked. All of you share a co-authorship in this thesis.

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About the author

ABOUT THE AUTHOR

Walter Rossi Cervi was born in 1989 in Ribeirao Preto/SP, and raised in São Joaquim da Barra/SP. He is passionate about tennis, motorsport and his soccer team Sao Paulo Futebol Clube, which were the few external things that occupied his mind during the PhD in the last five years. He holds a Bachelor degree in Geography (2012) from State University Londrina (Brazil) and a Master's degree in Agricultural Engineering (2015) from State University Campinas/ Unicamp (Brazil). After the second of year of bachelor, Walter started working with GIS and remote sensing analysis of the Brazilian land use. Since his Masters, Walter has been working on increasing the added-value of land change science by integrating the location effect on the sustainability of agricultural and bioenergy supply chains. Walter started his PhD in 2015 at Unicamp and established a Dual Degree agreement with Utrecht University in 2016. After that, he also worked in collaboration with Copernicus Institute for Sustainable Development funded by BeBasic/Netherlands and CAPES/Brazil. During his PhD period, Walter has published five journal articles (three out of his PhD thesis) and one conference article presented at Brazilian Bioenergy Science and Technology Conference.

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